Technical University of Denmark

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Modelling the Future Nordic Energy System with a High Penetration of Renewable Energy Sources

Master's Thesis, February 2016

DTU Management Engineering
Department of Management Engineering

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Preface

The present thesis was performed at the Department of Management Engineering at Technical University of Denmark (DTU). The main focus of the study is to investigate the effects of introducing two flexibility resources i.e. expansion of transmission capacity and demand-side flexibility, into the future energy system with a high penetration of renewable energy sources.

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Abstract

The Nordic countries has set ambitious long-term energy policy targets which aims to reduce the environmental greenhouse gas (GHG) footprint from the energy system. Therefore, the future Nordic energy system is expected to include a high penetration of both variable- and dispatchable renewable energy sources. The variable renewable energy sources (VRE) i.e. wind and solar, are characterised by a highly *variable* energy production, *uncertain* production due to forecasting errors, and *location specific* production since the primary energy resource used cannot be transported. These characteristics can cause increased system costs and challenges. To facilitate an efficient integration of the increased penetration of VRE in the future, four flexibility resources i.e. flexible generation, demand-side flexibility, energy storage facilities and transmission grid infrastructure, can be further introduced into the system. The main objective in the present thesis is to quantify options for integrating fluctuating renewable energy sources for electricity in the future Nordic energy system towards 2050 with emphasis on two of the flexibility resources, namely, transmission grid infrastructure expansions, and demand-side flexibility. This objective will be met by performing a theoretical literature study and further by implementing an energy system optimisation model. The quantitative assessment is conducted by use of the energy system optimisation model - Balmorel - which is an effective tool for long-term investment planning of the power and district heating. The Balmorel model is improved by expanding the geographic representation and updating the data base in order to simulate the future Nordic energy. The quantitative assessment include two case studies, 1) Assessment of future expansion og the transmission capacity, and 2) Assessment of demand-side flexibility. The results in the *first* case study shows that the transmission capacity is expanded in all investigated scenarios which illustrate the socio economic benefit of additional transmission capacity. In the Base scenario, a high utilisation of wood pellets CCS technologies is found, which is identified to be caused by the implemented CO_2 price. Furthermore, the annual average electricity prices, the electricity exchange and endogenous investment in additional generation capacity is investigated for the Base scenario, an Alternative scenario and four sensitivity scenarios. In the *second* case study demand-side flexibility (DSF) is introduced into the system. The results from the Balmorel simulation show a reduced amount of additional transmission capacity compared to the Base scenario. Furthermore, in general, the electricity prices will be reduced when introducing DSF. In addition to the long-term investment scenario, an hourly simulation for the demand-side flexibility scenario is conducted and illustrated for four representative weeks to clarify the functionality of the implemented demand-side flexibility.

CHAPTER 1

Introduction

1.1 Background

Climate changes and emissions of greenhouse gases (GHG) have received worldwide attention over the last decades (IPCC 2015). This on going debate has been elucidated by international parties, which have outlined possible scenarios for the future change in the average global surface temperature (IPCC 2015). As a result, several international climate negotiations have been agreed, which aim to reduce the environmental impact. The energy system is currently a contributor to global GHG emissions. This has prompted several agreements, both national and international, aiming at reducing the environmental GHG footprint from the energy system. In 2014, the European Council agreed on climate and energy related targets towards 2030. The policy framework supports the energy transition towards 2030, which aims to reduce the GHG emissions by 40%, compared to 1990 levels, and to increase the share of renewable energy to 27% (European Council 2014). As a part of the international agreement, several national energy targets have been proposed e.g. Denmark has set the ambitious long-term energy target of being independent of fossil fuels by 2050 and already by 2035 supply the entire demand for electricity and heat demand with renewable energy sources (RES) (the Danish Government 2013).

Collaboration between countries have led to regional long-term energy targets. Among the OECD member countries, the Nordic region is pioneer within implementation of RES and climate-change mitigation, due to a well-designed political framework and unique geographical conditions. The aggregated available resources for RES production in the Nordic region provide a promising perspective in terms of security of energy supply (NETP 2013). This has motivated a collaboration between the Nordic region, the IEA, and leading Nordic research institutions to conduct the project 'Nordic Energy Technology Perspective (NETP) 2013' in which the Nordic region has announced the ambitious long-term energy targets of decarbonising the entire energy system by 2050, along with pathways to meet this target (NETP 2013).

In order to meet the ambitious 2050 target, the Nordic energy system will in the future rely on a substantial penetration of both dispatchable RES e.g. hydro and biomass, and variable renewable energy sources (VRE), e.g. wind power and solar, since they promise limiting and potentially eliminating the carbon footprint of the energy generation.

Variable renewable energy sources are characterised by a highly *variable* energy production determined by the temporal weather conditions, *uncertain* production due to forecasting errors, and *location specific* production since the primary energy resource used cannot be transported (Borenstein 2012, Hirth 2013, Hirth et al. 2015). The electric power system has the intrinsic property that in each point in time a constant balance between supply and demand has to be fulfilled in order to maintain the system frequency and voltage (Lund et al. 2015). Thus, the integration of a high penetration of VRE into the energy system is thus related with

several technical and economic challenges in the balancing of electricity production and demand (Pinson 2013).
Extensive work has been conducted to investigate the challenges related to production variability (Borenstein 2008, Nicolosi 2012, and Hirth 2013). Smith et al. (2007), Holttinen et al. (2011), and have shown that a high penetration of VRE will affect the balancing costs due the difficulties of predicting production e.g. forecasting errors. Furthermore, the distribution and transmission networks will be extended in the future mainly due to the increased penetration of VRE.
As a consequence of an increased share of VRE, the utilisation of the conventional power plants will be lower, while the need for ramping power plants and reserve capacity will be increased (Ueckerdt et al. 2013). Furthermore, from a market perspective, VRE will substantially impact the electricity market dynamics by e.g the merit-order effect, due to their low marginal costs and potential prioritisation (Poyry 2010).
The costs of integrating a large penetration of VRE can be high (Hirth et al. 2015). A cost effective integration of VRE has therefore become a major challenge within the energy sector. Thus improved flexibility in the power system could minimise VRE integration costs, contribute to the balancing of supply and demand and ensure the security of supply and capacity adequacy (Lund et al. 2015).
The International Energy Agency (IEA 2014) distinguishes between four sources of flexibility, all of which aim to improve the VRE integration. The four flexibility sources are: 1) dispatchable generation, 2) demand-side flexibility (DSF), 3) storage and 4) grid infrastructure. Improved flexibility in the power system can support and facilitate long-term energy targets which aim to substitute the fossil fuels with RES, while providing the operational utilities that are required in the future Nordic energy system.
In addition to the above, the main objective of this thesis is to perform a quantitative assessment of the options for integrating a higher penetration of fluctuating RES-E in the future Nordic[1] energy system, with emphasis on the two flexibility options: transmission grid infrastructure and demand-side flexibility.

1.2 Thesis Objective

The objective of the present thesis is to:

Quantify options for integrating fluctuating renewable energy sources for electricity in the future Nordic energy system.

To address the thesis objective, two of the flexibility resources for integrating VRE will be investigated i.e. 1) transmission grid infrastructure and 2) demand-side flexibility.
Hence the thesis objective can be divided in two, where the *first* objective is to perform an assessment which will aim to quantify the need for extension of the transmission grid and the *second* objective is to assess the influence of integrating demand-side flexibility in the future energy system.

To achieve the objectives the following learning objectives will be pursued:

- Identify the relevance of performing the assessments of the two flexibility resources i.e. 1) expansion of transmission capacity and 2) increased demand-side flexibility.
- Choose, lean and improve an energy system model, which allows for an assessments of the two flexibility resources.

[1] Nordic refer to: Denmark, Finland, Norway and Sweden. Iceland is not considered in the present thesis.

- Choose and implement an energy system scenario which achieve national and international energy policy targets. To facilitate the implementation of the energy system scenario, relevant data are collected and evaluated critically.

- Perform scenario assessments of 1) the future expansion of the transmission capacity, and 2) increased demand-side flexibility, for the future Nordic energy system by using the chosen energy system modelling tool. Validate and explain the results obtained by the model simulations and clarify the sensitivities of main assumptions through a sensitivity analysis.

1.3 Methodology

The main methods utilised to facilitate the assessments of the two flexibility resources are described in the following.
To facilitate the quantitative assessment of the future options for integrating RES in the Nordic energy system, an energy system optimisation model, which is strong in long-term planning of the power and district heating, will be utilised. For the purpose of the present thesis, the energy system model is improved by expanding the geographic representation. Furthermore, the model optimises the energy system by taken into account existing infrastructure and generation capacities, while allowing for endogenously investments, thus the input database is updated and modified in order to simulate the anticipative energy system scenario adopted from NETP (2016).
The energy system model has strength in long-term planning of the power and district heating, while including a high temporal resolution. In the present thesis both long-term investments simulations towards 2050 and an hourly simulation will be conducted.

1.4 Scope and Limitations

The present thesis investigates the long-term energy system planning, for the Nordic region and two surrounding countries, from a relative holistic perspective, which allows for synergies and interactions between the power and district heating sector and exchange of electricity between regions and countries, however, this approach is lacking w.r.t. high level of details within each of the considered countries. The scope of this thesis is to assess two flexibility resources i.e. 1) the future expansion of the transmission capacity, and 2) increased demand-side flexibility, thus the effects of other flexibility resources are excluded from the assessment.
In the following the scope and limitation of the present thesis is briefly described. A more thoroughly description of the geographical scope, temporal scope, model limitations can be found in Section 6.1.1, 6.1.2 and 5.3.
The geographical scope of the present thesis includes the Nordic countries and two surrounding countries i.e. Germany and Great Britain. Each country is divided into a number of regions. The number of regions in each of the Nordic countries is corresponding the currently division of price bidding regions in the NordPool spot market. The scope of the present thesis allow electricity exchange to be traded between the considered countries.
The temporal scope includes the simulated years i.e. 2014, 2020, 2030, 2040, and 2050. Due to high computation time, the temporal resolution within each simulated year is limited to include five Time-periods within each of the 52 Seasons (weeks) in the long-term investment scenarios. By utilising this aggregated time resolution approach, important information provided outside of the simulated time segments are lacked, which potential can influence the optimal solution.

The energy system contain both the power, heating, gas and transport sector, and the integration across different energy sectors is expected to be increased in the future, however in the energy system model utilised in the present thesis, the power-, district heating-, and to a very limited extent the transport sectors are included.
The energy system model utilised to facilitate the quantitative assessment is subjected to assumptions and limitations. The model assumes perfects competition, is deterministic and thus have perfect foresight up to one year, has myopic investments decisions and exclude transmission grid related issues such as voltage stability.
The approach of evaluating the effects of integrating RES in the future energy system can varies from investigating e.g. price effects to substitution effects to curtailment effects. In the present thesis, the results obtained by the model simulations are assessed with main emphasis on the electricity- production, trade and prices and investments in additional transmission- and generation capacity.

1.5 Outline of the Thesis

The structure and outline of this thesis will be as follows.
In Chapter 2, an introduction to the flexibility resources which can be used to integrate a higher penetration of RES will be provided. Furthermore, a literature review is performed which clarifies previous studies of each of the flexibility resources. Finally, two of the four flexibility resources are chosen to be assessed in the present thesis and the markets effects of introducing these into the electricity system are described.
In Chapter 3, the characteristics of the current electricity and district heating systems are described for each of the considered countries. Furthermore, the national and international energy policy targets are stated along with the future energy system planning for each of the countries. Lastly, the anticipative energy system scenario utilised in the present thesis is identified.
In Chapter 4, the energy system modelling approaches are presented, followed by a description of the important characteristics for the choice of energy system model in the present thesis. Furthermore, the choice of utilising the Balmorel model ad the energy system modelling tool is argued.
In Chapter 5, the main characteristics, functionalities and limitations of Balmorel model is described. In addition, the procedure of modelling the main dimensions in the Balmorel model is elaborated.
In Chapter 6, the model setup and improvements utilised to facilitate the modelling of the future Northern energy system are elaborated. Furthermore, this chapter provides the scenario setup and a thoroughly description of the collected and implemented data.
In Chapter 7, a case study investigating future expansion of the transmission capacity is presented. The results obtained from the model simulations includes the electricity- production, trade and prices and investments in additional transmission- and generation capacity. Finally a sensitivity analysis is carried out which clarifies the sensitivities of the main input parameters.
In Chapter 8, the second case study is presented which investigated the effects of introducing demand-side flexibility into the system. The results from the study includes the electricity prices and the discrepancies in the electricity production and the endogenously determined additional transmission capacity between the Flex and the Base scenario. Furthermore, an hourly simulation of year 2050 is carried out and the hourly electricity- production, demand, net import, and price will be illustrated for representative weeks.
Chapter 9 concludes on the findings of this project and gives an outlook for future possible studies.

CHAPTER 2

Flexibility in the Energy System

The Nordic energy system will experience a remarkable transition of the energy system in the future, heading towards energy production based on renewable energy sources. This will consequently influence both the technical and economical structure of the energy system. Furthermore, the integration of VRE into the energy system is related to challenges which potentially can be met by improved flexibility.
In this chapter the flexibility resources that can facilitate an efficient integration of VRE will be identified, followed by a description of the main characteristics of each of the identified flexibility resources. Based on a literature review, two of the four flexibility resources will be selected to be the main focus in this thesis. The market effects of introducing the two flexibility resources will be further clarified.

2.1 Flexibility Resources

The need for flexibility in the future appears mainly due to variable and uncertain demand, in combination with a large implementation of the VRE generation. The need for flexibility related to the increased implementation of VRE generation are caused by the characteristics of VRE, namely that they are *variable*, *uncertain* and *location specific*. As illustrated in Figure 2.1, the increased implementation of VRE can be facilitated by four flexibility resources and, in this way, ensure an efficient integration into the energy system. The International Energy Agency divides the flexible resources into four measurements, namely, flexible power generation, demand-side flexibility, storage and interconnection with adjacent markets i.e. expansion of the transmission capacity (IEA-ETP 2012, IEA 2014).

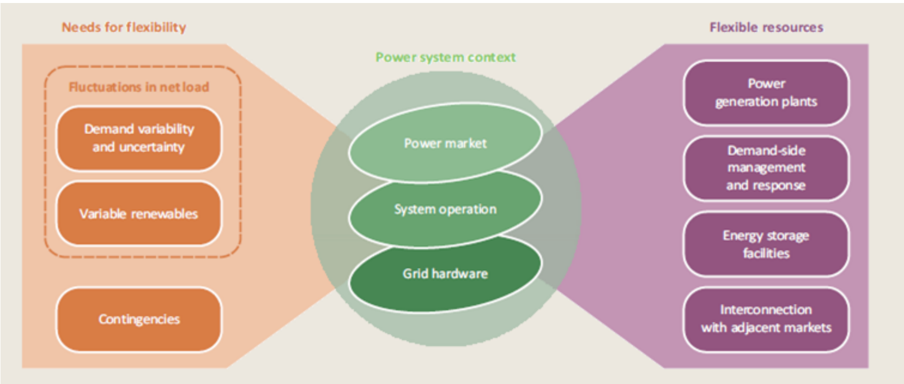


Figure 2.1: The need for flexibility is required as a consequence of production from VRE technologies. IEA divides flexibility into four flexible resources: flexible power generation, demand-side flexibility, storage and interconnection with adjacent markets (IEA-ETP 2012)

2.1.1 Flexible Generation

The need for flexibility, caused by variable energy demand, provided from dispatchable generation technologies is currently limited. However, in the future energy system, power generation technologies will be used to partly cover the gap of needed flexibility. In general, all controllable power generations have technologies that allow them to provide at least some flexibility, however, the ability to provide flexibility varies considerably between the generation technologies (DEA and Energinet.dk 2012).
In terms of the fastest start-up time from hot start, ramping rate and time from zero to full load, hydro generation has the highest ability to provide flexibility, however, considering the conventional fuel technologies, gas turbines are in general the fastest responding conventional peak power generation technology, while base-load generations have the ability to provide flexibility over longer time periods. Furthermore, future base-load generation technologies can be designed in order to increase the capabilities for providing flexibility, and older generation technologies can be retrofitted such that the potential for providing flexibility can be increased, however incentives for future investments in these generation technologies require changes in both regulatory and market structures (IEA-ETP 2012).

2.1.2 Demand-side Flexibility

Demand-side flexibility (DSF) refers to the mechanism in which the demand is controlled to respond at the demand side and thereby shift loads in time. In order to facilitate DSF, demand needs to be able to increase or decrease according to incentives e.g. price signals. Hence, the flexibility provided from demand response is suitable in the integration of a high penetration of VRE. Demand side flexibility can be applied in industry & commercial and residential loads by e.g. energy-intensive industrial processes, heat pumps (HP) and electric vehicles (EV).
Even though demand-side flexibility currently is the least used flexibility resource of the four main flexibility resources, it has promising potential due to the low costs of providing flexibility and thus it has received increasing attention in recent years (IEA-ETP 2012).

2.1.3 Energy Storage

Since the power system has the requirement to balance supply and demand at each point in time, energy storage is a well-known concept to provide flexibility to the system. The energy storage facilities convert electricity to other energy forms, stores the energy, and reconverts the energy back to electricity when it is needed. Despite the fact that this storing process is related to predictable losses, energy storage facilities such as pumped hydro storage, batteries, compressed air energy storage (CAES) and hydrogen are widely used as, or have promising long-term perspectives of being, appliances in the power system (IEA-ETP 2012).
Energy storage can be characterised both as demand and generation since the facilities consume and produce energy. The fast shifting-responses between consumption and generation makes storage facilities essential in providing flexibility to the power system. Furthermore, in energy systems with a high penetration of VRE, energy storage can store energy in times of excess power production and release energy in times of low production, which emphasises the potential of energy storage facilities in the future energy system.

2.1.4 Grid Infrastructure

The transmission and distribution networks facilitates the transfer of electricity between producers and consumers. In the future energy system with a higher penetration of VRE in combination with increased electricity demand due to the electrification of the heating and transport sector, the transmission system

is expected to facilitate two properties; namely, to supply the electricity demand and to provide flexibility (IEA-ETP 2012).
The transmission grid extension can be valuable in the future, since it can reduce the variability in the power system by connecting regions within countries and across-borders. Thus, the transmission grid is the only flexibility resource that can accomplish the challenges regarding the local VRE production.
Hence, interconnectors and the transmission grid, will be essential in an effective utilisation of the positive correlation between VRE sources e.g. wind and solar, as well as effective utilisation of delaying wind production e.g between the United Kingdom and Denmark.
Even though the existing transmission grid in the Nordic countries allows for having well-functioning electricity network, new transmission connections are already planned in the short-term, and further extensions are expected in the longer-term (Agora 2015).

2.1.5 Flexibility Provided from the Four Flexibility Resources

The need for flexibility resources in the future energy system is evident. In a recent study conducted by IEA (2014), the four flexibility resources are compared according to the ability of providing the needed flexibility due to the three main challenges: *variable*, *uncertain* and *location specific*. Table 2.1 shows, in a qualitatively way, the ability of the individual flexibility resource to provide flexibility in order to mitigate the three main challenges.

Table 2.1: Contribution of different flexibility options with regards to the three main challenges of integrate VRE i.e. *variable*, *uncertain* and *location specific*. Based on the work in IEA (2014).

	Uncertainty	Variability			Local constraints
		Ramps	Abundance	Scarcity	
Flexible Generation	✓✓	✓✓	✓✓ ✗✗	✓✓	✗
Demand-side flexibility	✓	✓✓	✓✓	O	✗
Energy Storage	✓	✓✓	✓✓	✓✓	✗
Grid Infrastructure	✓	✓✓	✓✓	✓	✓✓

Note: ✓✓:very suitable; ✓:suitable ; O :neutral; ✗: less suitable; ✗✗: unsuitable.

Evidently, the four flexibility resources are, in principle, capable of provide flexibility which partly mitigate the main challenges. However, different options are more suitable to mitigating the challenges regarding the uncertainty, variability or local constraints. As illustrated in Table 2.1, the challenges regarding uncertainty and variability can be facilitated by all four flexibility options, while the challenges regarding local constraints, as a consequence of the local VRE production, only can be facilitated by the grid infrastructure.
As presented in the Table 2.1, flexible generations, can to a certain extent, address the challenges of variability caused by abundance of VRE generation, in case the generation unit can reduce the power output quickly, while still being able at generate power for a short time after. However, in case the residual load becomes negative, flexible generation units are not capable of mitigating this challenge.
Since the flexibility resources potentially have the ability and the capability to provide the needed flexibility, metrics for the cost of the different flexibility resources could lead to valuable knowledge regarding which flexibility resource to use in the future energy system. In Figure 2.2, the relative costs of integrating the four flexibility resources is presented. The relative economics of integrate different flexibility resources shows

that demand-side flexibility can potentially be the cheapest solution, however the cost of implementing DSF can be very high as well.

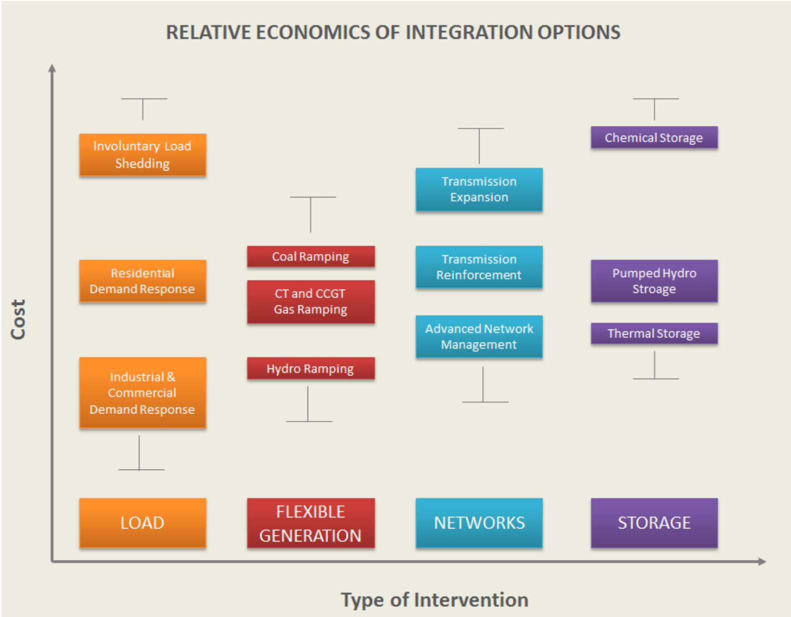


Figure 2.2: Relative costs of integrating each of the four flexibility resources. Based on the work in NREL (2014).

2.2 Literature Review of Flexibility Resources

The energy transition towards a future energy system with a substantial penetration of VRE has led to increased attention on flexibility resources. This has resulted in extensive research and development (R&D) work considering the need for flexibility and the effect of implementing flexibility resources for integrating a higher share of VRE.

The comprehensive research that has already been performed can be divided into two different categories namely 1) policy framework and market design, and 2) research investigating flexibility resources that enables mitigating the technical and economic challenges related to increased VRE deployment. Since the objective of this thesis is to quantify the flexibility resources that enables an increased deployment of VRE with emphasis at the technical and economic challenges, this will be the main focus in the following literature review. However, in order to facilitate a cost-effective integration of VRE, a coherent regulatory framework, and a well-designed energy market, needs to be established to create incentives for providing flexibility. This has been investigated by e.g IEA (2014) and will be further investigated in the future in different projects, e.g. Flex4RES[1]

Based on the three main challenges of integrating VRE and the four flexibility resources to mitigate these challenges, the following literature review will first include studies that investigate all the flexibility resources and, secondly, studies that consider individual flexibility resources to mitigate specific challenges.

[1] Flex4RES - Flexible Nordic Energy Systems is a project which *"will demonstrate how the challenge of integrating high shares of variable renewable energy in the energy system can be handled efficiently through a stronger coupling of energy markets across the Nordic region, thereby facilitating a zero-carbon energy transition."* Project period: 2015-2019 (Nordicenergy).

Studies which Include All Four Flexibility Resources

As adopted and used previously, IEA has conducted several studies in which the four flexibility resources are identified and investigated both from a technical and an economic point of view, with emphasis on the flexibility need in the integration of, in particular, wind and solar energy (IEA-ETP 2012, IEA 2014). The four identified flexibility resources are used in the comprehensive literature study conducted by Lund et al. (2015), in which close to 400 references are used to address the flexibility measures that allows integration of a substantial share of VRE. According to Lund et al. (2015), the increased implementation of VRE will affect the entire energy system and, in order to facilitate the system integration, different flexibility resources are suitable for different aspects both within and between various energy systems. The literature review will therefore focus on individual flexibility resources that had previously been investigated in different aspects and for energy systems with varying characteristics.

Flexible Generation

Historically, the supply side has primarily ensured the power balance (Lund et al. 2015), hence the ability of generation technologies to provide flexibility has been studied. In a recent review Pérez-Arriaga and Batlle (2012) investigated the impact that intermittent VRE had on the future power system and they found that the limited flexibility provided in regions dominated by thermal power generation can be a substantial challenge. The same conclusion was reached by Lund (2005) analysing the Danish energy system in 2005 which contained a substantial share of combined heat and power (CHP) production.

Therefore, a wide range of references present the main characteristics which includes flexibility measurements for different generation technologies (Lund et al. 2012, IEA-ETP 2012, Tveten 2015), all of which point to the same conclusion, namely that, for conventional fuel based generation technologies, gas turbines are the most suitable technology to mitigate the increased variations of the residual load due to higher deployment of VRE in the future, and nuclear power plants have the slowest ramping time and thus cannot contribute in the short-time balancing of the power system.

Based on this identification, numerous studies have been conducted in order to investigate how gas turbines can compensate for a varying residual demand in an energy system with a high penetration of VRE (Keyaerts et al. 2012, Qadrdan et al. 2010).

Furthermore, combined heat and power plants can, in addition, have some advantages in combination with VRE integration (Lund et al. 2015, Hirth 2013). From an energy system perspective Lund et al. (2012) focus on the integration of flexible CHP generation in the power balancing. They emphasise that for effective integration of VRE into the electricity sector, other sectors i.e. heating and transport sector needs to be taken into account. Furthermore, they found that by an efficient operating and regulating of the CHP plant a high penetration of VRE could efficiently be integrated in the system.

Hydropower as Dispatchable Generation Technology and as Storage Facility

As hydropower is considered as a dispatchable generation technology which has the capability of operating as a storage facility, therefore is hydropower one of the most preferable technologies to mitigate VRE integration. Furthermore, Lund et al. (2015) have identified hydropower as a mature technology, and emphasises the worldwide application of the hydropower technology.

As a consequence of these identifications for hydropower, and due to the scope of the present thesis, this literature review will include pumped hydro as the only storage facility.

In literature, studies considering this unique technology to compensate for increased variations in the residual demand have been conducted. Several studies utilising an energy system approach to investigate hydropower have previously been conducted. Holttinen et al. (2011) has concluded that the cost of integrating VRE in power systems dominated by hydro power generation is lower than in regions dominated by thermal power generation. Furthermore, Hirth (2013) argues that in regions with a high share of flexible hydro generation the variations in the short-time price is reduced since the hydro generation technology provides intertemporal flexibility.

As the main condition for hydropower to both provide flexibility and to operate the hydropower technology economically feasible is the availability of water i.e. wet or dry years. Thus, Benitez et al. (2008) state that the cost of integrating wind into the power system is lower in case hydropower reservoirs are available. Furthermore, Black and Strbac (2006) finds that pumped hydro storage increases the utilisation of wind, while Ueckerdt et al. (2013) argue that the integration cost of solar power is reduced when introducing pumped hydro, however large hydro storage facilities are needed in order to integrate wind power efficiently. Ueckerdt et al. (2013) emphasise, however, that large hydro storage will be essential in the successful integration of wind power.

Even though hydro power is studied extensively, Hirth (2013) concludes that there is a need for further research with special focus on hydro storage in the Nordic region.

Demand-side Flexibility

Demand-side flexibility has received increased focus in recent years, which is evidenced by the amount of publications concerning this topic. Lund et al. (2015) conducts a comprehensive review of over 100 studies, where different demand-side techniques, as well as potentials for Germany and Finland with regard to the residential, service and industry sector, are described. In addition, reviews regarding demand responds have been conducted by Aghaei and Alizadeh (2013) and O'Connell et al. (2014). Aghaei and Alizadeh (2013) investigated the demand response in a smart electricity grid, setting up the status quo of demand responds in USA, Europe and China, whereas O'Connell et al. (2014) investigated the benefits and challenges of demand response. O'Connell et al. (2014) identify the benefits of including the ability to mitigate variations caused by increased VRE implementation, increased economic efficiency and reduced amounts of required generation capacity. The challenges identified in this study includes the lack of real applied demand respond facilities, which can makes modelling of the field related to extensive assumptions. In order to apply demand respond facilities in reality, a reliable control strategy is needed, which potentially could be provided through aggregators and a well-defined market frameworks which enables optimal utilisation of demand response facilities is required as well.

Based on Gellings and Smith (1989) study, different options can change the load profile and thereby ensure flexibility, namely, reducing the load by conservation or peak shaving, increasing the load by load growth or valley filling and changing the schedule of the load by load shifting. Lund et al. (2015) identify load shifting as being beneficial in comparison with the other DSF options, since it has the same functionality as energy storage while having no energy conversion losses related to the process.

Even though large projects have been established e.g. iPower[2], to mitigate the lack of incentives for the consumer to reschedule the electricity consumption which has led to low price elasticity in short-term in the European power markets (Lund et al. 2015), further projects are currently being established e.g. Flex4RES. Extensive work has been conducted to investigate DSF in the individual sectors i.e. residential, service and industry and, as suggested by Tröster et al. (2011) and Hirth (2013), modelling of DSF including regional production from VRE, transmission grid which connect regions and thereby take into account regional pricing using an energy system model with high temporal resolution should be further studied in the future.

[2]iPower is a *"strategic platform for innovation and research in intelligent power"* Project period: 2011-2016 (iPower)

Grid Infrastructure

In the future energy system, an optimised transmission grid infrastructure is essential to ensure flexibility in the power system (Lund et al. 2015). Furthermore, optimising the future grid infrastructure is highlighted as a key challenge (NETP 2013), as it is the only flexibility resource that can facilitate the VRE integration challenge regarding the local constrained production (IEA 2014). Thus improved transmission grid infrastructure can enable cross-region electricity transfer, from regions with high VRE production to regions with low VRE production (IEA 2014).

Identified as a key challenge in the future energy system, extensive work has been performed investigating the need for improved transmission infrastructure. This need can be evaluated by dividing it into two main categories, namely with emphasis in 1) technical aspects or 2) economic aspects.

In the *first* category, regarding the technical evaluation of the need for transmission capacity, power flow models e.g. DIgSILENT Power Factory, are utilised to investigate e.g. the European grid towards 2030 and 2050 (Tröster et al. 2011). Tröster et al. (2011) confirm the significant need for extension of the transmission grid towards both 2030 and 2050.

In the *second* category, economic optimisation models are utilised to evaluate the need for improved transmission grid infrastructure in the future energy system with increased deployment of VRE. Even though, the two categories are highly related and points to the same findings, that grid reinforcements are needed in the future (Tröster et al. 2011, Agora 2015, Holttinen et al. 2011, Göransson et al. 2014), this thesis will, due to the objective which is to perform an optimisation of the social welfare based on an economical approached, thus further concern about the economical studies regarding the improved grid infrastructure in the future.

In a study Hirth (2013) highlight the need for further research of the importance w.r.t. long-distance interconnections. This topic is recent studied in the Agora project (2015) and by Göransson and Johnsson (2013), each of which investigated the increased integration of the electricity system between Germany and the Nordic region. With emphasis on the electricity generation and trade in the German and Nordic power system towards 2030 the Agora 2015 project utilises the energy system model - Balmorel. The comprehensive work performed in Agora 2015, points out the value of expanding specific transmission capacities within and across the countries and shows the future average electricity prices within each price bidding region. In this light, more projects will analyse and evaluate the value of improved transmission grid infrastructure, also in combination with other flexibility resources, in the future e.g. Flex4RES, which is also suggested by Hirth (2013).

Flexibility resources which will be investigated in the present thesis

In addition to the above, the need for flexibility resources in the future energy system are evident, and the four flexibility resources are potentially capable of mitigating these needs. The future energy system will entail combinations of the flexibility options, since thermal regions already are connected to hydro regions by interconnectors (ENTSO-E 2014). In such an energy system three flexibility resources are introduced i.e. grid infrastructure, storage (hydropower storage) and flexible generation (dispatchable hydropower and other conventional generation technologies which have the ability to ramp up and down (DEA and Energinet.dk 2012.

Combining reinforcement of the grid infrastructure and hydropower facilities will according to Ueckerdt et al. (2013) lead to an optimised integration of VRE. The main focus in this thesis is the future Nordic energy system, which has a high share of VRE in combination with hydro storage, however interconnections to Germany and Great Britain allows trade between the Nordic region and surrounding countries. In extension to the above conclusion from Ueckerdt et al. (2013) and the suggestion from Hirth (2013) that the importance of long-distance interconnections have to be further studied, therefore will the *first* main objective of this thesis investigate the extension of the transmission grid infrastructure in the future.

A combination of the different flexibility resources can lead to reduced overall cost of integrating VRE. Introducing demand-side flexibility can lead to a reduced need for an extension of the transmission grid capacity (Lund et al. 2015) and is a promising option in the future due to the low cost of providing flexibility (IEA-ETP 2012). The synergies in energy systems with increased demand-side flexibility in combination with interconnections between regional pricing regions and regional VRE production are essential to evaluate and are suggested to be further studied by Tröster et al. (2011) and Hirth (2013). Therefore, the *second* main objective of this thesis is to evaluate the influence of increased demand-side flexibility.

To facilitate the model-based evaluation of the two chosen flexibility resources i.e. transmission grid infrastructure and demand-side flexibility, Hirth (2013) emphasises the need for an energy system model which allows high temporal resolution, which include a large geographical area, take into account existing capacities i.e. generation and transmission connections and allows endogenously investments. Utilising energy system models which neglect the above suggestions from Hirth (2013), can potentially lead to an overestimation of VRE.

2.3 Market Effects of the Flexibility Resources

Based on the above, the emphasis in this thesis is on the two flexibility resources: 1) transmission grid infrastructure and 2) demand-side flexibility. Therefore, the following section will briefly present the theoretical background of the market effect, while introducing: 1) a large penetration of VRE, 2) the effects of having interconnectors, and 3) demand-side flexibility.

2.3.1 Market Clearing and Merit Order Effect

The electricity trade between the Nordic countries is facilitated by Nord Pool Spot. The Nord Pool power exchange includes both day-ahead and intraday markets. However, since this thesis will investigate the day ahead electricity prices, the following introduction of the market clearing in the Nord Pool market has been limited to Elspot, i.e. the Nord Pool day ahead market (Nordpool-Spot).
In Nord Pool, a market equilibrium model determines the spot price. The market equilibrium model aggregates all bids from producers into a market supply curve and all bids from consumers into a market demand curve. In order to facilitate the aggregation of the supply curve all bids from producers are horizontally added and thus results in the merit order curve. The spot price is determined by the intersection of the market supply and demand curves. Thus the equilibrium point reflects the cost of utilising the last needed production unit (MW) in the merit-order curve.
The impact of increased implementation of VRE on the day-ahead market has been studied extensively in previous works. There is a general consensus that an increased implementation of VRE impacts the electricity market and, furthermore, leads to a reduced average wholesale spot price. This effect is commonly known as the merit order effect (Poyry 2010).
The impact from VRE on the wholesale day a head spot price is illustrated in Appendix A. In the day-ahead market equilibrium model VRE enters the merit order curve from the left, since VRE i.e. wind and solar, has negligible marginal cost. Hence, VRE, due to their variable power production, impacts the merit order curve by shifting it to either the left or right depending on the forecast power outputs for that hour (Poyry 2010).
Additionally, the increased implementation of VRE has the indirect effect of reducing the utilisation time of the conventional generation units. This is attractive from an environmental point of view since the GHG emission and thereby the carbon footprint from the power sector is reduced and fossil generation technologies

are substituted by VRE. However, the reduced utilisation time in combination with reduced average spot prices may in the long-term push the more expensive thermal generation technologies out of the merit order curve and thus result in a generation portfolio dominated by VRE and peak generation technologies, which consequently leads to a steeper merit order curve (Nicolosi and Fürsch 2009).
In the case were a larger share of wind power is implemented into the power system, this effect will consequently make the future day ahead power prices highly volatile with substantial differences between maximum and minimum spot prices. However, in case of implementing a large share of solar power capacity, a reduction in price volatilities has been found since the hourly solar power production and the electricity demand profiles are strongly correlated (Tveten et al. 2013).
This means that the merit order effect for solar power is assumed to be higher compared to other VRE generation technologies due to the correlation between the maximum solar production and high electricity demand, which both occur during mid-day hours (Tveten et al. 2013).

2.3.2 Market Effect of the Extension of the Transmission Grid Infrastructure

In Nordpool spot, the price bidding regions are connected by transmission lines which allow electricity trading and transfer between the regions. As one of the main objectives in this thesis considers the transmission grid infrastructure, this section briefly presents the background and market effect of transferring electricity between regions.
The market effect of connecting two regions with diverse amount of VRE production is illustrated in Figure 2.3, where Region A is assumed to contain a high penetration of VRE capacity, while the share of VRE in Region B is negligible. By considering the two cases the effect of the transmission interconnection is explained using Figure 2.3 which illustrate the market situation and effects for Region A.

Figure 2.3: Market effect of having a sufficient transmission grid infrastructure

1) considering a case in which Region A has a high VRE production i.e. low residual demand, and thus entailing a low regional price level, while the market clearing in Region B results in a higher regional price level, as illustrated in Figure 2.3a. Since Region A and B are interconnected with an assumption of unlimited transmission capacity, the flow of electricity will be from Region A to Region B, due to the price difference. This will consequently lead to a common electricity price for both regions in the equilibrium point i.e. p^E, which is facilitated by a shift of the residual demand curve i.e. to the right in Region A and to the left in Region B, as illustrated in Figure 2.3a. Therefore, the producers in Region A receive a higher price, while the consumers in Region B pay a lower price, compared to a situation in which the two Regions were not connected, or were subjected to a limited transmission capacity below the transmitted power.
2) The second case represents the opposite case, since the VRE production in Region A is low i.e. high

residual demand and, thus, a high regional price level, as illustrated in Figure 2.3b. In this case Region A will import electricity from Region B which consequently shifts the demand curve to the left in Region A, and to the right in Region B.

In addition to the description of the two cases in Figure 2.3, the regional price volatilities are expected to be reduced in power systems with sufficient transmission capacity since the high prices in one Region and the low prices in another Region will flatten out due to the interconnection.
It should, however, be noted that regions can have correlations in profiles for VRE power production and demand which, to a certain extent, are correlated with neighbouring regions. Therefore, regions with a high VRE production share have the highest benefit with interconnecting with regions with low VRE share, different VRE generation technologies with different production profiles or with regions with storage facilities (Tveten 2015).

2.3.3 Market Effect of Demand-side Flexibility

The market effects of introducing demand-side flexibility as demand shift, are illustrated in Figure 2.4, where two time periods are presented. In the *first* time period, the VRE production in the region is low and thus leads to a high spot price. Therefore consumers with the capability of responding on price signals has the incentive to reduce the consumption[3]. Consequently, this will move the demand curve to the left and thus result in a lower market clearing price. The *second* time period presents a scenario in which a high VRE production in the region leads to a low spot price. Hence the price responsive consumers have the incentive to increase the consumption which consequently shifts the demand curve to the right. As a result of this effect, the VRE producers receive prices that will increase in the second time period, which is of high interest from producers installing VRE generation technologies.

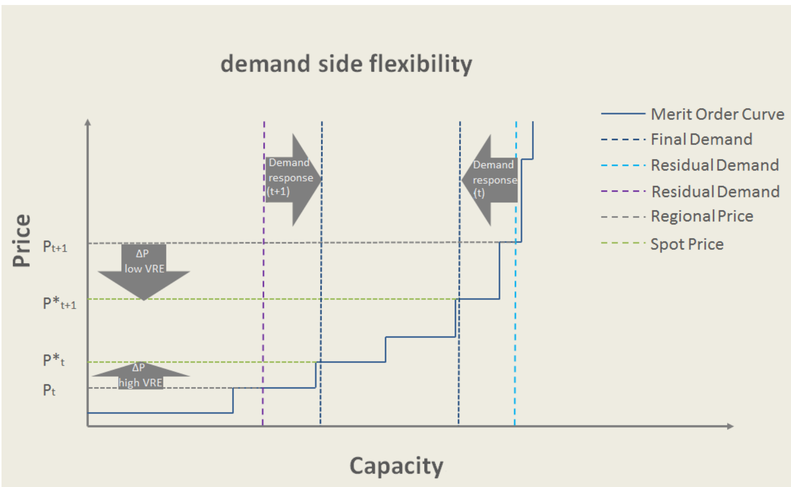


Figure 2.4: Market effect, due to the deployment of demand-side flexibility

[3]here it should be noted that the actual extent of the reduction in consumption also relies on non-economical properties such behavioural and technological preferences

CHAPTER 3

Energy- Systems, Policy Targets and Planning: Current and Future

The energy system is expected to experience a major transition in the future, however, in the first part of this chapter the main characteristics of the current electricity and district heating system in the Nordic- and surrounding countries will be presented.
As stated in Chapter 2, the flexibility resources can efficiently facilitate the integration of a substantial penetration of VRE in the future. To perform the assessment of the flexibility resources as an option for integrating a high share of VRE in the future, a scenario presenting the pathway towards a future energy system is required. As the pathway is affected by energy system researchers, specialists and policy makers, this chapter presents the main future energy policy targets and energy system plans. Finally, the anticipative energy system scenario, which holds promise of meeting the ambitious national energy policy targets and will further be implemented in the Balmorel model in Chapter 6 and utilised in the case studies in Chapter 7 and 8, will be identified.

3.1 The Current Energy System in the Nordic- and the Surrounding Countries

In this section, the main characteristics of the current electricity and district heating system in the Nordic- and surrounding countries will be presented.

3.1.1 The Nordic Countries

In the Nordic region the available energy resources includes for instance, biomass, hydro, wind and petroleum. The availability of energy resources varies among these countries, however the Nordic region has promising perspective with regards to security of supply when aggregating the energy resources across countries (NETP 2013).
In 2013 the total energy generation in the Nordic countries was approximately 550 TWh, whereas the electricity production was around 400 TWh and the total district heat production was approximately 150 TWh. The current electricity and district heat production in the Nordic countries are characterised by including a substantial penetration of carbon neutral generation technologies. To provide an overview of the electricity and district heating generation portfolio in 2013, Figure 3.1 presents metrics for the total electricity and district heating production divided by fuel types for each of the Nordic countries derived from IEA (2016a).
The Nordic energy generation primarily relies on energy produced by carbon neutral generation technologies, which, in 2013, accounted for 80% of the total energy generation. Furthermore, high penetrations of RES

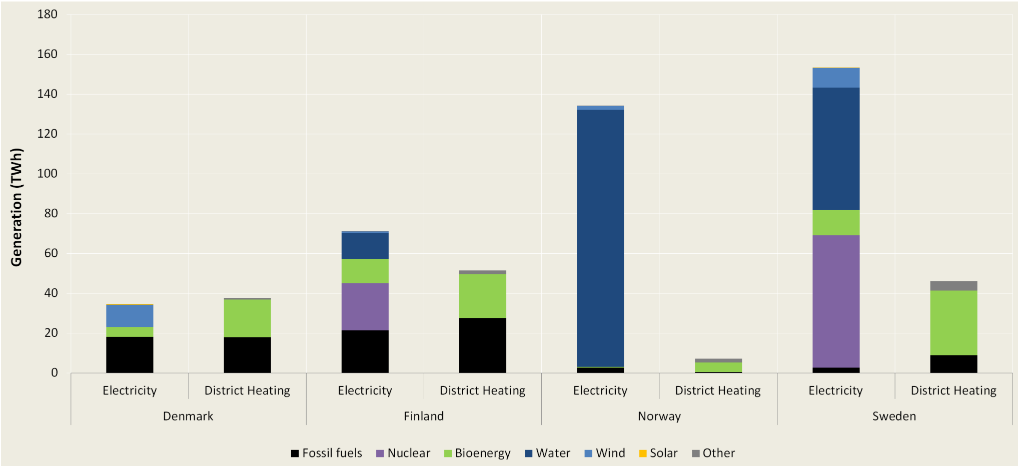


Figure 3.1: Electricity and district heat generation divided by fuels for each of the Nordic countries by 2013. Metrics derived from IEA (2016a).

are implemented in the Nordic countries which, in total, contributed with 63% of the total generation. Considering the electricity generation in the Nordic countries, hydropower is currently the dominating resource used and contributed, in 2013, with more than half of the total electricity production. Furthermore, nuclear power plants contributed 23% of the total electricity generation in 2013, however, various regulatory frameworks have been agreed upon w.r.t. nuclear power production, among the Nordic countries, as will be further elaborated, in Section 3.2. The share of VRE technologies in the Nordic electricity system was, in 2013, approximately 6% of the total Nordic electricity production, however varying shares can be observed among the countries. In the following paragraphs, the main characteristics of the electricity and district heating system will be elaborated for each of the Nordic countries.

Denmark

Denmark has an energy generation portfolio which, at present, is characterised by consuming a large amount of fossil fuels i.e. coal and natural gas. However the utilisation of bioenergy resources and wind power technologies are already, and will in the future continue to be, cornerstone technologies. Denmark is a leader in implementation of wind power and, in 2014, 39.1% of the electricity consumption in Denmark was covered by wind power, which was a world record (Energinet.dk 2015). This emphasises that Denmark is pioneering when considering the implementation of RES aided by strict climate change policies.

Denmark has an efficient energy system with close interactions between the power system and the district heat system. This allows renewable energy sources to be used as fuel in CHP plants e.g. biomass, and thus significantly contribute to the production of both electricity and district heating. In 2013 bioenergy and waste contributed with 33% of the total electricity and heat production.

In 200, 47% of the total Danish heat demand was covered by the district heating network (NETP 2013). This integration between the power and heat markets has been identified to allow implementation of larger markets shares of VRE technologies in the future (Münster et al. 2012).

Finland

Finland has one of the worlds' highest energy consumptions per capita which is due to the cold climate combined with energy intensive industries (IEA-Finland-Review 2013). The energy generation mix in Finland is, at the moment, very diverse. In 2013 almost 40% of the total electricity and district heating production was generated using fossil fuels, while 28% was generated using bioenergy resources and waste. Considering the electricity sector, nuclear and hydro power plants contributed, in 2013, respectively with 33% and 18% of the total electricity production.

Finland is the most forested country in Europe and, therefore, has the potential of incorporating a high share of bioenergy products. Thus biomass will play a prominent role in the entire energy system in the future including the power- heat- and transport- sector. With regard to the district heating sector, 49% of the Finnish heat demand in the service, residential and other sectors are covered by district heating in 2009 (NETP 2013).

Norway

Norway's national hydro resources are unique and allow 96% of the total Norwegian electricity production generated by hydro power technologies. This consequently makes the Norwegian electricity sector almost carbon neutral, however, natural gas is still marginally consumed. In addition, the utilisation of district heating in Norway had, in 2009, a share of 6% of the total Norwegian heat demand, which makes the potential of growth in the district heating network an good opportunity in Norway (NETP 2013).

Norway already plays and will, in the future, play a key role in ensuring security of energy supply and balancing of the Nordic power system. Regarding energy supply, Norway is a major producer of oil and gas and is, currently, exporting electricity which in total makes Norway the third-largest exporter of energy in the world (IEA-Norway-Review 2011). Additionally, Norway plays a key role in balancing the Nordic power system since Norway has unique national hydro resources which allow large storage facilities.

As stated in Section 2.2, in order to facilitate a successful integration of a high penetration of VRE technologies, large hydro storage facilities will be essential. By utilising the efficient pumped hydro technologies, the hydro reservoirs can facilitate the imbalances between supply and demand. Based on strategic decision, taken into account the opportunity cost, the hydro reservoirs can be 'charged' and 'discharged' which, in general, follows the pattern of 'charging' the hydro reservoirs in time-periods with low electricity prices and 'discharging' the hydro reservoirs in periods with high electricity prices.

Sweden

Among the IEA member countries, Sweden has the lowest share of fossil fuels in the entire energy mix. Furthermore, the current Swedish electricity and district heating generation portfolio relies primarily on carbon neutral technologies with nuclear, hydro and bioenergy energy as primary supplying resources, while the energy contribution from fossil fuels into the electricity and district heating sector was 6% in 2013.

Bio-resources and waste contributes significantly to both the electricity and district heating system and was, in 2013, accounting for 23% of the total Swedish electricity and district heating production. With regard to the district heating network, in 2009, 55% of the Swedish heating demand was covered by district heating (NETP 2013).

Considering the Swedish electricity sector, hydro- and nuclear power are, at the moment, the dominant contributor and was, in 2013, accounting for 40% and 43% respectively of the electricity production. Moreover, in 2013 wind power contributed 6.4% of the electricity generation.

The current conditions of the electricity and district heating generation portfolio means that Sweden can easily phase out fossil fuels i.e. coal and natural gas, from these sectors in the future, however, policy targets, such as phase out of nuclear which will be elaborated in Section 3.2, makes the transition of the future energy sector more challenging.

3.1.2 The Surrounding Countries

In the surrounding countries i.e. Germany and the United Kingdom, the total electricity and district heating generation are more than double of the Nordic electricity and district heating generation. In 2013 the electricity production was approximately 1000 TWh, while the production of heat to the district heating network was around 150 TWh. The energy generation portfolio to supply approximately 1150 TWh is very diverse, and is presented in Figure 3.2.

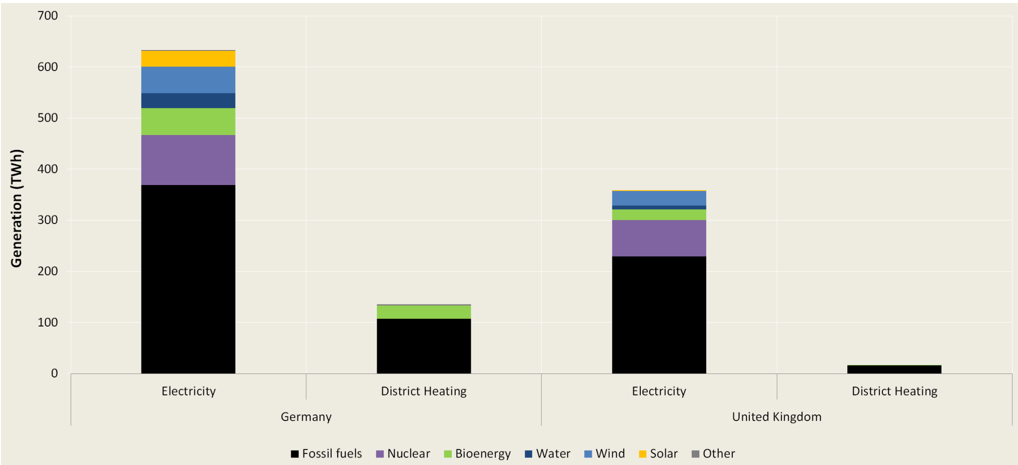


Figure 3.2: Electricity and district heat generation divided by fuels for Germany and the United Kingdom by 2013. Metrics derived from IEA (2016a).

The electricity and district heating production in these countries is primarily generated by fossil fuels, which, in 2013, accounted for 63% of the total production. Hence, carbon neutral generation technologies accounted for 37%, whereas 22% was renewable energy sources.
Considering the VRE generation in the electricity sector, approximately 11% of the total electricity production was generated by VRE generation technologies in 2013, whereas wind accounted for 8%, and solar PV accounted for 3%.

Germany
Among the IEA member countries, Germany had, in 2013, the highest total electricity and heat production (IEA 2016a). The production of electricity was 633 TWh, while the production of heat to the district heating network was 135 TWh. The production of heat to the district heating network covered approximately 14% of the total German heating demand in 2011 (AGFW 2011). Compared with the aggregated total electricity and district heating production in the Nordic countries, Germany's generation was 140% of total Nordic electricity and district heating in 2013.
The current electricity and district heating generation portfolio is very diverse, however fossil fuel resources are heavy used in both the electricity and district heating production and accounted for 62% in 2013.
Considering the electricity production portfolio the diversity of generation technologies is evident. The electricity production currently relies on heavy utilisation of coal, lignite and gas power plants, however carbon neutral energy sources such as bioenergy, nuclear, hydro, solar and wind are represented in the electricity generation portfolio. More than 40% of the electricity production is generated by carbon neutral generation technologies, and 26% is generated by RES technologies. With regards to VRE, Germany has currently approximately 5% of the electricity supplied by solar power, while wind power contribute with approximately 8%.

The United Kingdom

The United Kingdom has an energy generation portfolio which, currently, is characterised by consuming a large amount of fossil fuels e.g. coal and natural gas. The production of electricity was 360 TWh, while the production of heat to the district heating network was 17 TWh. The production of heat to the district heating network covers only around 2% of the total heating demand (DECC 2013).

The amount of electricity generated in the United Kingdom was around 90% of the total electricity generation in the Nordic countries in 2013. The electricity generation portfolio is very diverse as presented in Figure 3.2, however, it is primarily dominated by fossil fuels and nuclear power which have a total share of approximately 84% of the electricity generation in 2013. In addition, biomass and municipal waste has a share of 6%, and with regards to VRE generation, wind power had a share of 8% of the total electricity generation in 2013. The United Kingdom has significant wind resources and are leaders at installing wind farms. Thus the share of electricity generated by wind turbines is increased to 9.3% in 2014 (IEA-United-Kingdom-Review 2012, RenewableUK 2015).

3.1.3 Electricity Exchange

Interconnectors between the Nordic countries allow electricity to be traded. Currently, as stated in Section 2.1.4, the existing transmission grid between the Nordic countries forms a well-functioning electricity network[1]. Figure 3.3 presents the exchange of electricity from each of the Nordic countries to the countries they are interconnected with. Furthermore, the figure presents the metrics for the physical quantities of electricity exchanged (TWh) (ENTSO-E). Among the countries considered in this thesis, Norway and Sweden were, in 2014, net exporters of electricity with 15.6 TWh and 16 TWh net electricity exported, while Denmark, Finland and Germany were net importers of electricity with quantities of 3.4 TWh, 17.9 TWh and 1.6 TWh net electricity imported. However, it should be noted that the exchange of electricity varies from year to year and Figure 3.3 only represents the metrics observed in 2014. In addition to the power exchange from the Nordic countries, Great Britain were, in 2014, electricity net importer with an import of 19.5 TWh electricity (ENTSO-E).

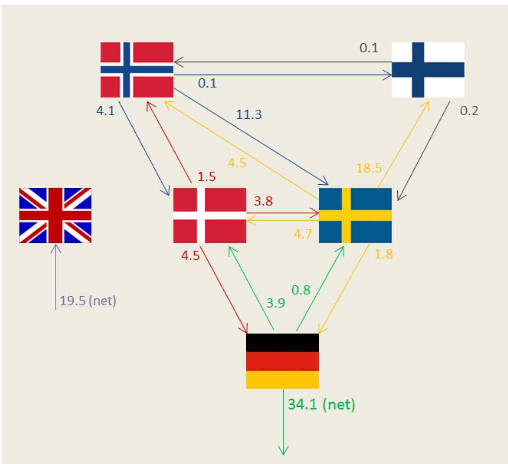


Figure 3.3: Nordic electricity exchange in 2014 (TWh). Metrics derived from ENTSO-E (2015).

[1] It should be noted that the transmission network in Germany, which primarily transfers electricity from the northern part to the south, is more frequently congested which is also a trend expected to continue in the future (IEA-Germany-Review 2013)

3.2 Energy Policy Targets

The energy system is currently a contributor to the global GHG emissions. However, in the future, the environmental GHG footprint from the energy system will be reduced aided by national and international agreements.

In 2008, the European Union concurred climate and energy targets which should be fulfilled by 2020 i.e. 20/20/20 targets (European Council 2008). These targets state that by 2020; 1) GHG emissions from the EU have to be reduced by at least 20% compared to 1990 levels, 2) renewable energy sources should cover at least 20% of EU energy consumption and 3) improved energy efficiencies which allows a reduction of 20% in primary energy consumption compared to the projected levels. To achieve these targets, each country has agreed on a certain burden-sharing part, which varies between countries.

In 2011, the European Commission announced the EU Energy Roadmap 2050 which aims to reduce the GHG emission by 80-95%, compared to 1990 level, by 2050. In order to achieve this ambitious 2050 target, the policy framework supports the energy transition by the intermediate target of reducing GHG emission by 25% in 2020, and by 40% in 2030 (European Commission 2011). In addition, the European Council has, in 2014, stated that the share of renewable energy should be increased to 27% by 2030 (European Council 2014).

Along with the targets set at the European level, long-term and intermediate targets at the national level have been announced by each of the Nordic countries, Germany and the United Kingdom, which are presented in Table 3.1.

Denmark has set the ambitious target of achieving an energy system by 2050 which is independent of fossil fuels, which will correspond to a reduction of approximately 85% GHG emission compared to 1990 levels. In order to meet this ambitious target, the former Government announced in 2013 the following intermediate targets (Energiaftalen 2012); By 2020: 50% of power production will be covered by wind power. By 2030: oil used for heating in buildings, and all coal use, are phased out. By 2035: Electricity and district- and individual heating will be supplied 100% of renewable energy sources[2].

In addition to the above stated vision Denmark has, according the to the burden-sharing agreement set in the 20/20/20 targets, an energy target of 30% renewable energy share by 2020 (IEA-Denmark-Review 2014).

Finland's long-term vision is to reduce the domestic GHG emissions by 80% in 2050 compared to 1990 levels. In order to fulfil this vision, Finland has set targets for reducing the consumption of oil, peat, coal and natural gas by 2025. Furthermore, Finland is currently using nuclear power plants, that reduce the carbon footprint from the energy sector, however, in the future, the Finnish Parliament has to make decisions on licences to adopting new nuclear power plants. Approximately 60% of the Finnish electricity production can be expected to be supplied by nuclear power plants in 2025 in case all planned nuclear projects are completed (IEA-Finland-Review 2013).

With regards to the 20/20/20 targets, ambitious goals are set by Finland which aims to achieve 38% of the final gross energy consumption covered by RES by 2020. In order to meet this target, biomass is expected to play a key role since Finland is the most forested country in Europe (IEA-Finland-Review 2013).

Norway has set the long-term target aiming to achieve a carbon neutral energy system by 2050, where international trade of carbon credits are allowed. Furthermore, Norway has announced that in case an ambitious international climate agreement is agreed then their energy system will become net carbon neutral

[2] Here it should be noticed that the intermediate targets for 2030 and 2035 are stated by the former Danish Government and can potentially be changed.

Table 3.1: Energy policy targets for the considered countries. Main reference: NETP (2013).

	GHG emission reduction targets (CO_2 equivalents) (reference: 1990)				Renewable energy targets, gross final energy consumption		Climate- and energy-related constraints or targets, examples
	2012 (Kyoto)	2020	2030	2050[1]	Reference 2005	2020 (EU)	
Denmark	-21%	-20%[3] (non-ETS) -40% (ETS and non-ETS)		100% renewable energy supply[2]	17.0%	30% (35% national decision)	• An energy system which is independent of fossil fuels by 2050. • All use of coal phased out by 2030[4]. • 100% renewable electricity and heating (District and individual heating) in 2035[4]. • Phase-out of oil for heating in buildings by 2030[4]. • Wind power covers 50% of power production by 2020.
Finland	0.0%	-16%[3] (non ETS)		-80% (domestic)	28.5%	38% (20% renewables in road transport)	• Regulations on the use of water resources (e.g. hydro power) by the Water Act. • Decisions on licences for new nuclear to be adopted by the Parliament.
Norway	+1%	-30% (net, - 40% if climate agreement)	-100% (net, if climate agreement)	-100% (net)	58.2%	67.5%	• Protection Plan for Watercourses, protection of water resources from hydro power. • Two-thirds of emission reductions in 2030 will be domestic (rest through flexible mechanisms).
Sweden	+4%	-40% (non ETS)	Fossil-fuel-independent transport fleet	-100% (net)	39.8%	49% (50% national decision)	• Law to protect some rivers from hydropower. • Phase-out of nuclear power production by 2050[5].
Germany	-21%	-40%	-55%	-80%	5.8%	18%	• Phase-out of nuclear power production by 2022. • Reduction in primary energy of 20% by 2020 and 50% by 2050 compared to 1990 level. • Reduction in electricity consumption: 10% by 2020 and 25% by 2050 compared to 2008 level. • Renewable energy resources in gross electricity consumption: 35% by 2020 and 80% by 2050.
The United Kingdom (Great Britain)	-12.5%	-16%[3] (non-ETS) -34% (ETS and non-ETS)	-50% (by 2027)	-80%	1.5%	15%	• Decarbonising power generation. • Insulating homes better to improve their energy efficiency. • Replacing inefficient heating systems with more efficient, sustainable ones. • Ultra-low carbon vehicles, e.g. electric vehicles.
European Union	-8%	-20% (-30% if climate agreement)			8.5%	20% (10% renewables in transport)	
EU roadmap		-25%	-40%	-80%			

1) Emission reduction targets for Norway (all), Sweden (2050) and Iceland (2050) may include offsets. Finland's 2050 target includes domestic reductions only. 2) Denmark does not have a 2050 target for GHG emissions only, but a target of 100% renewable energy in 2050. Calculations by the Climate Change Policy Commissions show that this target would lead to a reduction of approximately 85% of GHG. 3) Reference year: 2005. 4) Targets set by the Danish Government 2013. 5) Target used in NETP 2016.

Sources: Denmark, Finland, Norway, Sweden: NETP 2013. Germany: Energy Policies of IEA Countries – Germany – 2013 Review. The United Kingdom (Great Britain): Energy Policies of IEA Countries – The United Kingdom – 2013 Review.

by 2030. Today Norway's supply of electricity, and use of energy in buildings are almost carbon neutral, therefore the GHG that are emitted from e.g. the transport and industry sectors, and thus reduction of GHG emission, is challenging. Considering "non-net" targets, Norway has announced the ambitious goal of reducing GHG emissions by 30% by 2020 compared to 1990 levels. according to the 20/20/20 targets, by 2020, Norway has to achieve an energy system in which 67.5% of the total energy use is covered by renewable energy sources (IEA-Norway-Review 2011).

Sweden's long-term vision aims at eliminating net GHG emissions by 2050. Since the energy production in Sweden is almost carbon neutral, the reduction in GHG emissions is related to other sectors, therefore in order to achieve the 2050 target, Sweden has set the ambitious goal of being independent of fossil fuels in the transport fleet by 2030. Regarding the 20/20/20 targets, Sweden has the target of covering 49% of the gross final energy consumption by RES by 2020. Furthermore, by 2020, the policy framework supports 20% reduction of energy intensity, 10% renewables in transport and 40% reduction of GHG emissions compared to 2005 levels, in sectors which are outside the EU Emissions Trading Scheme (ETS) (IEA-Sweden-Review 2013). In addition, decisions regarding use of nuclear power plants in Sweden is discussed, however in NETP (2016) the production from nuclear power plants are phased-out by 2050.

Germany has announced the long-term target of reducing the GHG emissions by at least 80% by 2050 compared to 1990 levels. This target will be achieved by an environmental strategy which includes the intermediate targets; By 2020, 40% reduction in GHG emissions; By 2030: 55% reduction; By 2040, 70% reduction. As an extension to the GHG targets, the German government has announced a set of additional targets: reduction in primary energy of 20% by 2020, and 50% by 2050 compared to 1990 levels, reduction in electricity consumption by 10% by 2020, and by 25% by 2050 with 2008 as reference year; increased share of renewable energy resources of gross final energy consumption to 18% by 2020, 30% by 2030, 45% by 2040 and 60% by 2050, and for renewable energy resources in gross electricity consumption the share has to be 35% by 2020, 50% by 2030, 65% by 2040 and 80% by 2050. In addition, policies regarding nuclear power production was replaced in 2011, such that Germany's future energy strategy includes a phase-out of nuclear power by 2022 (IEA-Germany-Review 2013).

The United Kingdom has stated a long-term vision of reducing GHG emissions by 80% by 2050 compared to 1990 levels, with the intermediate targets of achieving 34% by 2020 and a 50% reduction by 2027. In addition, the UK have to reduce the GHG emissions by 16% by 2020, compared to 2005 levels, in sectors which are outside the EU Emissions Trading Scheme (ETS).
Moreover, as a part of the 20/20/20 targets, 15% of the gross final energy consumption will be covered by renewable energy sources by 2020. Achieving this target means that the share of RES in the UK has to increase more than fourfold compared to 2010. In order to achieve this target, an increment in wind is expected to play a key-role, and the government estimates the electricity production from wind to increase more than seven times from 2010 to 2020 (IEA-United-Kingdom-Review 2012).

3.3 Energy System Planning

Extensive research has been performed in energy system analysis aiming at developing and describing pathways to a future energy system which ensures that the national energy policy targets are achieved.

In Denmark, several studies have presented pathways towards a fossil independent energy system by 2050, where among others, the Danish Energy Agency (DEA) has announced four fossil free energy scenarios towards 2050 (DEA 2014a), and the Danish Commission on Climate Change Policy (2010) presented "the road to a Danish energy system without fossil fuels". In DEA (2014a), the scenarios for the future Danish energy system represents two main pathways, namely towards a bioenergy based energy system, or an energy system relying primarily on wind power. Actions have to be taken now, however, the scenarios illustrate that fossil free Danish energy system can be realised by 2050.

In Finland, research investigating the future energy system have resulted in e.g. "Low carbon Finland

2050" (VTT 2012) and "Energy and Climate Roadmap 2050" published by the Finnish Ministry of Employment and the Economy (2014), each of which aims at achieving the energy policy targets stated in Section 3.2. As Finland has significant bioenergy resources, evidently available resources are expected to play a key role in the entire energy system in the future. In contrast to the other Nordic countries, the energy policy makers in Finland have agreed to expand the nuclear power capacity in the future. The Finnish Parliament has approved construction of new nuclear power plants in the future, which corresponds to more than double the current capacity. Thus the future Finnish energy generation portfolio is expected to rely primarily on forestry-related renewables and nuclear power.

In Norway, the Norwegian Society of Engineers and Technologists (NITO) has presented the Norwegian scenario and action plan for the entire energy system towards 2050 (NITO 2009). As stated in Section 3.1.1 the current Norwegian electricity and district heating system are almost carbon neutral. Thus the composition of the electricity supply portfolio is expected to remain almost the same in the future, and the unique hydro resources which allow large storage facilities are expected to play a key role in balancing the future Nordic power system. However, cheap wind generation technologies can be a larger part of the Norwegian power system in the future.

In Sweden,the Swedish Environmental Research Institute has outlined a future energy system scenario in "Energy Scenario for Sweden 2050" which presents a pathway towards an energy system supplied almost by 100% RES (IVL 2011). This work is, to some extent, built upon the lines of "Swedish long-term low carbon scenario (IVL 2010). As the scenario projects an energy system relying on almost 100% renewable energy sources by 2050, fossil fuels and nuclear power are phased out. Since nuclear power production, in 2013, was corresponding to 43% of the Swedish electricity generation, the transition of the future energy system becomes more challenging, however, the scenario describes a pathway in which bioenergy, hydro and wind power become key technologies by 2050.

In Germany, the Federal Government announced the energy concept in 2010 which presents Germany's energy policy framework towards 2050, which was based on one reference and eight alternative scenarios (BMWi 2010). However, as stated in Section 3.2, the policy regarding nuclear power generation was changed. Thus new energy scenarios are conducted for Germany e.g. BMU (2012) in which long-term energy scenarios are conducted in order to facilitate an increment in renewables.
As a consequence of the energy policy-framework, Germany has promising perspective w.r.t. meet the Kyoto energy targets by 2020. Furthermore, to meet the long-term energy targets announced by the German government, transition towards a RES based energy system, energy efficiency and grid expansion are stated to be key-parameters in the future German energy system (IEA-Germany-Review 2013).
Along with the phase-out strategy of nuclear power production towards 2022, a significant reduction in the use of coal and lignite for electricity generation is expected according to the long-term energy targets. To facilitate the transition from an electricity generation portfolio primarily supplied by coal, lignite and nuclear power plants towards a RES dominated electricity mix, the transmission and distribution grid infrastructure is expected to be a key-element. Thus, cost-efficient investments, reinforcement and expanding the transmission and distribution grid is required in order to ensure a well-functioning German electricity network (IEA-Germany-Review 2013).
In Germany, the transition towards renewable energy sources are in the electricity sector, primarily encourage by considerable increments of both wind and solar PV (IEA-Germany-Review 2013).

In the United Kingdom, the UK energy research centre has presented a work in which a comparative analysis of seven low-carbon, resilient scenarios for the energy system in the UK by 2050 (UKERC 2013). In addition, the Sustainable Development Solutions Network (SDSN), and Institute for Sustainable Development and International Relations (IDDRI) has presented pathways to deep decarbonisation in the United Kingdom, in which three scenarios are presented which project three different pathways (Pye 2015).
The United Kingdom is in the decade where a large generation capacity of fossil fuels and nuclear power are planned to be closed down. Therefore, investments in new generation capacity has to be decided soon. Since the government of the United Kingdom has expressed their intention with regard to increased deployment of low-carbon emitting generation technologies, there are an expectation of a new efficient generation mix which includes higher penetrations of clean energy technologies (IEA-United-Kingdom-Review 2012).
The policy-framework is challenged with regard to. deliver a plan which fulfils the long-term energy and climate policy targets. However, in order to meet the 2020 goal of 15% RES in the gross final consumption, the share has to be increased by more than four times compared to 2010 levels. To facilitate the RES deployment in the electricity sector, wind energy is expected to experience a significant increment. Furthermore, deployment of wind energy technologies are, due to significant wind resources in Great Britain, expected to continue the trend and will thus contribute significantly to meet the long-term energy targets by 2050 (IEA-United-Kingdom-Review 2012).
In addition to the wind power production, the scenarios presented in Pye (2015) show varying utilisation of nuclear power, and that CCS technologies can be a key technology in the future energy system.

Choosing Energy System Scenario

Since each of the above national energy system scenarios are developed using different energy system modelling tools, are based on different assumptions and, to some extent, are modelled as an island system, energy system scenarios for regions including several countries are conducted which take into account the interactions between the countries, e.g. electricity trade (Agora 2015, NETP 2016).
The anticipative Carbon-Neutral Scenario (CNS) outlined in NETP 2016 expresses a pathway for the Nordic regions energy system, which can potentially reduce the aggregated emissions by 85% compared to 1990 levels[3](NETP 2013). The Nordic Energy Technology Perspective (2016), is, for the Nordic countries, using input data adopted from IEA's global ETP-scenarios, whereas the surrounding countries are constructed in order to follow the trend of the 2DS-scenario[4]. The NETP 2016 scenario is acknowledged, and takes into account interactions between countries while hold promise of achieving the national energy policy targets. Thus, in this thesis, the NETP2016 scenario is adopted as an metric for the energy system for each country.

The NETP 2016 scenario will be presented and utilised as follows; Since synergies between the electricity and the district heating system already appears and are expected to be stronger in the future, both the electricity and district heating systems are considered in the present thesis. In Section 6.3 elaborates the implemented and utilised NETP 2016 data e.g. the electricity- and district heating demand for each of the countries. The data input adopted from NETP 2016 are utilised in the model simulations in Sections 7 and 8.

[3] It should however be noted that in order to achieve an energy system which completely is carbon neutral, the reduction of the remaining 15% GHG emissions are obtained by international carbon credits (NETP 2013).

[4] The 2DS scenario is the scenario in ETP, which describes an energy system, which provides at least a 50% chance of limiting global average temperature increase to 2^{o}C. The scenario presents the pathway in which the energy- and process-related CO_2 emissions are reduced by more than 50% by 2050 (compared to 2012) and ensuring to continue the declining trend (ETP, 2012).

CHAPTER **4**

Energy System Modelling Approaches

To meet the thesis objective stated in Section 1.2, an energy system modelling tool is needed. Therefore, in this Chapter, different energy system models using different approaches are presented. Furthermore, the model characteristics required to model the future Nordic energy system in this thesis will be identified. Based on this, the energy system model used in this thesis will be justified.

4.1 Different Approaches for Energy System Modelling

The increased focus on climate change has resulted in both national and international agreements aiming at reducing the environmental footprint caused by GHG emissions. The transition from conventional fossil fuel based energy system towards the future energy system dominated by RES which, furthermore, includes a substantial penetration of VRE, calls for energy system models which can identify the impact of higher penetrations of VRE and, furthermore, present different pathways towards the future energy system.
In the future stronger interactions between the different sectors in the energy system i.e. power, heat and transport, are expected. Thus increasing the penetration of VRE will consequently affect other parts of the energy system. Hence, energy system models can provide valuable information in this regard.
Based on a comprehensive review of 37 existing energy system models, Connolly et al. (2010) state that different energy system modelling approaches are suitable for different purposes, and are depending on the specific research question to be answered. Furthermore, Connolly et al. (2010) differentiate the energy system models based on the following types of terminologies: *Simulation-, Scenario-, Equilibrium-, Top-down-, Bottom-up-, Operation optimisation- and Investment optimisation-* models, however the specific energy system model is allowed to be included in several categories. In the following each of the approaches will briefly be presented.

Simulation models simulates the operation of the energy system in order to supply the specified demands. The time steps in this type of energy system model are typically with a hourly resolution and are simulated over a one year time period. Among others the STREAM model and EnergyPLAN are simulation tools which include the entire energy system, and allow simulating with a hourly time resolution.

Scenario models rely on an approach in which a series of years are combined into a long term scenario. Hence the time-steps are typically one year and the long-term scenarios are typically 20-50 years. Among the analysed energy system models by Connolly et al. (2010) most of the models are capable of be categorised as a scenario model, however, as an example, both Balmorel and TIMES are within this terminology.

Equilibrium models describes the economy by explaining the behaviour of supply, demand and prices.

The equilibrium is identified utilising the assumptions of a competitive market and thereby producers act as price takers. Within the category of equilibrium models, a distinction can be made between two main groups, namely 1) General equilibrium models which includes the whole economy and 2) Partial equilibrium models which mainly has emphasis on few parts of the economy i.e. energy, power, heat. The Balmorel model is an example on a partial equilibrium model which consider the power and heating markets.

Top-down models rely on macroeconomic theory and utilises macroeconomic data to compute general trends e.g. in terms of energy prices and demand. Based on a holistic economic approach aggregations metrics are needed which reduce the level of details. Among others, the STREAM model and the TIMES model can be partly categorised within this terminology.

Bottom-up models have emphasis on sectoral and specific energy technologies and typically allow identification of options for investments. Hence, this terminology of energy system models allow investigations of the energy generation portfolio and allow least costs solutions. Typically, scenario and partial equilibrium models are included in the bottom-up terminology. Hence, both TIMES and Balmorel are included in this terminology.

Operation optimisation models find a solution in which the operation of the energy system is optimised. Energy system models within this terminology are typically simulation models e.g. EnergyPLAN. Furthermore, partial equilibrium models which enable high time step resolution e.g. Balmorel, can facilitate optimisation of dispatch problems including hourly dispatch of the energy production.

Investment optimisation models allow optimisation of investments decisions e.g. generation technologies and transmission capacities. Scenario and equilibrium models e.g. Balmorel, TIMES are included in this terminology as well.

In extension, of the above, the stated model approaches could further be divided by the level of details w.r.t. *temporal resolution* and the *geographical areas*. In general, the computational time increases with the level of temporal steps and included geographical areas. Thus both the temporal resolution and the included geographical area, varies depending on the model and thereby the purpose of the study.
Top-down and general equilibrium models typically has low temporal resolution i.e. in the range of years, however, the geographical detail includes country, continent or global levels. Simulation models e.g. STREAM and EnergyPLAN, and operation and investments optimisation models e.g. Balmoral and TIMES, are typically characterised as models with a high or medium temporal resolution.

In addition to the above, Connolly et al. (2010) have identified the sectors i.e. power, heat and transport which are included in each of the energy system models. Among the energy system models, STREAM, TIMES and EnergyPLAN encompass the entire energy system including all sectors, while BALMOREL includes the power and heating sectors, however BALMOREL has previously been used to partly model the impact of electric drive vehicles (Juul 2011).

4.2 Important Characteristics for the Choice of the Energy System Model

Based on the above, evidently the different energy system model approaches are suitable for different purposes aiming at answering different research questions. Therefore, this section will present the characteristics of the energy system model which can answer the research question by performing a quantitative assessment of the options for integrating a higher penetration of fluctuating RES-E in the future Nordic energy system, with emphasis on the two flexibility options: transmission grid infrastructure and demand-side flexibility. The important characteristics for the energy system model utilised in this thesis are as follows:

- A *bottom-up* model which allows for a detailed description of the specific generation technologies in the sectors of the energy system. Since interactions between the different sectors of the energy system are expected to be stronger in the future, thus the energy system model is required to include both the power and district heating sector.
- A *partial equilibrium* model which allows utilisation of a *scenario* approach, toperform a *simulation* and facilitate an *optimisation* is requested. The model optimisation i.e. maximising social welfare is required to be based on economic theory taking into account the system perspective, and ensuring energy balancing between supply and demand. Furthermore, *investment optimisation* is required in order to allow endogenous investment decisions in e.g. transmission capacities or new generation technologies.
- high *temporal resolution* and covering a large *geographical area* are required since the future Nordic energy system is expected to entail a substantial penetration of VRE. Thus the energy system model in this thesis is required to be capable of modelling the characteristics of VRE mentioned in Section 2.1 e.g. variability and location specificity. To model the variations caused by VRE technologies, a high temporal resolution is needed, whereas location specific VRE generation can be facilitated by including a large geographical area.
  Furthermore, since this thesis focuses on the future Nordic energy system, the energy system model is required to enable a geographical structure which includes all countries and allows the trade of electricity between countries and regions within the country e.g. regions as in NordPool.

The above identified characteristics for the energy system model in this thesis is in accordance with the recommendations from Hirth (2013) which concludes the following: *"In terms of methodology, we conclude that any model-based evaluation of the value of VRE needs to feature high temporal resolution, account for operational constraints of power systems, cover a large geographic area, take into account existing infrastructure, and model investments endogenously."* (Hirth 2013, p. 234).

4.3 Choice of Energy System Model

Based on the important characteristics of the energy system model, the Balmorel model was chosen since it fulfils the stated criteria. The Balmorel model relies on a bottom-up approach and is a partial equilibrium model in which the temporal resolution and the geographic areas can be manually defined and modified. Furthermore, the Balmorel model takes into account the existing generation technologies and transmission lines, and allows for new endogenous investments.
The original Balmorel model includes the Nordic countries and Germany, however, a modified and improved Balmorel model has been developed in this thesis (Section 6.0.1).
The Balmorel model is used by several universities e.g. DTU and NMBU and consultancies e.g. Ea Energy Analyses and The Danish Energy Association. Among others the Balmorel model has been used in NETP (2016) with the purpose of analysing the future Nordic energy system including flexibility options. In Agora (2015) the Balmorel model was applied with the emphasis on investigating the increased integration of the Nordic and German electricity systems towards 2030. The Balmorel model has furthermore been a part of Tveten (2015) in which the effects, challenges and integration options for renewable energy in the Northern

European power markets were investigated.
Hence, the Balmorel model is widely applied in acknowledged projects within energy system analysis and is thus suitable for the purpose of the present thesis.

CHAPTER 5

Balmorel - Energy System Model

In this chapter the energy system model chosen for this thesis - Balmorel - will be thoroughly described. The main characteristics and the modelling framework will be presented, followed by a presentation of the objective function and the subjected main constraints. A simplified overview of the model dynamics, including the main constraints, are presented. Furthermore, a simplified description of the structure through a subdivision into its main dimensions are provided. This chapter provides therefore an overview of the structure of the Balmorel model, which further will be used in Section 6.0.1 in order clarify the model developments. Finally, the main model limitations will be critically identified and discussed.

5.1 Characteristics of the Balmorel Model

BALMOREL (BAltic MOdel of Regional Energy Liberalisation) is a linear optimisation model which includes both the electricity and district heating sectors (NordicModels 2001). As aforementioned, the Balmorel model relies on a bottom-up modelling approach and is, furthermore, a deterministic, partial equilibrium model which assumes perfect competition (Juul 2011). The objective of the model is to maximise social surplus subjected to electricity and heat balance equations, technical conditions which include e.g. generation and transmission capacity, and the potential of energy resources within a geographical area.
The Balmorel model entails a comprehensive representation of technical components in the current energy system e.g. electricity and heat generation technologies and transmission capacities and the important related bottlenecks. Furthermore, it computes the conversion of primary energy to electricity and heat which, subsequently, are transferred to the end-user through the transmission and the distribution grid.
The Balmorel model allows both exogenous and endogenous investment decisions. Exogenous investments refer to planned new transmission and generation capacities. While endogenous investments are internally determined by the Balmorel model and are therefore a result of the solution e.g. new generation capacities (wind, biomass, coal, gas, etc.) or new transmission capacities between regions as a consequence of an increased penetration of VRE in the future.
Constructing different scenarios in Balmorel is facilitated by modifying the input data (Juul 2011). Furthermore, the temporal resolution in Balmorel is user defined and the structure of the Balmorel allows model-developments such as including more countries and increasing or reducing the levels of detail e.g. regions and areas within the country, depending on the research question.
For these reasons, the Balmorel model is very suitable for both long-term planning and for the planning of short-term operation e.g. of dispatchable power plants in both the power and the district heating sectors (Ravn 2001).

5.2 Functionalities in Balmorel

The following section will present the functionalities of the Balmorel model. By introducing the objective function and the main constraints, the model dynamic will briefly be presented. To clarify the model input, the complex structure of Balmorel will be simplified and a graphical representation of the simplified algorithm in Balmorel will be presented.

5.2.1 The Objective Function and the Subjected Constraints

The objective function in Balmorel maximises consumer's utility minus the cost related to generation and transmission, which is equivalent to minimise the costs related to generation and transmission minus the consumer's utility. The mathematical representation of the Balmorel model is presented in Appendix A.

$$
\begin{aligned}
&\textit{minimise Objective function} = \\
&\qquad\qquad\qquad \textit{Fuel costs} \\
&\qquad\qquad\qquad \textit{O\&M costs (fixed and variable)} \\
&\qquad\qquad\qquad \textit{Hydro with storage} \\
&\qquad\qquad\qquad \textit{Transmission costs} \\
&\qquad\qquad\qquad \textit{Capital costs (new units)} \\
&\qquad\qquad\qquad \textit{Emission taxes} \\
&\qquad\qquad\qquad \textit{Fuel and energy taxes} \\
&\qquad\qquad\qquad \textit{- consumer's utility relative to nominal utility of consumption}
\end{aligned}
\tag{5.1}
$$

In the present thesis, the demand is assumed to be inelastic and thus maximising the social surplus is equivalent to minimising the costs for the entire energy system. Hence, the Balmorel model performs a least-cost optimisation, since costs of supply are minimised when considering a fixed exogenously defined demand.

The objective function is subjected to a set of constraints. Based on a simplified general description, the main constraints are presented in the following.

- Production constraints
  - ◦ Electricity and heat generation technologies in operating areas
  - ◦ Production of dispatchable and non-dispatchable generation technologies
  - ◦ Emissions
  - ◦ Fuel potential
- Capacity constraints
  - ◦ Production constraints on capacities
- Balance constraints
  - ◦ Balancing electricity and heat supply and demand
  - ◦ Balances of storage facilities
- Transmission constraints

In the following paragraph, an overview of the model dynamics with emphasis on the above presented constraints is introduced.

5.2.2 Model Dynamics with Emphasis on the Constraints

The structure of the Balmorel model is complex and entails several linkages in the conversion of primary energy to final electricity and heat consumption. Interactions between the electricity and heating sectors are facilitated by the model, while fulfilling the defined constraints. With emphasis on the specified constraints Figure 5.1 provides a simplified overview of the interactions in the Balmorel model.

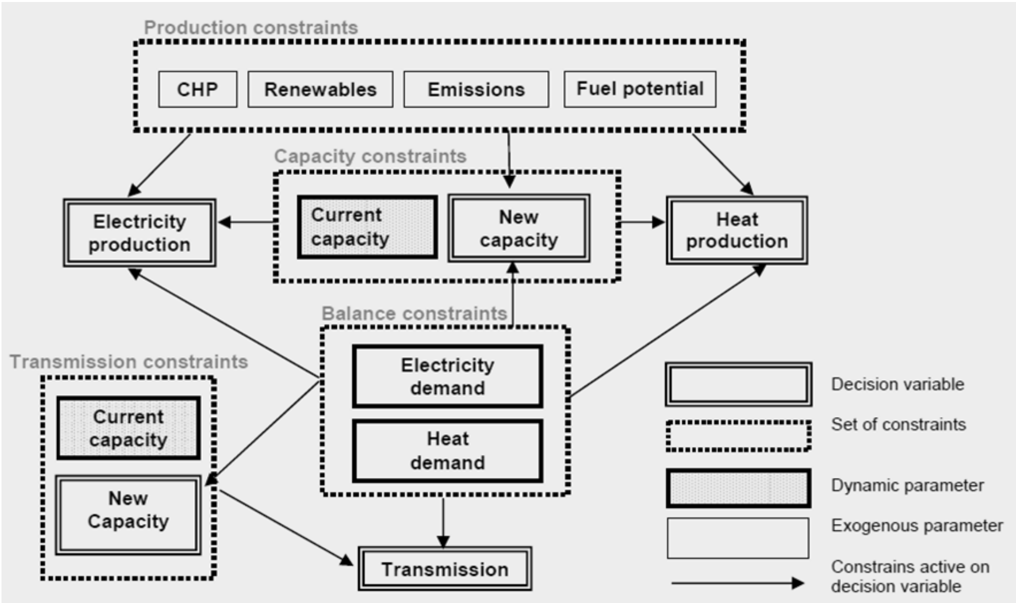


Figure 5.1: Model dynamics - which shows a simplified overview of the interactions in the Balmorel model with emphasis on the constraints. Illustration taken from (Hindsberger 2003).

The *balance constraints* for electricity and heat are essential in Balmorel, and requires balancing between supply and demand at each time point. The nominal demand for both heat and electricity are exogenously defined and can be specified to be either elastic or inelastic, see Sections 5.2.4, 6.1.3 and 6.3.2. In order to meet the demand Balmorel computes the combination of generation possibilities i.e. current and new installed technologies, which are needed, while taking into account the amount of imported or exported electricity which are determined by the exogenously defined existing capacity, and the endogenously computed new transmission capacity.

The *production constraints* restrict the operation and production of the generation technologies and include the general boundaries e.g. GHG emissions and available resources, which are related to the production of electricity and heat. The economic parameters for each generation technology e.g. investments and O&M costs and efficiencies are exogenously defined and in combination with prices for primary energy, which are regionally dependent, the decision to invest in new capacities are determined. However, *capacity constraints* of generation technologies exogenously restrict the deployment of new generation technologies.

In addition to the determination of the energy production within each sub-system, Balmorel allows electricity transfer between regions[1] based on an optimisation process considering the costs of generation within each region. Thus the generation cost is minimised for the entire energy system since the price differences are balanced by electricity transmission. Based on the optimisation process, Balmorel has the possibility to invest in new transmission capacity in case it provides social benefit and thus contributes to the optimal solution, however, the *transmission constraints* are required to be fulfilled.

[1] The Geographical representation in Balmorel is presented in Section 5.2.3

5.2.3 Dimensions Included in the Balmorel Model

As presented in the previous section, the Balmorel model is a complex model, however the following section presents the main dimensions i.e. *Geography, Time* and *Technology* which are utilised to specify the elements included in the Balmorel model. The main dimensions which will be specified in the following section provides the structural background, which subsequently will be utilised in Section 6.0.1..

Geography

The Balmorel model permits a geographically distinction of entities. In the current Balmorel model, the geographical representation includes three sub divisions i.e. Countries, Regions and Areas, which are illustrated in Figure 5.2.

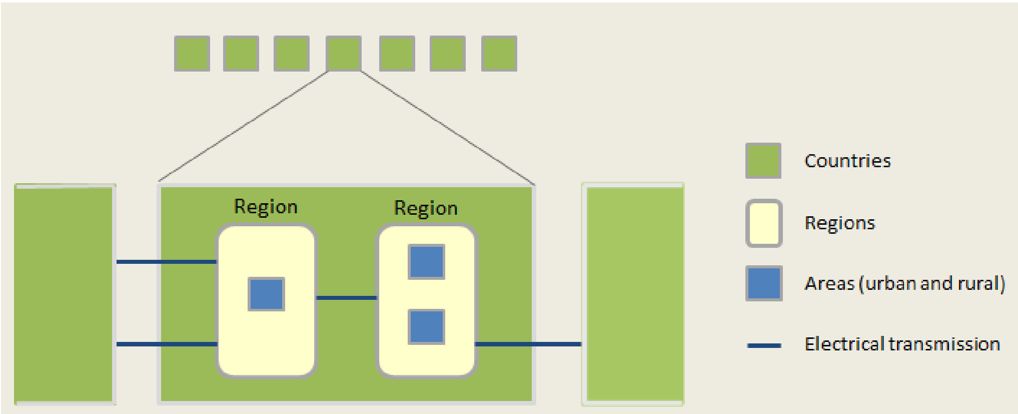


Figure 5.2: The geographical structure in Balmorel has the following sub division; Countries, Regions and Areas, where Areas can be sub divided into either Urban or Rural areas. Furthermore, the possibilities of electricity transmission between regions and thereby countries are presented. Based on (Ravn 2012).

As illustrated in the figure, the geographical structure in Balmorel is characterised by the subdivision in which Countries are constituted by Regions which includes Areas which subsequently can specified as either Urban or Rural areas. This geographical distinction of entities allows for specifications of geographical characteristics e.g. resource potential, generation- and transmission capacities, policies etc.
The geographical characteristics specified at the Country level include e.g. national energy and environmental policies, taxes and resource potential (Ravn 2012).
At the Regional level the Balmorel model deals with e.g. the geographical constraints w.r.t. electricity transmission and the electricity balance constraints. Hence the exogenously variable electricity demand is defined for each Region, and the model subsequently generates, endogenously, the electricity price for each Region.
Areas can be sub divided into either urban or rural areas. At the Area level district heating is distributed. As illustrated by Figure 5.2.3, the district heating network between Areas are not connected and thus heat is not allowed to be exchanged between areas[2]. Among other entities which are related to the Area level are profiles for both VRE generation technologies, which produce according to a variable production profile e.g. wind, solar, run-of-river hydro power, and dispatchable hydro power generation which includes the annual quantity and seasonal variations w.r.t. the availability of water from the hydro reservoirs.

[2]It should be noted that an addon is developed which allows for transfer district heat between Areas. However it is not used in the current Balmorel model

Temporal Structure

The temporal dimension in Balmorel permits different temporal resolutions depending on the specific research question to be answered. In the current Balmorel model, the temporal structure includes three sub divisions i.e. Year, Season and Time.
The Balmorel model computes one Year at a time by utilising the specified metrics for the simulated Year e.g. annual electricity and heating demand and the available capacity for electricity and heat generation.
The Year is sub divided into Seasons, which typically has a temporal resolution of 4 (seasons of the year), 12 (months) or 52 (weeks) time segments.
Furthermore, an hourly time resolution can be obtained by utilising the segment Times, which is the subdivision of Seasons. This time-segment represents the highest time resolution and provides the highest level of detail. Hence this high temporal resolution is used for the purpose of performing unit commitment simulations of the energy system, or simulating an energy system which has a high penetration of VRE generation technologies which are associated with varying load profiles.

Generation Technologies

In order to meet the electricity and heat demand, Balmorel computes the combination of generation possibilities i.e. current and new installed technologies. In the current Balmorel model, 13 basic technology types for the generation of electricity and heat are defined. The distinction of the generation technologies includes both technical and economic specifications i.e. fuel type, efficiency, possibility of generation of both electricity and heat, emissions and investment- and O&M-costs. In Appendix A, a representation of the feasible operation areas for each of the generation technologies is provided.
Technologies can, in general, be characterised by either dispatchable or non-dispatchable generation technologies. Dispatchable generation technologies are dispatched depending on the market conditions and the specifications related to the energy product performed by the technology e.g. efficiency, O&M- and fuel costs. Non-dispatchable generation technologies are primarily VRE technologies which have a varying production profile and, furthermore, have a negligible marginal cost of operating. Thus from a market perspective, the expected increment in implementation of VRE generation will, due to their low marginal costs, have an impact on the electricity market i.e. the merit-order effect, as described in Section 2.3.

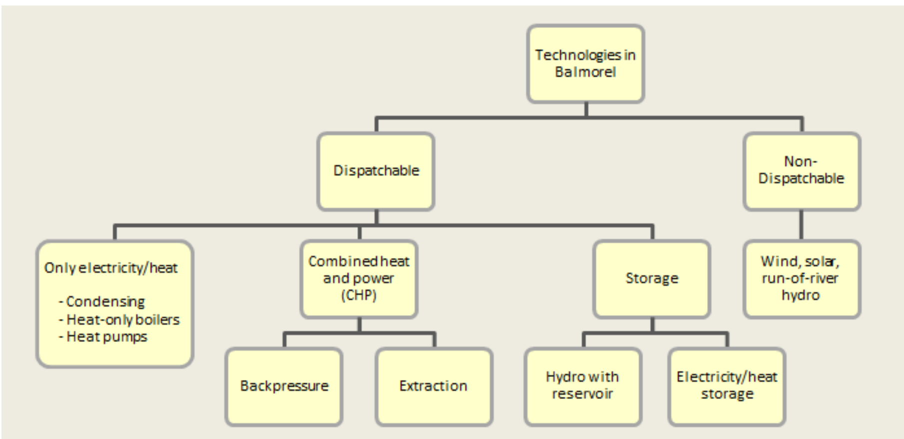


Figure 5.3: Structure of generation technologies in Balmorel. The generation technologies are characterised under two umbrella groups. i.e. dispatchable and non-dispatchable generation technologies. Based on work in Dittmar (2006).

Figure 5.3 provides an overview of the structure of the generation technologies in Balmorel. The generation technologies in Balmorel can be characterised under two umbrella groups. i.e. dispatchable and non-dispatchable generation technologies, as illustrated by Figure 5.3. As illustrated by the figure, the category of dispatchable generation technologies are further distinguished by the following sub-categories i.e. Only electricity and heat producing technologies, combined heat and power (CHP), and storage technologies. The sub-category 'only electricity and heat producing technologies' include condensing power plants, heat-only boilers and heat pumps/electric heaters.
Combined heat and power plants can be operated in either back-pressure or extraction mode. In Appendix A, a representation of the feasible operation areas for both back-pressure- and extraction- CHP plants is provided. Evidently both generation technologies are producing both electricity and heat, however, back-pressure plants produce electricity and heat determined by a fixed ratio, whereas in extraction plants the electricity to heat ratio can vary.
The sub-category 'storage technologies' entails hydro power with storage facilities and electricity or heat storage technologies.
The non-dispatchable generation technologies includes VRE generation technologies which have a variable availability profile i.e. wind power, solar power (PV), solar heat, run-of-river, and wave power.

5.2.4 Demand

With emphasis on demand-side flexibility as one of the flexibility options to facilitate the increased penetration of VRE in the future energy system, the modelling procedure of the electricity and heat deamad introduced in Balmorel are essential to introduce. However, a more thorough description of modelling demand-side flexibility in Balmorel will be presented in Section 6.1.3.
As described in Section 5.2.3 the electricity demand is specified for each Region while the heating demand is specified at the Area-level. This specification, for both the electricity and heating demand, includes the following three elements which are specified for each geographical entity (Elkraft-System 2001).

- A nominal value for the demand i.e. electricity or heat, which are specified for each year included in the simulation period. This nominal value is thus an annual quantity.
- A nominal demand profile, which defines the distribution of the annual demand quantity over the defined time periods (Season and Time) within the Year.
- A demand elasticity function, which defines the relations between the consumed quantity of electricity or heat and price for deviations from the nominal demand profile.

The nominal demand and demand profile are exogenously specified in the model. In case the demand is assumed to be inelastic, the specified nominal demand following the demand profile is equivalent to the actual demand. Furthermore, in this case maximising the social surplus is equivalent to minimising the total system cost. However, in case the demand is specified to follow the characteristics of the demand function assuming own-price elasticity, the last element stated in the above, is considered. By introducing an own-price elasticity function in Balmorel, which refers to the relative change in the demanded quantity divided by the relative change in the price, the model endogenously computes deviations from the nominal demand profile at each point in time (Ravn 2012).

5.2.5 Flow Diagram

The Balmorel model is a deterministic energy system model assuming perfect foresight within one year. However, by utilising Balmorel in long-term planning of the energy system, the optimisation process is computed on yearly basis. The endogenously determined results, obtained by the yearly optimisation process e.g new generation capacity, are transferred to the following simulated year. Therefore, investments-decision in the Balmorel model relies on the simulated year since the model does not have perfect foresight over the full modelling period. This dynamic modelling approach ignores future changes in e.g. fuel prices, introduction of CO_2 emission quotas, etc., and thus includes the possibility of making non-optimal long-term investment decisions which consequently results in higher system costs. In Figure 5.4 a simplified algorithm presents the dynamic linkages of endogenously computed results between the simulated years.

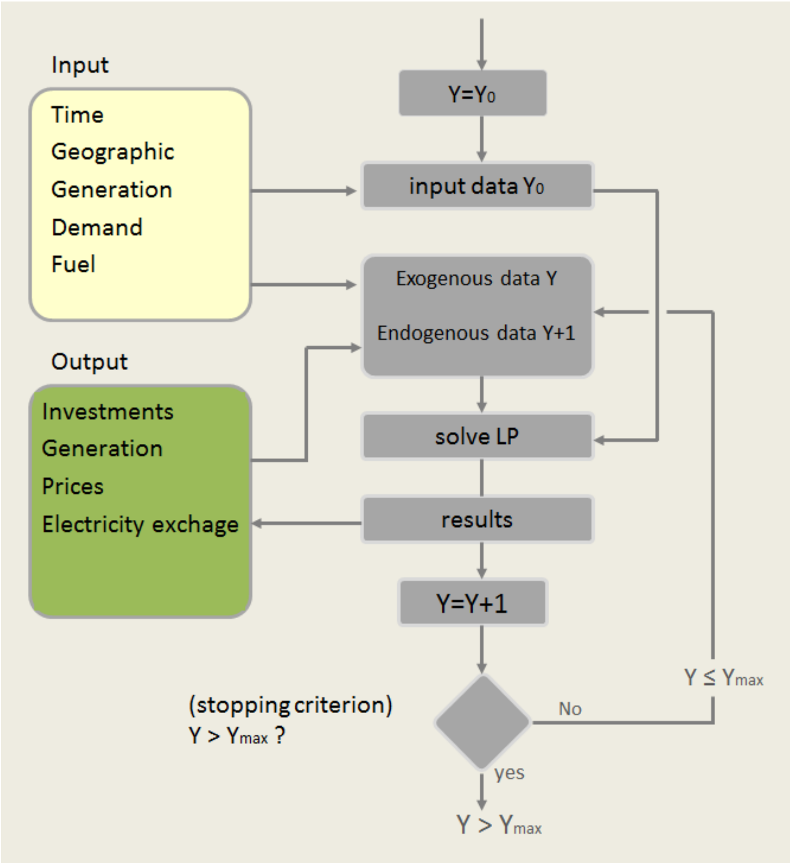


Figure 5.4: Flow diagram, which shows a simplified algorithm that presents the dynamic linkages of endogenously computed results between the simulated years and the how the exogenous defined data are fed into the Balmorel model. Based on work in Felstedt and Pedersen (2005).

In addition to the dynamic modelling approach and the linkages of investments decisions between the modelled years, the main input data are organised according to the dimensions in Balmorel, as described in Section 5.2.3 and 5.2.4. Furthermore, the main results obtained by the model simulation are presented in the figure and include prices, investments-decisions, fuel consumption, electricity transmission, etc.

5.3 Limitations of the Balmorel Model

Although the Balmorel model fulfils the important criteria of an energy system model, as stated in Section 4.3, and furthermore is a complex dynamic model, which is strong in long-term planning of the power and district heating systems, the model is subjected to assumptions and limitations regarding e.g. the market structure, technological utilisation and uncertainty of collected data. In this section, the five main model limitations are listed.

Perfect competition is assumed for the market structure in Balmorel. It refers to a theoretical market structure in which four preconditions have to be fulfilled (Boisselau 2004) i.e. 1) Atomicity: No single buyer or producer has the market power to affect the price due to a large amount of buyers and producers, 2) Homogenous products: identical products provided by the competitors, 3) Free entering or exit to the market for any competitor, 4) Perfect information about the prices set by all producers. Since this assumption excludes the aspect of strategic behaviour by market players, and the producers act as price takers and thus bids into the market at their marginal cost, the equilibrium and thereby the spot price is determined in Balmorel. However this theoretical market structure is hardly to achieve in any real energy markets.

The Balmorel model is a *deterministic* energy systems model, and assumes perfect foresight up to one year. Thus, the model cannot solve events which are characterised by stochastic properties. In Balmorel, the stochastic nature of the energy production generated by VRE technologies or the energy demand are modelled by fixed (though time-varying) time-series. Relying on this modelling approach, the Balmorel model only includes the variation in the energy production or consumption, caused by VRE and the demand profiles, and therefore does not include imperfect predictability issues related to e.g. wind forecasts.

Myopic investment decisions characterises the model dynamic implemented in the Balmorel model and refers to a optimisation process in which the model is computed on yearly basis. This implies that the model computes each year separately and thus presents the decisions of new investments e.g. generation and transmission capacities, without information regarding the future externalities. Relying on this modelling approach, the Balmorel performs endogenous investments which do not affect or take into account the future exogenously defined input data[3].

The electricity transmission system is connected by Regions in the Balmorel model. Within each Region, the electricity is transferred to the consumers by an unconstrained distribution grid. Since in reality the Region covers a large geographically area, this assumption would require extensive investments in the existing distribution grid. However, the Balmorel model allows new Regions to be included in the model, and thus provides a more realistic representation of bottlenecks within the electricity transmission system.

Furthermore, a wide rage of transmission grid related issued are not included in the Balmorel model. Since the Balmorel relies on the assumption of electricity balance between supply and demand at all points in time, the first step in ensuring frequency stability is taken, however the Balmorel model does not include issues related to voltage and angle power system stability. Moreover, the issues related to control of the power system and the ancillary services required to facilitate stable operation of the electricity are not included e.g. primary- and secondary reserves.

Uncertainty of input data is always a main issue in the performance of a proper and realistic modelling of the future energy system, since the computed model simulation results are highly dependent on the availability of relevant and valid input data which have the sufficient levels of detail. In particular, input data regarding predictions for the future e.g. fuel prices, are associated with uncertainties since these projections are dependent on many different parameters which increase the complexity of the projections.

[3]It should be noted that a new version of the Balmorel model currently is under development which allows simultaneously optimisation exogenous and endogenous investments for all Seasons and Time steps over all Years.

CHAPTER 6

Modelling the Future Energy System - Setup, Improvements and Data Collection

In extension of the choice and description of the energy system and the energy system model, this Chapter will elaborate, in accordance with the thesis objectives presented in Section 1.2, the modelling setup, main assumptions and data included, which allow modelling of the future Nordic energy system.
Based on a brief description of the basic model setup, the geographical representation and temporal resolution utilised in the model simulations will be presented. Furthermore, the modelling approach utilised to facilitate appropriate demand-side flexibility, which will be used in the second case-study in Section 8, is thoroughly described.
Following the description of the model setup, a brief description of the anticipative scenarios assessed in this thesis will be presented. As identified in Section 5.3, in order to facilitate an appropriate and realistic energy system assessment, the input data are required to be relevant, valid and include an adequate detail level. Therefore, the collection of data and the assumptions made in the implementation of the data in Balmorel, are presented.

6.0.1 Model Developments and Improvements

In accordance with the thesis objectives presented in Section 1.2, the Balmorel is improved as a part of this thesis. Therefore, the main model improvements are briefly described in this section and will further be elaborated later in the thesis (Section 6.1.1, 6.1.3, and 6.3).

Geographical representation. As identified in Section 4.2, the energy system model utilised to assess the future Nordic energy system with entails a substantial penetration of VRE is required to cover a large geographical area. The original Balmorel model entails several countries, however, since the input data has not been updated for all the included countries, then these countries are excluded (Russia, Poland, Estonia, Latvia, and Lithuania). In the original Balmorel model the Nordic countries and Germany are included, however, in addition, the model utilised in this thesis has been developed to include Great Britain.
Furthermore, as described in Section 5.2.3, the detail level within each country is defined by the number of Regions and Areas that are included. In the Nordic region the trade of electricity in the Nordic countries is handled by the NordPool spot market. Since the Nordic countries are modelled in this thesis, the Regions within each country are extended to be in accordance with the price bidding-regions represented in Nordpool. Moreover, the original Balmorel model has previously been utilised to perform assessments with strong focus on the Danish heating system. Thus the original Balmorel model include many Areas in Denmark e.g. 21, however in another study the Areas in Denmark were aggregated to 10 Areas, which, for the purpose of

the present thesis, is adequate.

Updated input database. To facilitate a proper and realistic energy system assessment, the input database in the original Balmorel model was required to be updated with relevant, valid input data which includes the adequate level of details. The updated data implemented in the Balmorel model includes e.g. existent electricity and heat production capacities, and existent and planned transmission capacities. In addition to the modified input data regarding the existent electricity and heat production capacities, the corresponding generation technology specific data has been updated by means of costs, efficiencies, ramping times etc.
In addition, the construction of the scenario in Balmorel is facilitated by changing the input data with regard to future; electricity and heat generation capacities or physically amount produced, energy demands, fuel prices, GHG emission taxes, etc. A further elaboration of the collected and updated input data will be presented in Section 6.3.

6.1 Model Setup

Modelling the future energy system requires an adequate model setup. The present thesis has emphasis on two flexibility resources i.e. transmission grid infrastructure and demand-side flexibility, which will be investigated through two case-studies. In order to facilitate the modelling of the two flexibility resources, two different model setup are utilised w.r.t. optimisation option, temporal resolution and electricity demands. In the Balmorel model three different options to perform the model simulation are allowed:

- Simultaneously optimisation of exogenous investments for all Seasons and Times within a Year.
- Simultaneously optimisation of both exogenous and endogenous investments for all Seasons and Times within a Year.
- Optimisation of exogenous investments of one Season at a Time, forwards through Seasons[1].

For the purpose both the case-studies, the model is required to include possibility to endogenously invest in both additional generation and transmission capacity. By allowing endogenous investments in additional transmission capacity, an assessment of utilising the transmission grid infrastructure as a flexibility resource can be facilitated, which is the purpose of the first case-study, Chapter 7. In addition, by utilising the option in which endogenous investments are allowed, discrepancies between the composition of the production of electricity and district heat can be investigated for different scenarios e.g. scenarios in the sensitivity analysis and perform a comparison between the two case-studies.
In addition, the approach for facilitate the modelling of demand-side flexibility in Chapter 8 is as follows. *First* the modelling options is chosen to include endogenous investments in both generation and transmission capacity, in order to perform a comparative analysis of the discrepancies in the composition of the production of electricity and district heat and the endogenous investments additional transmission capacity between the Base scenario and the Flex scenario. *Secondly* the results obtained in the Flex scenario is exogenously implemented in the model, which subsequently is run utilising the option in which an simultaneously optimisation of exogenous investments are performed in order to present the hourly results obtained from the model simulation. The temporal scope chosen for the assessments are further elaborated in Section 6.1.2. In the simulations in which simultaneously optimisation of both exogenous and endogenous investments is utilised are allowed, the model is allowed to perform investments in additional generation- and transmission

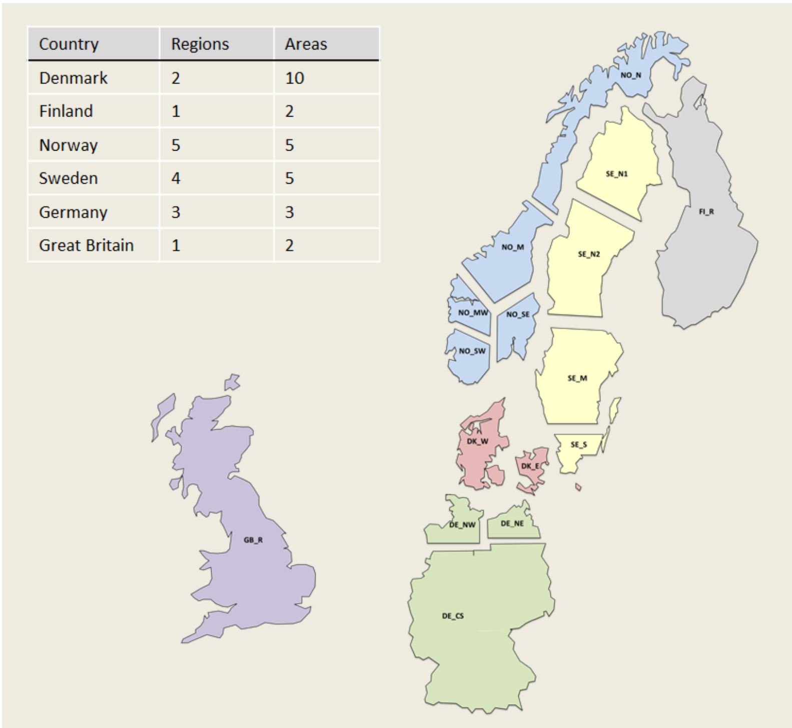
[1]As stated in the previously Chapter, a new version of the Balmorel model currently is under development which allows simultaneously optimisation exogenous and endogenous investments for all Seasons and Time steps over all Years.

capacity from 2021 and 2026. The planned transmission capacity until 2025 is exogenously implemented in the Balmorel model, which will be further elaborated in Section 6.3.3.

6.1.1 Geographical Scope

Modelling the future energy system requires a well defined geographical scope which allows a realistic representation of both the electricity transmission- and the district heating systems. As described in Section 5.2.3, the transmission of electricity appears between Regions, whereas district heating is distributed within Areas and is not allowed to be transferred between Areas.

As stated in Section 6.0.1, the geographic scope is modified for the purposes of the present thesis. The model developments allow a Regional representation of the price-bidding Regions in accordance with the current NordPool market. This representation is illustrated in Figure 6.1.



Country	Regions	Areas
Denmark	2	10
Finland	1	2
Norway	5	5
Sweden	4	5
Germany	3	3
Great Britain	1	2

Figure 6.1: Geographical representation of the Countries and Regions included in the present Balmorel model. Furthermore, the table included in the figure, provides information regarding the numbers of Regions and Areas within each Country. Based on: map constructed by EA-Energy Analysis.

In addition to the illustrated geographic representation, a table is presented in Figure 6.1 which provides information regarding the numbers of Regions and Areas within each Country.
As illustrated by the figure, Germany is represented by 3 Regions, however, in the current German electricity market includes only one price-zone. Increasing imbalances between supply and demand appear due to technically infeasibilities caused by limited transmission capacity. Hence, congestion managements are required to handle and solve these imbalances. Thus in the literature the single price zone in Germany is studied to investigate the effects of introducing two price zones in the German electricity market (Egerer et al. 2015). In this thesis, three price bidding Regions are included in the Balmorel model due to the better representation of the transmission network and potential bottlenecks in the grid. It should, however, be noted

that the Region DE_CS includes the highest share of electricity demand and generation units, which will be thoroughly elaborated in Section 6.3.
In accordance with the thesis objectives Great Britain is modelled and included in the geographical scope. In order to perform this modelling, several assumptions have been made. Great Britain is assumed to be connected to Germany by a transmission line between GB_R and DE_CS. However, in reality this transmission line from Great Britain is connected to the Netherlands. Thus, in the present Balmorel model, transmission connections to the Netherlands are implemented to the central south Germany, this modelling choice is further described in Section 6.3.
Furthermore, Great Britain is modelled as one Region including three district heating Areas. This choice is made even though the current district heating network in Great Britain not is developed, as described in Section 3.1 and 6.3. However, since Great Britain is modelled to include three district heating Areas, the ability to model scenarios for Great Britain in which a higher share of heat provided by the district heating network appears.

6.1.2 Temporal Scope

In addition to a well-defined geographical scope, the specification of the temporal scope is of high importance when an assessment of the options for integrating VRE generation technologies in the future Nordic energy system, as identified in Section 4.2.
In accordance with the thesis objectives described in Section 1.2, two case-studies will be performed assessing two different flexibility resources 1) the future expansion of the transmission capacity and 2) demand-side flexibility. The temporal scope utilising to perform the two assessments are diverse, and thus in the following paragraph be described separately.

Assessment of Future Expansion of the Transmission Capacity
In the first case-study the model is simulated utilising the option in which the model performs an investment analysis which allows for a determination of the optimal investment decisions within the simulated year of both generation and transmission capacities, while the model is subjected to the specified constraints. Based on this, the model computes the optimal energy system configuration up to 2050 by simulating the base year which is 2014 and from 2020 simulating with ten-year steps.
As the Balmorel is utilised to perform a long term anticipative scenario in which endogenous investments are allowed, the Balmorel model is simulated utilising an aggregated time resolution in which each of the 52 Seasons are divided into five Time-periods.
Based on this time aggregation, each Year is simulated with a time resolution i.e. 260 time segments per Year. The temporal model setup illustrates that the level of details of the simulation in the Balmorel model could be increased, however according to the scope of this project and due to the computation time of the model simulation, the above presented temporal model setup is chosen for the long-term investment simulations[2]. Utilising this time resolution to perform long-term investments scenarios is applied previously in e.g. Karlsson and Meibom 2008.

Assessment of Increased Demand-side Flexibility
As stated in Section 6.1, to facilitate the modelling of demand-side flexibility two model simulations are performed. *First*, the long-term investment simulation is performed which utilises an identical temporal

[2]It should be noticed that the temporal model setup should be changed in cases where the investigated research question concerns a dispatch problem. In such case, a hourly time resolution is required in order to determine the optimal dispatch for the investigated energy system. These dispatch analysis requires longer computation time, and thus typically only one year is simulated.

resolution as described in the above. *Secondly*, to assess the implementation of demand-side flexibility on an hourly time scale, an hourly simulation is conducted for year 2050, which includes the additional generation and transmission capacity which is endogenous determined in the long-term investment simulation.

6.1.3 Model Setup - Demand-side Flexibility

As stated in Chapter 2, the type of demand-side flexibility which is investigated in the present thesis is load shifting. Load shifting is beneficial in comparison to other DSF options, since it has the same functionality as energy storages while having no energy conversion losses related to the process, as identified in Section 2.2. In order to facilitate the modelling of DSF in Balmorel, different approaches can be utilised.
As stated in Chapter 5, the Balmorel model is prepared to facilitate elastic demands by utilising a demand function which rely on the concept of own-price elasticity. This approach has previously been utilised in Grohnheit and Klavs (2000). However, for the purpose of the present thesis, where the the investigated effects are related to load shifting demand side flexibility, this approach con not be used, since the demand either will growing or disappear, following the description in Gellings and Smith (1989).
However in this thesis the following modelling approach will be utilised. In the description of the modelling approach, previous applications of the specific demand side flexibility aspect will be presented.

Approach utilised to model demand-side flexibility
Load shift as DSF option has previously been investigated utilising Balmorel. In Agora (2015), load shift in the German electricity system is modelled as a virtual storage facility for electricity which have no associated costs or losses. This entails that the total electricity demand is unaffected over the considered period. To facilitate the modelling, the maximum size of the virtual electricity storage was defined to 4 hours of load. Thereby the modelling approach allow a maximum defined amount of energy to be shifted in time without losses and costs associated to the process.
In Agora (2015), the demand-side flexibility is modelled as one part of energy which is allowed to be shifted in time. The modelling procedure do not take into account properties for specific technologies e.g. electric vehicles or hydrogen. Therefore, to increase the level of details in the modelling of demand-side flexibility, previous developed add-on's for modelling electricity vehicles and hydrogen can be utilised.
In Balmorel, electric vehicles is modelled utilising a profile in which variation of electricity demand from electric vehicles are based on a combination of night and day charging. The profile is developed by EA Energy Analyses in EA (2011) and is illustrated in Appendix A.
In addition, hydrogen produced by electrolysis can potentially provide flexibility in the future, as iterated in DEA (2014a) and Danish-Energy-Association (2015). Therefore to investigate the effects of electrolysis in the future energy system, a module is already existing in the Balmorel which relies on the approach presented in Karlsson and Meibom (2008).

In the present thesis, the flexible demand is thus distinguished between three demands, namely, 1) demand modelled as a virtual electricity storage, 2) demand for electric vehicles and 3) demand for hydrogen. The electricity demand modelled utilising the virtual electricity storage relies on the approach utilised in Agora (2015), assuming 4 hours of load and a process which not are associated with costs or losses.
The demand for electric vehicles are model utilising the smart charging profile which is presented in Appendix A.
Hydrogen is modelled utilising the previous developed add-on, however as will be described in Section 6.3, the national electricity demand implemented for electrolysis is very low and thus the effect caused by the hydrogen demand is limited.

6.2 Scenario Setup

The research question in this thesis will be answered by performing two case-studies which assess two different flexibility resources: 1) the future expansion of the transmission capacity and increased and 2) increased demand-side flexibility. To perform these assessments, data from the anticipative scenario outlined in the NETP 2016 project representing a pathway towards a decarbonised energy system in 2050 are utilised in this thesis.

The anticipative Carbon-Neutral Scenario (CNS) outlined in NETP 2016 expresses a pathway for the Nordic regions energy system, which can potentially reduce the aggregated emissions by 85% compared to the 1990 levels[3](NETP 2013). Identical input data as used in the NETP 2016 model simulation of the anticipative CNS scenario are utilised as input data to the Balmorel model in this thesis.

Different approaches can be utilised in order to conduct the anticipative NETP 2016 scenario. Among others, 1) the capacity can exogenously be defined, 2) constraints can ensure a certain amount of a fuel to be used or set either a maximum or a minimum amount of fuel used, 3) the model can be driven by the CO_2 prices which phase out utilisation of fossil fuels based on the economic markets conditions. In the present thesis, the strength of the model is utilised by implementing the CO_2 price as one of the main driver from the investments in RES technologies. Relying on this approach, the model is not fixed and changes between different scenarios can be observed and analysed.

Table 6.1 provides an overview of important parameters implemented in Balmorel which thus create the scenario and, subsequentlyn affects the results.

Table 6.1: Important parameters implemented in Balmorel to create the anticipative CNS scenario which is adopted from NETP (2016).

	Nordic countries (Denmark, Finland, Norway, Sweden)	Surrounding countries (Germany, Great Britain)
Demand	NETP 2016 – CNS scenario, which are based on ETP 2015 -scenarios	Adopted from EA Energy Analyses, identical demands as utilized in NETP 2016 – CNS scenario, which are derived from ETP 2015 -scenarios
RES deployment	Existing capacity are exogenously defined. Investments are driven by the CO2 price, making RES-E deployment attractive	Existing capacity are exogenously defined. Investments are driven by the CO2 price, making RES-E deployment attractive
Conventional generation capacity	Existing capacity are exogenously defined. Nuclear development fixed: Finland: expansion according to NETP 2016 Sweden: phase out according to NETP 2016 Fossil development model optimised	Existing capacity are exogenously defined. Nuclear development fixed: Germany: Phaseout until 2022. Great Britain: average between DECC's "Reference" and "Existing policies" scenarios Fossil development model optimised
Fossil Fuel prices	NETP 2013, which are based on IEA ETP 2012	
Biomass prices	Medium scenario of Ea & DTU analysis for DEA	
CO2-prices	NETP 2016, based on IEA ETP 2015	

[3]It should however be noted that in order to achieve an energy system which is completely carbon neutral, the reduction of the remaining 15% GHG emissions are obtained by international carbon credits (NETP 2013).

6.3 Data Collection and Assumptions

To facilitate the assessment of the future Nordic energy system, relevant and valid input data are required. This Section presents the input data utilised in the present thesis along with the main assumptions made to facilitate the implementation of the input data in the Balmorel model.
The presentation of the collected data is divided into three main parts: 1) general data i.e. fossil and bio-fuel prices are presented, 2) geography specific data i.e. energy demands, RES potential, deployment of carbon neutral energy sources and time series 3) technical data i.e. existing and future generation- and transmission-capacities. In addition, the national energy policy targets, presented in Section 3.2, are implemented in the Balmorel model.

6.3.1 General Input-data

Prices Implemented in Balmorel

The prices for fossil and bio-fuels are parameters that potentially have a sustainable influence of the final results. In the present thesis, the price projections for fossil fuels i.e. hard coal, crude oil and natural gas are adopted from NETP (2013) which are based on the prices projections presented in IEA-ETP (2012), and the bio-fuel price projection are adopted from EA&DTU (2013). The fuel prices in Balmorel are implemented based on the simplification that assumes identical prices in all countries, unless other is stated. The fuel prices utilised in the present thesis are presented in Figure 6.2.

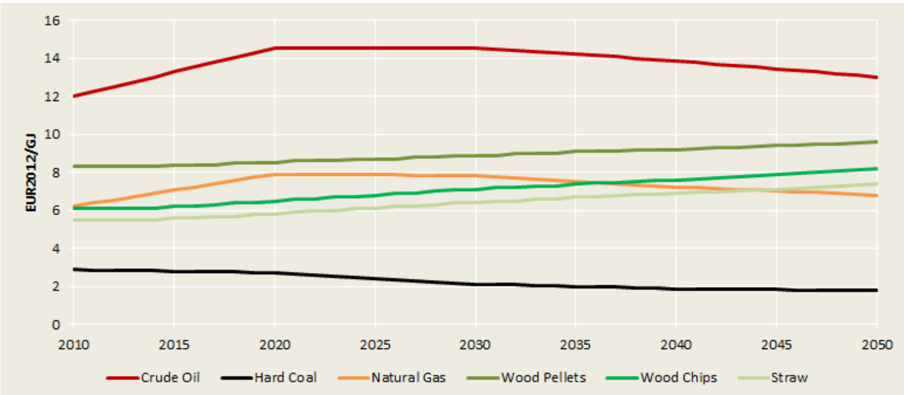


Figure 6.2: Prices for fossil and bioenergy resources. Price projections for fossil fuels are adopted from NETP (2013), and the bio-fuel price projection are adopted from EA&DTU (2013).

Fossil fuel prices: The projections of the fossil fuel prices shows declining prices after 2030 which is due to a global reduced demand of fossil fuels in the 2DS scenario, caused by strict policy frameworks regarding CO_2 emissions (NETP 2013)[4]. Regarding the natural gas fuel prices, it is assumed that the prices in Norway and Sweden are different compared to the Danish prices i.e. 10% higher cost in Sweden, due to higher infrastructure costs and 10% lower cost in Norway due to better gas availability (EA&DTU 2015).
In addition to the fossil fuel prices presented in Figure 6.2, prices for other fossil fuels are implemented in Balmorel such as light oil, fuel oil and lignite. The prices for light and fuel-oil are determined based on DEA (2014b) in which the fuel oil price is assumed to be 88% of the crude oil price, light oil is implemented with a price level 116% of the crude oil price. Furthermore, the prices are implemented assuming identical future

[4]here it should be noticed that the oil price have experienced a remarkable drop in price from approximately 110$/bbl in January 2014 to approximately 30$/bbl in January 2016 (IEA 2016b). However, as the price projections in the oil market are related with high uncertainty, the price projections in NETP (2013) are utilised in the present thesis.

trends as the crude oil prices since they are extracted from the same primary resource (DTU 2015). The fuel price for lignite is implemented assuming a price corresponding to 50% of the hard coal price over the considered period (DTU 2015).

Biomass fuel prices: The projections of the biomass prices are adopted from NETP (2016) which subsequently have utilised biomass prices based on the EA&DTU (2013). The projections of the biomass prices are an output from the Global Assessment Model (GCAM) which includes input parameters such as; base price level for biomass, transport distance and imported biomass share which are transported by ship. The biomass prices utilised in the present thesis are the medium price level[5] which are presented in Figure 6.2. As the scenarios presented in EA&DTU (2013) take into account transport distance, the assumption on adopting identical values in all Regions are a strong simplification. It should, furthermore, be noticed that, the biomass prices could potentially be higher, as the surrounding counties in the NETP 2016 project are assumed to follow the 2DS scenario, and thereby increase the global demand for biomass-products.

Carbon emission price: The CO_2 price projection which is presented in Figure 6.3, is adopted from NETP (2016) which, in turn, is based on IEA-ETP (2015). The CO_2 price reflect the marginal abatement cost of carbon which is an estimated price of the cost to reduce emissions by the last unit needed to achieve the energy policy target.

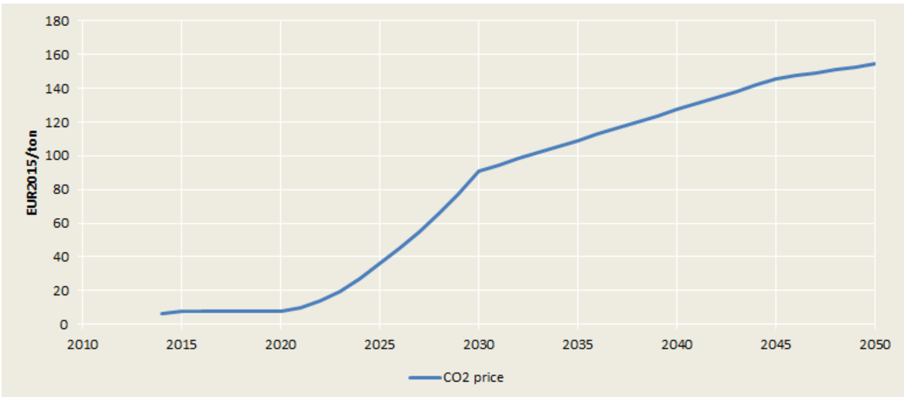


Figure 6.3: CO_2 price projection towards 2050. Adopted from IEA-ETP (2015).

The IEA-ETP (2015) projection of the CO_2 price show an price increase from 6.5€/ton to 154.6€/ton between 2014 and 2050. As presented in Figure 6.3, a steep increase in the CO_2 price appear between 2020 and 2030. Furthermore, the increasing trend for the CO_2 price continues from 2030 until 2050.

Price of Additional Transmission Capacity: As one of the main focus points in the present thesis is to investigate the future need for expanding the transmission grid, evidently the costs of expanding the transmission grid capacity is essential, and thus valid sources are required to be utilised. For the purpose of the present thesis, the costs of expanding the transmission capacity between Regions are adopted from NETP 2016, which in turn utilise the price estimates presented in EA (2014). In Appendix A, an overview of the cost of grid expansion implemented in Balmorel is presented.
The price estimates represent an average price of expanding the transmission grid between two Regions. The

[5]Three scenarios were constructed i.e. low, medium, high, where the high scenario corresponds to a scenario based on the scenario in which the global average surface temperature increased at approximately 2.5C until 2100, in the low scenario, the global demand of biomass is low and in the medium scenario, no policies regarding GHG emissions and no changes in the diet is included. The biomass price determined in the three scenarios varies up to ±28% by 2050 depending on the biomass product.

prices are determined based on an approach utilising the distance between the centres of the Regions, which consequently overestimate the prices, however as reinforcement of the local grid are not included, this can be compensated by the overestimated cost. It should, however, be noticed that since the Balmorel model does not take into account grid related issues such as grid stability, the costs related to these issues are not reflected in the estimated prices (NETP 2016).

The prices for the specific transmission lines utilised in the present thesis can vary compared to the prices presented by ENTSO-E (ENTSO-E 2014). However investigating the prices of transmission grid expansion presented in ENTSO-E (2014) the estimated costs varies more than ± 50% of some of the specific transmission connections.

6.3.2 Geography Specific Input-data

Energy Demand

As the Balmorel model is driven by the exogenously defined demands for electricity and district heat, the specification of the implemented annual demands for each country are elaborated in this paragraph.

The demand for district heating is assumed to be identical in the two case studies and therefore will this demand first be presented in this section. However, to model the two case studies, different metrics for electricity demand is applied. In the first case-study where expansion of transmission capacity is investigated, the electricity demand is assumed to be non-flexible. However, in the second case study, where the demand-side flexibility is investigated, the demand is distinguished as follows: 1) Non-flexible electricity and district heating demand, 2) Electric vehicle demand, and 3) hydrogen demand. In addition a specified amount of energy is assumed to be flexible and thus is allowed to be shifted in time utilising an approach in which the flexible electricity demand is modelled as a virtual electricity storage without any associated losses and costs, as described in Section 6.1.3.

District Heating Demand

According to the modelling scope in Balmorel, the demand for heat is limited only to include the heat distributed by the district heating system. Thus individual technologies providing heat are not included in the Balmorel model. As presented in Section 3.1, the share of heating provided by the district heating network are varied between the considered countries.

The annual national district heating demand is adopted from NETP 2016 and is illustrated in Figure 6.4.

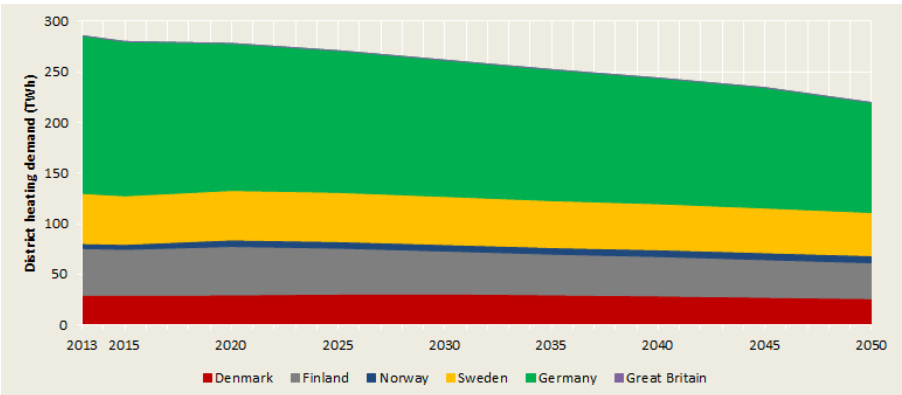


Figure 6.4: District heating demand. Adopted from NETP (2016).

The figure presents a relative constant projection of the annual national district heating demand, except

Germany which show a trend in which the district heating demand is declining. Furthermore, as stated in Section 3.1, the district heating demand in Great Britain is currently 2% and thus is neglected in the present thesis.
This projection illustrated in Figure 6.4 includes both heat savings e.g. in the building sector and increased share and utilisation of the heat distributed by the district heating network are included.
The demand for district heating in each Area is defined by a specific share. In Appendix A, an overview of the division of the district heating demand is provided.

Electricity Demand
As different metrics for electricity demand are applied in the two study-cases, this paragraph will be twofold. First the non-flexible electricity demand utilised in the first case-study will be presented and secondly the electricity and hydrogen demands implemented in the second case-study will be presented.

First Case-Study
Figure 6.5 presents the annual national electricity demand, which are adopted from the NETP 2016 project and utilised in the first case-study.

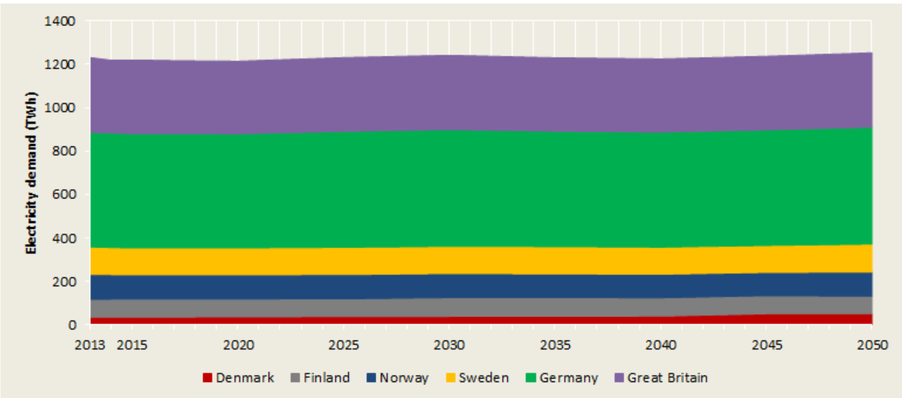


Figure 6.5: Total electricity demand which is used in the first case study. Adopted from NETP (2016).

The annual electricity demand adopted from the NETP 2016 project is provided at Country level, however, in Balmorel, the annual electricity demand is specified at Regional level as stated in Section 5.2.3. Thus the annual national electricity demand is divided according to the number of Regions within each Country, as illustrated by Figure 6.1. This segmentation of national annual electricity demand is accomplished utilising the fixed percentage shares which are presented in Appendix A. The same percentage division of the electricity demand is applied in the second case-study as well.

Second Case-Study
The demand side flexibility is investigated in the second case-study. Figure 6.6 illustrate the national electricity consumption, which is distinguished by non-flexible, electric vehicles demand and electricity demand used in electrolysis plants. The metrics utilised for the three electricity demands are adopted from the NETP (2016) project, which assumes that by 2050, 50% of the electricity used in the transport sector and 90% of the electricity used for electrolysis is flexible. In Appendix A, an overview of the temporal development of the shares which are assumed to be flexible is provided. In order to ensure that the total electricity demand is identical in both case studies, the non-flexible electricity demand is determined as the total electricity demand illustrated in Figure 6.5, minus the flexible electricity demand for electric vehicles

and electrolysis.

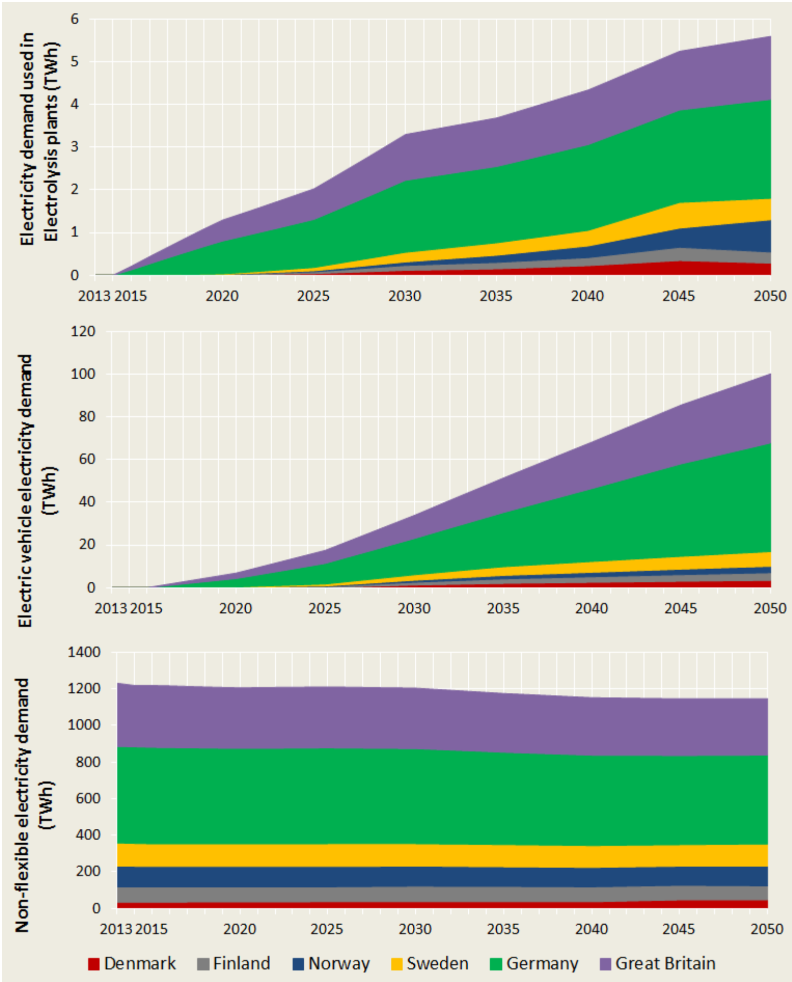


Figure 6.6: Electricity demands implemented in the second case study. The electricity demand is divided into: non-flexible, electric transport and electrolysis. The electricity demands are adopted from NETP (2016).

The flexible electricity demands are modelled utilising the approach described in Section 6.1.3.
In addition to the above, a virtual electricity storage is implemented to simulate load shifting as an demand-side flexibility option. The modelling procedure is described in Section 6.1.3 and the size of the virtual electricity storage, in energy terms, is presented in Table 6.2. It should, however, be noticed that the provided metrics are the maximum energy that can be shifted in time, while the actual levels of energy which are shifted in time are optimised endogenously by the Balmorel model.

Resource Potential of Renewable Energy Sources

The resource potential for renewable energy sources which are available for the electricity and district heating generation, are constrained by either Country or Regional level and can be expressed by either a maximum fuel use (GJ) or a maximum installed capacity (MW).

Bioenergy potentials: The resource potential for bioenergy products are expressed as a maximum fuel use (GJ) and are restricted at Country level. Bioenergy products are expected to play a key role in the entire

Table 6.2: Maximum energy per year which is allowed to be shifted in time utilising the approach of a virtual electricity storage without any associated losses and costs. Based on assumptions similar to NETP (2016).

TWh/year	2013	2015	2020	2025	2030	2035	2040	2045	2050
Denmark	0	0	2	2	4	4	3	3	3
Finland	1	1	4	3	6	6	5	5	5
Norway	1	1	5	5	9	9	8	8	7
Sweden	1	1	6	11	14	14	16	16	17
Germany	5	5	24	41	59	63	68	70	72
Great Britain	3	3	15	26	37	40	43	45	46

energy system. As sectors like industry and transport experience a challenging future transition towards almost carbon neutral sectors, the use of bioenergy products are required to be allocated between the different energy sectors. Thus assumptions are made regarding the resource potential for the electricity and district heating sector. Based on EA (2014), the local bioenergy resources are estimated. The bioenergy potentials for biogas and straw is assumed to be 90% and 80%, respectively, of the total resources throughout the considered period. Regarding other bioenergy resources e.g. forestry residues, wood waste and energy crops, the available energy resources are 75% by 2015, while by 2050 it is assumed that 25% will be available. The reduced amount of available resources by 2050 is a result of the exception of increased utilisation of these products in other sectors e.g. energy crops utilised to produce bio-fuels for transportation.
Wood and wood pellets are assumed to be an international good which can be traded between Regions and Countries. Thus the utilisation of wood and wood pellets are not constrained in the present thesis.
In Table 6.3, the bioenergy resource potentials used in the present thesis are presented.

Table 6.3: Bioenergy potentials for the electricity and district heating sector by 2050.

(PJ)	Wood+ wood pellets[1]	Biogas	Straw	Wood waste	Total
Denmark	-	3	21	0	24
Finland	-	8	13	120	141
Norway	-	0	6	0	6
Sweden	-	13	17	90	120
Germany	-	134	142	0	276
Great Britain	-	32	78	0	110

[1)] The potential for wood and wood pellets are not restricted, since this fuel type can be traded.

Sources: General: Electricity Grid Expansion in the Context of Renewables Integration in the Baltic Sea Region, prepared for BASREC by Ea Energy Analyses (2014).
Values for Denmark, Finland, Sweden, Germany and Great Britain are based on the source: How much bioenergy can Europe produce without harming the environment? By European Environment Agengy (2006).

Wind potential: In Balmorel wind turbines can be installed within each Region, at either onshore, nearoff-shore, offshore or faroffshore. Thus the wind potentials are defined at this geographic level. In Balmorel the potential resources of wind are expressed by a maximum installed capacity (MW). The wind potentials utilised in this thesis are mainly adopted from EA (2014) and are presented, in aggregated form, in Table 6.4.

The onshore wind potential in Great Britain are adopted from DECC (2010), while the Danish onshore wind potential estimated to 10 GW. Among different sources, estimated for the onshore wind potential in Denmark varies from 3.5 GW in DEA (2014a), to 12 GW in Energinet.dk (2015), with an intermediate value of 4.5 GW in EA (2014). Thus, estimating the potential for onshore wind is related with high uncertainty, however

Table 6.4: Wind potentials for each of the countries. Wind power technologies can be installed in four different areas: onshore, nearoffshore, offshore and faroffshore.

(MW)	Onshore	Nearoffshore	Offshore	Faroffshore	Total
Denmark	10000[1]	5100	29000	97500	141600
Finland	10000	5000	13500	16000	44500
Norway	15100	18000	70500	1500	105100
Sweden	17500	13200	26400	3600	60700
Germany	82400	16600	56000	2500	157500
Great Britain[2]	27000	-	-	-	-

[1)] The potential for onshore wind in Denmark is based on Energinet.dk, which have identified a potential up to 12GW
[2)] Potential for offshore wind in Great Britain are assumed to be unconstrained

Sources: Electricity Grid Expansion in the Context of Renewables Integration in the Baltic Sea Region by Ea Energy Analyses (2014), Great Britain: 2050 Pathways Analysis by Department of Energy and Climate Change (2010), Energinet.dk – Analyse for potentialet af landvind i Danmark i 2030.

for the present thesis the onshore potential for installing wind is 10 GW, which also is used in NETP (2016).

Full load hours for wind power production: The full load hours (FLH) for the wind power production varies between the Regions included and the Year of simulation, however in Table 6.5 the full load hours utilised in this study are presented as intervals for each Country illustrating the lowest FLH- and highest FLH value. The full load hours of operating for onshore wind turbines are determined base on estimations of

Table 6.5: full load hours for wind power technologies in each of the countries. Data from the current Balmorel at DTU.

	Onshore	Offshore
Denmark	1600 – 3500	3700 – 4500
Finland	1600 – 1700	3200 – 3400
Norway	1900 – 2700	3500 – 4000
Sweden	1300 – 2300	3600 – 3900
Germany	1700 – 2300	3700 – 4400
Great Britain	3300 – 3500	4200 – 4500

the frequency distribution of the wind speed, which are derived from the Global Wind Atlas, and calculated utilising a power curve for a specific wind turbine (DTU-Wind 2016). With regard to full load hours of offshore wind turbines, the metrics utilised are the values already implemented in the Balmorel model, which are comparable with the values utilised in EA (2014).

Deployment of Carbon Neutral Energy Sources

To utilise the strength of the Balmorel as being an optimisation model allowing both exogenous and endogenous investments, the deployment of carbon neutral energy sources are mainly driven by the CO_2 price, as described in Section 6.3.1, however, the existing capacity are exogenously defined. In the following the actions made to facilitate the deployment of carbon neutral energy sources in the Balmorel model will be listed.

- The generation capacities of hydropower are fixed, since the model are not allowed to invest in additional hydropower capacity
- The capacity of nuclear power plants are exogenously defined in order to achieve the energy policy targets stated in Section 3.2. The exogenously implemented capacities of nuclear power plants are

adopted from NETP (2016)

- The implementation of RES generation capacity is constrained according to the potentials of wind and bioenergy, as described in Section 6.3.2

- The model is required to utilise the availiable municipal waste resources

6.3.3 Technical Input-data

Technology Data
The technology database in the present Balmorel model is modified and updated for the purpose of this thesis. The modifications include: 1) Technology characteristics and 2) Capacity of generation technologies within certain geographical Areas.
The technological characteristics contain the existing and future technological data e.g. costs, efficiencies, etc., for the generation technologies included in the Balmorel model. These characteristics are updated and modified based on EA Energy Analyses database for technologies characteristics, which is used in e.g Agora (2015) and NETP (2016). The collection of data regarding the technologies characteristics facilitated by EA Energy Analyses is comprehensive where e.g. data for Danish generation technologies are adopted from 'Technology Data for Energy Plants' by DEA and Energinet.dk (2012) and the updated version from 2014. Furthermore, since the geographical scope in this thesis has extended the geographical representation in Balmorel, as stated in Section 6.0.1 and 6.1.1, the input data regarding the capacity of generation technologies within a certain geographical Area are modified based on EA Energy Analyses database for capacity of generation technologies, which is used in e.g Agora (2015) and NETP (2016). The collection of data regarding the capacity of generation technologies facilitated by EA Energy Analyses is again comprehensive where e.g. data for the current installed generation capacities in Denmark are based on e.g. Energy Producer Account (DEA(2014c). Since the data collection contains a comprehensive and high level of detail w.r.t. existing energy generation technologies, aggregations are performed in order to adapt the data into the Areas represented in the Balmorel model.

Transmission Capacity According to the thesis objectives, the implemented exogenous transmission capacities connecting the Regions in the Balmorel model are essential. The current installed transmission capacities are adopted from the Agora 2015 project and the NETP 2016) project which is based the European Network of Transmission System Operators for Electricity (ENTSO-E) Ten-Year Network Development Plan 2014 (ENTSO-E 2014). The current installed transmission capacities are illustrated in Figure 7.2. Regarding the future development of the transmission capacities, the data are adopted from (Agora 2015 and NETP 2016) which is based on (ENTSO-E 2014). The included transmission capacities in the present Balmorel model includes the transmission capacities which are planned to be completed by 2025.
Exogenous defined transmission capacity appears until 2025, while from 2025 to 2050, the expansion of transmission capacity is determined by endogenous investments decisions. To facilitate this investment decision costs of additional transmission capacity is implemented in Balmorel for each of the defined transmission connections, as described in Section 6.3.1.

CHAPTER 7

Case Study - Assessment of Future Expansion of the Transmission Capacity

In this case study an assessment of the future expansion of the transmission grid will be performed. This assessment is motivated by the increased attention of expanding the existing transmission capacities and the installation of new interconnectors between Regions. Furthermore, as identified in Chapter 3, transmission capacity and interconnectors are, in an efficient way, capable at facilitate the integration of an increased penetration of both RES- and VRE generation technologies. This quantitative assessment will provide an indication of where it would be beneficial to expand the existing transmission capacity or, additionally, installing new transmission connections.
This quantitative assessment will identify the future electricity and district heating generation portfolio, based on the setup and data input stated in Chapter 6. However, as the main focus of the quantitative assessment is on the electricity system, the following chapter will primarily presents results which are related to the electricity system. Furthermore the additionally endogenously computed transmission capacity, the amount of net imported electricity and the market effects will be presented and evaluated. In addition, an alternative scenario is presented, which shows a pathway without investment in wood pellets CCS technologies. To evaluate the robustness of the presented scenarios a sensitivity analysis is performed with emphasis on the influence of three relevant price parameters i.e. price of wood & wood pellets, the CO_2 price, and the price of expanding the transmission capacity.

7.1 Scenario Results

The results presented in this section represent the Base scenario and are obtained from the model simulations in Balmorel which rely on the assumptions stated in Chapter 6. The results presented include the future generation portfolio, additional endogenously computed transmission capacity, the amount of net imported electricity and the annual average electricity prices for each Region.

7.1.1 Generation Portfolio

As stated in Chapter 2 and 3, the energy generation portfolio will experience a major transition in the future towards an energy system which primarily rely on carbon neutral generation technologies. This is aided by the strict energy policy targets as stated in Section 3.2.
In Figure 7.1 the future electricity generation portfolio which is endogenously optimised after 2020 is presented while in Appendix B, an overview of the endogenous investments in new generation technologies is provided together with a graph illustrating the future generation portfolio for the district heating systems.

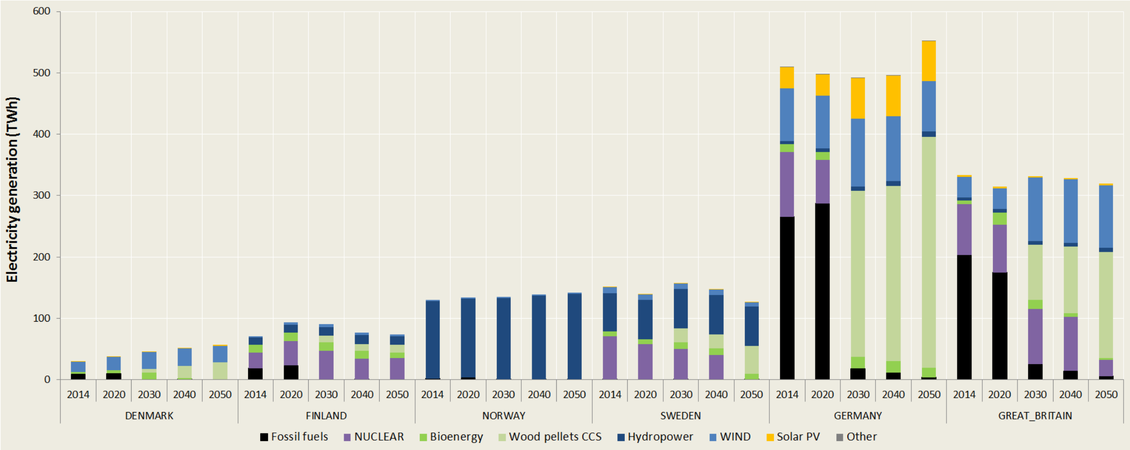


Figure 7.1: Electricity generation in the Base scenario.

Figure 7.1 illustrates an almost total phase-out of fossil fuels across all the considered countries, which is in accordance with the energy policies stated in Section 3.2. Furthermore, the figure illustrates the phase-out of nuclear power production in Germany and Sweden.

As illustrated by Figure 7.1, a large reduction of fossil fuel production can be observed between 2020 and 2030 which is due to the steep increase in CO_2 price, as shown in Figure 6.3. The high CO_2 price makes generation plants using wood pellets as fuel and are equipped with the CCS technology very attractive after 2020, since they absorb CO_2 and thereby receive the CO_2 price. Thus the phase-out of fossil fuels and nuclear power production are primarily substituted by the high utilisation of wood pellets. The utilisation of wood pellets are, for the present thesis, assumed to be unconstrained since wood pellets are considered to be a fuel that is allowed to be traded across Regions and Countries as stated in Section 6.3.

From investigations of the national generation portfolios in Figure 7.1, the trends for the future generation mix can be identified. According to the obtained results, Denmark's generation portfolio will be dominated by bioenergy and wind power, while Finland's electricity generation will primarily be supplied by nuclear and hydro power. In Norway, the electricity production will, as expected, continue to be dominated by hydro power. In Sweden, the phase-out of nuclear power will be substituted by bio-resources and in particular wood pellets equipped with the CCS technology. Since the hydro power production in Sweden will remain at the same level, the Swedish electricity production will primarily be supplied by bio-resources and hydro power.

The surrounding countries i.e. Germany and Great Britain, will, according to the presented scenario, experience a major transition of the electricity generation portfolio in the future. In particular, between 2020 and 2030, the electricity generation portfolio will shift from a fossil fuel dominated electricity generation mix towards higher utilisation of renewable energy sources.

In Germany, an almost phase-out of fossil fuels and the total phase-out of nuclear power production are primarily substituted by wood pellet CCS power production. In addition, the electricity production from wind turbines and solar PV will increase between 2020 and 2030, while the power production from wind technologies will, according to the presented scenario, decreases from 2030 to 2050.

In Great Britain, the production from fossil fuel generation technologies will be reduction over time and almost be phased out in 2050. In Great Britain, an increased production from wind and wood pellet CCS generation technologies can be observed from 2020 to 2030. While the electricity production from wood pellet CCS technologies continue the increasing trend towards 2050, the production from wind turbines will be reduced, as presented in Figure 7.1.

The results in the Base scenario shows a high utilisation of generation technologies fuelled by wood pellet and equipped with the CCS technology. The CCS technology is point out to be a key factor in NETP (2013), in particular in the European countries. Furthermore, in NETP (2013) the technical challenges related to the development of the CCS is emphasised. Since the CCS technology still is under development, and the technology not yet is implemented in many places, the costs estimates are related with high uncertainty. Therefore, presenting a scenario which is dominated the wood pellets CCS technology should be done with careful considerations, thus sensitivity analyses will clarifies the sensitivities related to the main assumptions made. Since the CO_2 is directly reflected in Figure 7.1 and thereby in the future development of the energy system, a sensitivity analysis on the CO_2 price will be performed in Section 7.3. Furthermore, in this scenario a high utilisation of bioenergy resources appears, which could potentially lead to higher biomass prices, thus a sensitivity analysis of the price of wood & wood pellets will be carried out in Section 7.3.

7.1.2 Regional Electricity Prices and Expansion of the Transmission Capacity

As electricity is allowed to be traded inside and between countries, this section will present the annual average electricity prices for each Region and the expansion of the transmission capacity. The Regional electricity prices and the expansion of the transmission lines are presented by maps in which different colour codes illustrate different Regional price.

In Figure 7.2, the Regional electricity prices and the transmission capacity in 2014 are presented. These results are obtained from the Balmorel model which is simulated without allowing investments in new generation- or transmission capacity.

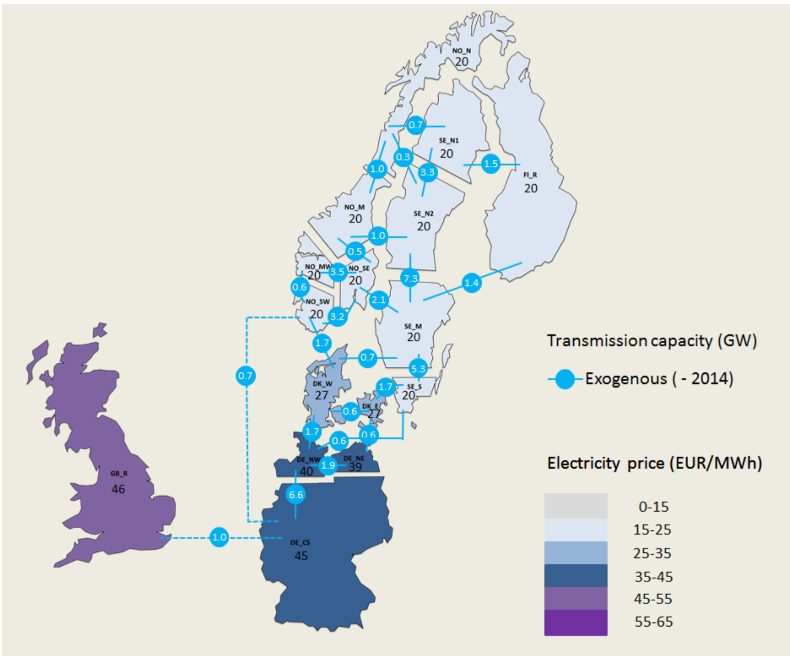


Figure 7.2: Map illustrating the situation by 2014. The map shows the endogenous computed regional electricity prices, and the current installed transmission capacity between the regions which is an exogenous input to the Balmorel model.

The figure presents the annual average electricity price level in each Region. Considering the Regional prices, evidently the highest annual average electricity prices appear in the surrounding countries i.e. Great

Britain and Germany, and the lowest prices appear in Norway, Sweden and Finland which receive almost identical price levels.
Comparing the annual average Regional electricity prices obtained by the Balmorel model with the real metrics seen in the Nordpool spot market (see Appendix A), the annual average electricity price in the Regional level achieve values which are in the interval for the observed values between 2014 and 2015.
The price differences presented in Figure 7.2 appear due to limited transmission capacity between the Regions, as described in Section 2.3. Hence, incentives for expanding- or installing new transmission capacity between the Nordic countries and the surrounding countries are evident. Thus allowing investments in new transmission capacity can provide indications of where new or additionally transmission capacity can be beneficial from a social economic point of view, however as stated in Section 5.3, the power system stability and control issues are not taken into account in the present thesis and could potentially change the investment decisions of additional transmission capacity.

The annual average electricity price in each Region and the additional transmission capacity in 2030 are presented in Figure 7.3. As stated in Section 6.1 the Balmorel model is allowed to perform new investments in both generation- and transmission capacities. As presented in Figure 7.1, the optimised simulation, of year 2030, include large investments in new generation technologies which are expected to influence the price of electricity. With regard to investment decisions of additional transmission capacities, the transmission capacities until 2025 are exogenously defined, while the model endogenously performs investment decisions in additional transmission capacity until 2030.

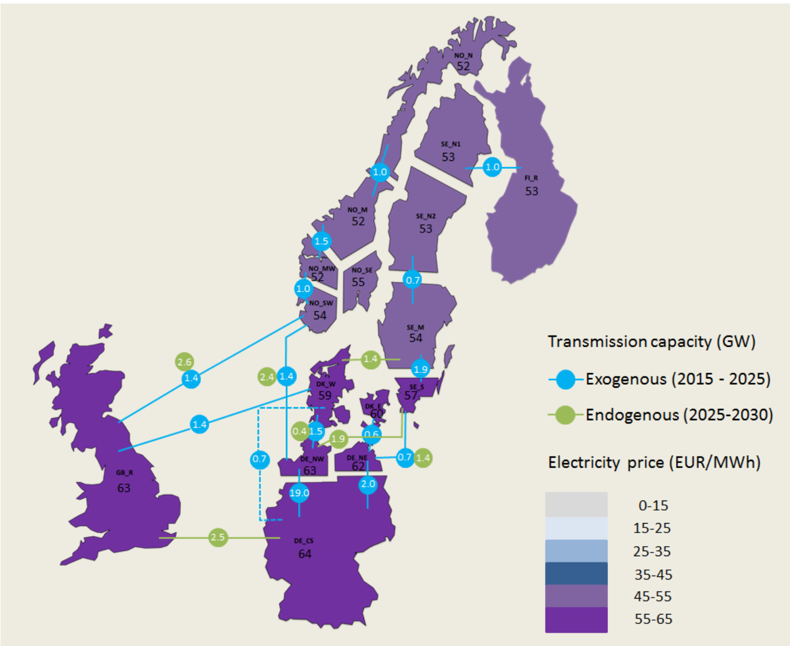


Figure 7.3: Map illustrating the situation by 2030. The map shows the endogenous computed regional electricity prices, and the exogenous defined additional transmission capacity up to 2025 (by blue in the figure) and the endogenous computed additional transmission capacity from 2025-2030 (by green in the figure).

From investigations of Figure 7.3 and comparing the annual average electricity prices with the 2014 values, evidently the Regional prices have increased, which is explained by the substantial change the energy system has experienced between 2020 and 2030, where the large amounts of investment in new generation

technologies appears due to the steep increased CO_2 price.
Considering the additional transmission capacity in Figure 7.3, there is a distinction between exogenous and endogenous investments. The exogenously defined additional transmission capacity are in total 21.8 GW which means that more international and coherent electricity grid is already planned, however, as shown in the figure, endogenous investments in additional transmission capacities are performed and account for additionally 12.9 GW in total. In particular, endogenous investments in additional transmission capacity appear from Great Britain in which the endogenous investments are 6.4 GW. Furthermore, additional transmission capacity between the south of Sweden and the north-west and the north-east of Germany is endogenously determined to be social beneficially. As the north-east part of Germany only holds 1% of the German electricity demand and has furthermore a limited transmission capacity to the central part of Germany, as presented in Figure 7.3, the interconnection between the south of Sweden and the north-west of Germany is beneficial as well.
The total additionally transmission capacity will be 34.7 GW by 2030. The additional transmission capacity leads to less bottlenecks and thus more homogenous electricity prices, as described in Section 2.3.2. This market effect can clearly be observed when comparing Figure 7.2 and 7.3.

To present the temporal development in the annual average electricity prices and the expansion of the transmission capacity, Figure 7.4 shows the model results for the simulation of year 2050.

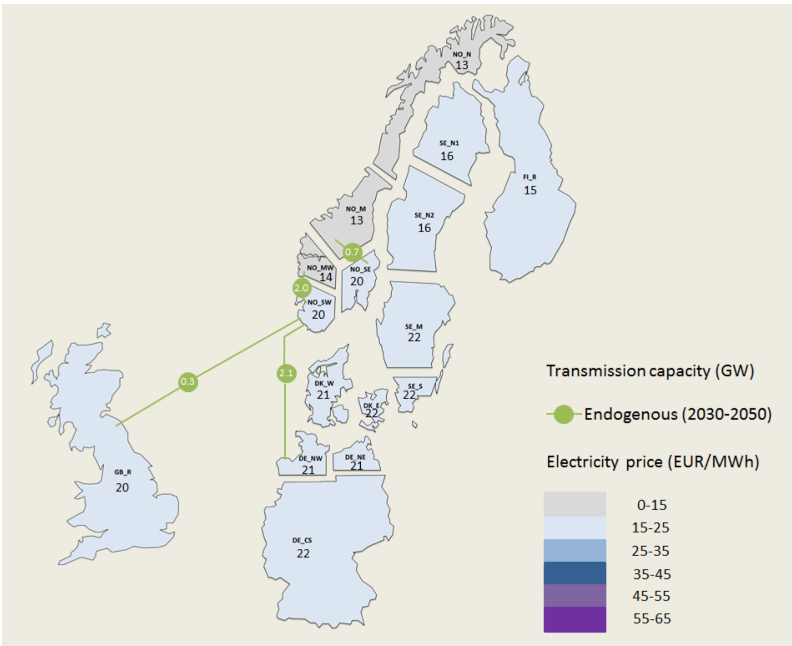


Figure 7.4: Map illustrating the situation by 2050. The map shows the endogenous computed regional electricity prices, and the endogenous computed additional transmission capacity from 2030-2050 (by green in the figure).

Considering the annual average electricity prices, evidently the prices are reduced compared to the results obtained by simulating year 2030. The reduced annual average electricity prices in 2050 appear since the system has already invested in new generation capacity, thus the marginal cost of producing one unit more is lower since the model do not need to invest in a new plant, furthermore, the reduced annual average electricity price can be explained by the merit order effect, as described in Section 2.3.
The endogenous investments between 2030 and 2050 are presented in Figure 7.4. Compared to the large

amount of investments in additional transmission capacity up to 2030, the investments in additional transmission capacity between 2030 and 2050 are computed to be 3.4 GW in total. Therefore, the Regional price differences which can be observed in 2050 are almost identical to the observed Regional price differences in 2030.

7.1.3 Net Import/Export of Electricity

Further to the quantification of the development of additional transmission capacity, the physical amount of the yearly net electricity exchange for each of the countries are presented in Figure 7.5.

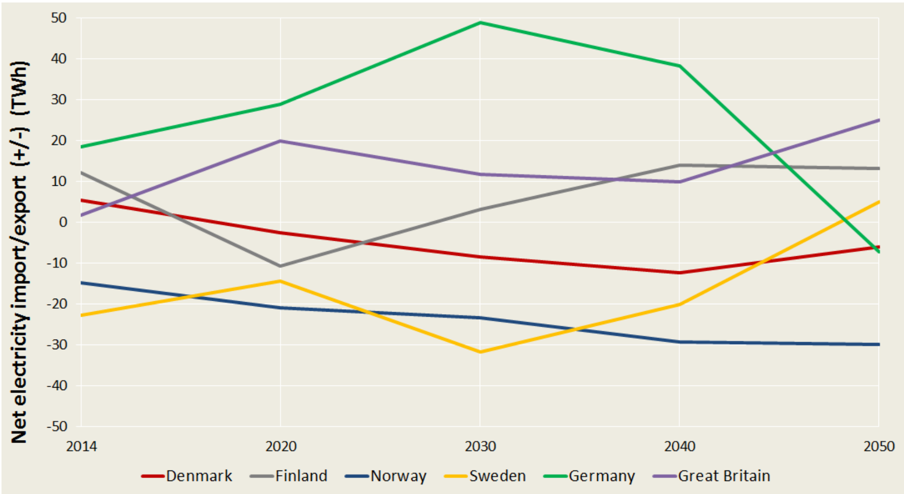


Figure 7.5: Net electricity import/export (+/-).

Figure 7.5 provides information on the physical quantity of the yearly net electricity exchange from each of the considered countries. From investigations of the figure, evidently the yearly net electricity exchange varies between the simulated years. By aggregating the quantities of the yearly net electricity exchange for the Nordic countries and the surrounding countries, it has been found that the Nordic countries are net exporters in 2014 with a quantity of 20 TWh (see Appendix B). The Nordic region remain to be net exporter of electricity, with the highest export of 60 TWh by 2030. In 2050, the net exported electricity to the surrounding countries is approximately 20 TWh. In addition, Norway is a net exporter of electricity over the considered period, while Great Britain is a net importer of electricity, as illustrated in the figure.
The German electricity exchange experiences variations in the amount of net electricity import. In the beginning of the considered period, Germany is a net importer of electricity. The amount of net electricity imported to Germany increases up to 2030, where, as illustrated in Figure 7.1, a major transition of the electricity generation appears towards a electricity generation portfolio dominated by technologies using wood pellets and are equipped with CCS. This, consequently, leads to a larger dispatched electricity production in Germany and thus reduces the need for net imported electricity to cover the German electricity demand. In the end of the considered period leads the market conditions to an electricity generation in Germany which exceeds the national electricity demand, and therefore are Germany net exporter of electricity by 2050. However, it should however be noted that the geographical modelling scope utilised in this study, exclude the electricity trade from Germany and Great Britain to non-Nordic neighbouring countries. Germany and Great Britain is currently a net exporter to other non-Nordic countries, as illustrated in Figure 3.3. This issue could potentially be eliminated using a fixed electricity trade to the to non-Nordic neighbouring countries, however for the present thesis a fixed electricity trade is not included due to the fact that the

electricity trade varies between years and are highly dependent on weather conditions such as wet or dry year in hydropower Regions and amount of wind production, a the development of the generation portfolio in the non-Nordic neighbouring countries. Furthermore, the availability of the transmission connection between Denmark-West and Germany-North-West is for the purpose of the modelling assumed to have a fixed varying profile, which in total has an average availability at 90%. The variable electricity production from wind turbines in the western part of Denmark and the north-western part of Germany are correlated, which in practice leads to situations where Germany reduces the availability of the transmission connection between Denmark and Germany, since the electricity flow from north to south in Germany are restricted by bottlenecks inside Germany.

7.2 Alternative NO-CCS Scenario

The results in the Base scenario showed a high utilisation of generation technologies fuelled by wood pellets and equipped with the CCS technology. Presenting a scenario in which the future electricity generation portfolio is dominated by a technology which is under development and therefore are related with high uncertainties regarding the costs, should be done with careful considerations[1]. Therefore, in addition to the Base scenario an alternative scenario which excludes the opportunity for the model to invest in wood pellets CCS technologies is conducted.
In Figure 7.6, the development of the electricity generation portfolio for each of the countries are presented. Further information regarding the amount of investments in new generation technologies and the temporal development of the generation portfolio to supply the district heating systems are provided in Appendix C.

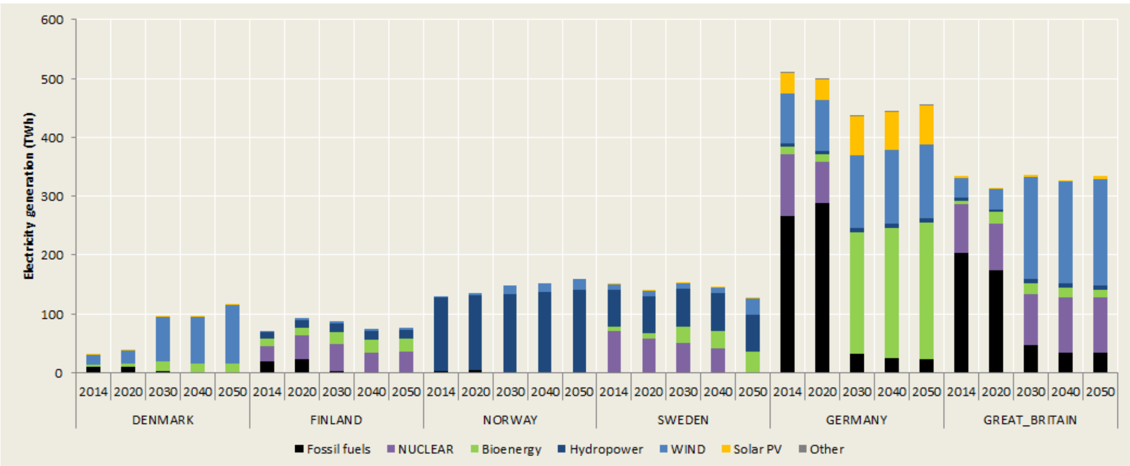


Figure 7.6: Electricity generaion in the NO-CCS scenario

Based on Figure 7.6, the main differences between the Base- and the Alternative NO-CCS scenario will be elucidated. In the NO-CCS scenario, evidently the total utilisation of bio-resources are significantly reduced, while the production from wind turbines are increased. From further investigations, especially Denmark and Great Britain experience a substantial increase in the electricity production from wind turbines between 2020 and 2030. In addition, the production from nuclear power in Great Britain is increased as well as the utilisation of fossil fuels, even though the same CO_2 price is applied.
In Figure 7.6, a reduction of total electricity production in Germany can be observed between 2020 and 2030.

[1]It should however be noticed that Pye (2015) presents energy scenarios for United Kingdom which includes a substantial share of CCS generation technologies.

The increased CO_2 price along with the exclusion of investing in wood pellets CCS generation technologies leads to a situation in Germany, where it is more beneficial to import a larger amount of electricity to Germany compared to investing in new generation technologies. Therefore, the import of electricity to Germany is increased in the same period, in order to meet the national electricity demand, as shown in Appendix C. In addition, the electricity production from wind in Denmark increases between 2020 and 2030, as illustrated in the figure. By considering the physical quantity of the exchanged electricity between the countries, evidently, the largest changes between 2020 and 2030 can be observed for Germany and Denmark, as illustrated in Appendix C. By 2030, Germany is net importer of electricity while Denmark is net exporter of electricity, with quantities of 105 TWh and 57 TWh, respectively, while by 2050 the quantities are 90 TWh and 67 TWh, respectively.

Denmark becomes net export of electricity due to high electricity production from wind turbines. By utilising the resource potentials and full load hours of operation for wind turbines which are presented in Section 6.3, Denmark will, in the NO-CCS scenario, experience large investments in wind generation technologies. However, as the resource potentials for installing onshore wind turbines varies among different sources e.g. DEA (2014a), EA (2014) and Energinet.dk (2015), as stated in Section 6.3, the results are related with this uncertainty. By utilising another potential for installing onshore wind turbines in Denmark, will change the amount of wind produced in Denmark, and shift the production to other Regions.

It should, however, be noted that in this scenario by 2050, the wind penetrations in Sweden, Germany and Great Britain are comparable with the production levels stated in; Sweden IVL (2011), Germany Agora (2015) and Great Britain Pye (2015).

7.2.1 Regional Electricity Prices and Expansion of the Transmission Capacity in the Alternative Scenario

The Alternative scenario include a new composition of the generation portfolio which differs from the Base scenario in the endogenously determined investments in additional generation capacity. As a consequence of the new generation portfolio, the amount of electricity exchanged between the countries varies compared to the Base scenario. These new results has an influence on both the investments decisions regarding additional transmission capacity and the Regional electricity prices.

In Table 7.1, the main differences between the Base- and the Alternative scenario are highlighted with regard to: the annual average electricity price and the endogenous investments in additional transmission capacity, however in Appendix C, a complete overview of the obtained results in the Alternative scenario is presented.

Table 7.1: Main discrepancies between the Base- and the Alternative scenario

	Base scenario	Alternative scenario
Endogenous investments in transmission capacity (GW)	17.5	29.6
Annual average electricity price: 2030 (EUR/MWh)	57.8	65.3
Annual average electricity price: 2050 (EUR/MWh)	19.4	68.0

In Table 7.1, the total average system electricity price is provided for year 2030 and 2050. Since the endogenous investments in additional transmission capacity in the Alternative scenario is larger than in the Base scenario, even more homogeneous annual average electricity prices are obtained from the model simulations. Therefore, only the total annual average system price is provided, however in Appendix C, the temporal projection of the annual average electricity price is presented for each of the considered countries. Considering the annual average electricity prices in the system, the findings for 2050 indicates a large discrepancy between the scenarios. The electricity price reflects the cost of producing one additional unit of electricity and thus the price is determined by the last dispatched unit. The price of producing electricity utilising wood pellets CCS technologies is low, due to the implemented CO_2 price, compared to the plants in operation in the NO-CCS scenario. Furthermore, as illustrated in Figure 7.6, fossil fuels are dispatched through out the considered period, which according to the utilised CO_2 price is associated with a high price in the operation of the plant. In addition, the amount of additional generation which is endogenously determined is larger in the NO-CCS scenario compared to the Base scenario. As a consequence of the above mentioned, the electricity price in the NO-CCS scenario receives a higher value compared to the Base scenario.

7.3 Sensitivity Analysis

In the following section will a sensitivity analysis be carried out, which clarifies sensitivities of main assumptions made to facilitate the above presented assessment. The robustness of the results obtained in the Base scenario will be tested by separately varying three parameters i.e. the price of wood & wood pellets, the CO_2 price, and the price of interconnectors.
Due to the computation time of the Balmorel model, the changes in the three considered parameters investigated in the sensitivity analysis are chosen carefully. The changes in the three parameters are as presented in Table 7.2.

Table 7.2: Table which provide information with regard to the changed parameter and value.

Sensitivity Analysis	
	Change
High_W&WP _price[1]	+ 50%
Low_CO_2_price	- 50%
Price of interconnectors[2,3]	+ 50%
	- 50%

[1] Based on: Ea Energy Analyses (2014)
[2] Based on: Estimations in ENTSO-E TYDP (2014)
[3] High_ATC_price and Low_ATC_price (Additional Transmission Capacity (ATC)).

Price of biomass and wood pellets: The results in the Base scenario show an increased utilisation of bioenergy resources. Furthermore, as stated in Section 3.3, bioenergy resources are expected to be used in the entire energy system e.g. power and heating systems, transport and industries. Thus the demand for bioenergy resources could potentially lead to an increased price of bioenergy products. Therefore is a sensitivity analysis conducted to investigate the sensitivity of the Base scenario results. The price of biomass and wood pellets are increased by 50%, which is in accordance with the increment in the bioenergy resource price utilised in EA (2014).

CO_2 price: The CO_2 price is adopted from IEA-ETP (2015) and is a main driver for the long term development of the generation portfolio in both the electricity and district heating systems. Therefore a

sensitivity analysis is performed to test the robustness of the results by varying the price for emitting CO_2. To facilitate the sensitivity analysis, the IEA-ETP (2015) CO_2 price projection is reduced by 50%.

Price of additional transmission capacity: Since the present thesis has focus on the future expansion of the transmission grid, evidently the costs of additional transmission capacity is a central parameter. The implemented costs of additional transmission capacity in the Balmorel model relies on an approach which identifies general prices of connecting different Regions. As stated in Section 6.3.1, the estimated costs of additional transmission capacity can varies more than than ± 50% for a specific interconnector (ENTSO-E 2014). Thus for the present sensitivity analysis, the sensitivity of the results are tested by varying the costs of additional transmission capacity by ± 50%.

7.3.1 Results of Sensitivity Analysis

The results obtained from the Base scenario are tested by changing the metrics for three relevant data input i.e. price of wood & wood pellets, CO_2 price and the price of additional transmission capacity, according to Table 7.2. By changing each of the parameters separately, the effects of four type of results will be elucidated, namely, 1) electricity production, 2) electricity price in the system, 3) endogenous investments in aditional electricity generation capacity, and 4) endogenous investments in additional transmission capacity.

Generation Portfolio

The effects of excluding an investment option in a specific generation technology in the Balmorel model led to an optimal solution in which the production of electricity is supplied by different generation sources, as illustrated by the Alternative scenario. Therefore will a comparative analysis of the electricity generation portfolio obtained from the Base scenario and the four sensitivity scenarios be carried out for the year 2050. Figure 7.7, present the electricity production divided by fuel for the investigated scenarios.

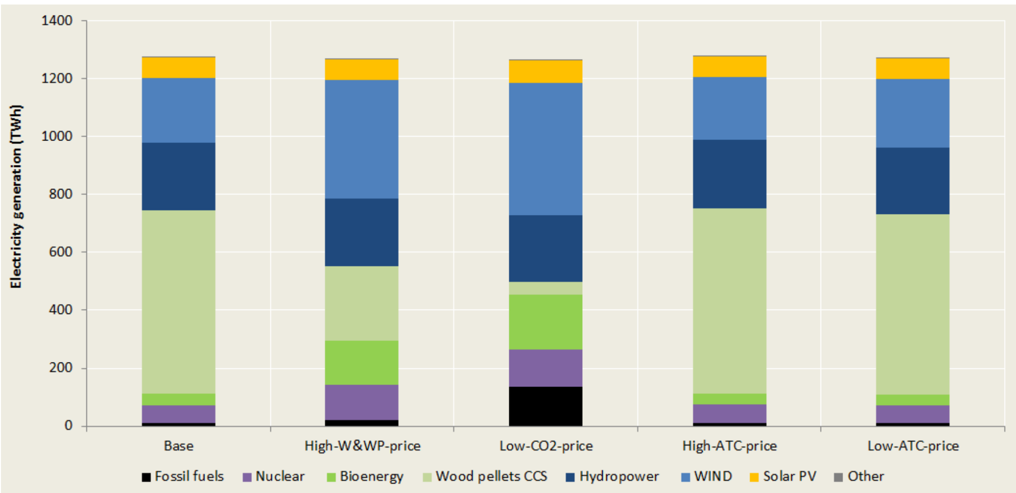


Figure 7.7: Electricity generation in the Base scenario and in each of the sensitivity scenarios

Figure 7.7 illustrates large discrepancies in the composition of the generation portfolio between the Base scenario and the High-W&WP-price scenario and the Low-CO_2-price scenario, while minor differences can be observed between the Base scenario and the scenarios where price of additional interconnectors are changed.

Increasing the price of wood pellets by 50% leads to a large reduction in the electricity produced by wood pellet CCS technologies in the High-W&WP-price scenario. In addition, an increased electricity production from bioenergy is illustrated, which mainly is supplied by generation technologies fuelled by wood, even though the price of wood is increased by 50%. As presented in Section 6.3, the price of wood pellets are higher than the price of wood, and since the prices are increased by identical percentages, the increment in the actual monetary value is higher for wood pellets compared to wood. Furthermore, the main substitute for the reduced electricity production from wood pellet CCS technologies, in the High-W&WP-price scenario, is wind power generation,

Considering the Low-CO_2-price scenario, major discrepancies can be observed in the electricity production generated by wood pellet CCS technologies compared to the Base scenario. The reduced production from wood pellet CCS technologies are covered by increased electricity production from fossil fuels, wood and wind generation technologies.

As illustrated in the figure, the Low-CO_2-price scenario includes the highest penetration of VRE generation technologies, which is caused since wood pellet CCS technologies are less attractive in this scenario, due to the lower income from CO_2 prices. Furthermore, this scenario contain the lowest total share of bioenergy, however the share of electricity produced by technologies fuelled by wood is the highest.

Moreover, in the Low-CO_2-price scenario, electricity generation technologies using fossil fuels are dispatched. The primary dispatched fossil fuel is natural gas which by 2050 contribute with 9% and 18% of the electricity generation in Germany and Great Great Britain, respectively. Furthermore, the contribution from coal is 3% of the electricity production in Germany and Great Britain by 2050.

In addition of the above, by considering the total amount of electricity produced in each of the scenarios, discrepancies can be observed, where the total electricity production in the High-W&WP-price- and Low-CO_2-price-scenario are lower compared to the Base scenario. This is a result of less investments in heat pumps in these scenario compared to the Base scenario.

Electricity prices

The price of electricity is of high interest for both producers and consumers. In the present thesis, the Base scenario and the Alternative scenario found an optimal solution with discrepancies in the generation portfolios and electricity price levels. To perform a comparative analysis of the effect on the electricity price by changing the sensitivity parameters, the average system electricity prices are utilised and are illustrated in Figure 7.8.

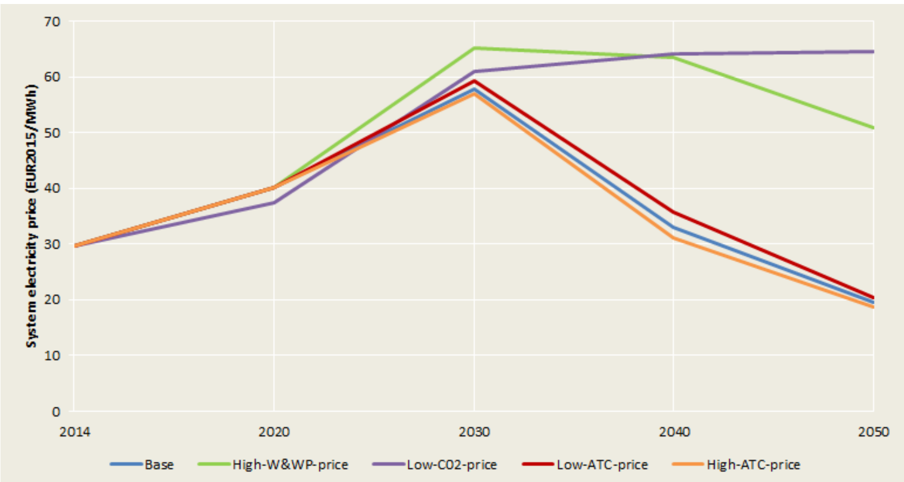


Figure 7.8: Annual average electricity price in the Base scenario and in each of the sensitivity scenarios.

The figure shows that the results obtained in the Base scenario are sensitive to the applied changes in the High-W&WP-price- and Low-CO2-price-scenarios, while the results are robust regarding changes in the costs of additional transmission capacity. The electricity prices are related to the discrepancies identified in Figure 7.7 since the electricity price reflects the cost of activating the last needed MW i.e. the marginal cost of the last dispatched generation unit in the merit-order curve.
In the Low-CO2-price scenario, the composition of the electricity generation and the achieved electricity price levels are comparable with the results obtained in the NO-CCS scenario. Therefore can the explanation given in Section 7.2 be applied for the Low-CO2-price scenario.
The electricity prices achieved in the High-W&WP-price scenario, shows the highest electricity price level by 2030, which is due to higher fuel prices along with the applied IEA-ETP (2015) CO_2 price. By 2050, the electricity price level for the system is approximately 50 €/MWh, which is higher than the Base scenario but lower compared to the Low-CO_2 price scenario.

Endogenous investments in additional generation capacities

In the following paragraph will the total amount of endogenous investments in additional generation capacity in each of the scenarios be presented. In the model, metrics for existing generation capacity are implemented and are identical for all the investigated scenarios. However, the model can decide either to dispatch an already existing generation technology or to invest in new generation capacity. This entails that the discrepancies in the generation portfolios, which are presented in Figure 7.7, appears. To elaborate the endogenous investments in each of the specific sensitivity-scenarios, Figure 7.9 illustrate the investments in new generation capacity in each of the scenarios.

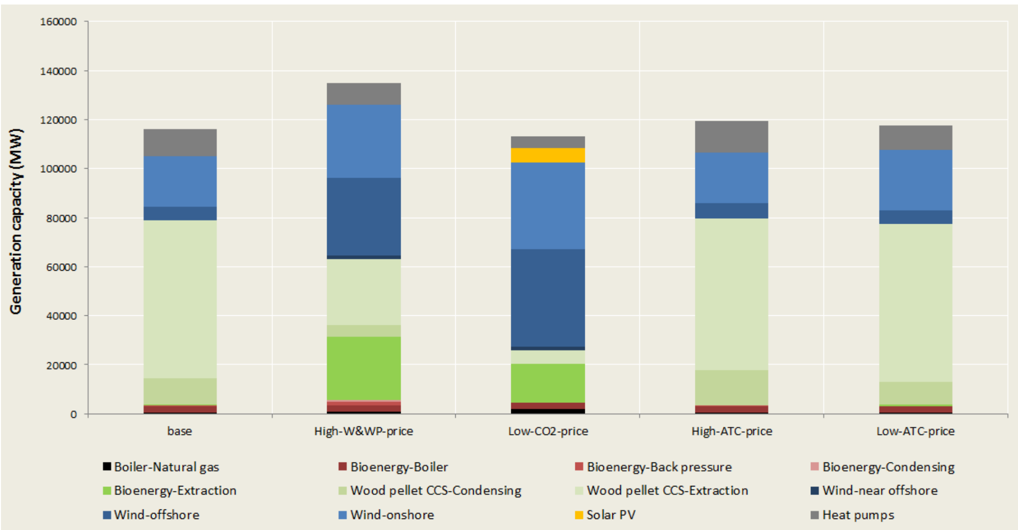


Figure 7.9: Total additional generation capacity by 2050 which is endogenous determined in the Base scenario and in each of the sensitivity scenarios

As illustrated by the figure, the investment decisions in additional generation capacity are sensitive to changes in wood & wood pellet prices and the CO_2 price, while the investments decisions are robust with regard to changes in the price for interconnectors.
In general, the investment decisions in additional generation capacity is in accordance with the aforementioned. In the Base scenario, investments in wood pellet CCS technologies are attractive, while investments in these technologies are lower in the in the High-W&WP-price- and Low-CO_2-price-scenarios. Furthermore, investments in additional wind generation capacity are more attractive in the High-W&WP-price- and

Low-CO_2-price-scenarios.
As a consequence of higher electricity price levels in the High-W&WP-price- and Low-CO_2-price-scenarios, the amount of investments in heat pumps are reduced, due to a less economic benefits og integrating heat pumps in the district heating system. Furthermore, in the Low-CO_2-price scenario investments in solar PV are found, however due to the low full load hours of operating, the increased electricity production from solar PV are hard to identify in Figure 7.9.
In the High-W&WP-price and Low-CO_2-price scenarios less investments in wood pellet CCS technologies entails that countries which has installed a large amount of wood pellet CCS technologies in the Base scenario needs to either install another generation technology or increase the amount of imported electricity. The net electricity imported to Germany for the High-W&WP-price and Low-CO_2-price scenarios are illustrated in Appendix D and E. In the High-W&WP-price scenario the net electricity imported to Germany is 105 TWh by 2030 and 61 TWh by 2050, while in the Low-CO_2-price scenario, the net electricity import to Germany is 103 TWh by 2030 and 128 TWh by 2050.
By identifying these amount of net import of electricity to Germany, the endogenous investments in additional transmission capacities will in the following paragraph be presented.

Endogenous investments in transmission capacities

As the main focus in this case-study is to investigate expansion of transmission capacity as a flexibility resource, the effect on the endogenously computed additional transmission capacity caused by changing the three main data input i.e. price of wood & wood pellets, CO_2 price and the price of additional transmission capacity, are investigated. Figure 7.10, present the results regarding the endogenous determined additional transmission capacity in each of the considered scenarios.

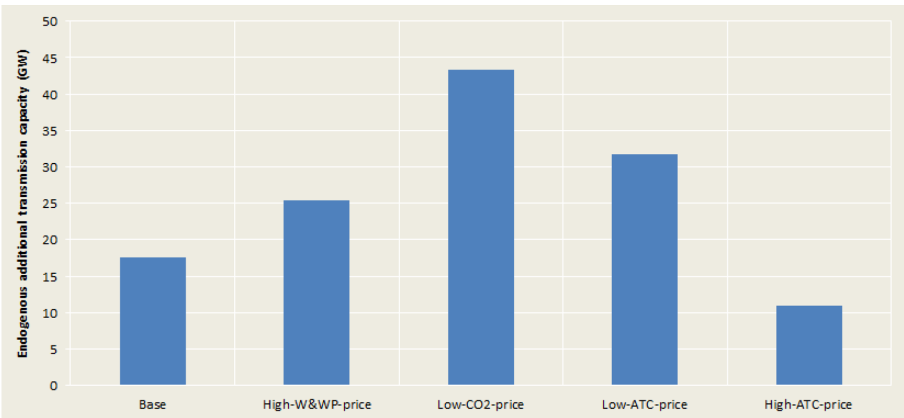


Figure 7.10: Total additional transmission capacity by 2050 which is endogenous determined in the Base scenario and in each of the sensitivity scenarios

The figure shows that the Base scenario result regarding endogenous determined additional transmission capacity is sensitive to the applied changes in the four sensitivity scenarios. It is evident that increasing the prince of additional transmission capacity lead to less investments, while reducing the price of additional transmission capacity lead to a higher amount of investments, which is illustrated by Figure 7.10.
The highest amount of additional transmission capacity is found in the Low-CO_2-price scenario. This can be explained by an increased electricity production from VRE technologies and the large amount of net imported electricity to Germany. The high penetration of VRE technologies requires a larger need for flexibility sources to balance the production and demand, as stated in Chapter 2.

7.4 Summary of Results

The results obtained by the Balmorel model simulations, showed that the transmission capacity is expanded in all scenarios, which illustrate the socio economic benefit of additional transmission capacity.
The results obtained in the Base scenario show that an almost phase-out of fossil fuels by 2030 appears due to the steep increase in the implemented CO_2 price and are substituted mainly by a high utilisation of wood pellets CCS generation technologies. Furthermore, the temporal development in electricity prices showed an increasing trend from 2014 up to 2030 where the annual average electricity prices for the system reached a level of 57.8 €/MWh and then was declining to the average electricity price of 19.4 €/MWh by 2050.
In addition to the Base scenario, an alternative scenario was conducted to elucidate the effects of excluding the investment option in wood pellets CCS technologies. The results showed a significant change in the composition in the production of electricity and higher electricity prices which by 2050 received an average system value of 68 €/MWh.
A sensitivity analysis was performed to clarify sensitivities of main assumptions. The robustness of the results was tested by separately varying three parameters i.e. the price of wood & wood pellets, the CO_2 price, and the price of interconnectors. The results from the sensitivity analysis showed that the generation portfolio, electricity prices and endogenous investments in additional generation capacities are sensitive to the implemented changes in the wood&wood pellets prices and the CO_2 price, while the results showed to be robust w.r.t. changes in the price of interconnectors. However, investigating the endogenous investments in additional transmission capacity, all considered sensitivity scenarios showed significant variations compared to the Base scenario.

CHAPTER 8

Case Study - Assessment of Demand-side Flexibility

Combination of the different flexibility resources can potentially be cost beneficial for the integration of VRE generation technologies. Introducing demand-side flexibility can lead to a reduced need for extension of the transmission grid infrastructure (Lund et al. 2015) and is a promising option in the future, due to the low cost of providing flexibility (IEA-ETP 2012). The synergies in energy systems with increased demand-side flexibility in combination with interconnections between regional pricing regions and regional VRE production are essential to evaluate and are suggested to be further studied by Tröster et al. (2011) and Hirth (2013). Therefore will this chapter evaluate the influence of increased demand-side flexibility in the future energy system.

To facilitate the assessment of increased demand-side flexibility, the Base scenario, presented in Chapter 7, will be utilised, however the electricity demands are changed according to the description in Section 6.3.2. To represent the demand-side flexibility the demand is distinguished by 1) non-flexible electricity and district heating demand, 2) flexible electricity demand for electric vehicles, and 3) flexible electricity demand for electrolysis. In addition to these flexible electricity demands a virtual electricity storage is implemented to simulate the effects of load shifting as a demand-side flexibility option.

The approach utilised to facilitate the modelling is elaborated in Section 6.1.3, which stated that:

1) The demand for electric vehicles are model utilising the smart charging profile which is presented in Appendix A.

2) Hydrogen is modelled utilising the previous developed add-on, however the national demand implemented for hydrogen are low, as shown in Section 6.3.2.

3) The electricity demand modelled utilising the virtual electricity storage relies on the approach utilised in Agora (2015), assuming 4 hours of load and a process without any associated costs or losses.

8.1 Scenario Results

The results obtained from the model simulations of the demand-side flexibility - Flex scenario - will be presented as follows: *First*, the effect on the electricity generation portfolio will be elucidated by presenting the discrepancies in the electricity production between the Flex and the Base scenario. *Secondly*, the obtained annual average electricity prices will be presented along with discrepancies in the endogenously determined additional transmission capacity between the Flex and Base scenario. *Thirdly*, in accordance with the model setup described in Chapter 6.3, an hourly simulation of year 2050 is carried out and the hourly electricity-production, demand, net import, and price will be illustrated for representative weeks.

8.1.1 Generation Portfolio

In this paragraph, the effects of introducing demand-side flexibility into the future energy system will be elucidated. To elaborate the effects, Figure 8.1 presents the discrepancies in the electricity production between the Flex and the Base scenario.

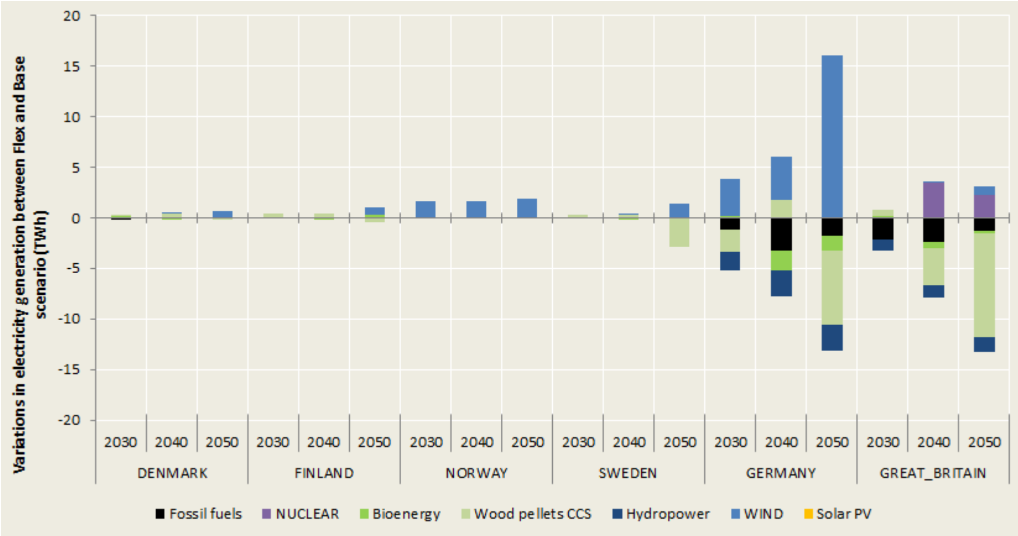


Figure 8.1: Discrepancies in the electricity production between the Flex and the Base scenario.

The results presented in Figure 8.1 show that the inclusion of demand side flexibility lead to less electricity production from thermal plants, while the electricity generation from wind and nuclear are increased. This illustrate the benefits for VRE generation technologies when demand-side flexibility is introduced in the future energy system.

Furthermore, as illustrated in the figure, the most significant discrepancies in the electricity production can be observed for Germany and Great Britain, while the changes in the electricity production levels in the Nordic countries are limited. As described in Section 6.3.2 the amount of flexible electricity demand in Germany and Great Britain are significant larger compared to the flexible electricity demand in the Nordic countries, thus by comparing discrepancies in physical electricity production, Germany and Great Britain will experience larger changes.

The largest changes in the electricity production levels between the Flex and Base scenarios appears by 2050, where the highest amount of flexible electricity demand is introduced, in accordance with Section 6.3.2. Considering the electricity generation in Germany by 2050, almost 15 TWh electricity produced by dispatchable generation technologies are replaced by the VRE technology, wind. Great Britain experience an increased production from nuclear power plants. In Great Britain the full potential of installing cheap onshore wind turbines are used, which limits the expansion of additional wind generation capacity to offshore wind turbines. By introducing demand-side flexibility, the utilisation of the wind production can be shifted in time and thus flatten out the variations in the electricity production. This can potentially lead to higher electricity production from the Base load plants e.g. nuclear in the Flex scenario compared to the Base scenario.

Considering the Nordic countries, evidently higher implementation of wind generation technologies are found in the optimal solution. Comparing the electricity generation between the Flex- and the Base scenario in Norway, additional electricity generation from wind can be observed over the considered period, while no generation technologies experience a reduced electricity production. The increased electricity production

from wind turbines in Norway can be explained by the high full load hours presented in Section 6.3.2 compared to other countries. Thus the model find it optimal to utilise the suitable wind resources in Norway instead of installing wind in other countries.
By introducing demand side flexibility into the future energy system, reduction of fossil fuels can be observed. By 2040 and 2050 natural gas is the primarily fossil fuel which is used to produce electricity, since it is a fast responding peak generation technology and are needed even though the high CO_2 price is implemented. Since, in this scenario, electricity demand can be shifted in time, and taken into account that the Balmorel model has perfect foresight with the simulated year, the need for the natural gas plants can be reduced to a limited extent.

8.1.2 Electricity Prices and Expansion of the Transmission Capacity

Discrepancies in the composition of the electricity generation was found between the Flex- and Base scenario. This paragraph presents the annual average electricity price for each Region along with the identified discrepancies in the endogenously determined additional transmission capacity between the Flex- and Base scenario.
Figure 8.2 presents the Regional electricity prices and the discrepancies in the additional transmission capacity between the Flex and Base scenario by 2030.

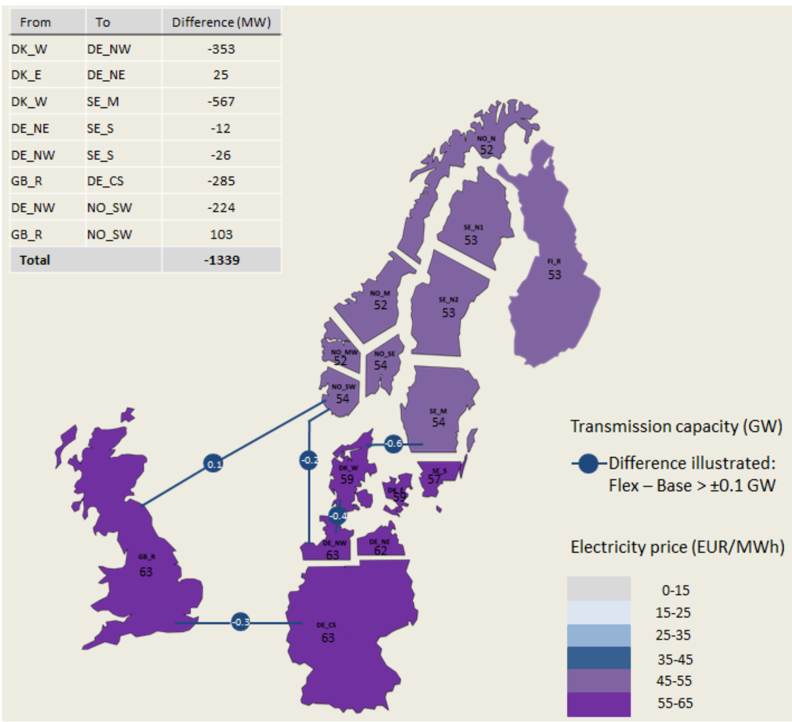


Figure 8.2: The map presents the results of annual electricity prices and discrepancies in the additional transmission capacity between the Flex and Base scenario which are obtained from the Balmorel model simulation of year 2030. The figure show a reduced amount of additional transmission capacity in the Flex scenario compared to the Base scenario. Only differences in additional transmission capacity which are greater than ± 0.1 GW are illustrated in the map, while all identified discrepancies are presented in the Table.

The figure shows that the total investments in additional transmission capacity is lower in the Flex scenario compared to the Base scenario. This findings was expected, since, as stated Chapter 2, introducing demand-side flexibility can lead to a reduced need for extension of the transmission grid infrastructure (Lund et al.

2015).

Furthermore, comparing the annual average electricity prices with the prices found in the Base scenario, small changes can be identified. The total average electricity price in the system is reduced by 0.15 €/MWh compared to the Base scenario. Considering the variations at Country level, the electricity prices in Denmark, Sweden, Germany and Great Britain are reduced, while they are increased in Finland and Norway. For more information regarding the electricity prices, see Appendix H.

To present the temporal development in the annual average electricity prices and the discrepancies in the expansion of the transmission capacity, Figure 8.3 shows the results for the simulation of year 2050.

From	To	Difference (MW)
SE_M	SE_S	3
DK_E	DE_NE	25
DK_W	DE_NW	-353
NO_M	NO_SE	162
DK_W	SE_M	-310
DE_NE	SE_S	-12
DE_NW	SE_S	-26
NO_MW	NO_SW	46
GB_R	DE_CS	-285
GB_R	NO_SW	692
DE_NW	NO_SW	-645
Total		-704

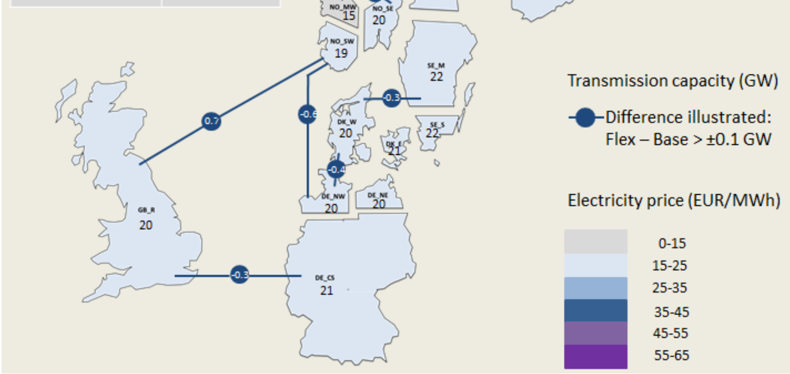


Figure 8.3: The map presents the results of annual electricity prices and discrepancies in the additional transmission capacity between the Flex and Base scenario which are obtained from the Balmorel model simulation of year 2050. The figure show a reduced amount of additional transmission capacity in the Flex scenario compared to the Base scenario. Only differences in additional transmission capacity which are greater than ± 0.1 GW are illustrated in the map, while all identified discrepancies are presented in the Table.

Considering the results presented in Figure 8.3, evidently the total investments in additional transmission capacity is reduced in the Flex scenario compared to the Base scenario, with a total reduction of 0.7 GW. From further investigations of the figure, it can be observed that the additional capacity of the interconnector between Norway and Great Britain is increased by 0.7 GW. As shown in Figure 8.1, the total electricity production in Great Britain is reduced, while the electricity production is increased in Norway. Therefore the higher investments in additional transmission capacity in the interconnection between Great Britain and Norway in the Flex scenario compared to the Base scenario, can partly be explained by a better utilisation of the wind resources in Norway, since Great Britain has reached the potential of installing onshore wind turbines.

From a comparison of the annual average electricity prices, it is found that the average system price in the Flex scenario is reduced by 0.7 €/MWh compared to the prices received in the Base scenario. In Appendix

H, the annual average electricity prices for each Regions are provided and shows that the highest identified price difference is found in northern Norway with a reduced electricity price of 2.5 €/MWh. The flexible demands are implemented in Balmorel by utilising an identical fixed share at the country level. Since the national demand is divided into the Regions by a fixed percentage share, northern Norway will have the same percentage flexible demand as the other Regions in Norway. Therefore in northern Norway, which has significant hydro and wind resources, the introduction of demand-side flexibility entails a local system which efficiently can shift electricity demand in time in order to utilise the hydro and wind resources in an economic optimal way. Since the Balmorel model finds the optimal solution in which additional transmission capacity from northern Norway not is included, this local system appear which results in lower electricity prices.

8.1.3 Hourly Simulation

The inclusion of demand-side flexibility in the long term investments scenario resulted in a higher electricity production from wind turbines, while the electricity production from thermal plants was reduced and, additionally, the need for expansions of the transmission capacity was reduced. In order to investigate the functionality of the implemented demand-side flexibility more thoroughly, an hourly simulation of the year 2050 is conducted. The hourly electricity- production, demand, net import, and price will be presented for two representative winter weeks for both the Nordic region and the surrounding countries, while two representative late summer weeks will be presented for the Nordic region in order to elucidate the main differences between the summer and winter seasons for the Nordic countries.

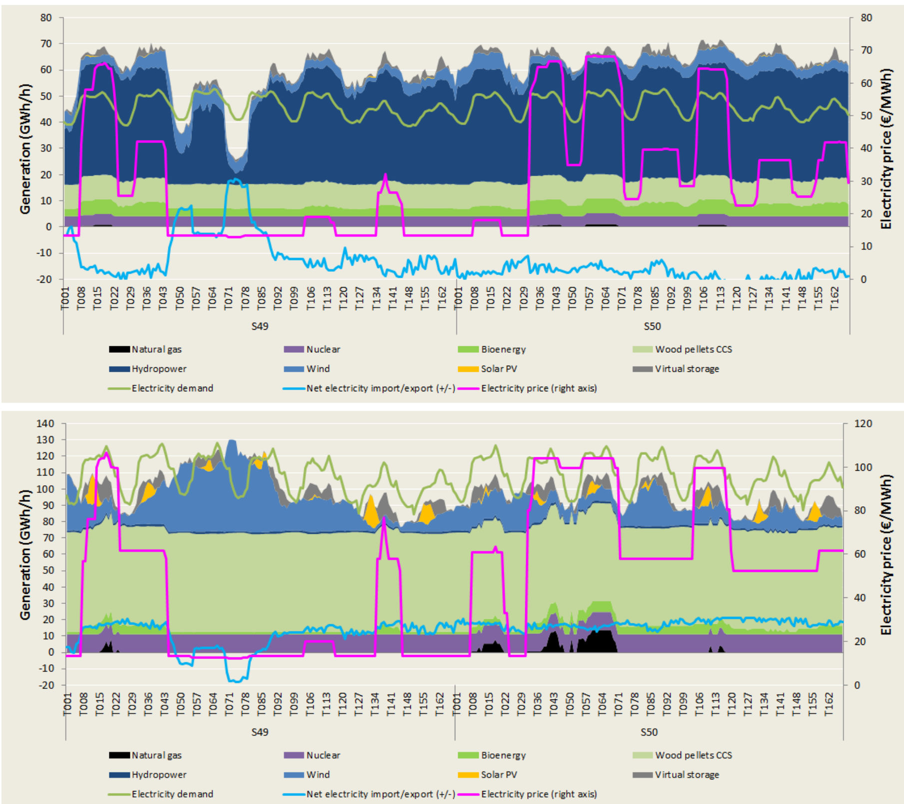


Figure 8.4: Hourly simulation of week 49 and 50 by 2050. The graphs shows the electricity- production, demand, net import, and price for the Nordic countries (Top) and the surrounding countries (Bottom).

Figure 8.4 shows the electricity- production, demand, net import, and price for both the Nordic- and surrounding countries obtained by the model simulation of year 2050 and the winter weeks; 49 and 50.
In the figure, the variable electricity generation i.e. wind and solar PV are represented by the blue and the yellow areas, respectively. The green line represents the electricity demand, while the pink line shows the average electricity prices received in the Nordic region and in the surrounding countries, respectively. The cyan line indicates the aggregated net import for to two systems.
In the two systems, the electricity price increases in time periods where natural gas plants are dispatched, while low prices can be observed in time periods with high wind power production in the surrounding countries. In addition small price peaks appear in peak load hours. In the Nordic countries the maximum average electricity price which can be observed is approximately 70 €/MWh, while in the surrounding countries the average electricity price reach up to approximately 100 €/MWh.
The aggregated net import of the systems are indicated by the cyan line and shows in general that the Nordic region is net exporter of electricity. However, in time periods with high wind production in the surrounding countries the production from hydropower is reduced, and the Nordic region becomes a net importer of electricity.
The effects of introducing demand-side flexibility in to the system is partly indicated by the virtual electricity storage facility, which is indicated by the grey area in the figure. In addition, the electricity demand utilised for electric vehicles is a part of the electricity demand and thus indirect presented by the green line in the figure.
Considering the virtual electricity storage, the electricity storage will be loaded, which corresponds to increasing the electricity demand, in time periods with low electricity prices and low electricity demand, while the electricity storage will be unloaded, which is corresponding to reducing the electricity demand, in time periods with high prices and high electricity demands. In the figure, exactly this process is clearly illustrated.

Since the Nordic region is the main focus in the present thesis, the main differences between the summer and winter seasons for the Nordic countries will be elucidated. In Figure 8.5, the electricity- production, demand, net import, and price are presented two representative late summer weeks.

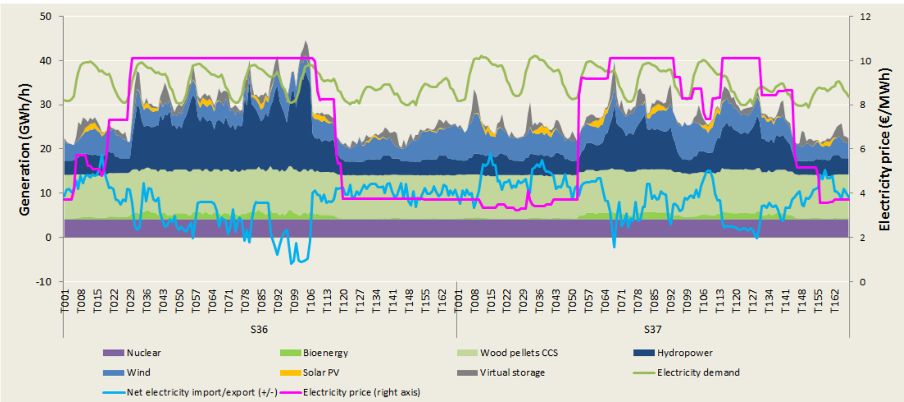


Figure 8.5: Hourly simulation of week 36 and 37 by 2050. The graphs shows the electricity- production, demand, net import, and price for the Nordic countries

The figure shows that the electricity demand and prices in general are lower during the late summer weeks compared to the winter weeks. In some periods, the Nordic region has a composition of the electricity generation which not includes bioenergy excluded CCS which consequently leads to the lowest electricity

prices. Due to the high utilisation of wood pellets CCS technologies in the surrounding countries along with higher electricity production from solar PV, the Nordic region relies more on imported electricity and thus saving the hydro resources to periods with higher electricity demand.
In addition, the virtual electricity storage follows the same pattern as previously described. To supplement the description, evidently in weekend periods which, in general, are characterised by a lower electricity and smaller peak loads, the functionality of the virtual electricity storage works in smaller time intervals, compared to working days where unloading the virtual electricity storage is saved to the morning and afternoon peak demands.

8.2 Summary of Results

The results in this case study showed a reduced amount of endogenous investments in additional transmission capacity compared to the Base scenario. This findings was expected, since, as stated Chapter 2, introducing demand-side flexibility can lead to a reduced need for extension of the transmission grid infrastructure (Lund et al. 2015). Furthermore, the results show, in general, that lower annual average electricity prices will be received when introducing demand-side flexibility in the system.
The results from the comparative assessment of the discrepancies in the composition of electricity production between the Flex and Base scenario show that a higher electricity production from wind and nuclear was achieved in the Flex scenario on expense of thermal electricity generation.
The functionality of the implemented demand-side flexibility was more thoroughly assessed by an hourly simulation of the year 2050. As the electricity demand for electric transportation is integrated in the electricity demand, the effects cannot directly be observed. However, the hourly simulation provided information of the operating of the virtual electricity storage which simulated a simplified and ideal version of demand-side flexibility. It was found that the virtual electricity storage was loaded, which corresponds to increasing the electricity demand, in time periods with low electricity prices and low electricity demand, while the electricity storage was unloaded, which is corresponding to reducing the electricity demand, in time periods with high prices and high electricity demands.

Chapter 9

Conclusion

The main objective of the present thesis was to quantify options for integrating fluctuating renewable energy sources for electricity in the future Nordic energy system towards 2050 with emphasis on two of the flexibility resources i.e. 1) transmission grid infrastructure and 2) demand-side flexibility. This objective was met by performing a theoretical literature study and further by implementing an energy system optimisation model. The relevance of performing the assessments of the two flexibility resources was identified based on literature studies, which showed a need for further studies in both flexibility sources. In the future energy system, an optimised transmission grid infrastructure is essential and is highlighted as a key challenge to reduce the variability in the power system since it is the only flexibility resource that can facilitate the VRE integration challenge regarding the local constrained production. Introducing demand-side flexibility can lead to a reduced need for extension of the transmission grid infrastructure and is a promising option in the future, due to the low cost of providing flexibility.

To facilitate the quantitative assessment of the future options for integrating RES in the Nordic energy system, the energy system optimisation model - Balmorel - which is an effective tool for long-term investment planning of the power and district heating while including the option for a high temporal resolution, was utilised. For the purpose of the present thesis, the Balmorel model was improved by expanding the geographic representation. Furthermore, since the model optimises the energy system by taken into account existing infrastructure and generation capacities, while allowing for endogenously investments, the input database was updated and modified in order to simulate the anticipative energy system scenario adopted from NETP (2016). The NETP 2016 scenario was chosen since it takes into account interactions between countries while hold promise of achieving both national and international energy policy targets.

The quantitative assessment included two case studies, 1) Assessment of future expansion og the transmission capacity, and 2) Assessment of demand-side flexibility.

In the *first* assessment, a Base scenario, an alternative 'NO-CCS' scenario and four sensitivity scenarios was investigated. The results showed that the transmission capacity will be expanded in all scenarios which illustrate the socio economic benefit of additional transmission capacity. The results in the Base scenario showed that an almost phase out of fossil fuels by 2030 appear due to the steep increase in the implemented CO_2 price and are substituted mainly by a high utilisation of wood pellets CCS generation technologies. In the Base scenario the annual average electricity price for the system by 2050 was found to 19.4 €/MWh. To clarify sensitivities of the main assumptions, a sensitivity analysis was conducted, where the robustness of the results was tested by separately varying three parameters i.e. the price of wood & wood pellets, the CO_2 price, and the price of interconnectors. The results from the sensitivity analysis showed that the generation portfolio, electricity prices and endogenous investments in additional generation capacities are sensitive to the implemented changes in the wood&wood pellets prices and the CO_2 price, while the results showed to be

robust w.r.t. changes in the price of interconnectors. However, investigating the endogenous investments in additional transmission capacity, all considered sensitivity scenarios showed significant variations compared to the Base scenario.
In the *second* assessment, where demand-side flexibility was introduced in the system, the results showed a reduced amount of endogenous investments in additional transmission capacity compared to the Base scenario. Furthermore, when introducing demand-side flexibility in the system, the annual average electricity prices will, in general, tend to be lower compared to the Base scenario. Moreover, a comparative assessment of the discrepancies in the composition of electricity production between the Flex and Base scenario was conducted and showed that higher electricity production from wind and nuclear was achieved in the Flex scenario on expense of thermal electricity generation. Finally an hourly simulation was performed and showed for four representative weeks which clarified the functionality of the implemented simplified demand-side flexibility.

Due to the scope of the present thesis, interesting questions that calls for further research have appeared.
Since the first objective of the present thesis was to investigate the expansion of transmission capacity in the Nordic countries and two neighbouring countries, the electricity exchange in the presented model was limited to include electricity flows between the considered countries. Since the electricity flows are affected by the electricity supply and demand in other European countries, a natural extension of this project, would be a further elaboration of the model to include a representation of all European countries.
The applied energy system model includes the electricity and district heating sectors. However, as the energy system contain electricity, heat, gas, and transport sectors, and the interactions between the sectors are expected to be increased in the future, expanding the model to include a holistic representation encompassing all sectors would be of interest.
In the present thesis, a simplified representation of demand-side flexibility is applied. The demand-side flexibility is modelled as an aggregated energy volume, thus a more detailed representation of various consumers could provide valuable information regarding the effects of each of the demand-side flexibility sources. With regard to the present thesis, evaluating the effects from introducing electric vehicles and the virtual electricity storage separately would provide more insight and is a natural extension of this project.

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Appendices

Appendix A

Merit order effect

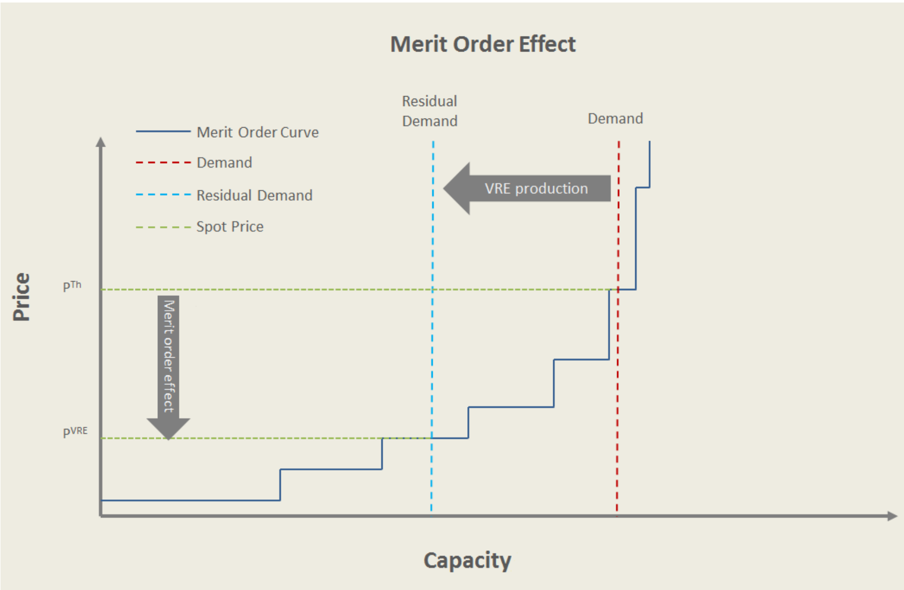


Figure 1: Merit order effect

The objective function in the Balmorel model

The mathematical formulation of the objective function is in the following presented as a minimising problem.

$$V_{obj} = \sum_{C,R,A,G,T} (C^{fuel}_{A,G,T} + C^{O\&M}_{A,G,T} + C^{trans}_{A,G,T} + C^{inv}_{A,G,T} + T^{fuel}_{C,G,T} + T^{ems}_{C,G,T} + T^{other}_{A,G,T} + \Delta U^{elec}_{R,T} + \Delta U^{heat}_{A,T}) \quad (1)$$

The objective function is the sum of the costs included in the calculations in the simulated year. The notations in the mathematical expression is as follows:

$C^{fuel}_{A,G,T}$ represents the fuel costs for generation technology G in Area A at Time T
$C^{O\$M}_{A,G,T}$ represents the fixed and variable operation costs related to the generation technology G in Area A at Time T
$C^{trans}_{R,T}$ are the transmission costs related to electricity exchange between Regions R at Time T
$C^{inv}_{A,R,G,T}$ represents the investment costs in new generation technologies G in Area A and transmission lines between Regions R at Time T.

In case taxes are introduced to the system:
$T^{fuel}_{C,G,T}$ represents the fuel taxes for generation technology G in Country C at Time T,
$T^{emissions}_{C,G,T}$ represents the emission taxes e.g. CO_2 price
$T^{other}_{A,G,T}$ represents other taxes which can be related to district heating and heat only generation technologies in Area A, for generation technology G at Time T.

In case elastic demands for electricity and heat are introduced:
Δ $U^{elec}_{R,T}$ changes in consumers utility of electricity consumption relative to nominal utility of consumption
Δ $U^{heat}_{A,T}$ changes in consumers utility of heat consumption relative to nominal utility of consumption

Representation of the feasible operation areas for each of the generation technologies

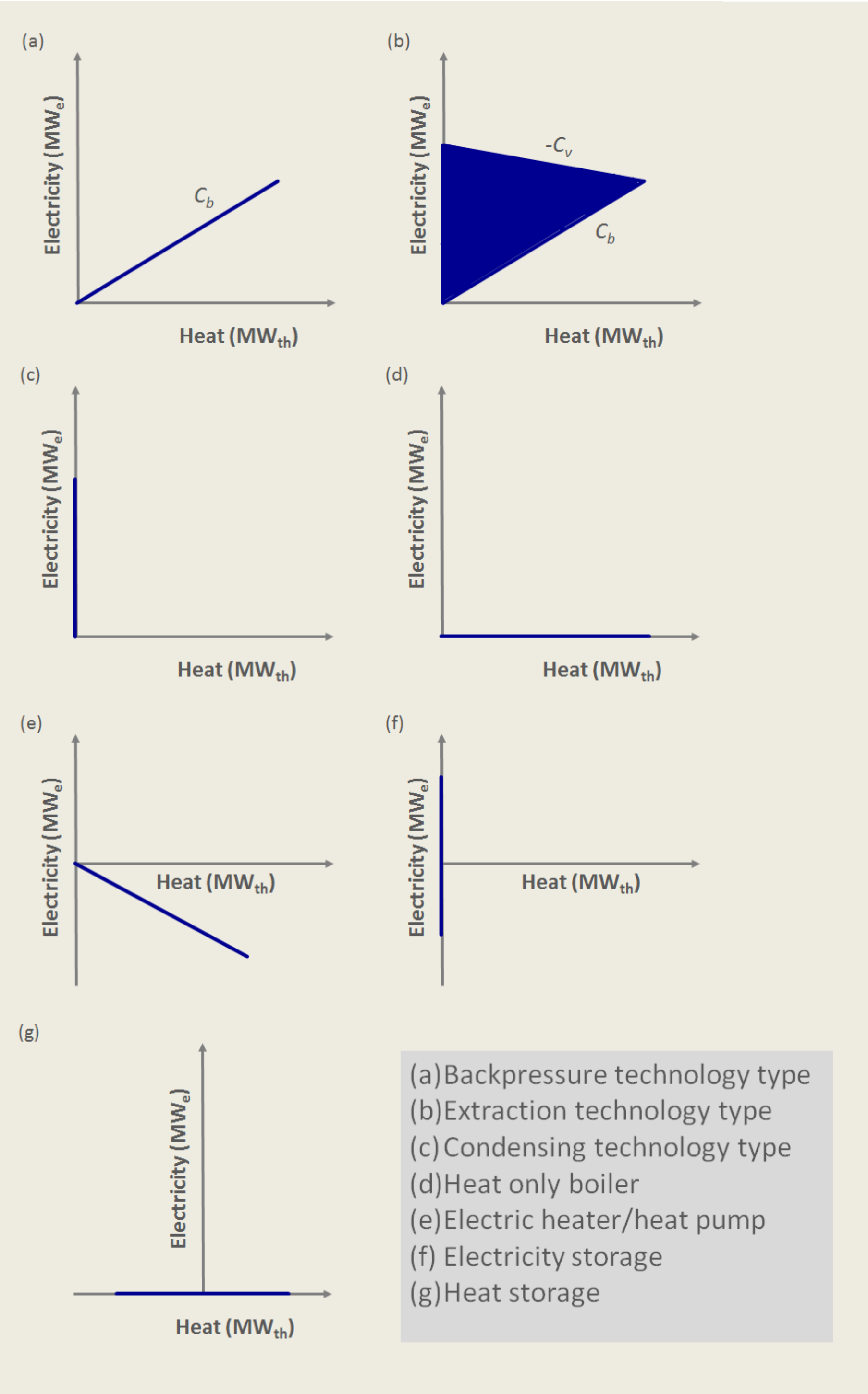


Figure 2: Representation of the feasible operation areas for each of the generation technologies

Table 1: Annual electricity prices in the NordPool spot market by 2014 and 2015

EUR/MWh	2015	2014
DK_W	22.90	30.67
DK_E	24.49	32.15
FI_R	29.66	36.02
NO_SE	19.82	27.33
NO_SW	19.82	27.23
NO_MW	19.75	27.14
NO_M	21.28	31.54
NO_N	20.43	21.44
Total SYS	20.98	29.61

Sources: Nordpool.com

EV-charging-profile

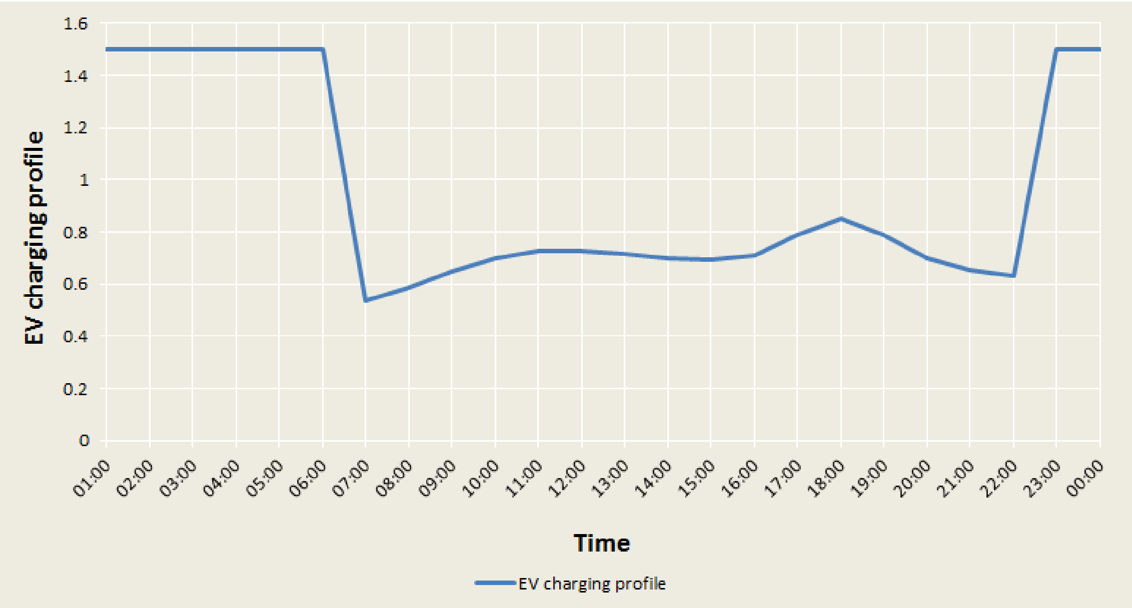


Figure 3: EV-charging-profile

Table 2: Percentage share of district heating demand

Country	Area	Share (%)
Denmark	DK_E_Large	25%
	DK_E_Medium	5%
	DK_E_MedSmall	2%
	DK_E_Rural	6%
	DK_E_Small	0%
	DK_W_Large	27%
	DK_W_Medium	12%
	DK_W_MedSmall	6%
	DK_W_Rural	16%
	DK_W_Small	1%
Finland	FI_R_Rural	80%
	FI_R_Urban	20%
Norway	NO_SE_Rural	27%
	NO_SW_Rural	27%
	NO_M_Rural	15%
	NO_N_Rural	5%
	NO_MW_Rural	27%
Sweden	SE_N1_Rural	5%
	SE_N2_Rural	5%
	SE_M_Rural	20%
	SE_S_Rural	31%
	SE_M_Urban	39%
Germany	DE_NE_A1	3%
	DE_NW_A1	13%
	DE_CS_A1	85%
Great Britain	GB_R_Rural	100%

Table 3: Percentage share of electricity demand

Country	Region	Share (%)
Denmark	DK_E	39%
	DK_W	61%
Finland	FI_R	100%
Norway	NO_SE	28%
	NO_SW	27%
	NO_M	17%
	NO_MW	13%
	NO_N	14%
Sweden	SE_N1	8%
	SE_N2	11%
	SE_M	63%
	SE_S	18%
Germany	DE_NE	1%
	DE_NW	11%
	DE_CS	88%
Great Britain	GB_R	100%

Table 4: Percentage share of electricity demand which is assumed to be flexible

	2013	2015	2020	2025	2030	2035	2040	2045	2050
Electricity for electrolysis	1%	1%	5%	20%	40%	54%	66%	78%	90%
Transport	1%	1%	5%	20%	40%	50%	50%	50%	50%
Industry	1%	1%	1%	1%	2%	2%	2%	2%	2%
Residential	1%	1%	8%	8%	15%	15%	15%	15%	15%
Service	1%	1%	8%	8%	15%	15%	15%	15%	15%
Agriculture	1%	1%	1%	1%	1%	1%	1%	1%	1%
Flexible electricity demand in industry, residential, service and agriculture is aggregated and are used as a metric for the energy amount in the virtual battery.									

Table 5: Planned Transmission capacity until 2025

Project	From	To	Capacity (MW)	Year	Estimated Cost (M€)	Estimated Cost (M€/MW)
National connections in the Nordic countries. Source NETP 2016 and Agora 2015, data derived from ENTSO-E - TYNDP 2014.						
Sydvastlanken	SE_M	SE_S	1200	2016	-	-
RES/SoS Norway/Sweden phase 1	SE_M NO_M	SE_N2 NO_MW	700 1500	2019 2020	560-930	0.37-0.62
NordBalt Cable Phase 2	SE_S	SE_M	700	2023	170 - 270	0.24 - 0.39
Res in mid-Norway	NO_M	NO_N	1200	2023	870 - 1500	0.73 - 1.25
National connections in Germany. Source NETP 2016, data derived from Netzentwicklungsplan 2014 (Scenario B).						
TTG-007	DE_NW	DE_CS	1000	2018	-	-
P21	DE_NW	DE_CS	1000	2022	-	-
P24	DE_NW	DE_CS	1000	2022	-	-
A01, C05	DE_NW	DE_CS	4000	2022	-	-
P36	DE_NE	DE_CS	1000	2018	-	-
P34	DE_NE	DE_CS	1000	2020	-	-
C06mod	DE_NW	DE_CS	2000	2022	-	-
C06WDL	DE_NW	DE_CS	2000	2023	-	-
North South Western German Corridor	DE_NW	DE_CS	8000	2025	-	-
Interconnectors between the countries. Source NETP 2016 and Agora 2015, data derived from ENTSO-E - TYNDP 2014.						
3rd AC Finland-Sweden	SE_N1	FI_R	1000	2025	64-120	0.06 – 0.12
NordLink Cable	NO_SW	DE_NW	1400	2020	2500	1.79
West Denmark to Germany	DK_W DE_NW	DE_NW DK_W	860 1000	2019	220 - 270	0.22 – 0.27
Kriegers Flak	DK_E DE_NE	DK_KF DE_KF	600 400	2019	300	0.21
Westcoast	DK_W	DE_NW	500	2022	170 - 210	0.34 - 0.42
Hansa PowerBridge	SE_S	DE_NE	700	2025	200 - 400	0.29 - 0.57
Cobra Cable[1]	DK_W	NL_R	700	2019	560 - 680	0.8 - 0.97
Norway-Great Britain	NO_SW	GB_R	1400	2020	1700	1.21
Viking Cable	DK_W	GB_R	1400	2022	-	-

1) Cobra Cable is originally from Denmark to the Netherlands. In this thesis, the cobra cable is modelled as an interconnector between Denmark and Germany (DK_W to DE_CS)

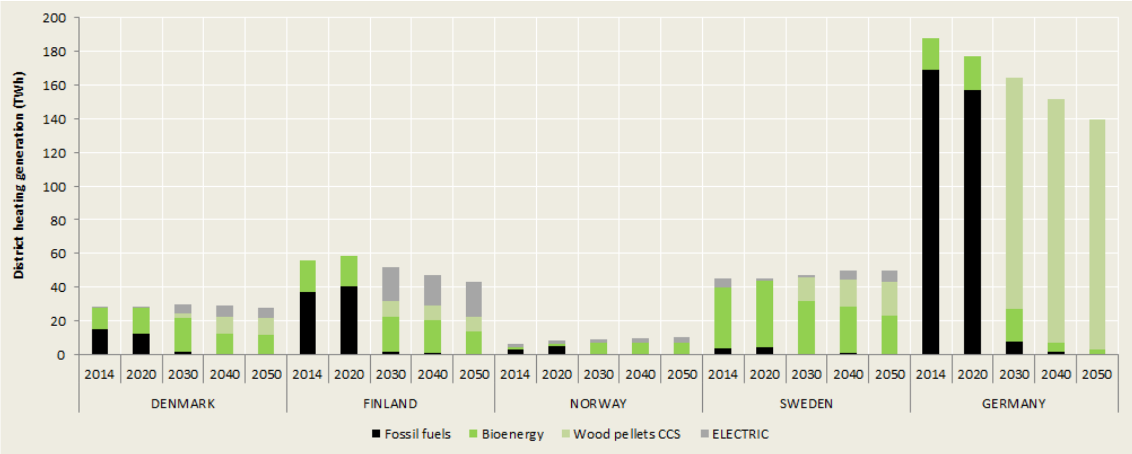
Table 6: Cost of additional transmission capacity

From	To	Cost (EUR/MW)
DK_E	DK_W	519724
DK_E	SE_S	426173
DK_E	DE_NE	478146
DK_W	SE_M	789981
DK_W	NO_SW	706825
DK_W	DE_NW	582091
DK_W	GB_R	1216156
SE_N1	SE_N2	582091
SE_N1	NO_N	498936
SE_N1	FI_R	582091
SE_N2	SE_M	582091
SE_N2	NO_N	550908
SE_N2	NO_M	582091
SE_N2	FI_R	779587
SE_M	SE_S	582091
SE_M	NO_SE	582091
SE_M	FI_R	810771
SE_S	DE_NE	738009
SE_S	DE_NW	862742
NO_N	NO_M	582091
NO_N	FI_R	582091
NO_M	NO_MW	519724
NO_M	NO_SE	582091
NO_M	NO_SW	582091
NO_MW	NO_SE	530119
NO_MW	NO_SW	498936
NO_SE	NO_SW	519724
NO_SW	DE_NW	1205761
NO_SW	GB_R	1236944
DE_CS	DE_NE	582091
DE_CS	DE_NW	582091
DE_CS	GB_R	893927
DE_NE	DE_NW	457358

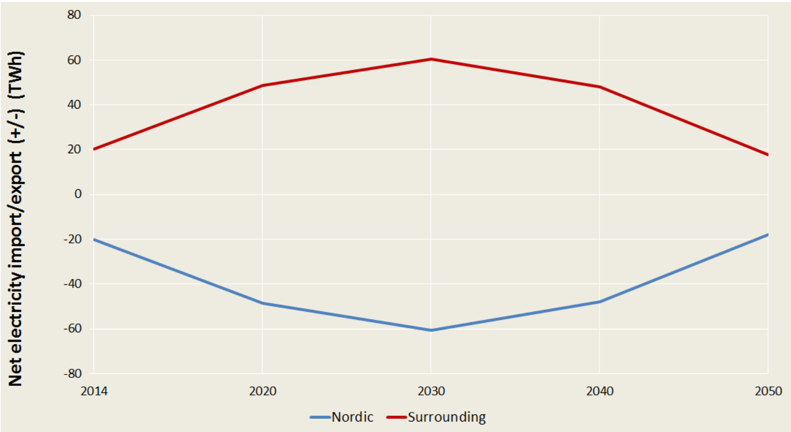
Appendix B

Additional results from the Base scenario:

District heating generation



Import and export of electricity between the Nordic region and the surrounding countries



Total endogenous investments in generation technologies by 2050

Generation technology	Capacity (MW)
Boiler-Natural gas	510
Bioenergy-Boiler	2547
Bioenergy-Back pressure	233
Bioenergy-Condensing	0
Bioenergy-Extraction	340
Wood pellet CCS-Condensing	10939
Wood pellet CCS-Extraction	64484
Wind-near offshore	0
Wind-offshore	5473
Wind-onshore	20566
Solar PV	0
Heat pumps	10915
Hydrogen	0
Total = 116006 MW	

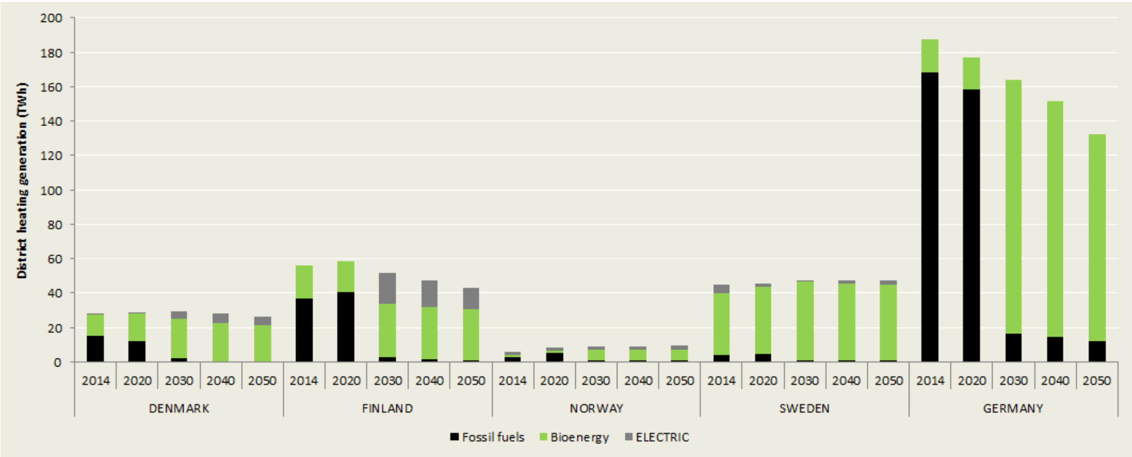
Total endogenous investments in transmission capacities by 2050

From	To	Transmission capacity (MW)
DK_W	DE_NW	353
NO_M	NO_SE	692
DE_NE	SE_S	1367
DK_W	SE_M	1367
DE_NW	SE_S	1857
NO_MW	NO_SW	1955
GB_R	DE_CS	2520
GB_R	NO_SW	2874
DE_NW	NO_SW	4551
Total = 17538 MW		

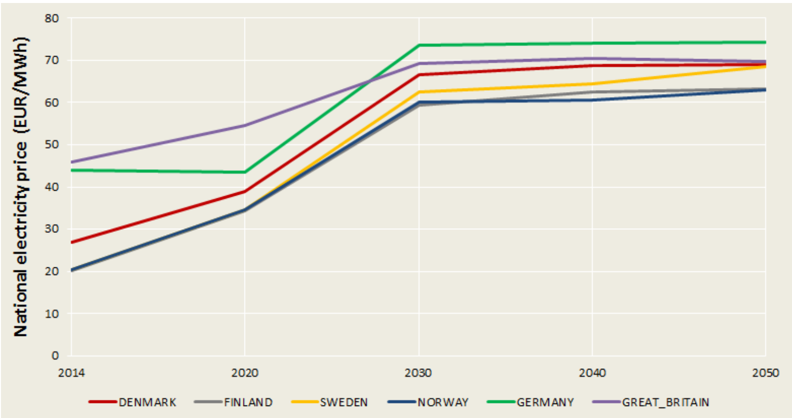
Appendix C

Additional results from the Alternative NO-CCS scenario:

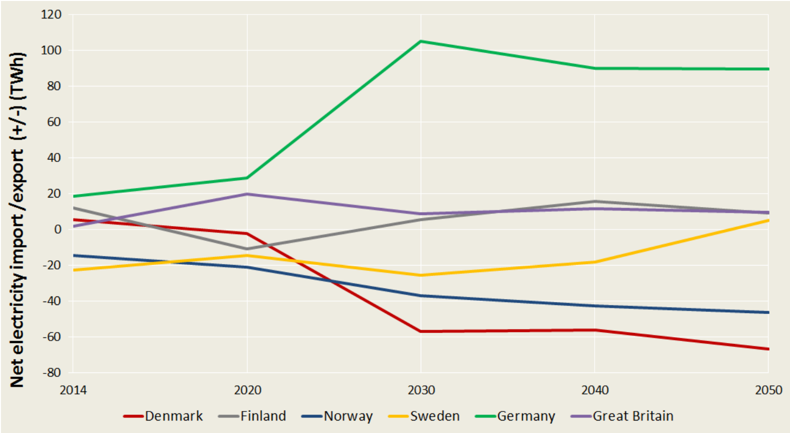
District heating generation



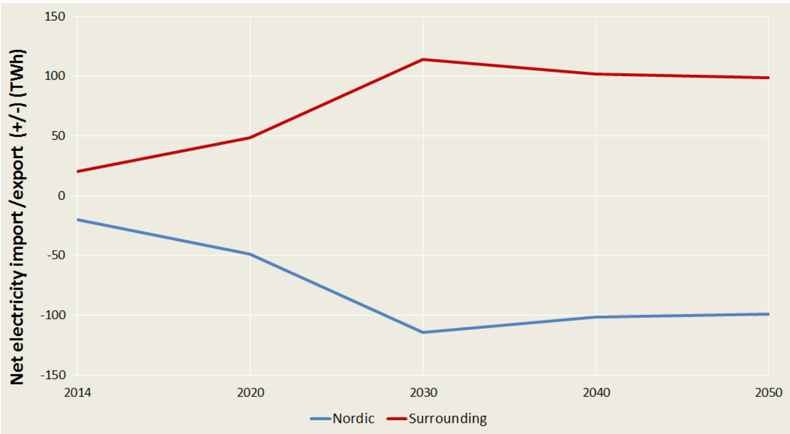
Annual average electricity prices for each country



Import and export of electricity between the countries



Import and export of electricity between the Nordic region and the surrounding countries



Total endogenous investments in generation technologies by 2050

Generation technology	Capacity (MW)
Boiler-Natural gas	969
Bioenergy-Boiler	2778
Bioenergy-Back pressure	2137
Bioenergy-Condensing	1878
Bioenergy-Extraction	29813
Wood pellet CCS-Condensing	0
Wood pellet CCS-Extraction	0
Wind-near offshore	1250
Wind-offshore	40616
Wind-onshore	31912
Solar PV	3526
Heat pumps	8361
Hydrogen	0
Total = 123240 MW	

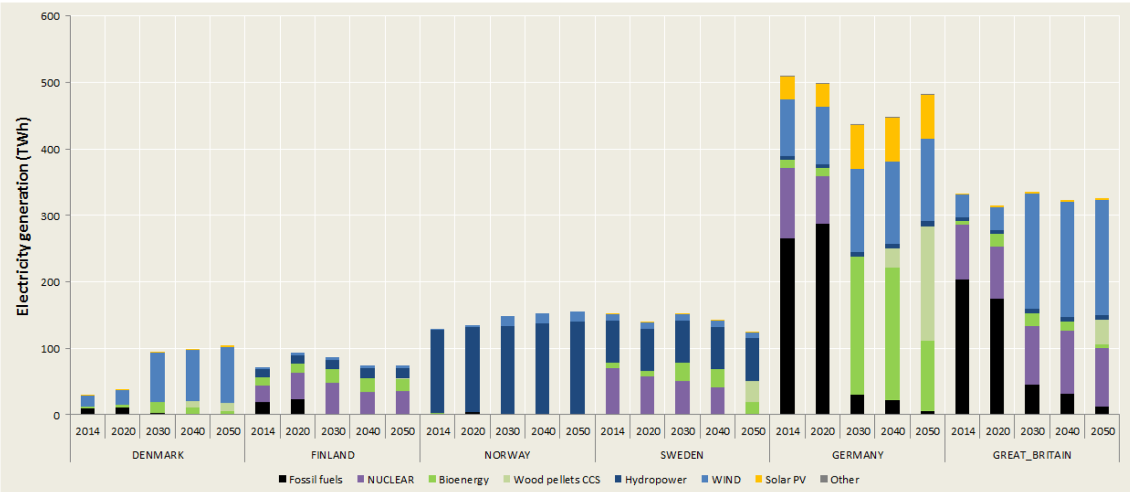
Total endogenous investments in generation technologies by 2050

From	To	Transmission capacity (MW)
NO_N	SE_N1	78
DE_NW	NO_SW	273
NO_N	SE_N2	422
NO_M	NO_SE	841
SE_N2	SE_M	886
DK_W	NO_SW	1032
DE_NE	SE_S	1500
DE_NW	SE_S	1879
DK_W	SE_M	2488
NO_MW	NO_SW	2707
DK_W	DE_NW	5182
GB_R	DE_CS	5466
GB_R	NO_SW	6813
Total = 29565 MW		

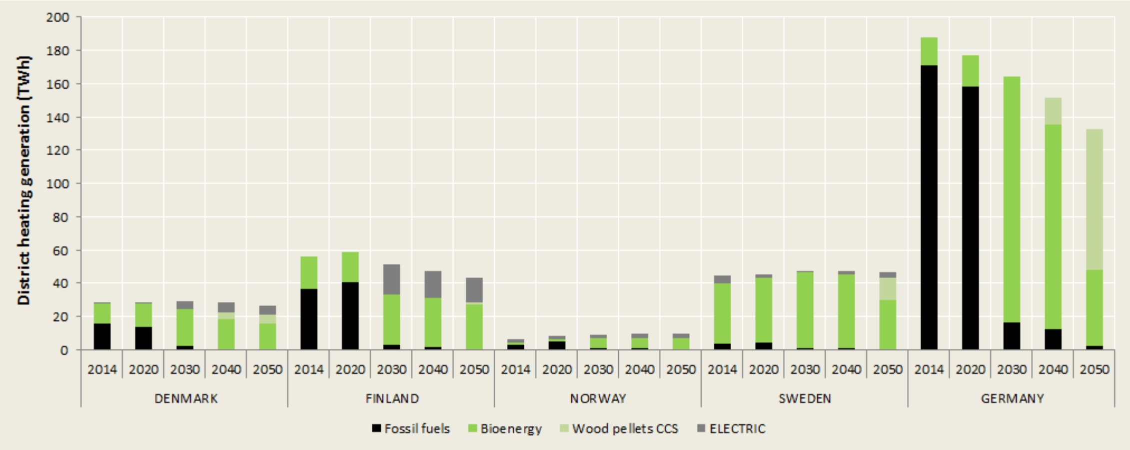
Appendix D

Additional results from the High-bio-price scenario:

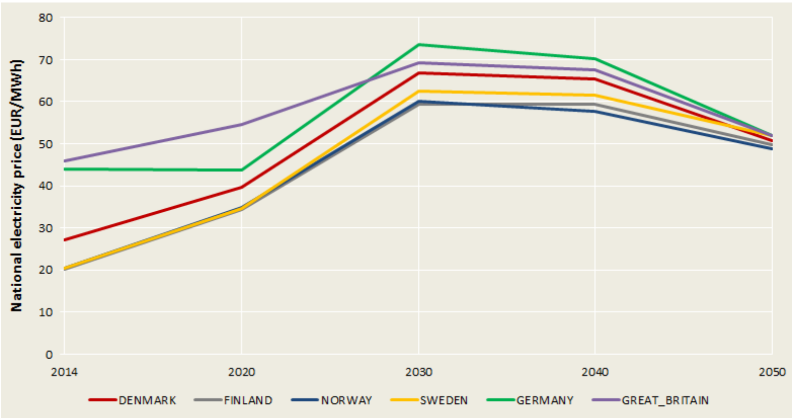
Electricity generation



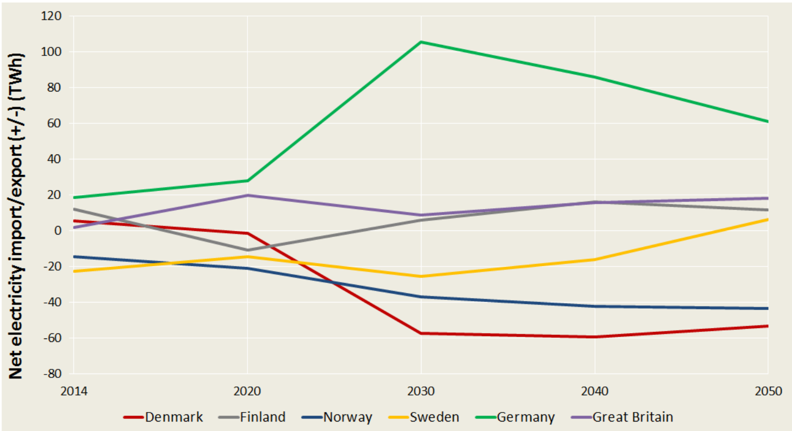
District heating generation



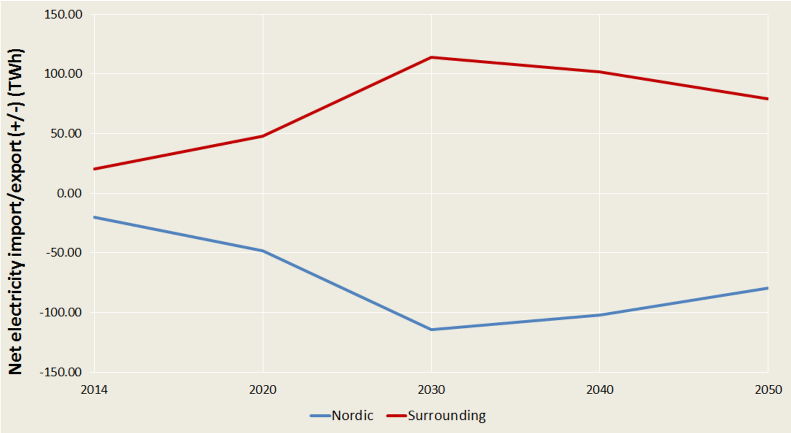
Annual average electricity price



Import and export of electricity between the countries



Import and export of electricity between the Nordic region and the surrounding countries



Total endogenous investments in generation technologies by 2050

Generation technology	Capacity (MW)
Boiler-Natural gas	666
Bioenergy-Boiler	2630
Bioenergy-Back pressure	1641
Bioenergy-Condensing	798
Bioenergy-Extraction	25826
Wood pellet CCS-Condensing	4491
Wood pellet CCS-Extraction	27125
Wind-near offshore	1250
Wind-offshore	31842
Wind-onshore	29638
Solar PV	0
Heat pumps	9129
Hydrogen	0
Total = 135037 MW	

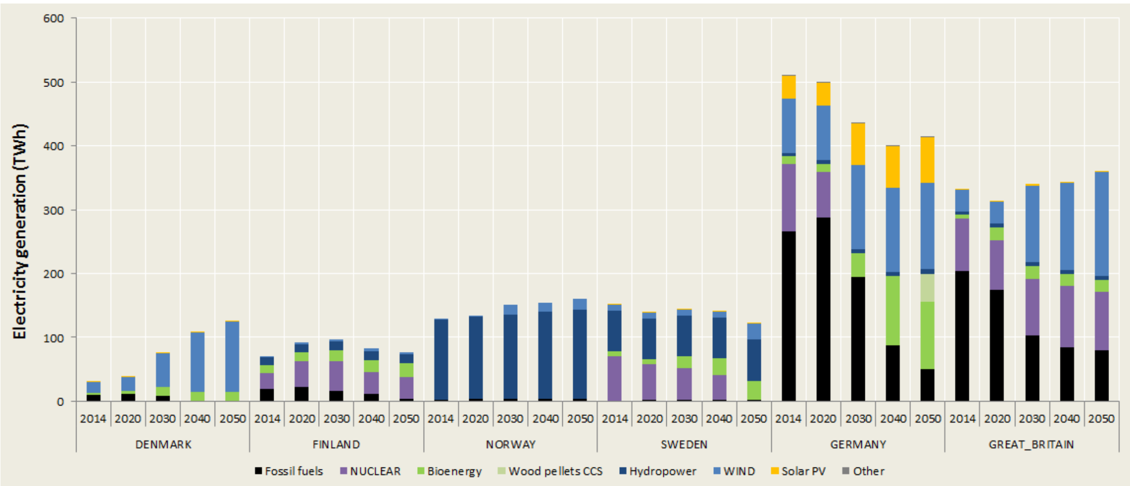
Total endogenous investments in generation technologies by 2050

From	To	Transmission capacity (MW)
DK_W	NO_SW	13
NO_N	SE_N1	81
DE_NW	NO_SW	356
NO_M	NO_SE	532
DE_NE	SE_S	1508
DE_NW	SE_S	1822
NO_MW	NO_SW	2231
DK_W	SE_M	2332
GB_R	DE_CS	4698
DK_W	DE_NW	4928
GB_R	NO_SW	6831
Total = 25332 MW		

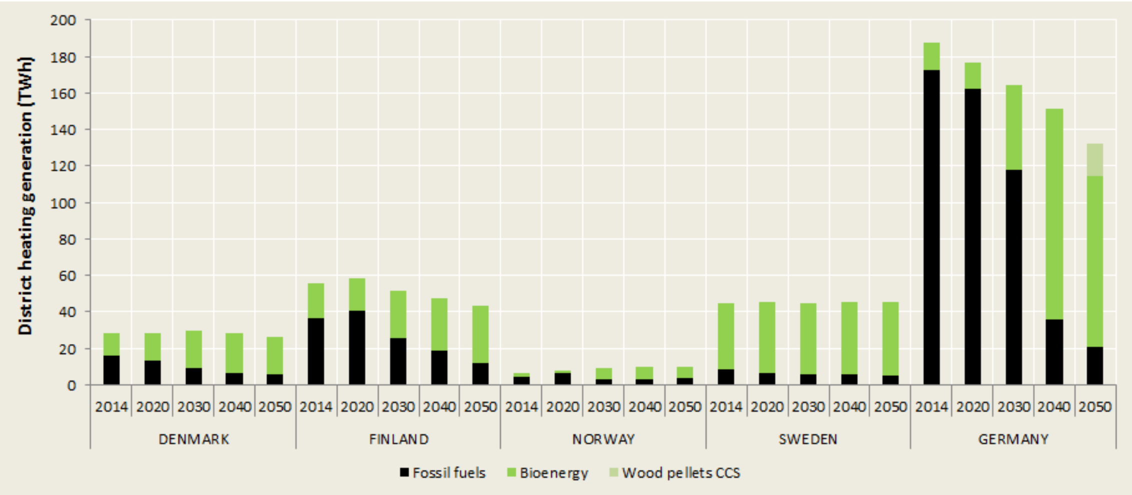
Appendix E

Additional results from the Low-CO_2-price scenario:

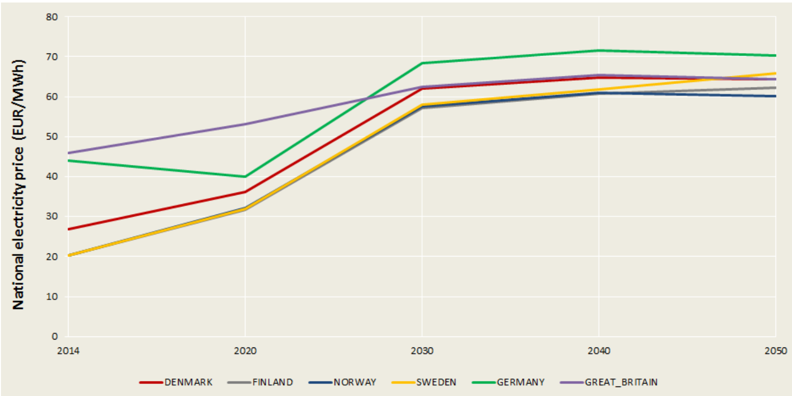
Electricity generation



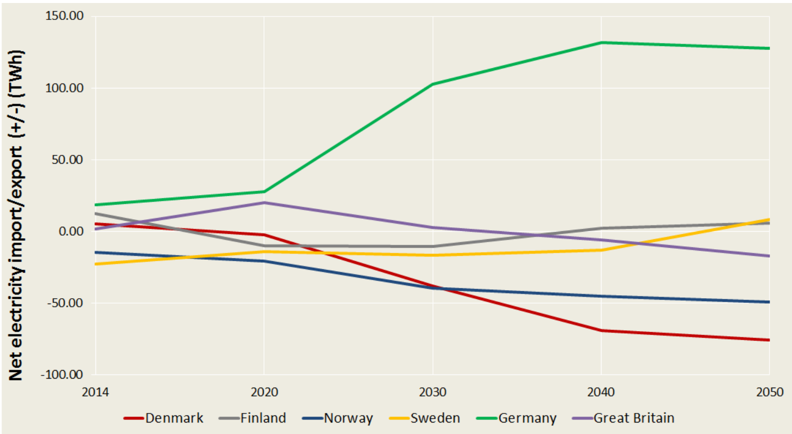
District heating generation



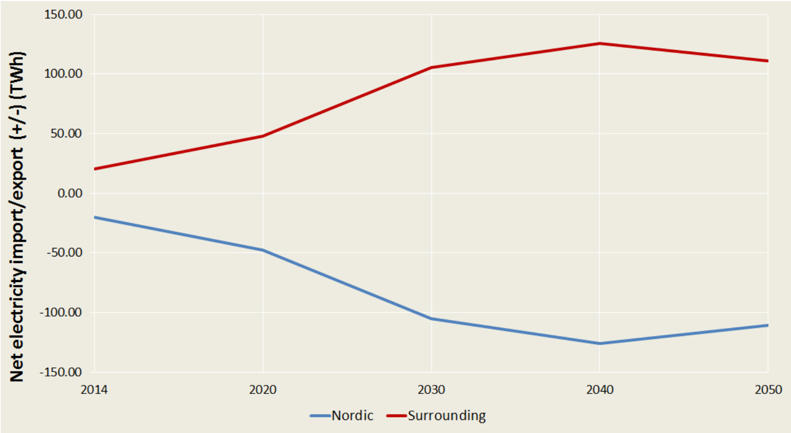
Annual average electricity prices for each country



Import and export of electricity between the countries



Import and export of electricity between the Nordic region and the surrounding countries



Total endogenous investments in generation technologies by 2050

Generation technology	Capacity (MW)
Boiler-Natural gas	1828
Bioenergy-Boiler	2547
Bioenergy-Back pressure	305
Bioenergy-Condensing	0
Bioenergy-Extraction	15797
Wood pellet CCS-Condensing	0
Wood pellet CCS-Extraction	5479
Wind-near offshore	1250
Wind-offshore	39843
Wind-onshore	35247
Solar PV	6120
Heat pumps	4654
Hydrogen	0
Total = 113069 MW	

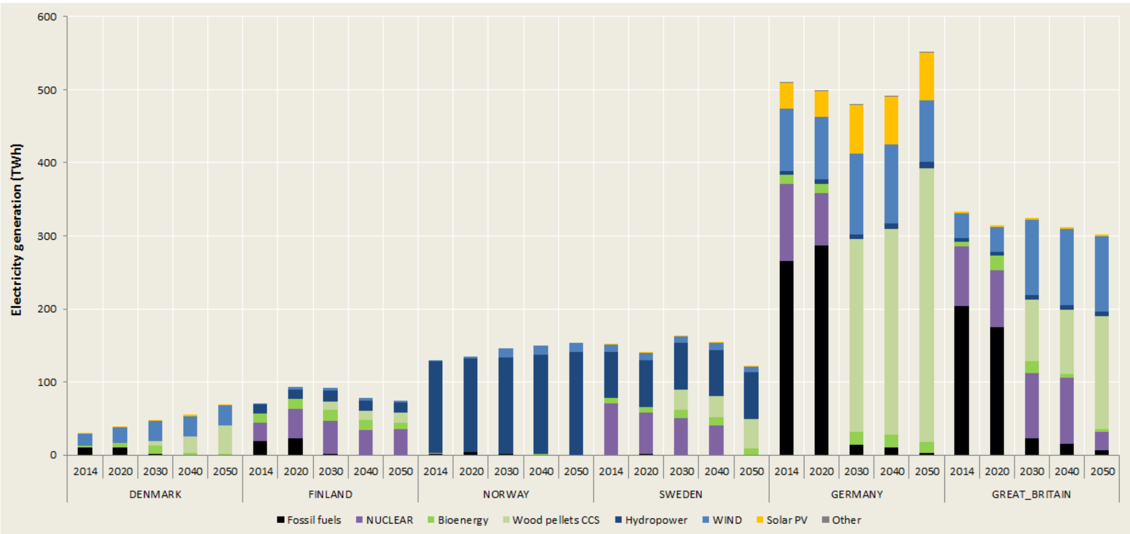
Total endogenous investments in generation technologies by 2050

From	To	Transmission capacity (MW)
NO_M	NO_SE	149
GB_R	NO_SW	428
DK_W	SE_M	753
NO_MW	NO_SW	919
DE_NE	SE_S	1216
DE_NW	SE_S	1937
DK_W	NO_SW	4388
GB_R	DE_CS	5378
DE_NW	DK_W	6477
Total = 21644 MW		

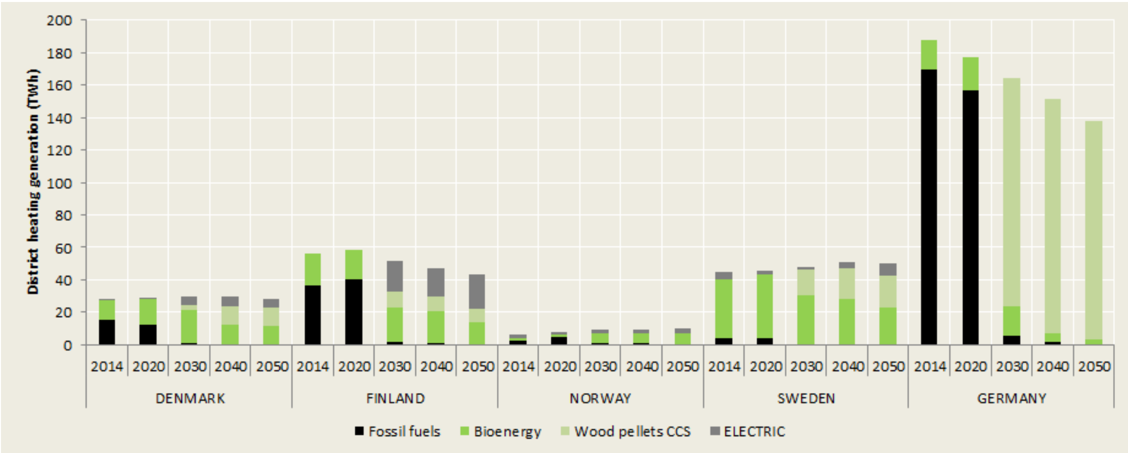
Appendix F

Additional results from the Low-trans-price scenario:

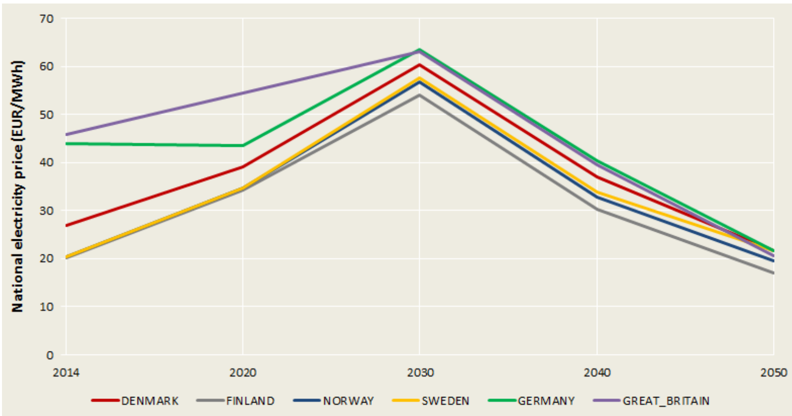
Electricity generation



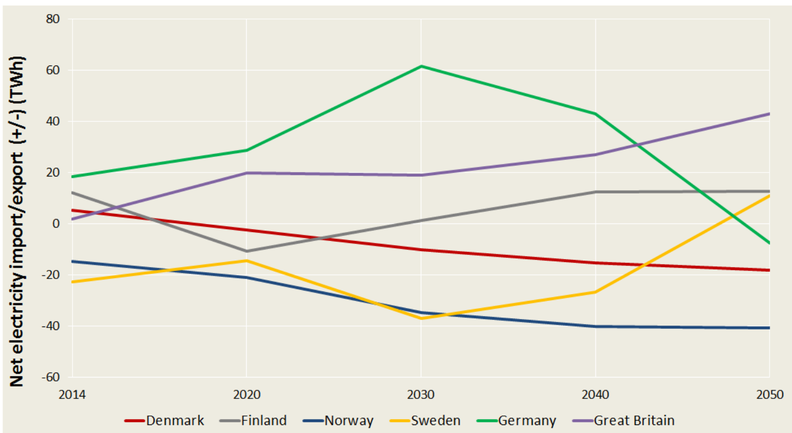
District heating generation



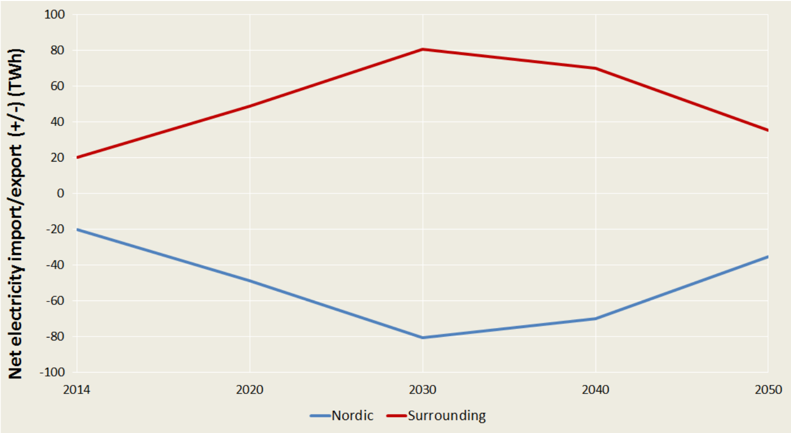
Annual average electricity prices for each country



Import and export of electricity between the countries



Import and export of electricity between the Nordic region and the surrounding countries



Total endogenous investments in generation technologies by 2050

Generation technology	Capacity (MW)
Boiler-Natural gas	469
Bioenergy-Boiler	2557
Bioenergy-Back pressure	172
Bioenergy-Condensing	0
Bioenergy-Extraction	401
Wood pellet CCS-Condensing	9415
Wood pellet CCS-Extraction	64486
Wind-near offshore	0
Wind-offshore	5504
Wind-onshore	24571
Solar PV	0
Heat pumps	10045
Hydrogen	0
Total = 117620 MW	

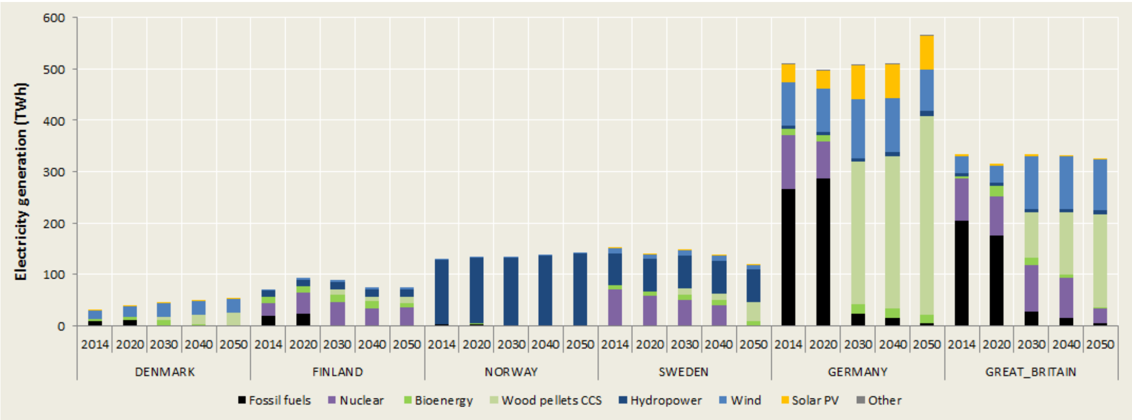
Total endogenous investments in generation technologies by 2050

From	To	Transmission capacity (MW)
DK_E	DE_NE	99
NO_N	NO_M	404
SE_M	SE_S	542
NO_N	SE_N2	1087
DE_NE	SE_S	1195
NO_N	SE_N1	1250
NO_M	NO_SE	1327
SE_N2	SE_M	1879
NO_MW	NO_SW	2289
DE_NW	SE_S	2489
DK_W	DE_NW	2608
DE_NW	NO_SW	3220
GB_R	DE_CS	4097
DK_W	SE_M	4098
GB_R	NO_SW	5088
Total = 31672 MW		

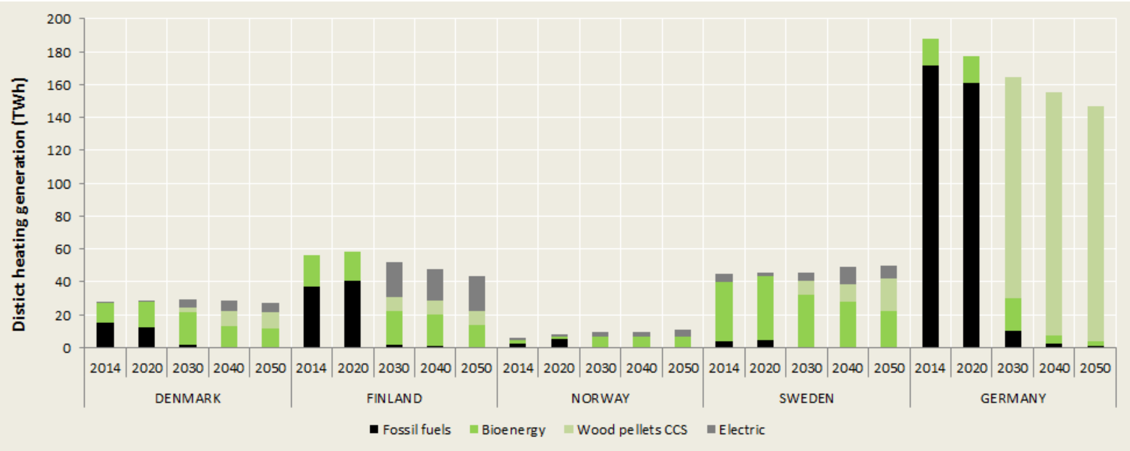
Appendix G

Additional results from the High-Inter-price scenario:

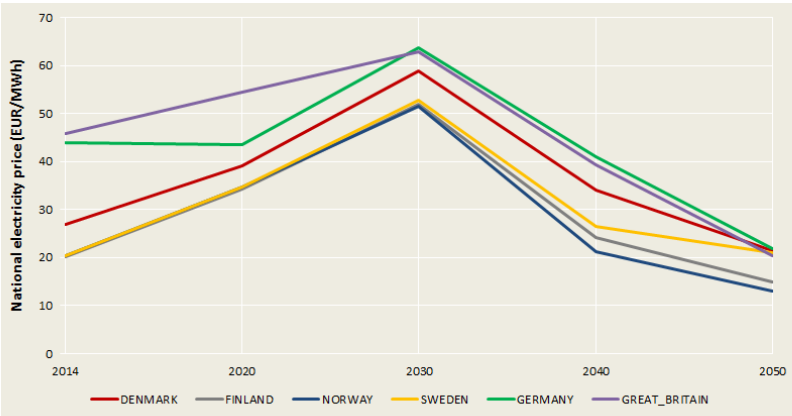
Electricity generation



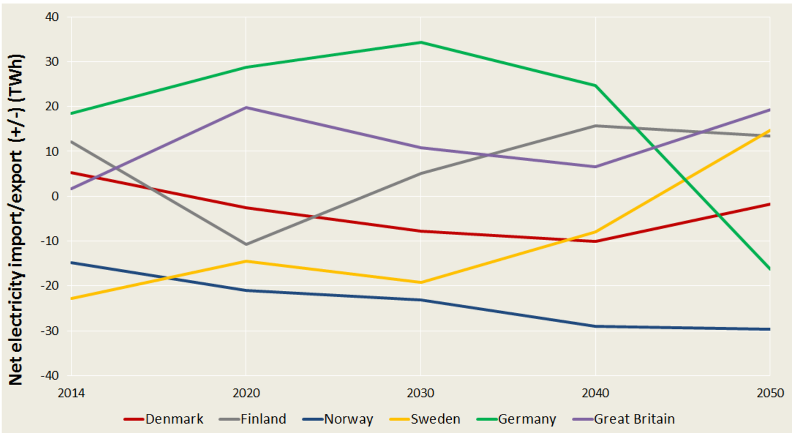
District heating generation



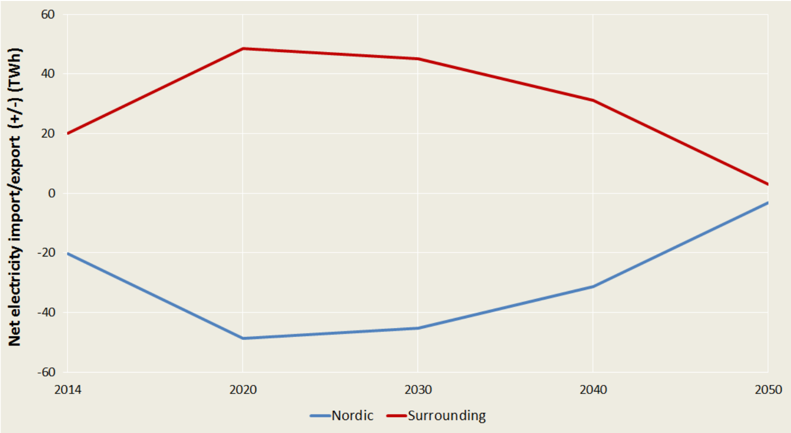
Annual average electricity prices for each country



Import and export of electricity between the countries



Import and export of electricity between the Nordic region and the surrounding countries



Total endogenous investments in generation technologies by 2050

Generation technology	Capacity (MW)
Boiler-Natural gas	445
Bioenergy-Boiler	2547
Bioenergy-Back pressure	261
Bioenergy-Condensing	0
Bioenergy-Extraction	300
Wood pellet CCS-Condensing	14193
Wood pellet CCS-Extraction	61987
Wind-near offshore	0
Wind-offshore	6293
Wind-onshore	20566
Solar PV	0
Heat pumps	12721
Hydrogen	0
Total = 119312 MW	

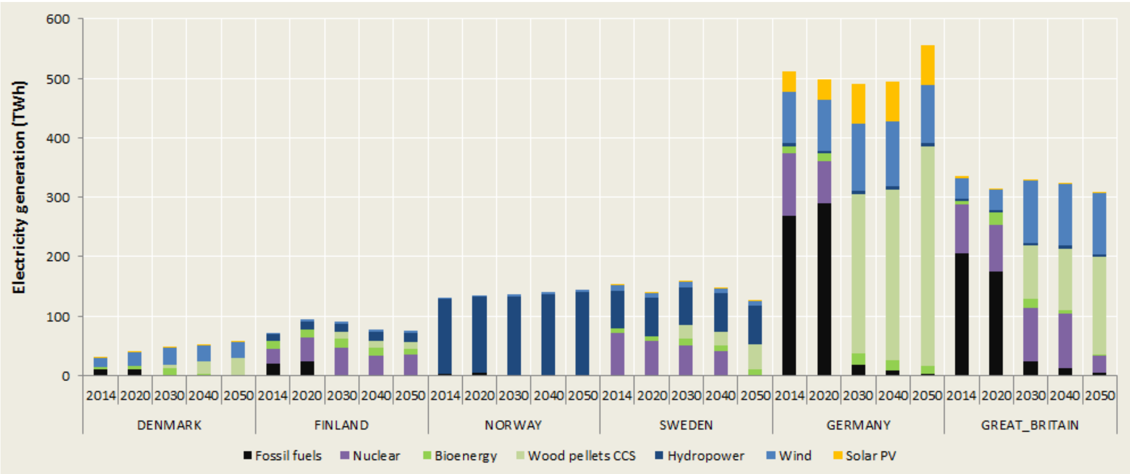
Total endogenous investments in generation technologies by 2050

From	To	Transmission capacity (MW)
DK_W	NO_SW	823.3754
DE_NE	SE_S	1388.112
GB_R	DE_CS	1404.129
DE_NW	SE_S	1520.543
NO_MW	NO_SW	1760.126
GB_R	NO_SW	1786.532
DE_NW	NO_SW	2263.107
Total = 10946 MW		

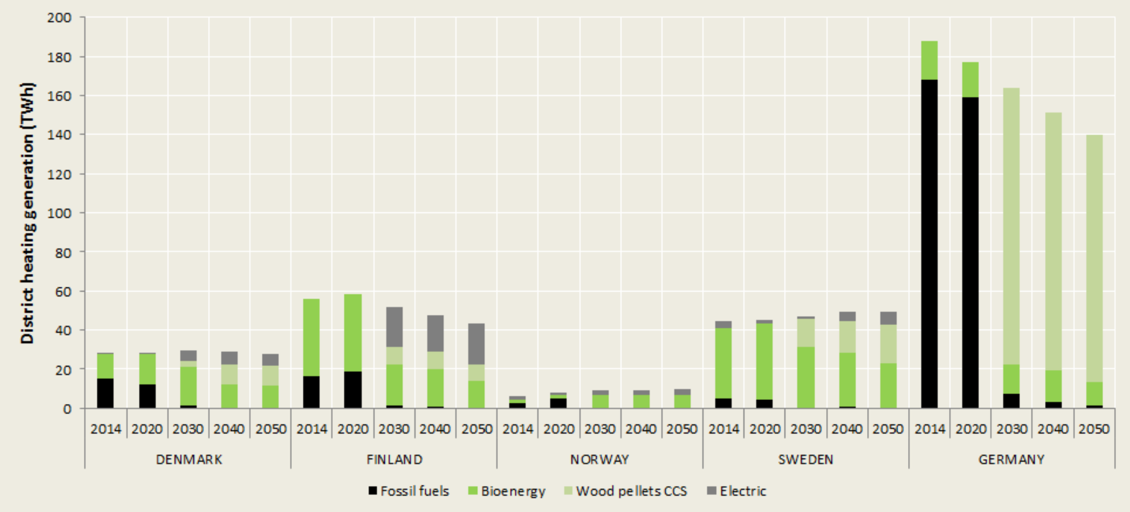
Appendix H

Additional results from the Flex scenario:

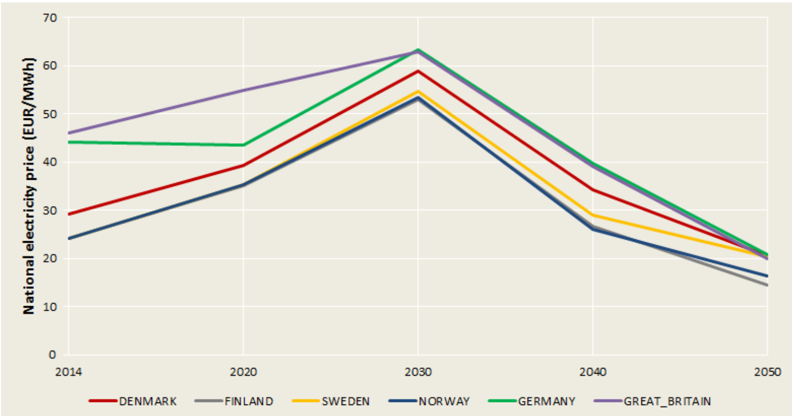
Electricity generation



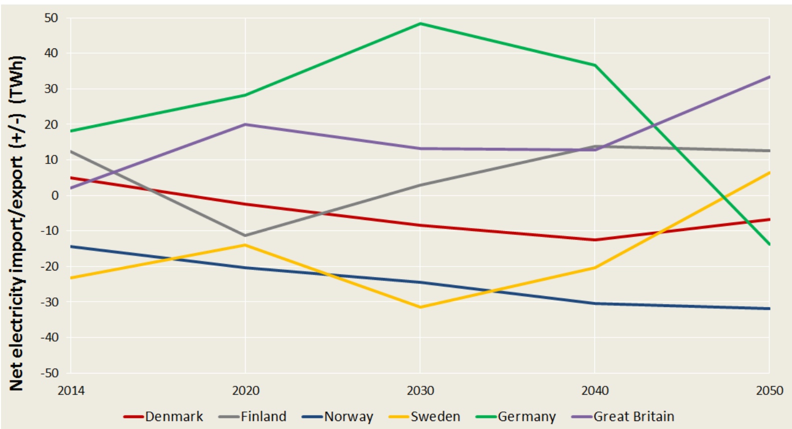
District heating generation



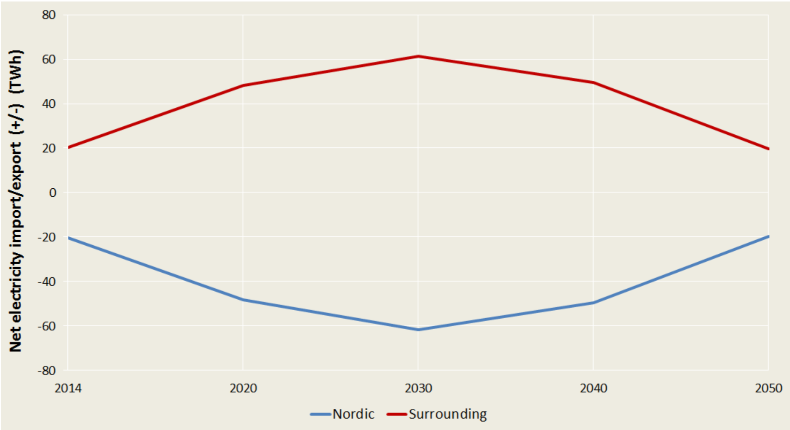
Annual average electricity prices for each country



Import and export of electricity between the countries



Import and export of electricity between the Nordic region and the surrounding countries



Total endogenous investments in generation technologies by 2050

Generation technology	Capacity (MW)
Boiler-Natural gas	469
Bioenergy-Boiler	2540
Bioenergy-Back pressure	229
Bioenergy-Condensing	0
Bioenergy-Extraction	334
Wood pellet CCS-Condensing	19590
Wood pellet CCS-Extraction	53284
Wind-near offshore	0
Wind-offshore	6293
Wind-onshore	21190
Solar PV	0
Heat pumps	10967
Hydrogen	7647
Total = 122544 MW	

Total endogenous investments in generation technologies by 2050

From	To	Transmission capacity (MW)
SE_M	SE_S	3
DK_E	DE_NE	25
NO_M	NO_SE	854
DK_W	SE_M	1057
DE_NE	SE_S	1355
DE_NW	SE_S	1832
NO_MW	NO_SW	2001
GB_R	DE_CS	2235
GB_R	NO_SW	3566
DE_NW	NO_SW	3906
Total = 16834 MW		

Difference in electricity prices between the Flex and the Base scenario

	Difference in electricity prices (EUR/MWh) Flex - Base		
Region	2030	2040	2050
DK_E	-0.27	-0.91	-0.98
DK_W	-0.28	-0.77	-0.86
FI_R	0.05	0.10	-0.59
GB_R	-0.21	-0.39	-0.47
DE_CS	-0.41	-1.00	-0.95
DE_NE	-0.37	-0.69	-1.08
DE_NW	-0.39	-1.19	-1.07
NO_N	0.50	-1.39	-2.46
NO_M	0.50	-0.81	-0.13
NO_MW	0.50	-0.52	0.38
NO_SW	-0.31	-0.60	-0.22
NO_SE	-0.13	-0.77	-0.21
SE_N1	-0.03	0.24	-0.55
SE_N2	-0.03	0.24	-0.55
SE_M	-0.18	-0.79	-0.79
SE_S	-0.01	-0.61	-0.63