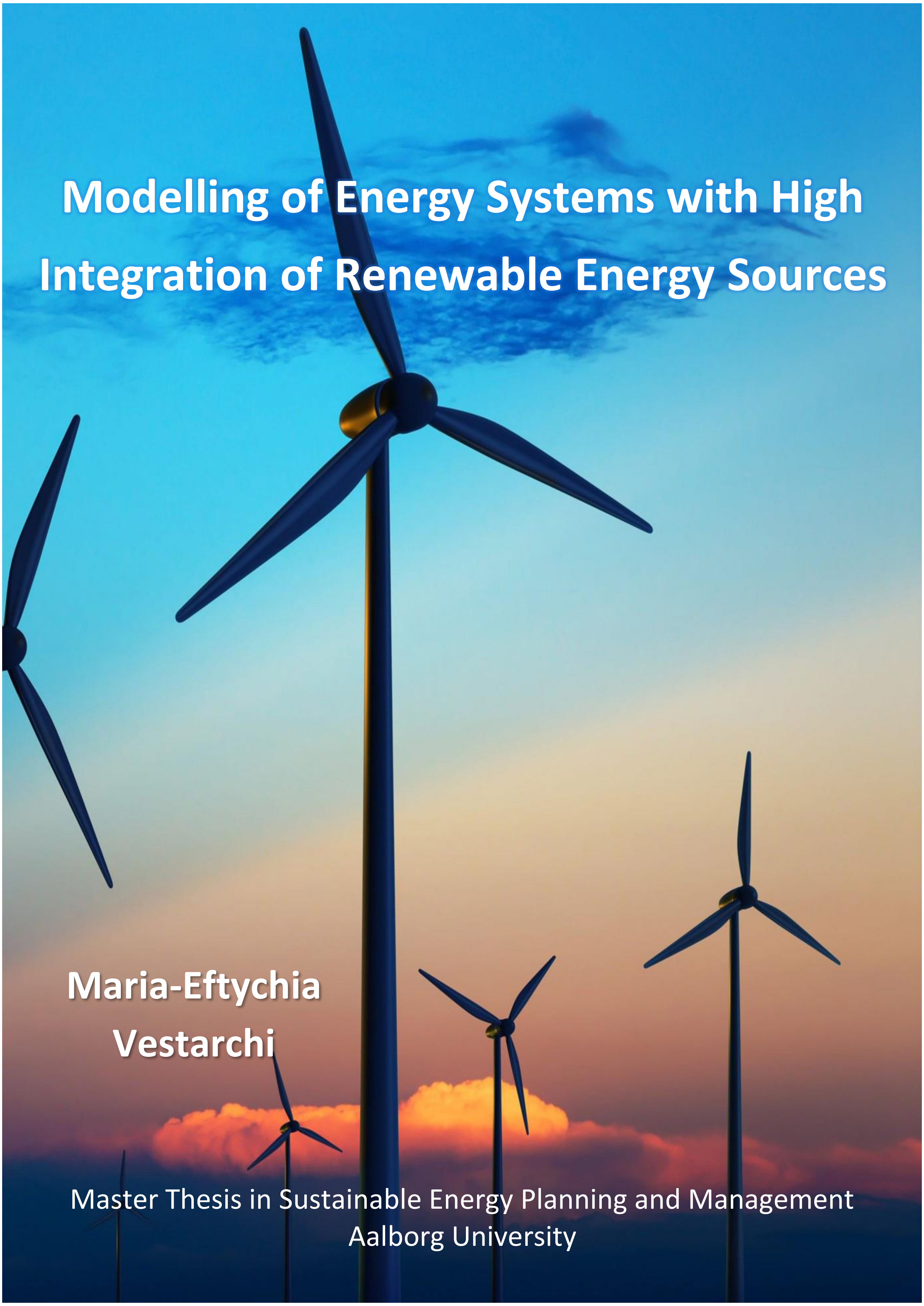

Modelling of Energy Systems with High Integration of Renewable Energy Sources

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Master Thesis in Sustainable Energy Planning and Management
Aalborg University

Abbreviations

AC	Alternate Current
APF	Advanced Pulverised Fuel
BEV	Battery Electric Vehicle
CCGT	Combined Cycle Gas Turbine
CHP	Combined Heat and Power
CO2	Carbon Dioxide
DC	Direct Current
ENTSO-E	European Network of Transmission System Operators for electricity
EOP	End of Pipe
EU	European Union
EV	Electric vehicle
GAMS	General Algebraic Modelling System
GHG	Green House Gases
GW	Gigawatt
GWh	Gigawatt hours
HVDC	High Voltage Direct Current
IEA	International Energy Agency
Kg	Kilogram
KJ	Kilojoule
KV	Kilovolts
KWh	Kilowatt hours
LPG	Liquefied Petroleum Gas
MIP	Mixed Integer Programming
MW	Megawatt
MWh	Megawatt hours
Nat_gas	Natural gas
NO_x	Nitrous oxides
O&M	Operation and Maintenance
OECD	Organisation for Economic Co-operation and Development
PHEV	Plug-in Hybrid Electric Vehicle
PV	Photovoltaic
RE	Renewable Energy
SO_2	Sulphur Dioxide
TEN-E	Trans-European Energy Network
TIC	Techno-Institutional Complex
TSO	Transmission System Operator
TYNDP	Ten Year Network Development Plan
UC	Unit commitment
V2G	Vehicle to Grid

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USB sticks

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Abstract

This project examines the Nordic and the German energy systems using the energy model Balmorel. Two core scenarios in 2030 including additional RE capacities, interconnectors and EVs, are examined with and without the option of Balmorel to implement unit commitment to power plants, in order to include inflexibility in the systems and approach a more realistic representation of their operation. It will be researched what impacts will the different scenarios have to the energy generation, total system costs, electricity prices and the operation of the energy systems in an attempt to answer the following research question:

"What are the differences when energy systems with high penetration of fluctuating renewable energy sources are modelled with and without unit commitment?"

The main findings of this project are that more fossil fuels, biomass and wind is used when UC is applied. Moreover, the total costs are increased when UC is applied, to some extent due to the additional start-up costs but mainly due to the raised fuel and CO_2 costs. In addition, the electricity prices are increased and present high peaks, due to the operation of more expensive power plants in the UC. Furthermore, in the UC less curtailment of the wind is noticed. It is concluded by the author, that this study indicates that the simulations without UC provide a better representation of the actual operation of the today's energy systems, since there is uncertainty of how the market will operate in the future and the simulations are carried out using current UC data.

Preface

This thesis is conducted for the fourth semester of the Master of Science in "Sustainable Energy Planning and Management" of Aalborg University from the 2nd of February until the 3rd of June 2015. It was written under the supervision of the professor Brian Vad Mathiesen and the support of two consultants, Anders Kofoed-Wiuff and János Hethey of Ea Energy Analyses in Copenhagen.

The APA style of the Microsoft Word is used for the references of this report. The last name of the author is mentioned first followed by the year of the publication, i.e. (Last name of the Author, Year of publication). In cases where sources from the same author are mentioned, the reference has the following format: (Last name of the Author, Name of the reference, Year of publication).

The appendix of this report contains two USB sticks, where some of the scenarios' output of Balmorel model and an excel with various results are included.

A number of persons have supervised and assisted on this report. Special thanks to Brian Vad Mathiesen, for providing supervision and precious insight during this thesis. Also, to one of the partners of Ea Energy Analyses, Anders Kofoed-Wiuff and the consultant János Hethey, for providing inspiration for the topic of this thesis, guidance throughout it and proofreading it. Many thanks to the consultant Lars Pauli Bornak for assisting with general problems concerning the energy model Balmorel, the consultant Bjarne Bach for introducing the author with the unit commitment option of the model and the consultant Christian Bang for providing data concerning electric vehicles. Finally, I would like to thank all the other partners, employees and students at Ea for providing an inspiring and pleasant working environment. The time spent during writing the Master's thesis at EA has been a priceless and valuable experience.

Contents

1 Introduction

Many countries have developed ambitious action plans and strategies to increase the share of renewable energy in the power system in order to reduce the greenhouse gas emissions, be independent of the use of fossil fuels and reduce the total energy costs. The operation of the power plants and their flexibility in the electricity supply is nowadays challenged by the increasing integration of renewable energy sources. Due to the intermittent nature of renewable sources, measures have to be undertaken to improve the flexibility of the whole energy system. (Lund & Mathiesen, 2015)

Flexibility is considered to be an ability that every energy system should require to cope with unpredictable situations and unforeseen problems that may occur during the operation of the energy systems, as the power system is dependent on the everyday flexible operation of the power plants and the grid. Flexibility ensures the ability to generate or absorb power at different rates and respond immediately to every change (Dragoon & Papaefthymiou, 2015). It is expected that the improvement of this ability will result into a more robust grid, which will ensure the security of supply, even at cases with excess or scarce load and peak demands and result into a more efficient utilisation of the energy sources. It should be noted that the volatile nature of some renewable energy sources (wind and solar power) demands a more flexible power system in order to be able to cope with fluctuations. (European Network for Transmission System Operators for electricity (ENTSO-E), 2014)

Investments in wind and solar energy are growing and becoming competitive with the conventional generation of energy. However, relying on these sources is challenging due to their dependency on weather forecasts, i.e. the availability of wind and sun. Through the years, the demand was supplied by the utility companies and the transmission system operators by some adjustments made on the outputs of power plants which also tried to maintain the frequency of the grid in a certain band, i.e. 50Hz. Nowadays, this has become more crucial due to the variable generation of the RE sources and the need of fast response to all the changes in the load. For instance, in cases with rapid changes in the weather fronts i.e. partly windy or cloudy days, the generators should be able to respond quickly enough to these changes. In addition, it should be taken into account that in some cases, the generated energy is higher than the demand or when the capacity of the transmission is not sufficient enough to distribute the power, some of the produced energy remains unusable. (Dragoon & Papaefthymiou, 2015)

Consequently, a transformation of the power system is imperative to facilitate the future transition and improve the system’s ability to make adjustments and balance the supply and the demand. Flexibility is already a characteristic of the power systems. The baseload plants are the plants that operate at a constant rate in order to meet the energy demand. But, these plants present limited dispatchability, due to their long start-up and shut-down time, so it is more cost efficient to run at their full capacity without interruption. Some examples of these types of plants are the nuclear power plants or the old coal fired plants. On the other hand, there are the hydro plants or open cycle plants that can be regulated faster in order to meet peak demands.

However, assessing flexibility needs further research and additional effort. Actions, that concern the supply, the demand, the network and the market, should be taken towards this road in order to facilitate the integration of renewable energy sources (RE). More particularly, as far as it concerns the supply, changes in the operation of power plants such as sub-hourly dispatch of baseload and mid-load generators can increase the flexibility of the energy system. Moreover, demand side management can contribute to flexibility, by controlling the demand with a number of processes implemented by the industries, such as energy storages, water pumping, wastewater treatment, air and water heating and cooling systems and electric vehicle charging. As far as it concerns the network, a measure to increase the flexibility is to increase the capacity of the transmission system. In addition, a dynamic reactive control, i.e. the transformation of the grids into "smart" ones, is possible to improve the distribution of rapidly changed power flows. Finally, it is a fact that zero or negative electricity prices have been noticed due to a large integration of RE. Negative electricity prices are not per se a bad thing, and even when they occur, electricity from RE sources is sold in the market. But they are attributed to the inflexibility of the conventional power plants and if this ability is not improved then the hours with negative electricity prices will increase drastically. (Agora Energiewende, 2014) As a result, a possible reformation of the market with price incentives could contribute in a more efficient use of the low cost energy. (Dragoon & Papaefthymiou, 2015)

It should be noted that in order to suitably design a future energy system and evaluate all the different alternatives for the transformation of it, there are various energy system model tools. These tools are mainly used to simulate the future projections on energy demand and supply in countries and regions within the countries. They are used to investigate and explore alternatives for the future energy development including different assumptions for a country's policies regarding technology choices and investments in the energy sector. As mentioned in the "Introduction to Energy Systems Modelling" report ***"they are used in an exploratory manner"*** taking into account different assumptions, such as electricity generation, fuel consumption, electricity prices etc., based on the researched project. However, based on the study and the results that should be extracted by it, many choices of energy models exist. (Herbst, Toro, Reitze, & Jochem, 2012)

Every simulation is expected to deviate from reality up to a certain degree, since it is based on forecasts and past trends and there is always scepticism and doubt about how the energy systems will evolve in the future. As a result, it should be kept in mind that energy models represent a simplified interpretation of the energy systems and the economy, even if a detailed and accurate representation of today's energy system is provided to the model. The results should also be handled critically, keeping in mind the level of uncertainty and reliability on the data used. (Herbst, Toro, Reitze, & Jochem, 2012)

This study is focusing on the Nordics' and German energy system, their future plans for additional deployment of RE and the use of the energy model Balmorel to represent some future scenarios. In the next subchapter, the problem formulation for this project is presented and the research question is formulated. In addition, in the end of the introduction an outline with all the chapters included in this thesis can be found.

1.2 Project formulation

It is a fact that, the Nordic countries and Germany have adopted future plans and policies in order to integrate more RE and decarbonise their energy systems. Due to the intermittent nature of the RE sources, a large integration of them into the existing energy systems will create challenges to their operation of the energy systems, and in particular to the electricity generation, as the energy systems rely on the balance of supply and demand at each time. Considering the volatile nature of wind, photovoltaics and hydropower, although the last one is considered appropriate for electricity balancing, not many things can be gained by regulating these sources. So, their integration is expected to be facilitated by the operation of the surrounding energy supply system, i.e. power plants and CHP plants. Some examples to deploy more RE and introduce flexibility in the grid are heat pumps, electric boilers, electric vehicles and other energy storage technologies. (Lund H. , 2010)

Although the focus of the national plans of these countries relies on investments on new generation of RE capacities, on the projection of the electricity demand, on measures to increase the energy efficiency and on the establishment of new interconnectors' capacity, another issue is raised. It is noted that, thermal power plants operate at a high level in Germany – and in to some extent in Denmark – in situations of high penetration of wind power in their systems, which forces the base energy production plants to produce more energy than it is required at the exact moment. One out of the possible reasons for that is that their operation is planned based on forecasted data of the energy production and consumption. Consequently, the generated energy is probable to be more than the demand, which will lead to surplus of unused energy and curtailment of the wind production. Low electricity prices are observed and sometimes even negative ones in cases of high generation of fluctuated RE, i.e. in Denmark in December 2014 and in Germany in January 2015, which also indicates the inflexibility of their power system. Possible factors that influence the low prices are ancillary services (system stability), combined heat and power production, unit commitment (cost of startup and shut down of generators), day-ahead market functioning, regulatory issues (feed in-tariffs, subsidies and other tariff structures).

For this project, the Nordic and the German energy system is going to be analysed, using the energy model Balmorel. Firstly, a reference scenario for 2013 will be modelled in an attempt to represent the current energy systems. Afterwards, a core scenario in 2030 is created, which includes additional investments in RE capacities and interconnectors. The first simulation of this scenario does not include the option of the model to input any restrictions and constraints in the operation of power plants and as a result, they operate quite flexible. This is considered a simplification of the model and does not correspond in the way that power plants operate in reality. Consequently, another run is made including the introduction of the unit commitment option of Balmorel, in order to include inflexibility in the systems and approach a more realistic representation of the operation of energy systems. The simulations are followed by another scenario, in an attempt to introduce more flexibility to the grid, by adding additional energy demand for EVs. This simulation is also executed with and without unit commitment.

1.3 Research question

The additional future deployment of RE will in fact have an impact in the operation of the energy systems. In this project, it will be researched through different scenarios how the mentioned development is represented in a more accurate way through the energy model Balmorel and particularly the use of unit commitment and what impacts will it have to the energy generation, total system costs, electricity prices and the operation of the energy systems. The focus will be in the Nordics' and Germany's energy system and an attempt to answer the following question will be made:

"What are the differences when energy systems with high penetration of fluctuating renewable energy sources are modelled with and without unit commitment?"

In order to answer the research question, the following sub-questions need to be answered as well:

- What is the current energy system of the case study countries and what are their future plans concerning the RE development?
- How the energy systems operate in terms of electricity generation, total system costs, electricity prices and CO_2 emissions for the different researched scenarios?

1.4 Project Outline

Chapter 2 Theoritical Framework

- In this chapter, the theoritical framework of this report is presented. It includes theory about the planning process, the carbon lock-in theory and the choice awareness.

Chapter 3 Methodology

- In this chapter, the methodologies used in order to answer the sub-questions and the research question are described. They include the literature study, the case study and the energy model Balmorel.

Chapter 4 Tecnological Background linked to Balmorel inputs

- In this chapter, relevant to this project theory concerning different types of power plants, electric vehicles and the benefits of interconnection is included. Also, these technologies are linked with examples of how they are modelled in Balmorel.

Chapter 5 Current Energy Systems and Policies

- In this chapter, the current situation of the electricity systems, the national goals concerning the deployment of RE, GHG emissions and the transportation sector for each country are described. In this chapter, the first sub question is anwered.

Chapter 6 Scenarios

- In this chapter, the scenarios that are going to be analysed are presented. They include additional RE deployment, additional interconnectors and EVs. The are also simulated with and witout the Balmorel's option to apply unit commitement to power plants.

Chapter 7 Results

- The results of the modelling are presented in this chapter. They concern the electricity generation by fuel, the total costs, the electricity prices, the CO_2 emissions and the operation of the energy systems. In this chapter, the answer to the second subquestion is provided.

Chapter 8 Discussion

- The most important findings of this report are discussed in this chapter. The different scenarios are compared with each other in order for conclusions to be drawn and the research questioned to be answered.

Chapter 9 Conclusion

- In this chapter, the most important findings of this report are summarised and the answer to the reserach question is included.

2 Theoretical Framework

In this chapter, the theoretical framework for this thesis is presented. It is based on the theory concerning planning, the carbon lock-in and the theory of the choice awareness.

2.1 Planning

Many definitions exist to describe what is planning. One of them is that planning is what scientists do in order to apply scientific and technical knowledge to certain actions. Planning precedes the decision making process. The following activities are engaged in the planning process:

- Definition and description of the problem
- Modelling and analysing the situation
- Design and research solutions to the identified problem
- Evaluate the proposed solutions/alternatives based on their technical and economic feasibility. (Friedmann, 1987)

In the figure to follow, the planning process of this report following the mentioned bullets above, can be seen. In chapter 1 the researched problem for this thesis is identified. Then in chapters 2 and 3 follows, the theoretical framework and the methodology that is used to analyse it. Also the relevant to Balmorel technological background and information concerning the current and the future situation of the energy systems is provided in chapters 4, 5 respectively. Afterwards, in chapter 6 the scenarios are formed to explore a solution to the problem and in the last two chapters of this report a comparative discussion between the different scenarios is drawn and the conclusions are presented. In the next pages, two theories are mentioned in relation to planning and policy approaches.

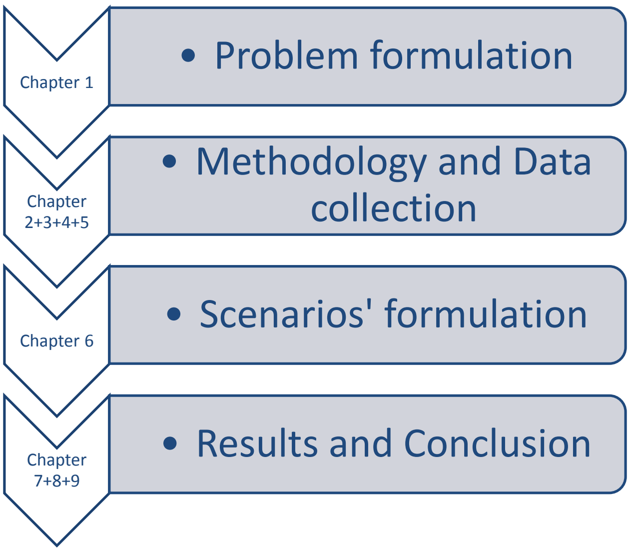

Figure 1: Planning process of this report.

2.2 Carbon Lock-in

A challenge that energy policy makers experience is the change of the already acknowledged and established technologies towards climate change while at the same time they try to maintain the societal balance. It is a fact that there is a policy inertia towards this path. Nowadays, the energy systems and the industrial economy are based on fossil fuels through organisational, technological, institutional and social co-evolution. This fact is called carbon lock-in and it creates policy delays and failures in the introduction of carbon saving technologies, even though studies and the implementation of some of those technologies, i.e. wind turbines, have shown environmental and economic benefits. (Unruh, Escaping carbon lock-in, 2002) (Unruh, Understanding carbon lock-in, 2000)

The carbon lock-in derives from the Techno-Institutional Complex (TIC), since large technological systems, such the electricity generation, distribution and consumption, cannot be conceptualised as independent and distinct technological systems but as complex systems interacting with each other and influenced by the public and private institutions. TIC is developing through co-dependent processes among the technological infrastructures and the different organisations and institutions. In cases that a technology is locked-in, it is very difficult to lock-out other possible alternatives, even though they can be promising advantages and improvements. As mentioned in the "Understanding carbon lock-in" report: "***carbon lock is not conceptualised as a permanent condition, but instead a persistent state that creates systematic market and policy barriers to alternatives***". (Unruh, Understanding carbon lock-in, 2000)

The above mentioned report states three different policy approaches on the technological development towards environmental change:

1. No changes to the system but treat emissions, in order to maintain as much as possible the existing system. This is called end-of-pipe (EOP) approach.
2. Modify certain components or processes of the system, but maintain the overall system architecture in order to facilitate the transition, which is called continuity.
3. Replace the system entirely, which is called discontinuity and includes radical changes.

An example in order to clarify the two last approaches, since many technologies can be involved in both of them is the wind turbines or the photovoltaic panels. In the first approach, they can be just connected to the already existing electricity grid and taking part in the electricity generation along with the fossil fuelled power plants. In the second approach, they will not be connected to the electricity grid but create a system of distributed generation. (Unruh, Escaping carbon lock-in, 2002)

It should be noted that technological alternatives do exist, but the restrictions posed by the techno-institutional lock-in are the ones that create constrains on policy option and delay any system changes. In the following figure, an illustration of the electricity generation TIC is presented, in order to explain how the conditions of lock-in are established and maintained. The technological system, the private and public institutions that create and operate the system and the bigger societal institutions that the systems are incorporated are illustrated in the figure. As it can be noticed, in the figure there is no point of start, but if it is assumed that government provides incentives for additional generation capacity, the system will expand, it will be more accessible and the costs will be decreased. Then the consumption will probably increase and the secondary industries will invest in new technologies. As a result, the government will approve investments in more generation capacity and a new cycle will start again. (Unruh, Understanding carbon lock-in, 2000)

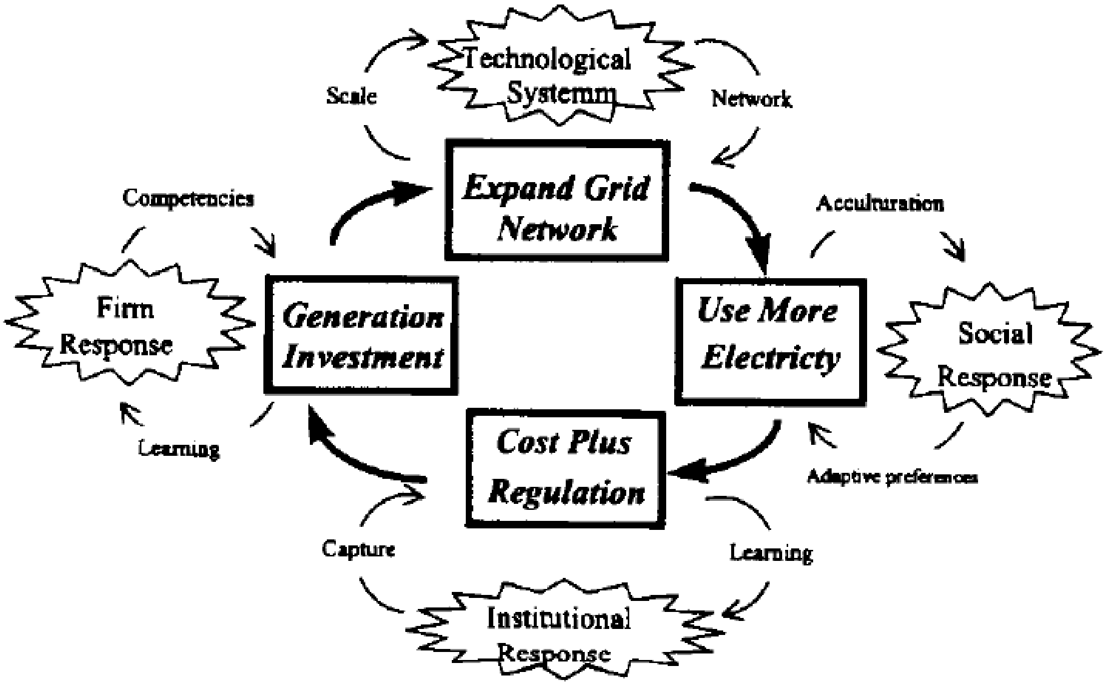

Figure 2: Illustration of TIC that support lock-in in the electricity sector. (Unruh, Understanding carbon lock-in, 2000)

In this project no further institutional barriers or policy approaches are mentioned, but this sub-chapter is pointing out the difficulty to lock-out alternatives and change the already established energy system. It is followed by the choice awareness theory to point out the fact that there are always alternatives into a decision making process.

2.3 Technological Change and Choice Awareness

Radical technological change occurs when one of the five elements, which defines a technology, i.e. technique, knowledge, organisation and products, evolves or changes. Technique is defined as the work processes and the necessary tools to create a technology. Knowledge is the scientific knowhow of how to produce the technology. Organisation refers to both the technical and the social organisation concerning the production of the technology. At last, based on these three elements, a product is created. (Muller, Remmen, & Christensen, 1984)

It should be noted that every society should aim towards this direction. Various are the reasons that can justify this. Firstly, due to the fact that fossil fuel are a limited resource, actions should be taken for energy security to be ensured at every moment. In addition, economy is considered a major force in this development taking into account the dependence of the energy systems on oil prices. Finally, due to the climate change, the protection of the environment is a vital goal, so cleaner ways to generate energy should be pursued. (Lund H. , 2010) (Hvelplund, 2005)

It should be noted that every alteration should be done following democratic processes and should always take into account the needs and preferences of the whole society. However, this is not always the case, since institutions and organisations are trying to exercise their power to promote their political and economic interests and influence the decision making process on their advantage. For instance, in Denmark in 1995, the authorities favoured the old technologies while the new ones were not taken into consideration and public meeting were held only after the decisions were made. (Lund H. , 2010)

Choice awareness theory is applied on the implementation of radical technological changes, such as the path toward 100% renewable energy systems. It describes precise and thorough strategies, in order to conduct feasibility studies, present technological alternatives or propose public regulation methods. It describes the influence and the power that various institutions and organisations have and exercise during the decision making process. (Lund H. , 2010) For this project is used to provide consciousness and understanding on how can the power plants operate more flexible. Some alternatives such as an additional amount of renewable energy deployment and electric vehicles integration to the energy systems will be researched.

Consequently, as Lund states in order to raise the awareness on all possible options in a decision making process a number of steps should be followed.

- Firstly, the possible existing alternatives should be presented and promoted. This is quite important, as it indicates that choices do exist and that the public is informed about them and has the right and the ability to choose one of them. Actually, this step is linked to the goals and the energy policies set by each country. For this project, the flexible operation of the power plants is researched, and although there are more alternatives that can contribute towards this path, such as heat pumps and storages, the scenarios researched are focused on the deployment of the RE based on national and international policies and the integration of EVs to the grid.

- The theory of choice awareness includes economic feasibility studies that should be carried out based on the assumptions and the interests of the involved organisations. Consequently, the second step focuses on the economic goals and objectives that the society in question has set. A combination of business and socioeconomic analyses can contribute to reveal the suitable and more beneficial alternative. (Lund H. , 2010) For this study, the total cost of the different scenarios, which include investment costs, O&M costs, fuel costs, CO_2 costs and in some scenarios start-up costs, are going to be calculated using the energy model Balmorel.

- Subsequently, regulations measures are the third step that raises the awareness. The implementation of new technical solutions most usually demands new institutional condition in order to be promoted. It is a fact that new technologies are not always represented well since the old conventional ones are protected from the political and economic interest groups that gain profit from them. Sometimes changes in taxes or new subsidies are necessary to be introduce. (Lund H. , 2010) This thesis does not includes this step of the choice awareness theory, although it is considered essential for both the increased RE and EVs deployment in the future.

- Last but not least, several reasons such as lack of knowledge and organisation may delay the implementation of the new chosen technologies. For example, many are the plans for certain grid interconnectors that have been delayed through the years. A way to avoid this is a stakeholder analysis, where all the key actors that can influence a project are included. As a result, the last step proposed by this theory is the promotion of a new democratic infrastructure. (Lund H. , 2010) This step is also exclude from the project, since it is more focused to the technical operation of the energy systems.

3 Methodology

In this chapter, the methodologies that are used in this thesis in order to answer the research question and the sub questions are described. These methodologies include the literature study, the case study and the energy model Balmorel. At the end of the chapter, the validity and the reliability of the model and of the collected data are also examined.

3.1 Literature study and Case study

For this thesis, the energy systems of Germany and the Nordics are going to be examined. As their operation is going to be modelled using the energy model Balmorel, a literature study is carried out. Since no actual data was produced for this project, i.e. qualitative primary data from interviews with involved stakeholders, secondary data is used in order to formulate and answer this project's problem. (Bryman, 2012) This method is used in order to present the theoretical framework in which this thesis is established, relevant theory concerning the technologies that are inputted in Balmorel, i.e. power plants, EVs, and also to find the background information regarding the current energy systems of the researched countries and their future policies and goals. It is also used in order to gather the necessary data for building the different scenarios for the analyses of the energy system, i.e. electricity demand, electricity generation by fuel, future investments on RE and interconnectors, electricity demand for electric vehicles, investment and O&M costs for the different technologies, start-up costs, minimum up and down time and etc.

The data is collected through various sources, including information found on websites in the form of articles or reports, such as the website of the International Energy Agency or of the European Network of Transmission System Operators for Electricity etc., or from the online Aalborg University Library, where scientific articles and books can be found. Moreover, quantitative data from a number of reports and also Balmorel, such as the exact capacities of the RE that are going to be deployed in the future or the different characteristics of the power plants, i.e. energy efficiencies, fuel use, emissions and etc. were also collected and used for this thesis analysis.

It should be mentioned that literature study is considered crucial for the understanding of each study and the topics or parameters that refer to it (Briggs, Coleman, & Morrison, 2012). For this project, it was used in the first chapters, i.e. Introduction, Theoretical Framework, Methodology, Technological Background linked to Balmorel inputs, Current Energy Systems and Policies and of course the Scenarios chapter.

Another method that is used in order to answer the research question is the case study of the energy systems of Germany and the Nordics. Case study is a type of qualitative research. It can be used as an instructional and informative example, which conclusions can be used for further examinations (Briggs, Coleman, & Morrison, 2012). It is also considered as scientific contribution into the creation of new theories, in the cases that they include concrete and cross-examined information (Flybjerg, 2006). Different ways exist in order to perform a case study, such as literature study of written materials, interviews with stakeholders or visiting relevant to the study sites (Wellington & Szczerbinski, 2007).

It is expected that by studying the way the energy systems in the mentioned countries operate, useful conclusion will be drawn concerning the use of unit commitment and how close to reality can the energy systems be represented, that can potential be used in other studies.

In the next subchapter, detailed information about the energy model Balmorel that is chosen for this thesis is provided. The reason behind the choice of Balmorel is the fact that it is used to model hourly the energy sector emphasizing on the electricity and combined heat and power sector and it can also represent a number of countries and provide a number of results concerning the energy mix, the environment and the economy. EnergyPlan could have been another energy model relevant to this project, since it also performs hour-to-hour simulations of regional or national energy systems, including electricity, individual and district heating and transportation. But since the main topic of this thesis concerns the use of unit commitment and the thesis is carried out with the support of the company Ea Energy Analyses, Balmorel is preferred.

3.2 Modelling Tool: Balmorel

Balmorel is a modelling tool used to analyse the electricity and the heating sector. It is an open source coding model, coded in General Algebraic Modelling System (GAMS) language. It is also a partial equilibrium model and as result all endogenous investments are balanced economically and they have no effect on the exogenous inputted parameters. It should be noted that its basic principal is to perform the least cost optimisation based on the declared framework conditions. It is used to either model the optimal system dispatch and operation (i.e. bb1 run for annual optimisation or bb3 run for seasonal optimisation) of the generation units or to optimise the investments on a future power system (i.e. bb2 run).

Balmorel is geographically oriented and it was firstly developed for the Baltic Sea countries. However, since then it has been applied into a number of projects in the Nordic countries, Germany and the surrounding countries i.e. Belgium, France, Italy, Netherlands, Switzerland, Austria, Czech Republic, Great Britain and Ireland, East Africa, China, Canada and Mexico. It has been used to study several projects concerning the technical and economic analysis of a country's energy system, the analysis of the electricity market, wind power integration, heat transmission, hydrogen technologies, electric vehicles, emission trading, flexible demand and security of supply. (Balmorel, 2015) In the figure below some studies modelled with Balmorel are shown.

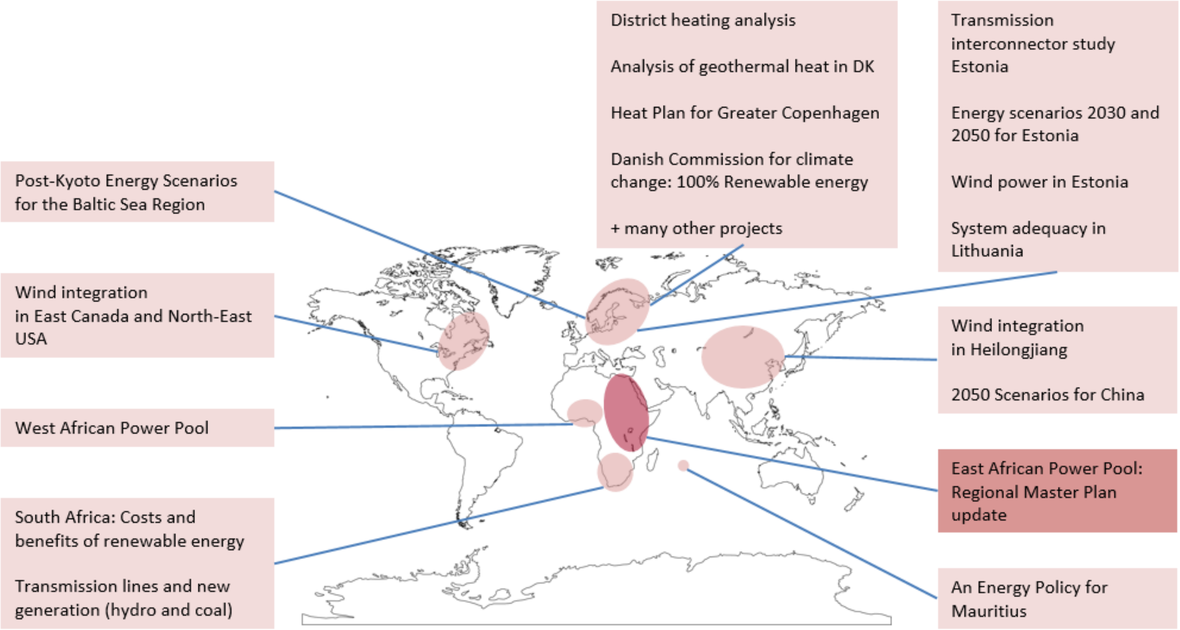

Figure 3: Few examples of studies that have been analysed using the Balmorel. (Ea Energy Analyses, 2015)

The data implemented in Balmorel is collected from international studies on forecasts concerning the energy demand and the energy generation technologies. The existing data is included in the model's inventory submitted by its developers and is updated regularly based on the existing energy systems. (Grohnheit & Larsen, Balmorel - Data and Calibration, March 2001) (Ravn F. H., March 2001) In addition, data for the existing electricity system for Germany, the Nordics, Estonia, Latvia, Lithuania, Poland, Czech, Austria, Swiss, France, Belgium, the Nederland, Great Britain and Italy are inputted and obtained by Ea Energy Analyses from collaborations with stakeholders during certain projects

Structure of Balmorel

a. Geography

The model has three different geographical entities, namely Areas, Regions and Countries. Each country is segregated into regions and each region may include one or more areas. The Countries describe the environmental policy, the taxes and the availability of certain fuels of all the different regions that belong to the country. For instance, Denmark has two regions, Western and Eastern (DK_W and DK_E) where the maximum emission level and the $C0_2$ taxes are the same.

Data like the electricity demand, the electricity prices as well as data relevant to electricity transmission and distribution and availability of fuels is included in a regional basis. For each region, the electricity balance should be achieved.

The areas are "*building blocks*", which include inputs like the heat demand and distribution, fuel prices and data relevant to the generation technologies, i.e. initial capacities of the generation technologies, investment costs etc. The different geographical entities can be seen in the map to follow. (Grohnheit & Larsen, March 2001) (Ravn F. H., March 2001) (Ravn F. H., Balmorel Model Structure, September 2011)

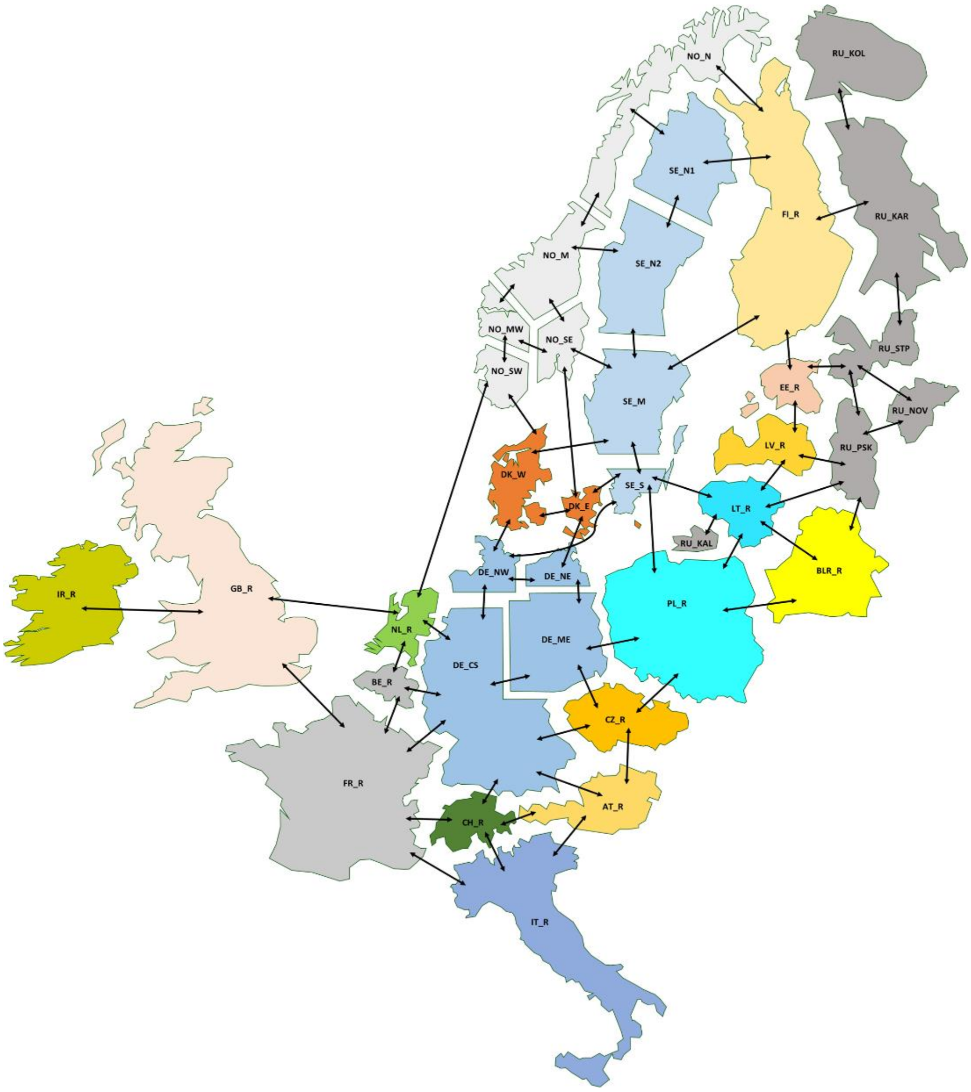

Figure 4: The different countries are represented in different colours and subdivided into different regions, represented by the different fractions. (Ea Energy Analyses)

b. Time

In Balmorel, time is structured into three different entities, i.e. years, seasons and timesteps. 52 seasons (weeks) represent a year and each season is represented by 168 timesteps (hours). In order to improve the run time of the model, the simulated time can be aggregated into less seasons, i.e. 4 seasons, which represent the autumn, winter, spring and summer. But that depends on the project that is simulated and the type of results that are necessary for each study. Most common use of time is either the hourly runs or the aggregated time into a number of seasons based on the results that needed for each study. (Ravn F. H., March 2001) (Ravn F. H., Balmorel Model Structure, September 2011)

c. Energy technologies

There are four different types of technologies implemented in Balmorel. The thermal power generation technologies divided into condensing[1], extraction[2] and backpressure[3] technologies, the electricity and heat storages, i.e. pumped pressure storage and heat accumulator, the heat generation technologies, i.e. heat boilers and heat pumps and the intermittent technologies i.e. wind power, photovoltaics, and hydro plants. In the following figures, the feasible areas of operation for condensing, backpressure and extraction unit can be seen.

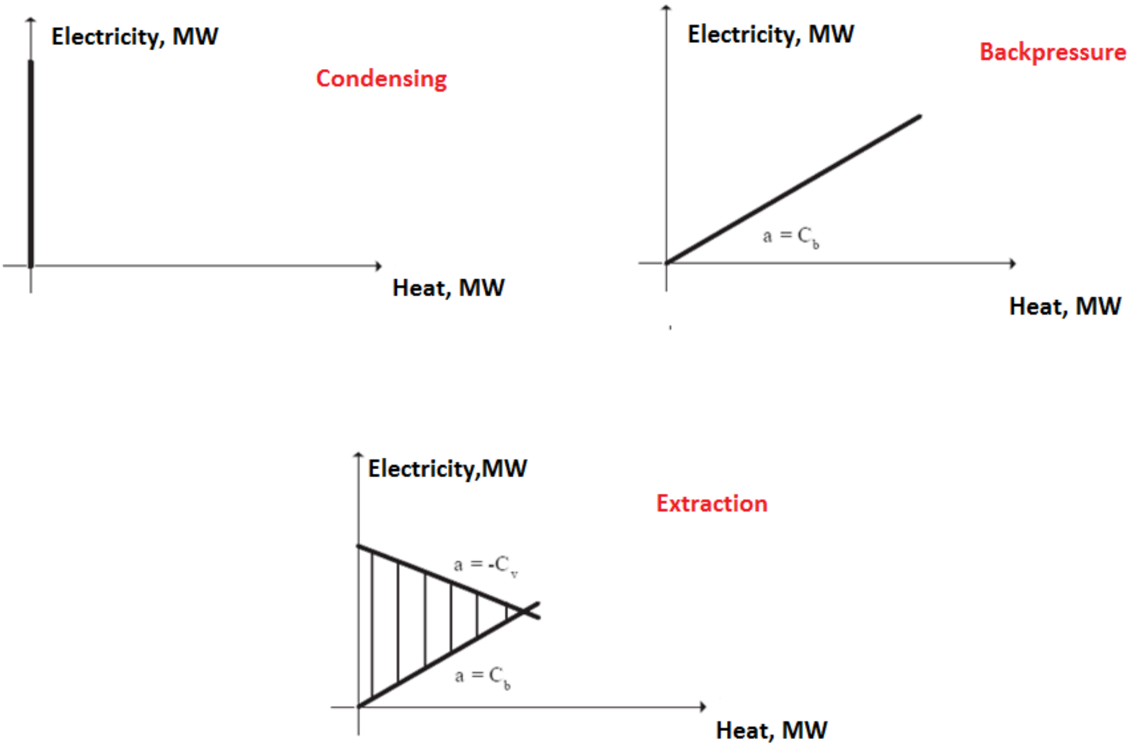

Figure 5: Feasible area of operation for condensing, backpressure and extraction units. (Ea Energy Analyses)

Each one of these technologies is described by some parameters such as the type of fuel i.e. oil, natural gas, biomass, wind etc., the capacity, the efficiency (COP), the C_b[4] and C_v[5] values for extraction and backpressure CHP plants, NOx, SO_2 and CO_2 emissions, fixed annual production, investment costs and unit commitment data such as the minimum generation of the plant, the start-up cost, the minimum up and shut down time

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[1] Condensing are the units that produce only electricity-

[2] Extraction units are the ones that produce electricity and heat at a non-fixed ratio. Usually, they are the large centralised units that can switch between condensing and combined heat and power (CHP) mode.

[3] Backpressure units are the ones that produce electricity and heat at an almost constant ratio. They are usually CHP plants or combustion engines.

[4] C_b-value specifies the ratio between electricity and heat.

[5] C_v-value specifies the loss in electricity when producing heat for maintained fuel consumption.

and the ramp up and down time. (Ravn F. H., March 2001) (Grohnheit & Larsen, March 2001) (Ravn F. H., Balmorel Model Structure, September 2011)

d. Demand

For each region, an electricity demand is specified and for each area, a heat demand is specified. In particular, an annual nominal value for each year is inputted in the model with the parameters DE and DH for electricity and heat respectively and also a nominal profile specifying the distribution of the demand over the year. Then an elasticity function is used to project the deviations from the profile between the quantity (i.e. nominal demand) and the prices. (Grohnheit & Larsen, March 2001) (Ravn F. H., March 2001) (Ravn F. H., Balmorel Model Structure, September 2011)

e. Data handling

As mentioned before Balmorel performs a least cost optimisation based on the declared conditions. The inputted data can be:

- Electricity and heat demands
- Existing and planned capacities of the generation technologies and the transmission lines
- Resource potentials and limitations of fuel usage such as wind, solar profiles etc.
- Fuel and CO_2 prices
- Technology data such as fuel use, fuel cost, investment costs, operation and maintenance costs etc.
- Policies, such as taxes and subsidies

The model is handling the data by trying to provide a solution based on the minimisation of costs, by taking into account:

- Supply and demand balances. For instance, for every hour the electricity generation should be equal to the electricity demand.
- Resource constraints and fuel consumption.
- Technology constraints
- Transmission constraints. For instance, the electricity transmission can be less or equal to transmission capacity.
- Policy targets

Concerning the results that can be:

- Electricity and heat generation distinguished by technology and fuel
- Transmissions capacities, imports and exports
- Fuel consumption
- CO_2 emissions
- Investments in production, storage and transmission
- Costs (Ravn F. H., Balmorel Model Structure, September 2011) (Ea Energy Analyses)

f. Unit Commitment

Unit commitment (UC) refers to the operational planning of power plants and their economic dispatch. It is considered a mathematical optimisation technique in order to solve the problem of meeting the demand by the least cost available generation technologies (Wright, 28 May 2013).

In the Balmorel model, unit commitment is executed as a mathematical mixed- integer[6] programming (MIP) with the introduction of integer variables. The decisions that have to be made are which units should run at a given time, and if a unit has to start its operation or shut down. The model in order to achieve this dispatch has to introduce some constraints as parameters of each generation technology, which are the start-up costs, the minimum operating capacity, the fuel consumption when they are online, the maximum upward and downward ramping and the minimum up and down time of the units.

The reason behind the use of unit commitment for this project lies in various facts. Firstly, the variable generation usually increase the number of the generations' start-ups, which increases the costs of the overall system. In addition, more generators' curtailment due to economic or technical conditions may occur due to the high minimum generation levels. So wind turbines or photovoltaics will not run at full capacity and their benefits are not fully exploited. Consequently, prices experience peaks and there are hours that even get zero or even below that.

In reality, units run between a minimum and maximum load. Without introducing the unit commitment in Balmorel the power plants have no constraints and they can operate quite flexible, which is a simplification of the reality. Due to the fact that Balmorel's unit commitment uses mixed- integer programming, the computation time is highly increased and as a result it is better to be implemented in smaller models.

The UC options that can be applies in Balmorel modelling are the following:

- UnitComm: If it is enabled then the minimum generation is applied in the power plants as well as the cost elements for the start-ups and shut downs.
- UnitCmin: If it is enabled then the minimum up and down times are included in the simulations.
- UnitCramp: If it is enabled then the ramping is included, i.e. the change in the production level of the generators.
- UnitRMIP: If it is enabled then the constraints are relaxed. It decreases the computation time but it also affects the results.

In the table below, it is shown in what types of run the different options of UC can be implemented. It should be noted that UnitCmin and UnitCramp option make sense only for hourly resolution of the model.

Types of run	UnitComm	UnitCmin	UnitCramp	UnitRMIP
bb1	X	X	X	X
bb2	X			X
bb3	X	X	X	X
Time aggregation	X			

Table 1: Restrictions in Balmorel. (Ea Energy Analyses)

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[6] Mixed integer programming refers to problems and formulas where only some of the variables are constrained to be integers.

The unit commitment data used in Balmorel is the following:

GDUC	Defines if the unit participates in unit commitment (0/1)
GDUCUNITSIZE	Standard size of unit type (MW)
GDUCGMIN	Minimum production (share of input capacity)
GDUCUCOST	Startup cost (Money/MW (standard size of unit)
GDUCF0	Fixed hourly fuel use (share of full load fuel use)
GDUCDTMIN	Minimum down time (hours)
GDUCUTMIN	Minimum up time (hours)
GDUCRAMPU	Ramp-up limit (share of input capacity/h)
GDUCRAMPD	Ramp-down limit (share of input capacity/h)

Table 2: Data introduced only for unit commitment run.

The efficiency of each unit at full load is included as an input in Balmorel. When the unit commitment is applied, then it allows a representation of part load efficiency, by adding a fixed fuel consumption when the unit is online by using the variable GDUCF0. In the following figure, the impact of UC on extraction units and on the plants efficiency can be observed due to the partial load and the partial load efficiency added to the model (Left side with no UC and right side with UC). As it can be observed the efficiency changes when the fixed fuel load is added. If the production is very low the fixed fuel load will count for a relatively larger part of the fuel consumption, which yield to a lower efficiency going towards the total one with full load.

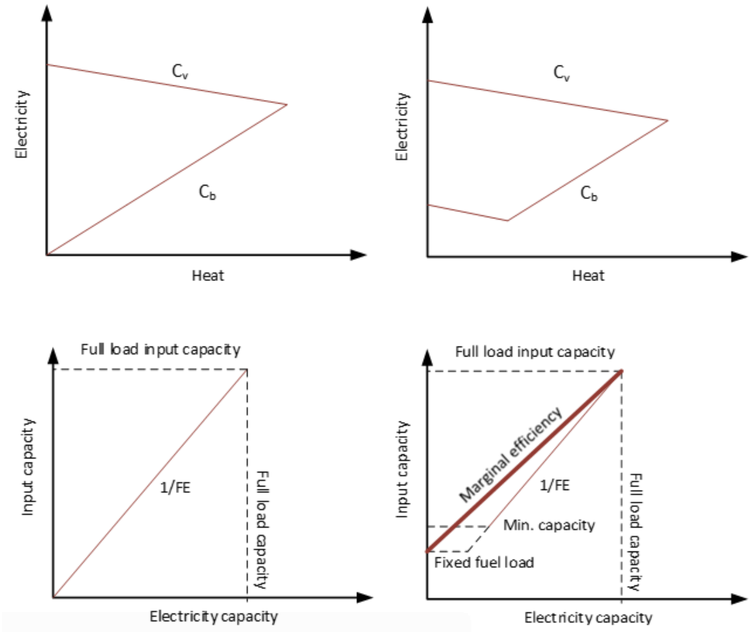

Figure 6: Impact of UC. (Ea Energy Analyses)

3.4 Validity and reliability of data

The validity of the data is determined by how accurate and trustworthy the data that is used in the project is. On the other hand, reliability determines how consistent the results are. In order for them to be reliable, every time the study is performed, using the exact same procedures and data, the results should be the exact same. These two concepts define the quality of each study. (Yin, 2009)

The information gathered from the literature study is considered valid enough, since it was crosschecked with various widely accepted scientific sources. Nevertheless, it should be noted that it is handled critically and with an open mind.

Regarding Balmorel, it is a fact that it is constantly updated. Although it is not user friendly and a lot of knowledge and experience is necessary to modify the inputs and the formulas, and handle the results, this can be considered as one of its strengths, since it is not a "black box", meaning that all the inputs can be modified based on the project's needs and various results can be concluded.

Despite its complexity, it is already used by consultancies and engineering companies to analyse different projects. Its reliability is not questionable, since if the exact same steps are followed for the exact same data, then the outputs will be identical. However, the validity of the results relies on the input uncertainty. The better data inputted in the model, the better the representation of the studied energy system.

Except of the input uncertainty, another simplification of the model is the assumption of the perfect prediction in dispatch of the energy. The model knows exactly at each and every hour what the demand will be and also the wind, solar profiles and water resources. This perfect foresight does not represent the real way that the energy systems work.

Another one of the limitation, mentioned in the unit commitment sub-chapter is the flexible way that the power plants operate, i.e. they do not operate between a maximum and a minimum load but between zero and their generation capacity. Moreover, the investment optimisation is myopic, as it is based on a specific specified year. Last but not least, it should be considered the fact that the level of outputted details is constrained by the computation time, i.e. hourly, weekly or annual runs, unit commitment runs etc.

Summing up, Balmorels' validity is based on the validity of the inputted data, but its reliability is not questionable since the same results will be generated, when the same data is imported into the model.

4 Technological Background linked to Balmorel inputs

In this chapter, theory is including concerning some of the main issues of this thesis. Firstly, some basic information is provided for different types of the power plants that are included in the simulations . Moreover, the benefits of additional interconnection capacity are going to be discussed along with some theory regarding the electric vehicles. This chapter is provided in order to realise the way that power plants operate and to provide some information concerning how interconnectors and transportation solutions can contribute to the flexibility of the grid and integrate more renewable energy. In the end of each subchapter is shown how these technologies are modelled in Balmorel in order to point out the difference and the simplifications that the model has compared to reality.

4.1 Power Plants

Energy efficiencies

As the technology data for energy pants states *"the total energy efficiency equals the total delivery of electricity plus heat at the fence, excluded own consumption, divided by the fuel consumption"* while *"the electricity efficiency equals with the total delivery of electricity to the grid divided by the fuel consumption".* (Energinet.dk; Energistyrelsen, May 2012)

It should be noted that efficiencies refer to full load operation of the power plants taking into account the start-ups and shut downs that may occur at a plant.

Steam Processes and Cogeneration values

Three different steam processes exist as also mentioned in the methodology chapter:

- Condensation mode: Where the units produce only electricity. The steam flows though the unit into a condenser.
- Back-pressure mode: Where the units produce both electricity and heat at an almost constant ratio. The steam has a higher pressure and temperature than in the condensing mode.
- Extraction units: Where the units produce both electricity and heat at a non-fixed flexible ratio. The steam can be extracted in order to produce heat.

C_b: is the backpressure coefficient defined as *"the maximum power generating capacity in back-pressure mode divided by the maximum heat capacity"*.

C_v: is the coefficient for an extraction stream turbine defined as *"the loss of electricity production, when the heat production is increased one unit at constant fuel input"*.

Regulation ability

Every type of power plant is described by its own regulation ability. There are power plants that can be regulated instantly in on/off mode but this is not always the case. The regulation ability, when the power plants are already in operation is described by the fast reserve, how many MW can a plant contribute to the grid per 15 minutes, and the regulation speed, how many MW can a plant contribute to the grid per minute. It is also described by the minimum load that a power plants can operate at, which is given as a percentage of the full load. More information will be provided for the following mentioned power plants.

Technologies

➢ Advanced Pulverised fuel power plant (APF)

The typical capacities for this type of plant range between 400-1000MW. The typical fuels are coal, wood pellets and natural gas. They generate mainly power but they can also generate heat.

These type of plants have high efficiencies, referring to both the electricity efficiency in condensing mode and the total energy efficiency in backpressure mode. The high efficiencies are not only for full mode load but also for partial load and they remain even after many years of operation. In particular, a steam turbine of 400-700MW capacity, fired with pulverised coal has electricity efficiency in the condensation mode between 44-48% and a minimum load of 18% of the full load. Moreover, a steam turbine of 250-400MW capacity, fired with wood pellets has the exact same electricity efficiency, while the minimum load is 20% of the full load. Finally, a steam turbine of 400MW fired with natural gas presents a slightly bigger electricity efficiency ranging between 45-48%. (Energinet.dk; Energistyrelsen, May 2012)

➢ Gas Turbine Single Cycle power plant

The gas turbines single cycle can be either large scale with typical capacities ranging between 40-125 MW, medium-scale (5-0 MW) or small-scale (0.1–5.0 MW). There are also the gas turbines ranging between 0.010–0.100 MW, called micro turbines. The fuels that are used in these types of power plants are natural gas and light oil, but there are cases where biogas or liquefied petroleum gas (LPG) is used. They produce electricity with an option to generate heat as well, with the use of a heat recovery boiler.

Concerning their regulation ability, they can start-up/shut down within minutes and that is the reason why they are used to cover peak loads. They can also operate on partial load, which reduces their electrical efficiency, since when they are operating at lower loads the emissions increase and this limits their regulation ability. The total efficiency of the gas turbines single cycle ranges between 80-85%, while the electricity efficiency is between 35-44% for the large units, 36-40% for the medium ones and 28-35% for the small ones. The minimum load for the large-scale ones is typically 40-60%of the full load. (Energinet.dk; Energistyrelsen, May 2012)

➢ Gas Turbines Combined Cycle (CCGT)

The typical capacities for the gas turbines combined cycle range between 100-400MW for large-scale power plants and 10-100MW for medium scale power plants. Exactly like the singe cycle, typical fuels are natural gas and light oil, but there are case where biogas or LPG is also used. They generate electricity and heat for district heating and industrial processes.

They are up and down regulated as one unit, meaning that the gas turbine operates even when the steam turbine is off. In addition, they are able to operate at a partial load with reduced electrical efficiency. The smaller units have lower efficiencies than the bigger ones. It should be noted that the natural gas fired combined cycle gas turbines have low capital costs, high electrical efficiency and short start-up times. In comparison to the single cycle gas turbines, the CCGT have bigger efficiencies and their large units (above 15MW) are preferred as CHP plants for district heating, since they provide a high ratio of electricity and heat generation.

The CCGT with steam extraction with generation capacity ranging between 100-400MW, present total efficiency ranging between 55-58% (condensation mode), while the CCGT with back-pressure steam turbines and the same generation capacity have quite bigger total efficiency ranging between 82-89%. The electricity efficiency for the last ones is between 41-55%. (Energinet.dk; Energistyrelsen, May 2012)

- Waste to energy CHP plant

This type of plant is used for incineration of municipal solid waste (MSW) and other types of waste from trade and industry. So, the fuels used in this type of power plant are combustible waste, gas oil or natural gas for the burners if they are installed and sometimes biomass for starts ups. As far as it concerns output they generate both electricity and heat. Typically, almost 35 tonnes of waste are incinerated every hour, which is attributed to a thermal input of 100-120MJ/hour.

Regarding their regulation ability, they can down regulate to 50% of their nominal capacity, because their limited from the ability of the boiler to provide enough steam with acceptable quality and environmental emissions.

One their main disadvantages is that they generate greenhouse gas emissions such as CO_2 and NO_x. Methane, CH_4 is not emitted during their operation. Their typical total efficiency is 98%, while the electricity one is 28%. (Energinet.dk; Energistyrelsen, May 2012)

- Biomass CHP, Steam turbine

The typical fuel for this type of plant is biomass, i.e. wood chips, peat, straw and energy crops, such as sugar canes. As a cogeneration power plant, it generates both electricity and heat. They exist either in medium capacities, i.e. 10-50MWe or in small ones, i.e. 1-10MWe. The capacities of these plants for providing heat to district heating systems are determines from the heat demands.

These plants operate usually as a base load due to high investment costs, although they can also be down regulated. Their electricity efficiency for the medium units fired with woodchips is 29%, while the heat efficiency ranges between 64-77%. Their minimum load is 20% of the full load. For smaller woodchip fired plants, the electricity efficiency drops to 25%, while their total reaches 103%. They also need around three hours for a warm start up. In addition, for straw fired medium units the electricity efficiency is 29% while the heat one ranges between 64-72%. For the smaller straw-fired plants the total efficiency is 90%, the electricity ranges between 29-30% and they need 2 hours for a warm start up. (Energinet.dk; Energistyrelsen, May 2012)

As mentioned in the introduction, the different types of power plants affect the flexibility of the energy system. Some of the power plants cannot regulate, they need many hours to start up and shut down and they also have restrictions of a minimum load. As a result, in cases that they need to start up or shut down due to scarcity of other energy sources or high generation of them respectively, the flexibility of the system is compromised. The report “Large combined heat and power plants in sustainable energy systems” states that the CCGT units are quite flexible and the most cost efficient, with less consumption of biomass, for large CHP plants in comparison with circulating fluidised bed (CFB) and APF, which are all using biomass as fuel. (Lund & Mathiesen, Large combined heat and power plants in sustainable energy systems, 2015)

Concerning the Balmorel modelling, an example is provided about how a combined cycle gas turbine in middle Sweden is actually modelled and what exact values Balmorel takes into account into the mathematical equations:

Unit	GDTYPE	GDFUEL	GDCV	GDCB	GDFE	GDCH4	GDNOX	GDDESO2	GDINVCOST0
SE_M_ CC - NG	3	2	0.13	1.5	0.58	5	10	0	0.39

GDOMFCOST0	GDOMVCOST0	GDFROMYEAR	GDLASTYEAR	GDMOTHBALL	GDUC	GDUCUNITSIZE
10.5	1.12	0	0	0	1	250

GDUCGMIN	GDUCUCOST	GDUCF0	GDUCRAMPU	GDUCRAMPD	GDUCUTMIN	GDUCDTMIN
0.38	115	0.2	6	6	4	2

The different values in the tables above are explained in the following bullet points:

- GDTYPE represents to the generation type of this technology. For this specific case, the number 3 refers to extraction units.
- GDFUEL represents to the fuel type. For this specific case, the number 2 refers to natural gas.
- GDCV represents the Cv-value (co-efficiency) for CHP extraction units.
- GDCB represents the Cb-value for CHP plants.
- GDFE represents the fuel efficiency.
- GDCH4 represents the CH_4-factor in mg/MJ.
- GDNOX represents the NO_x-factor in mg/MJ.
- GDDESO2 represents the degree of desulphurisation.
- GDINVCOST0 represents the investment cost in Mmoney/MW.
- GDOMVCOST0 represents the variable operating and maintenance costs in kmoney/MWh.
- GDOMFCOST0 represents the annual operating and maintenance costs in Money/MW.
- GDFROMYEAR represents the year from which the technology is available.
- GDLASTYEAR represents the year when the technology investment expires (blank or 0 implies no expiration).
- GDMOTHBALL represents the year when a unit is mothballed.
- GDUC indicates if the unit participates in unit commitment (0/1).
- GDUCUNITSIZE represents the standard size of unit type (MW).
- GDUCGMIN represents the minimum production (share of input capacity).
- GDUCUCOST represents the start-up cost (Money/MW).
- GDUCF0 represents the fixed hourly fuel use (share of full load fuel use).
- GDUCRAMPU represents the ramp-up limit (share of capacity/h).
- GDUCRAMPD represents the ramp-down limit (share of capacity/h).
- GDUCDTMIN represents the minimum down time (hours).
- GDUCUTMIN represents the minimum up time (hours).

4.2 Interconnectors

The grid network is a crucial parameter for the energy systems, since the supply of reliable and sufficient energy is considered imperative and necessary. As the ENTOS-E states grid integration is a “***prerequisite***” for additional investments in renewable energy sources. If there is lack in the grid capacity, then the investments in RE will be less, since they will not be deployed and the Europe’s plans for a carbon neutral future will be delayed. (European Network for Transmission System Operators for electricity (ENTSO-E), 2014)

There are various benefits arising from the potential implementation of more interconnection capacity. First and foremost, they are a mean of providing supplementary flexibility to the grid, which is essential for the everyday operation of the transmission system. For instance, in cases of excess load or shortage, which cannot be covered by the country’s energy system, it will then be handled by another’s country energy system in case they share a grid interconnector and their markets are integrated. So increased capacity of interconnectors ends up in reinforcing the grid and its flexibility. Consequently, a more robust grid will be created and the security of supply, i.e. providing electricity to cover the demand at each time, will be ensured.

In addition, a market integration of different European energy markets will benefit the socio-economic welfare, since the power trade will include more actors so the competition among them will increase and as a result it is expected to become more economic. Finally, an improvement in the optimal operation of the power plants is expected as the load will be distributed more properly, so as the newest power plants will operate at high load factors and the older power plants will carry peak lots of a short period. Consequently, it is expected that the power plants will operate in a more optimal economic way and the efficiency of the energy system will be improved. (Indus Institute of Technology and Engineering, 2015) (European Network for Transmission System Operators for electricity (ENTSO-E), 2014)

The interconnections are modelled in Balmorel with the following way. For example the NordLink cable, which connects south west Norway with north west Germany and has a capacity of 1400 MW for both ways and it is expected to be completed in 2019 is modelled:

```
XKINI(YYY,'NO_SW','DE_NW')$(YVALUE(YYY) ge 2019) = XKINI(YYY,'NO_SW','DE_NW')+1400;

XKINI(YYY,'DE_NW','NO_SW')$(YVALUE(YYY) ge 2019) = XKINI(YYY,'DE_NW','NO_SW')+1400;
```

It is also included in the model an investment cost for each transmission line with the name XINVCOST in EUR90/MW and a transmission loss between regions as a percentage of the transmitted capacity.

4.3 Electric vehicles

Electric vehicles (EV’s) can contribute towards a sustainable transport sector. A number of studies have been conducted regarding their potential benefits (Hedegaard, Karsten; Ravn, Hans; Juul, Nina; Meibom, Peter, 2012). Due to high oil prices, EVs present a potential to be introduced and utilised in a large scale. Changes in the operation of power systems are expected in cases of high integration of EVs. For instance, higher electricity demand and peaks during the charging hours are expected to occur, depending on the charging pattern. (Kiviluoma & Meibom, 2011)

The plug-in electric vehicles are divided into:

- Battery electric vehicles (BEVs) and
- Plug-in hybrid electric vehicles (PHEVs)

The BEVs are driving only with electricity, while the PHEVs have a battery to drive short distances and a combustion engine for longer ones. (Hedegaard, September 2013) If it is implemented a smart charging i.e. vehicle-to-grid (V2G) power capability[7], then the batteries serve as electricity storages and since the EVs can provide power to the grid within second, they can potentially contribute to a flexible energy system.

The EVs should be charged daily, as the most expected driving pattern during the week is driving to work early in the morning and returning home in the evening and as they only have an average driving range of 150km for BEVs and 20-80km for PHEVs, when they are fully charged. It should be noted that the current sale price of BEVs is quite higher in comparison to conventional cars. As mentioned, they have a short driving range and they also have long charging times, while the PHEVs are considered more competitive to the conventional ones due to their fuel flexibility.

In cases that the EVs are not charged in a smart way, i.e. being charged between 17:00 to 21:00 o'clock when people return from their work, which is also period when the electricity demand peaks, then it is assumed that natural gas and coal power plants will cover the electricity demand for EVs (Ea Energy Analyses, 2011) . An alternative smart way it will be to charge them during the night when the electricity prices are low and the wind is blowing. As a result with the utilisation of V2G power capability, power can be supplied to the grid by the EVs at hours with high consumption and high electricity prices, namely around 9:00 to 13:00 o'clock and 16:00 to 20:00 o'clock. (Energinet.dk, 2009)

It should be noted that based on studies the merge of electricity, heating and transportation sector with storage options will improve the flexibility of the energy systems in order to integrate more RE. Sources that contribute to flexibility are considered the solid, gaseous, liquid fuel storages, the thermal storages, the heat pumps and the EVs. Currently, the flexibility is based on the fuels for power plants, boilers and vehicles. The energy systems are based on infrastructures and storages of energy dense fossil fuels that can at any time cover the demand by transporting the fuels everywhere. Nowadays, the aim is to at least maintain and improve the flexibility of the energy supply with growing amounts of intermittent renewable energy.

The report "Smart Energy Systems for coherent 100% renewable energy and transport solutions" states that:

"connecting the electricity and transport sector enables more fluctuating renewable energy to be utilised and the transport sector should be electrified to the largest extent possible"

As a result the overall efficiency of the energy system will be improved, more RE will be integrated and an amount of fossil fuels will be replaced. In the study " Comparative analyses of seven technologies to facilitate the integration of fluctuating renewable energy sources", battery EVs are compared to hydrogen fuel cell vehicles and the first ones end up to be more ***promising transport integration technology***, since hydrogen

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[7] Vehicle-to-grid power technology is one of the energy storage technologies, i.e. the EVs can supply power to the grid, when they discharge during their parking connected to electric outlets. (Kempton & Tomic´, November 2004) Except of the fact that the EVs can deliver power from the vehicle to the grid, V2G refers also to the control of the power flow via a real time signal (Lund & Kempton, March 2008).

vehicles create more losses to the system and due to the electrolysers the use of power plants is increased (Mathiesen & Lund, 2009).

Except of the transport solutions, the merge of the electricity and heating/cooling sector is considered essential for the flexibility of the energy systems and for the way to 100% RE systems. This is accomplished with the integration of CHP plants with large heat pumps with thermal storages in district heating systems and it is not analysed in this report. (Mathiesen B. , et al., February 2015)

As far as it concerns the EVs modelling, they are treated as an additional demand which in inputted in certain areas created in each country corresponding to the demand of electricity that EVs will require. No investments costs are included for the EVs.

It should be kept in mind that all the data that refers to different technologies, i.e. investment costs, decommissioning years, fuel efficiencies, transmission costs and losses, electricity demand etc. are based on assumptions, which are trying to interpret the real operation of the energy system. However, the model cannot predict situations, when some of the power generators stop operating (break down) or cases when cables stop transmitting any power. Another fact is that as the years of operation pass by, the technologies are aged and their efficiency is also dropping, which is also not taken into account in the model. The actual data for the capacities of the invested RE, the interconnectors and the extra electricity demand for EVs are presented in the Chapter 6, where the different scenarios are formulated.

5 Current Energy systems and Policies

In this chapter, information is including concerning the policies and the current energy systems of the investigated countries, i.e. the Nordics and Germany in order to answer the first sub question and provide some insight of the energy systems of these countries. Firstly, some policies and goals, that the European Union has adopted in order to protect the environment, are presented. Moreover, the current energy system of each country is explained along with their future plans concerning the GHG emissions and the deployment of RE. Subchapters of the transportation sector for each country, focused on the projections of electric vehicles are also included. Afterwards, a short description is provided about the current grid interconnections.

5.1 European Union Policies

Climate change is a reality caused by a number of human activities, such as burning of fossil fuels, deforestation and livestock farming, threating the planet and its inhabitants. The temperature of earth is rising due to the everyday greenhouse emissions, i.e. carbon dioxide CO_2, methane CH_4 and nitrous oxide NO_X. Livestock farming, including the use of fertiliser and the animal waste, is responsible for the 14.5% of the global GHG. (Compassion in world farming, 2015). In addition, fossil fuels such as coal, oil and natural gas release CO_2 in the atmosphere when they are burned. Actually, CO_2 is responsible for 64% of all human made global warming. (European Commission, 2015) The International Energy Agency states that *"the power sector is responsible for 37% of the CO_2 emissions"*, since 40% of the electricity is generated from coal. (World Wide Fund (WWF), 2015)

It also predicts that if the trends continue the same then the CO_2 will double and the temperature of the earth will rise 6^{o}C (World Wide Fund (WWF), 2015). Scientists set as a threshold a rise of 2^{o}C in the earth's temperature. Beyond that the environmental situation of Earth is expected to get worsen and intense weather condition will occur more often and in a bigger scale, such as floods and droughts, the melting of icebergs and the rise of the sea level. (European Environment Agency, 2015)

European Union, being the third biggest emitter in the world (11% share in the global emissions) after China (29% share) and United States (16%), is taking serious actions to reduce the GHG gases. (European Commission, 2013) Under the Kyoto Protocol[8] three objectives have been set by 2020, known as the "20-20-20" targets. According to them, the GHG should be 20% reduced by 2020 in relation to the 1990's levels. The second target refers to the energy efficiency in the European Union (EU), which should be improved by 20%. Last but not least, the total energy EU consumption should be covered 20% by renewable energy sources. (European Commission, 2015)

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[8] Kyoto Protocol is an international treaty signed in Japan in December 1997 and entered in forced in February 2005, which commits its parties into reduction policies of the GHG emissions. (United Nations Framework Convention on Climate Change, 2015)

During the first commitment period (2008-2012) the total EU's GHG emissions were 19.2% lower compared to the base year (1990). For the second period (2013-2020), it is projected that EU will overachieve its targets and reach a 23% reduction of the GHG emissions. As a result, EU has set more drastic goals for the 2030, which includes:

- A 40% reduction of the GHG compared to the 1990's levels.
- A 30% improvement in the EU energy efficiency.
- At least 27% of the energy consumption to be generated by REs. (European Commission, October 2014)

As it can be observed from the following figure, the biggest share of emission in EU derives by the energy generation and utilisation including the transportation sector. In 2012, they were responsible for the 80% of the emissions. It is a fact that since 1990, all the sectors illustrated in the graph has decreased their emissions except of the transportation sector, which has increased them.

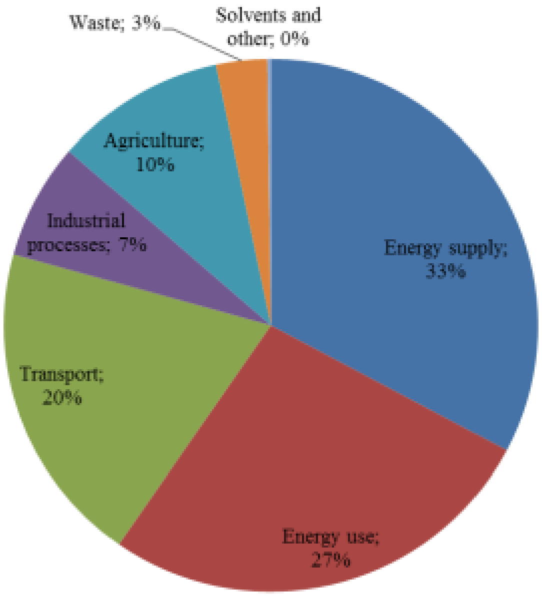

Figure 7: Emissions' shares by sector in EU in 2012. (European Commission, October 2014)

The emissions from the energy generation refer to the ones relevant to the production of electricity and heat from the thermal power plans and also from the petroleum refining industry and the manufacture of solid fuels, such as coal. It should be noted that the emissions from the electricity and heat represent the 27% of the total EU emissions. Regarding the energy utilisation, the biggest share of the emissions comes from the residential and commercial sectors (17 %) and the manufacturing industries (15%). From the transportation sector the biggest emissions comes from the road transport, which has a share of 94% of all the transport-related emissions followed by the domestic aviation with a 2% share of transport emissions in the EU. (European Commission, October 2014)

Apart from the plans for reduction of GHG, improvement of energy efficiency, further deployment of RE and greener transportation, EU has created policies to promote *"a truly competitive, interconnected, Europe-wide internal energy market"* (European Commission, October 2008). The Trans-European Energy Network (TEN-E) has been developed by EU to promote additional electricity grid interconnections. Also, the European Network of Transmission Systems Operator for Electricity, ENTSO-E has published the ten year network development plant (TYNDP) in 2014, including possible investments on interconnectors both regional and international in the Continental Europe, in the Baltic Sea Countries and in the North Sea countries. (European Network for Transmission System Operators for electricity (ENTSO-E), 2014)

In the next pages, the current energy systems of the researched countries and some of their future plans and goals concerning the energy sector are described.

5.2 Denmark

Current System

Denmark has a long history of energy policy making. Since 1961, it has joined the Organisation for Economic Co-operation and Development (OECD), which today has 34 member countries in order to identify problems, analyse them, find solutions about them and promote policies in specific sectors, such as the economic, scientific, educational and environmental sector. (Organisation for Economic Co-operation and Development (OECD), 2015). In the 1970's, Denmark's energy system was highly dependent on oil, since more than 90% of it was imported. Consequently, a lot of plans and studies were conducted and goals were set in order for Denmark to become independent of fossil fuels by 2050. The Danish Energy Agency in collaboration with the Ministry of Climate, Energy and Environment introduces and implements energy policies initiatives in order to strengthen the flexibility of the grid, improve the energy efficiency, the heating and electricity generation, integrate more RE and introduce new technologies. (International Energy Agency (IEA), 2011)

Nowadays, oil and natural gas contribute to Denmark's trade, since it is one of the main net exporters. In 2010, the oil share in this country's energy production was 54% while the natural gas was 31%. The rest of the energy was generated by 12% from biomass and the rest 3% came from the wind generation. As far as it concerns electricity in 2010, 44% was covered by coal, 20% by natural gas and the other 20% by wind. In addition, Denmark imports electricity from Norway and Sweden and exports an amount to Germany. (International Energy Agency (IEA), 2011) It should be noted that since 1993, Denmark is self-sufficient in oil and in 2012 the percentage of self-sufficiency reached the 155% (Danish Energy Agency, 2012).

The power in Denmark is produced by either a few large central combined power and heating plants (CHP) sited in Aabenraa, Aalborg, Aarhus, Copenhagen, Esbjerg, Herning, Kalundborg, Odense and Randers or by smaller decentralised CHP plants and wind turbines (The Danish Partenership for Hydrogen and Fuel Cells, 2015). The future of the power plants is quite uncertain. The ones that will be in operation after 2020 are expected to have a life of more or less 40 years from their commissioning year. However, according to Energinet.dk, it is quite difficult to estimate their lifespan, as they are expected to operate less due to more wind and solar energy. (Energinet.dk, April 2013)

The Energinet.dk states that "*2013 was a record-setting year for Danish wind power*". Actually 33.2% of the annual electricity consumption was supplied by the wind turbines, while in December this share reached

54.8%. (Energinet.dk, 2014) The installed capacity of the wind turbines in 2014 was 4800MW, from which 1142MW was generated from offshore wind farms, 56MW from near shore wind turbines in East Denmark, 74MW from near shore wind turbines in West Denmark, 583MW from onshore wind turbines in East Denmark and 2946MW from onshore wind turbines in West Denmark (Energinet.dk, September 2014).

In the following graph the evolution of generation of RE by energy product i.e. wind, wood, waste, straw, biogas and other sources such as solar energy and heat pumps is shown through the years 1990 to 2012. As the figure shows, the total energy production from RE has been following an increasing trend in this period.

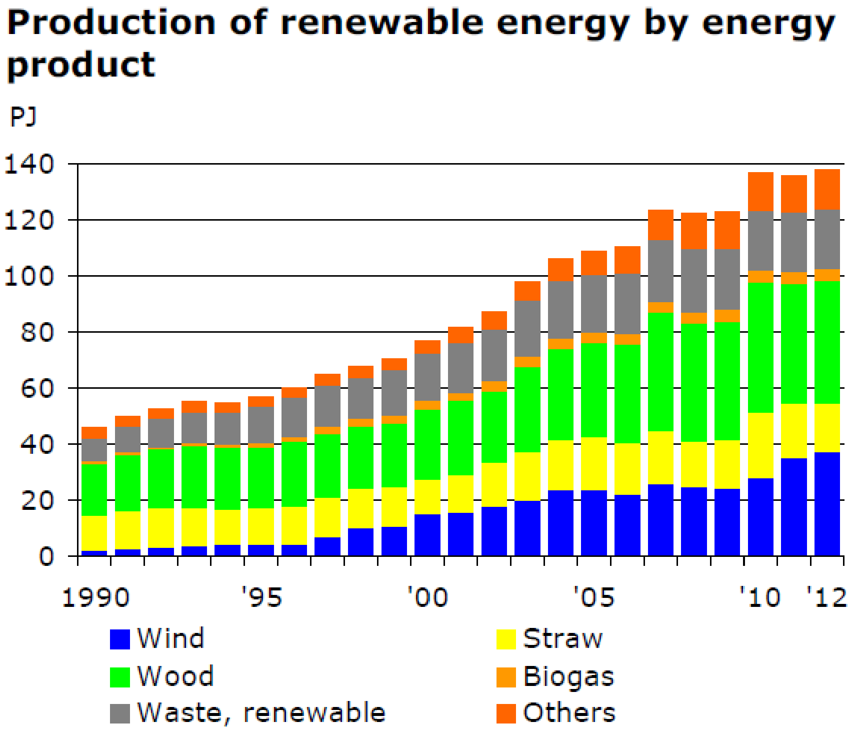

Figure 8: Generation of RE by energy product (Danish Energy Agency, 2012)

Future plans

In March 2012, a new energy agreement was introduced in Denmark, which sets the goal that by 2050 Denmark should use 100% RE in the energy and the transport sector. The aim of this agreement is for Denmark to be less dependent on fossil fuels, coal, oil and gas. This particular agreement includes the following targets:

- The final energy consumption must be supplied by more than 35% RE.
- Almost 50% of the electricity demand should be covered by the wind.
- The gross energy consumption should be decreased by 7.6% in relation to the respective one in 2010.
- The greenhouse gas emissions (GHG) should be decreased by 34% in relation to the ones in 1990. (Danish Energy Agency, December 2012)

The International Energy Agency suggests that almost 60% of the electricity demand can be covered by RE. However, in order this to succeed a transformation of the whole energy sector is mandatory. Investments in the electricity infrastructure, such as the creation of a smart grid and more grid interconnectors, both regional and international, as well as the promotion of electric vehicles are considered requirements for the future system transformation. Moreover, domestic policies for the reduction of GHG emissions to meet the goal of the 21% reduction from the base 1990 year are implemented and the reduction is currently on track with the Kyoto[9] protocol agreement.

Transport sector

The transport sector in Denmark accounts for the 26% of the CO_2 emissions (International Energy Agency (IEA), 2011). As a result, Denmark aimed to create a green transport sector with the creation of a Green Transport Policy in January 2009 and the establishment of a Centre for Green Transportation. 5 million DKK per year for the period 2010 to 2012 were allocated to a pilot test scheme for electric cars in order to obtain experience regarding their use and create the required infrastructure. This test scheme was also expected to test the use of the electric cars as flexible storages in order to alleviate the grid from the fluctuations of the RE. (Danish Energy Agency, 2015)

Furthermore, on January 2013 a new agreement was presented with 70 million DKK fund to establish recharging stations for the electric cars and infrastructure for gas and hydrogen in the heavy transport. As mentioned before Denmark's 2050 target is to supply all the energy demand with RE including the transport sector (Ministry of Climate, Energy and Buildings, April 2013). A more modest goal of the government is that by 2020 the share of RE in the transport sector to be 10% (International Energy Agency (IEA), 2011). In fact, in 2012 Denmark counted 1400 EVs. (Antikainen, 2015)

Interconnections

The Danish electricity transmission grid is connected with the Norwegian, Swedish and German one. It is separated into the Eastern and Western. The Eastern power system, i.e. Zealand, is synchronised with the Nordic power system while the Western one, i.e. Jutland and Funen, is synchronised with the continental Europe. (Energinet.dk, 2015)

Zealand is connected with both Sweden and Germany. The interconnection with Sweden consists of four AC cables, two of 132KV and two of 400KV. As Energinet.dk mentions, Eastern Denmark exports 1700MW to Sweden and import 1300MW from it. As far as it concerns the interconnection with Germany, it has a transmission capacity of 600MW and it is a 400KV DC cable connecting Koge with the German coastline.

Regarding the Western Denmark, it is connected with Sweden, Norway and Germany. The 285KV DC cable, which connects Western Denmark with Sweden, has a capacity of 740MW. Jutland export 740MW, while it imports 680MW. In addition, three DC interconnectors with a total capacity of 1000MW connect Western Denmark with Norway. Finally, the interconnection with Germany with an export of 1780MW and an import of 1500MW consists of four AC lines.

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[9] Kyoto protocol is an international treaty with international bidding emission decrease targets based on the global warming and the CO_2 emissions. (United Nations, 2015) Currently, the goal is that the levels of CO_2 in the atmosphere in 2020 should be reduced by 20% compared to 1990's levels. This goal is considered to be achieved since in 2013 the GHG were reduced by 19% in relation to the respective ones in 1990. (European Commission, 2015)

The two parts of Denmark are connected with each other with a 400KV DC cable with a transmission capacity of 600MW, namely the Great Belt Power Link. In the figure to follow, all the interconnections between Denmark and the Nordic countries and Germany can be seen. (Energinet.dk, 2015)

Figure 9: Interconnectors between Denmark and Sweden, Norway and Germany. (Energinet.dk, 2015)

5.3 Finland

Current System

Finland is a highly industrialised country with a sizeable forestry and paper industry. As the International Energy Agency states due to the intensive industries and the cold climate, it has one of the biggest energy consumptions per capita. Although Finland has a very diversified electricity generation mix, consisting of nuclear energy, hydropower, coal, natural gas, wood fuels and peat, it is highly dependent on imported fossil fuels, i.e. coal, oil and gas. The wind's power share is quite small but it is expected to grow. (Finnish Energy Industries, 2015) (International Energy Agency (IEA), 2013)

Nowadays, 120 companies that produce electricity exist in Finland and around 400 power plants, from which more than half are hydroelectric. It is a fact that almost one third of the electricity is produced in the combined heat and power plants (Finnish Energy Industries, 2015). In 2013, 28.4% of the electricity demand was supplied by the CHP plants, 27.1% by the nuclear power plants, 15.7% by hydropower, 9.7% by separated electricity production, 18.7% by electricity imports and only 0.9% by the wind turbines. (Finnish Energy Industries, 2015)

It should be noted that Finland has the fourth lowest share of fossil fuels in the energy mix following Sweden, France and Switzerland. Moreover, it has the largest share of biofuels among the IEA countries followed by Sweden and Denmark. It is one of the three IEA countries, i.e. Sweden and Ireland, that has peat in the energy mix, accounting for a 5.8% on the total primary energy supply in 2011. (International Energy Agency (IEA), 2013)

Future Plans

Decarbonisation is also a long-term goal for the future of Finland. It is already in track to meet the GHG emission reductions set by the European Union, i.e. 20% reduction by 2020 in relation to the respective levels in 1990.

Not only has the government changed the taxation on fuels for CHP plants and transportation, which are now based on the energy content of the fuel, but investments in renewable and nuclear energy are considered a priority. The overall goal is to reach a share of RE to 38% of the final energy consumption by 2020. In addition, since the 86% of the country is covered by forests, the government suggests measures to increase the use of the forest chips and wood based energy. Moreover, the Finish Climate and Energy Strategy suggests measures to ambitiously reduce by 11% the total energy consumption by 2020. These measures includes subsidies to increase the energy efficiency and savings in the buildings.

As far as it concerns the nuclear power, at the moment there are two nuclear power plants in operation with a capacity of 2700MW, each one of them with two nuclear power reactors, one in Olkiluoto and one in Loviisa. However, Finland has plans to expand its nuclear capacity by constructing two more reactors in Olkiluoto, Olkiluoto 3 with a capacity of 1600MW and Olkiluoto 4 with a capacity of 1800MW, and a new plant in the north of the country in Fennovoima with a capacity of 1800MW (Muranen Lauri Finish Energy Industry, 2012). As a result, it is expected that by 2020, seven units will be in operation covering 30% of the electricity demand, which can be doubled by 2025. (World nucler news, 2013) (International Energy Agency (IEA), 2013)

Transportation

The contribution of finish transport sector in the energy mix is among the lowest ones in the IEA countries (17.2% in 2011). The government predicts that the use of energy in transport will be reduced to 12.6% by 2030. It has also set the target that 20% of the renewable energy will be used in transportation. (International Energy Agency (IEA), 2013)

In 2011 the Finish Innovation Agency Tekes[10] initiated a new program about electric vehicles and their charging infrastructure which will run until 2015. The program sets the target of creating an international network with companies and researchers in order to develop and promote the EVs. (Tikkanen & Ornberg, 2012) Currently, 360 EVs are registered in Finland (Vuola & Lindgren, 2015).

Interconnections

Finland's grid is also a part of the synchronous Nordic power system. The Finish electricity transmission grid is connected to Sweden, Norway, Estonia and Russia. Two 400KV AC cables connect Finland with Sweden. Moreover, the two countries share a 220KV AC connector and two DC links with capacity of 550MW and 800MW (Fenno-Skan 1 from Rauma to Dannebo in Sweden and Fenno-Skan 2 from Rauma to Finnböle in Sweden respectively). Finland is also connected with a 220KV AC cable of 100MW with Norway.

Regarding the Estonia connection, two DC links exist, namely EstLink 1 with capacity of 350 MW and EstLink 2 with capacity of 650 MW. Finally, in order for the Russian hydropower plants to contribute to the Finnish grid, three DC lines of 400KV and one of 110KV exists. (International Energy Agency (IEA), 2013) (Fingrid, 2015)

5.4 Norway

Current System

The economy of Norway is based on natural gas and oil production. After Russia and Saudi Arabia, Norway is the third largest exporter of oil and gas in the world contributing to the energy security of the consuming countries. It is also a big exporter of hydropower, due to its low cost and the high availability of this resource in wet years and the significant reservoir capacity.

As mentioned, Norway's power system is based on the hydropower, since it contributes to the electricity generation by 95%. The rest 5% of the electricity generation is covered by 4% from the combined cycle gas turbine generation and by 1% from the wind turbines. Regarding the total energy supply, the mix is consisted by 34% of oil, 20% of gas, 5% of biomass and waste, 2% of coal, a very small percentage of wind and an almost remaining 48% of hydro. (International Energy Agency (IEA), 2011)

Future Plans

Norway has adopted a very strong climate policy towards environmental sustainability. It aims to reduce the GHG emissions by 30% by 2020 in relation to the 1990 levels and become carbon-free by 2050. Moreover, increase in the interconnection capacity of Norway with the neighbouring countries is also expected to occur, in order to ensure the security of supply especially in days with low hydro availability since it is the dominant

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[10] Tekes is the main public funding organisation for research and development (R&D) in Finland.

energy source of the country. In addition, plans to improve the energy efficiency of the buildings are introduced since 2007. It should be mentioned that, Norway will expand the investments in the offshore wind turbines (International Energy Agency (IEA), 2011)

Transportation

As far as it concerns the transportation sector, Norway intends to use some incentives including exemptions from taxes, free access to public parking lots and funding for infrastructure developments in order to promote the use of EVs. (International Energy Agency (IEA), 2011)

The Norwegian Electric Vehicle Association is trying to promote the electric vehicles for almost 20 years. With the cooperation of the Norwegian government, they have managed to register in 2014 more than 37000 EVs in a population of 5 million inhabitants. Moreover, in Norway exist more than 5 000 charging spots. As a result EVs have become quite competitive compared to the conventional fossil fuel cars. The goal is that by 2018 the number of EVs to reach the 50 000 and by 2020 the 100 000. (Norsk Elbilforening, 2015)

Interconnections

Statnett owns 90% of the transmission network of Norway and it is the state owned transmission system operator (TSO). As mentioned, Norway is interconnected with Denmark, Finland but also with Sweden, the Netherlands and Russia. In particular, the cable from Norway to Sweden has a capacity of 3450MW while on the other direction the capacity is 3000MW. Also, Norway is connected with the Netherlands with a subsea cable, namely NorNed, with a transmission capacity of 700MW. Finally, the cable link with Russia is used mainly from Norway to import electricity and has a lower capacity. (International Energy Agency (IEA), 2011)

5.5 Sweden

Current System

Sweden is the country with the lowest share of fossil fuels in the energy mix among the IEA countries. In 2011, the biggest share of the fossil fuels was hold by the oil with a percentage of 25.3% of the total energy supply, followed by the coal with a share of 4.1% and natural gas with a share of 2.4%.

In addition, Sweden has the second biggest nuclear power production following France. The share of nuclear in the electricity generation reached the 40.5% in 2011. Hydropower contributes to the electricity generation by 37.5%, CHP plants by 10% with biofuels as the main fuel, imported electricity by 8% and wind power by 4%. (International Energy Agency (IEA), 2013) (Swedish Energy Agency, February 2014)

Future Plans

The integrated climate and energy policy of Sweden sets a number of targets by 2020. According to this policy, a reduction of 40% in the GHG in relation to 1990 levels is planned. In addition, at least 50% of the energy should be generated by renewable energy (the current percentage is around 35%, 22.7% by biofuels and waste and 11.7% by hydro). Plans are also made to reach the target of 20% more efficient use of energy. Finally, 10% of renewable energy should be used in the transport sector by 2020. In the long term of 2050, Sweden intends to be carbon neutral. (Ministry of the Environment and Ministry of Enterprise, Energy and Communications, 2009) (International Energy Agency (IEA), 2013)

As far as it concerns the nuclear power plants, since 2010 the plans to phase out nuclear were cancelled and as a result seven of the nuclear power reactors are going to be upgraded and operate beyond 2030, while three of the already working reactors are going to be decommissioned between 2020 and 2030, after 50 operating years. (International Energy Agency (IEA), 2013) (Swedish Energy Agency, February 2014)

Transportation

A study made by Vatenfall and the City of Stockholm in 2009 has shown that Swedish organisations and companies have a high interest in buying EVs. In the period 2011 to 2014, a demand for almost 14000 EVs was expressed. Moreover, the Swedish government provides incentives, such as exclusion from the vehicles tax for the first five years, for those who buy EVs. (Elbilsupphandling.se, 2015)

Interconnections

As mentioned in the previous subchapters, Sweden’s electricity grid is connected with Denmark’s, Finland’s and Norway’s (International Energy Agency (IEA), 2013). Moreover, it is connected with Poland using a 450KV HVDC subsea interconnector with a capacity of 600MW namely SwePol link (ABB, 2015)Not forget to mention the existing 450KV HVDC interconnection with Germany, namely the Baltic cable, which is one of the world longest submarine cables with a capacity of 600MW. (ABB, 2015)

5.6 Germany

Current System

Germany’s main source of energy is oil, currently representing the 32% of the total primary energy supply though its use have been declined by 15% from 1973 to 2010 (International Energy Agency (IEA), 2013). Since it has a diversified energy system, the rest of the total primary energy supply is covered by coal (24% of TPES), by natural gas (22% of TPES), by nuclear (11% of TPES) and by hydro and renewable energy sources, i.e. wind and solar (11% of TPES). Since Germany does not have sufficient oil and natural gas production, but it has oil and gas infrastructure and cross border pipelines, its energy system relies also on imports. Moreover, most of the electricity is mainly supplied by the coal-fired power plants in North Germany and the nuclear power plants in the South Germany. (International Energy Agency (IEA), 2012)

Future Plans

Germany is on track to meet the Kyoto Protocol requirements concerning the GHG emissions. It is a fact that the last few decades, it has managed to decouple those emissions. Based on the German’s energy concept “Energiewende” 40% emissions reduction by 2020 in relation to 1990 levels is expected to happen.

Moreover, among the plans is the improvement of the energy efficiency. The target is that by 2020, the primary energy consumption will be reduced by 20%, reaching a 50% reduction by 2050 comparing to the 2008 levels. Furthermore, the Renewable Energy Act (EEG) introduces a number of strategies to integrate more RE, i.e. wind energy, solar energy and biomass by decreasing their costs and the feed in tariffs especially for PVs. (International Energy Agency (IEA), 2013) In particular, the total offshore capacity is going to be increased to 6.5GW by 2020 and to 15GW by 2030. As far as it concerns the onshore wind turbines, investments for 2.5GW per year are expected. In addition, the biomass production will be increased around

100MW per year and the solar capacity will follow an increase of 2.5GW per year with a limit of 52GW in total. (Federal Ministry of Environment, Nature Conservation and Nuclear Safety, October 2011)

After the Fukusima accident in 2011, Germany has decided to phase-out all the nuclear power plants by 2022. Eight of the reactors closed after the accident and the rest nine of them will be decommissioned in the future. In order to compensate this loss of energy generation, the government is going to invest in a new coal-fired power plants in which carbon capture and storage is going to be implemented. (International Energy Agency (IEA), 2013)

Transportation

Since 2012, Germany has announced plans to become a *"global leader"* in the market of low carbon vehicles. It is a fact that, although the GHG emissions have dropped by 21% in relation to the 1990 levels, the ones related to the transport sector has been increased by 1% since 2005.

At the moment Germany has registered more than 41 million cars. However, only 1452 of them are EVs. The plans are that by 2020, 1 million EVs will be on the road. The Ministry of Environment has not yet announced any incentives concerning the future EVs buyers, but suggests that electricity generated from renewable energy sources, such as wind and solar, should be used in order to charge them. (Worldwatch Institute, 2015) (Moulson, 2015)

Interconnections

The operation of the German grid is done by four different TSOs, namely EnBW Transoirtnetze, Tennet TSO, Amprion and 50Hertz Transmission. Germany shares a connection to the Netherlands with a capacity of 2449MW both ways. Moreover, there is a cable connecting it with France, with 3000MW flow from Germany to France and 1800MW flow from France to Germany. An interconnector with 2000MW capacity exists from Germany to Switzerland (4000MW flow from Switzerland to Germany). (Amprion, 2015) As mentioned Germany is also interconnected with Sweden (Baltic cable of 600MW) and with both East and West Denmark.

In the map to follow, the electricity flow, i.e. the electricity imports and exports of the Nordic power system on 10th April 2015 can be observed.

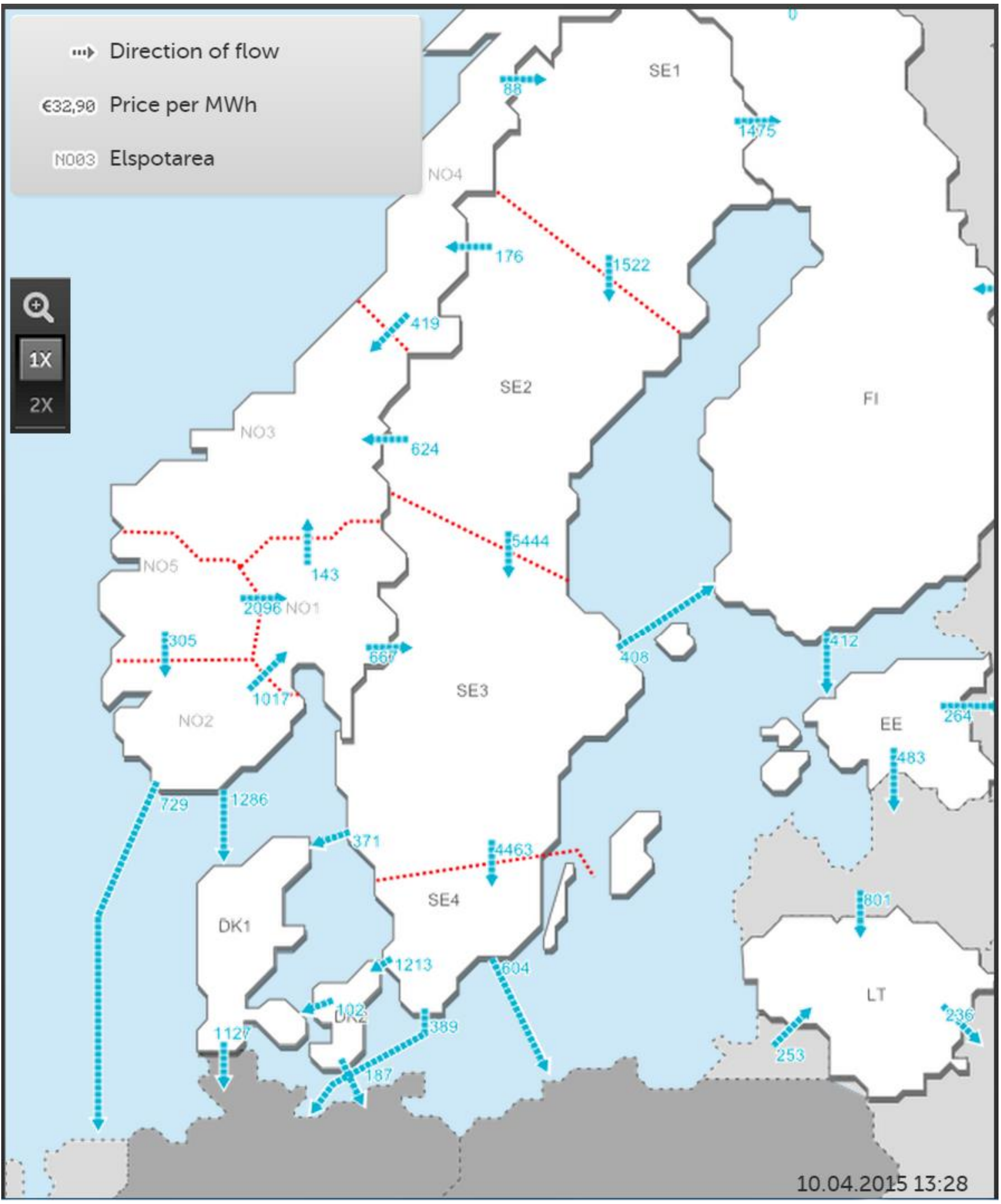

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Figure 10: Electricity imports and exports of the Nordic power system on 10th April 2015. (Energinet.dk, 2015)

As it can be summarised all the researched for this project countries have plans to invest on RE, follow energy conservation policies, diminish as much as possible the GHG and move towards a green transportation by introducing EVs and utilise the generated electricity from RE to the transportation sector. In the next chapter, the scenarios that are going to be explored with Balmorel for this project are presented for each country.

6 Scenarios

This chapter describes the different scenarios that are going to be researched with the energy model Balmorel. They include additional deployment of RE and additional electricity demand for all the researched countries and they are simulated with and without the implementation of unit commitment data for the power plants.

6.1 Acknowledgments

In this chapter, the scenarios that are going to be simulated in Balmorel in order to answer the research question of this project are analysed and presented in the table to follow. Firstly, a reference scenario of 2013, representing the present system of all the researched countries, is going to be analysed in an annual hourly basis without unit commitment. Also, a unit commitment run in the reference is going to be simulated in an annual hourly simulation as well. Afterwards, the reference scenario for 2013 is extrapolated in 2030, where it is assumed that more RE are integrated in the energy systems as well as grid interconnections among the countries. This scenario is also going to be simulated with unit commitment data.

The next scenario includes additional electricity demand for electric vehicles for 2030. The level of the renewable energy deployment and the grid integration plans among Germany and the Nordic countries are the same with the previous scenario. The last scenario concerns the introduction of electric vehicles to grid. Both of the scenarios will be simulated with and without unit commitment. The necessary data is inputted exogenously in the model and it has the exact same assumptions concerning the unit commitment data and the run times. More details concerning the exact Balmorel inputs are provided in the pages to follow.

Scenarios	NON UC	UC
Reference 2013	Annual hourly	Annual hourly
RE 2030	Annual hourly	Annual hourly
RE 2030 + EVs	Annual hourly	Annual hourly

Table 3: Researched scenarios for this project.

For the reference 2013 base scenario without the unit commitment enabled, a bb3 simulation is chosen, in order for Balmorel to determine the hourly deployment of the different generation technologies. For the rest of the simulations, i.e. the RE 2030 runs with and without EVs and V2G and also without the unit commitment implemented, a bb2 simulation is firstly enabled in order for Balmorel to invest in new technologies and new interconnection capacities. Subsequently, a bb3 run is executed in order to optimise the hourly dispatch and operation of the different generation technologies towards the defined timeframe. It should be noted that the model choose to invest either when the annual costs of the investment plus the fixed operating costs in the first year can be covered by the operational savings on other units or as long there is a marginal profit from investing after accounting the costs of capital. All the new investments are available from the beginning of the year simulated and the following years.

The timeframe for this project is 2030, while the simulations are conducted using the following years: 2013, 2030. Moreover, the core countries are Germany and the Nordics, i.e. Denmark, Finland, Norway and Sweden. The Netherlands is also inputted in the model but only due to the planned interconnection with Germany (Doetinchem-Niederrhein) and the cobra cable with Denmark.

The assumptions regarding the deployment of the RE are based on the national projections of the core countries as well as the vision 3 of the European Network of Transmission Systems Operator for Electricity (ENTSO-E)[11] Scenario outcome and Adequacy Forecast part of the Ten Year Network Development Plan (TYNDP). Vision 3 is the "Green Transition" scenario with a moderate deployment of RE. The reasoning behind this decision is attribute to the fact that the Vision 4, namely "Green Revolution" is a highly optimist scenario and a more realistic and conservative approach is chosen for this project.

As far as it concerns the grid interconnections are also based on the TYNDP and all the projects that refer to the relevant for this project countries and commissioned until 2030 are determined exogenously in the model.

Regarding the methodology about EVs, the energy demand for the passenger cars is collected by either the Energy Statistics report for Denmark (Danish Energy Agency, February 2014) or the Eurostat statistics for the rest of the countries (European Commission, 2015). Then a main assumption for an increase of 20% on the share of the EVs by 2030 is used for the calculations. Moreover, in the calculations for the EVs electricity demand, the difference in the motor efficiency between the EVs and the conventional cars is considered (conventional cars: 25% motor efficiency, EVs: 80% motor efficiency (Shah, Woolsey, Lodal, & Tonachel, 2009).

The source used to define the electricity demand is the National Renewable Energy Action Plan (NREAP) and the heat demand is based on the report "Energy trends 2030" of the European Commission. (European Commission, 2010) The fuel prices are coming from the "New Policies Scenario" from IEA's World Energy Outlook (WEO) published in November 2013 (International Energy Agency (IEA), 2013). IEA states that the prices of natural gas, coal and oil will increase in a moderate level, since the demand for fossil fuels is going to be decreased due to each country's effort to reduce greenhouse gas emissions and protect the earth from the climate change. The biomass and biogas prices inputted into the model are based on a study carried out by Ea Energy Analyses and DTU on behalf of the Danish Energy Agency (Ea Energy Analyses; DTU, 2013). Furthermore, the CO_2 quota price is from the WEO as well for the year 2030. The same prices are applied for all the countries, except the natural gas prices for Norway, which are assumed 10% lower due to local resources.

Regarding the unit commitment data, i.e. the minimum generation of each plant, the start-up cost, the minimum up and shut down time and the ramp up and down time are gathered from the Agora Energiewende report "Negative electricity prices: causes and effects" ("Negative Strompreise: Ursachen und Wirkungen") and a project of Ea Energy Analyses for the power plants in Ireland.

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[11] ENTSO-E is the European Network of Transmission Systems Operator for Electricity, which represents 41 electricity transmission system operators (TSO) of 34 European countries. (European Network of Transmission Systems Operator for Electricity (ENSO-E), 2015)

6.2 Denmark

The Danish energy system in Balmorel is quite detailed, especially compared to the other countries' energy systems. It is composed by a number of centralised and decentralised cogeneration power plants (CHP), allocated not only in the two regions of the country, i.e. West and East Denmark, but also in different areas of the regions, such as Aarhus, Copenhagen, Herning, Esbjerg, Skagen and etc. As mentioned, Denmark uses various fuels for energy generation but mainly coal, gas, biomass and wind.

Concerning the data, actual 2013 values and projections for 2030 are gathered from Danish TSO Energinet.dk.

Denmark	**Capacity (GW)**	
	2013	2030
Hydro	0	0
Biogas	0.1	0.1
Biomass	0.9	3.5
Solar	0.3	1.4
Wind offshore	1.3	3.7
Wind onshore	3.5	4.0
Nuclear	-	-

Table 4: Denmark's capacity values in GW for the different energy sources for 2013 and 2030. (Energinet.dk, September 2014)

For the second scenario concerning the EVs values, the passengers' cars energy demand is 100.4 PJ based on the Energy Statistics report for Denmark (Danish Energy Agency, February 2014). It was assumed that by 2030 the demand for EVs will represent a 20% of the overall energy demand for the passengers' cars. Consequently, the electricity demand for EVs by 2030 will be:

$$100.4 * \frac{25}{80} * 0.2 = 6.275PJ = 1\,743\,055.5MWh$$

6.3 Finland

Finland energy system is based on energy generation from the nuclear, hydro and CHP power plants. The RE 2030 scenario implies an increase on the wind capacity, both onshore and offshore, and also an increase in the hydro capacity. The projections for 2030 are based on the report "Low Carbon Finland 2050" of the Technical Research centre of Finland (VTT), which is a part of the Finish Ministry of Employment and Environment.

This report describes three different scenarios, namely "Tonni", "Inno" and "Onni". The first one is based on the growing energy demand, the second one on the assumption of a faster technological development with investments in RE and the last one includes changes in the industrial structure and of course investments in RE. However, all of them assume the same wind generation of 8TWh (approximately 3.3GW), while the national target for Finland is around 2.5GW for 2020. (Technical Research Center of Finland VTT, 2012)

Finland	Capacity (GW)	
	2013	2030
Hydro	3	3.7
Biogas	0	0
Biomass	2	3.2
Solar	0	0
Wind offshore	0	1.2
Wind onshore	0.3	2.1
Nuclear	2.7	5.7

Table 5: Finland's capacity values in GW for the different energy sources for 2013 and 2030. (Technical Research Center of Finland VTT, 2012)

For the scenario that includes the EVs, the total road energy demand for diesel and benzin is gathered by the Eurostat statistics, which is 94PJ and 57PJ respectively. It is assumed from the Danish experience and by using the road demands for diesel and benzin, that 34.3% of the diesel is utilised in the trucks and buses, while the benzin is utilised all as a passenger car fuel. So, the rest 65.7% represents the diesel used in the passenger cars. Consequently, the electricity demand for EVs by 2030 is:

$$(94 * 65{,}7\% + 57) * \frac{25}{80} * 0.2 = 7.422PJ = 2\ 061\ 666.6MWh$$

6.4 Norway

Norway's energy system is based on hydro generation, followed by wind, natural gas and biomass. Concerning the first scenario of the integration of more RE, the implemented data is gathered by the ENTSO-E TYNDP and particularly from the Vision 3 scenario, which is called "Green Transition" and assumes a moderate deployment of RE and reflects the national policies of each country. (European Network of Transmission Systems Operator for Electricity (ENTSO-E), 2014)

Norway	Capacity (GW)	
	2013	2030
Hydro	28.6	37.2
Biogas	0	0
Biomass	0	0
Solar	0	0
Wind offshore	0	0
Wind onshore	1.1	5
Nuclear	-	-

Table 6: Norway's capacity values in GW for the different energy sources for 2013 and 2030. (European Network of Transmission Systems Operator for Electricity (ENTSO-E), 2014)

For Norway's diesel and benzin demand in the road transport, data is gathered by the Eurostat statistics, and it is 91PJ and 41PJ respectively. Based on the same as in Finland assumptions, the calculated electricity demand for EVs by 2030 is:

$$(91 * 65{,}7\% + 41) * \frac{25}{80} * 0.2 = 6.299PJ = 1\ 749\ 722.2MWh$$

6.5 Sweden

Just like Norway, Sweden has a big energy generation coming from the hydropower. It also has CHP that uses as a fuel biomass. Moreover, there are three installed nuclear power plants, with plans to increase the number of the power reactors. The following table shows a future increase in the onshore wind power and it is based on the Swedish Energy Agency's Checkpoint 2015 Report. (Swedish Energy Agency, October 2014)

Sweden	**Capacity (GW)**	
	2013	2030
Hydro	16.4	16.6
Biogas	0	0
Biomass	2.4	2.8
Solar	0	0.1
Wind offshore	0.2	0.2
Wind onshore	4.5	6.9
Nuclear	9.4	10.1

Table 7: Sweden's capacity values in GW for the different energy sources for 2013 and 2030. (Swedish Energy Agency, October 2014)

The Eurostat statistics states that for Sweden, the diesel and benzin demand in the road transport, are 156PJ and 116PJ respectively. For the calculation of the electricity demand for EVs, the same assumptions as in Finland are used:

$$(156 * 65{,}7\% + 116) * \frac{25}{80} * 0.2 = 13.655PJ = 3\ 793\ 055.5MWh$$

6.6 Germany

The most utilised fuel sources in Germany are coal and lignite. The RE 2030 scenario is based on the framework of the German renewable energy act (EEG) (German Federal Ministry for Economic Affairs and Energy, August 2014), which projects an expansion of 55-60% of RE by 2035. In the table below the capacities implemented in Balmorel can be observed.

Germany	**Capacity (GW)**	
	2013	2030
Hydro	4.6	4.8
Biogas	0	0
Biomass	2	8.2
Solar	35	58.2
Wind offshore	1	14.5
Wind onshore	33	71.2
Nuclear	12	-

Table 8: Germany's capacity values in GW for the different energy sources for 2013 and 2030. (German Federal Ministry for Economic Affairs and Energy, August 2014)

As mentioned Germany by 2022 has plans to decommission all the nuclear power plants. Moreover as it can be observed from the table a big increase in the solar and wind energy is expected to occur.

As far as it concerns the EVs, the exact same methodology with Finland, Norway and Sweden is used, resulting to the following electricity demand:

$$(1223 * 65{,}7\% + 738) * \frac{25}{80} * 0.2 = 96.34PJ = 26\,761\,111.1MWh$$

6.7 Electric vehicles charging profile

In the following figure, the daily charging profile of the EVs applied in Balmorel is demonstrated. As it can be observed the EVs charge during the night hours when the electricity prices are usually below average and the electricity consumption is low. During the day, the charging profile follows a usual consumption profile of a household. This profile is constant and it is not adjusted based on the generation of other energy sources, i.e. wind. It is not a “smart” profile but it is considered flexible in the way that the EVs are charged when the electricity demand is low and the electricity prices are lower i.e. during the night.

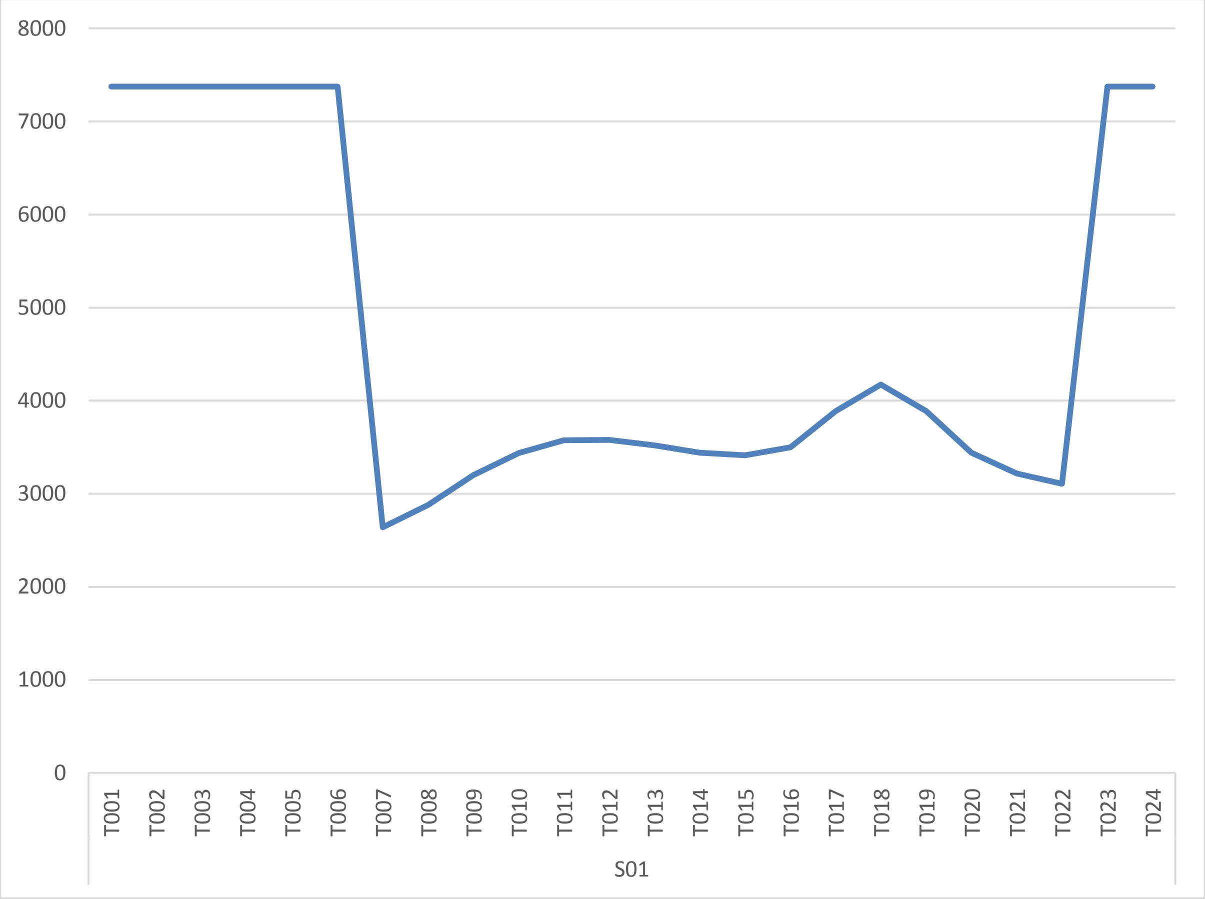

Figure 11: Daily charging profile for EVs

6.8 Grid Interconnections

The present grid of Europe as it is inserted in Balmorel in 2013 can be seen in the map to follow.

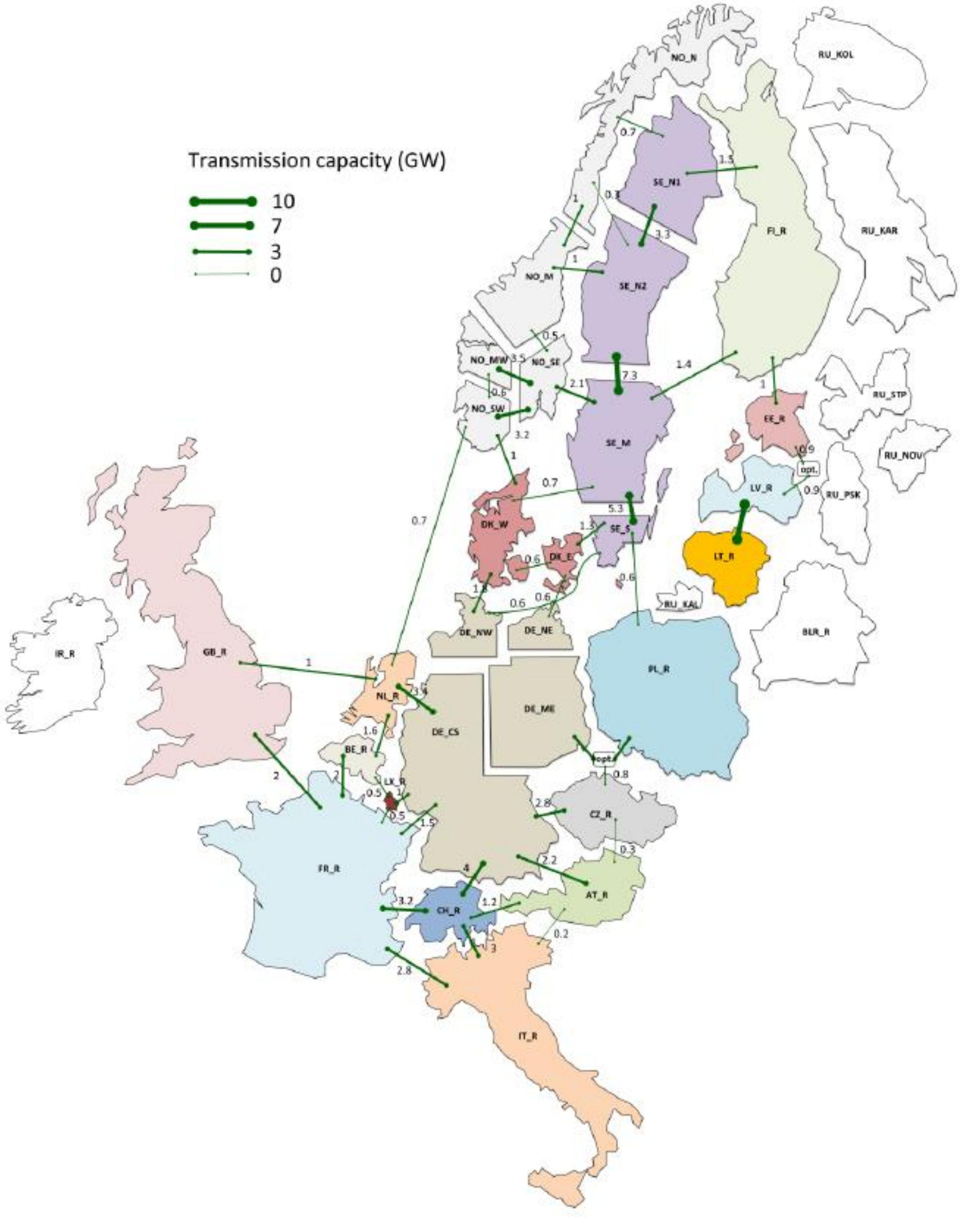

Figure 12: European grid interconnections in 2013 in Balmorel.

In the table below the grid interconnections, which are planned by the ENTSO-E in order to reinforce the grid in the core countries are presented. They are inputted exogenously in the model and they are simulated for all the scenarios for this project. It should be noted that they are additional capacities to the existing ones in

2013 and they are divided into interconnections between the core countries and internal reinforcements that are going to be commissioned until 2030. (European Network of Transmission Systems Operator for Electricity (ENTSO-E), 2014)

Project	From	To	Capacity (MW)	Year
Core Countries				
Skagerrak IV	DK_W	NO_SW	700	2015
Doetinchem-Niederrhein	NL_R	DE_CS	1400	2016
NordLink Cable	NO_SW	DE_NW	1400	2019
West Denmark to Germany	DK_W DE_NW	DE_NW DK_W	720 1000	2019
Kriegers Flak	DK_E DE_NE DK_KF	DK_KF DE_KF DE_FK	600 400 400	2019
Cobra Cable	DK_W	NL_R	700	2019
Westcoast	DK_W	DE_NW	500	2022
Hansa PowerBridge	SE_S	DE_NE	700	2025
3rd AC Finland-Sweden	SE_N1	FI_R	1000	2025
Finland-Norway	NO_N	FI_R	500	2030
West Denmark-Sweden	DK_W	SE_M	700	2030
Norway-North Sweden	NO_M	SE_N2	750	2030
East Denmark-Germany	DK_E	DE_NE	600	2030
Internal Reinforcements				
Sydvastlanken	SE_M	SE_S	1200	2015
RES/SoS Norway/Sweden phase 1	SE_M NO_MW	SE_N2 NO_SW	700 2250	2019 2020
NordBalt Cable Phase 2	SE_S	SE_M	700	2023
Res in mid-Norway	NO_M	NO_N	1200	2023
Great Belt II	DK_W	DK_E	600	2030
	SE_M	SE_N2	700	2030

Table 9: Additional interconnection capacities between the core countries and internal reinforcements until 2030. (European Network of Transmission Systems Operator for Electricity (ENTSO-E), 2014)

6.9 Power plants and Unit Commitment data

A detailed list of the different power plants that operate in each country and their inputted values in Balmorel are presented in the table to follow. The minimum loads, the minimum up time and down time are from a German report (Agora Energiewende, 2014) and the start-up costs are from a project made by Ea Energy Analyses for Ireland.

Type of power plant	Minimum load	Minimum up time (h)	Minimum down time (h)	Start-up cost (€/MW)
Natural Gas single cycle	20%	1	0	44
Natural gas CCGT	38%	4	2	115
Natural gas steam turbine	35%	4	2	107
Coal steam turbine	35%	4	2	183
Lignite steam turbine	35%	6	6	106
Waste steam turbines	70%	1.3	1.3	107

Table 10: Inputted data for the different types of power plants in Balmorel

7 Results

In this chapter, the results of the modelled with Balmorel scenarios are going to be presented. They include the electricity generation by fuel, the total costs, the electricity prices, the CO_2 emissions and the operation of the energy system for all the researched countries in order to answer the second sub question.

7.1 Annual el demand

In the table below, the annual electricity demand for the different scenarios is presented for all the countries for 2013 and 2030. As it can be observed, for Denmark more electricity is consumed in the west area. From 2013 to 2030, the total annual electricity demand is increased by 14.2% while the annual electricity demand in east area is increased by 14.6% and in the west by 1.9%. Regarding the 2030 RE with EVs scenario, the annual electricity demand is increased by 2.1% in total, 2% in the east area and 2.1% in the west area. Finland is not divided into areas. The total annual electricity demand is increased by 11.7% from 2013 to 2030 while with the addition of EVs it is increased by 2.3% in comparison to 2030. Concerning Norway, the biggest consumption is noted in the south west area. The total annual electricity demand is increased by 8.6% from 2013 to 2030 and by 1,4% when the EVs are added in relation to 2030. For Sweden, the most electricity is consumed in the middle area (SE_M, see figure 12). The percentage of the increase of the annual electricity demand from 2013 to 2030 is constant to 1.7% and to 2.9% with the addition of the EVs. Finally, in Germany most electricity is consumed in the central south area but from 2013 to 2030 there is a reduction of 0.5% in the annual electricity demand for all the areas. However, when EVs are introduced to the areas the electricity demand is increased by 5.1% in total. The electricity demand between the respective scenarios with and without unit commitment is the same.

GWh

Countries	2013	RE 2030	RE 2030 + EVs
DENMARK	35,006	39,973	40,803
DK_E	14,067	16,125	16,450
DK_W	20,939	23,849	24,354
FINLAND	84,044	93,907	96,054
NORWAY	127,843	138,832	140,774
NO_SE	35,910	37,454	37,973
NO_SW	34,751	37,618	38,138
NO_M	22,055	24,377	24,723
NO_N	18,262	20,421	20,709
NO_MW	16,864	18,962	19,232
SWEDEN	136,710	139,063	143,146
SE_N1	10,667	10,850	11,169
SE_N2	15,289	15,552	16,009
SE_M	86,438	87,926	90,507
SE_S	24,316	24,734	25,460
GERMANY	554,517	552,000	580,110

DE_CS	423,617	421,694	443,169
DE_ME	77,900	77,546	81,495
DE_NE	6,483	6,454	6,782
DE_NW	46,517	46,306	48,664

Table 11: Annual electricity demand in GWh for the different scenarios per country and area. Source for electricity demand in Germany: (AGEB, 2013) and in the Nordic countries: (Energi Styrelsen , Januar 2007)

Annual Electricity demand for Electric Vehicles by 2030

Annual Electricity demand for Electric Vehicles by 2030 (GWh)

Country	Balmorel results	Inputs in the model
DENMARK		
DK_E_EV	742	697
DK_W_EV	1121	1046
Total	**1863**	**1743**
FINLAND		
FI_R_EV	2148	2062
NORWAY		
NO_SE_EV	519	472
NO_SW_EV	519	472
NO_M_EV	346	315
NO_N_EV	288	262
NO_MW_EV	269	245
Total	**1942**	**1767**
SWEDEN		
SE_N1_EV	319	296
SE_N2_EV	457	424
SE_M_EV	2581	2398
SE_S_EV	726	675
Total	**4083**	**3793**
GERMANY		
DE_CS_EV	21475	20444
DE_ME_EV	3949	3759
DE_NE_EV	329	313
DE_NW_EV	2358	2245
Total	**28110**	**26761**

Table 12: Annual electricity demand for EVs in GWh per country and area.

The differences in the electricity demand between the balmorel results and what is inputted in the model. I due to the losses in the electricity distribution.

Losses in the electricity distribution (%)	
DENMARK	
DK_E_EV	0.060
DK_W_EV	0.067
FINLAND	
FI_R_EV	0.04
NORWAY	
NO_SE_EV	0.09
NO_SW_EV	0.09
NO_M_EV	0.09
NO_N_EV	0.09
NO_MW_EV	0.09
SWEDEN	
SE_N1_EV	0.07
SE_N2_EV	0.07
SE_M_EV	0.07
SE_S_EV	0.07
GERMANY	
DE_CS_EV	0.048
DE_ME_EV	0.048
DE_NE_EV	0.048
DE_NW_EV	0.048

Table 13: Losses in the electricity distribution (%)

7.2 Reference 2013 and RE 2030

Annual electricity generation

As it can be observed in the following figure for 2013, in Denmark almost 33.2% of the electricity is generated by coal, 32.1% by wind, 17.7% by biogas, 9.1% by biomass, 5.7% by municipal waste, 1.2 % by natural gas, 0.75% by sun and a small amount of oil. In Finland, the biggest percentage of the electricity is generated by nuclear (34.2%), followed by 16.1% by hydro, 15.6% by coal, 13.6% by biomass, 7.5% by natural gas, 5.8% by peat, 5.3% by municipal waste, 1.8% by wind and a small percentage of 0.1% is generated by oil. Norway's electricity generation is based on hydro (96.4% of the total electricity generation). The rest is covered by natural gas (1.9%), wind (1.6%) and municipal waste (0.1%). As it can be seen from the figure, Sweden's electricity system is based on water (43% of the annual electricity generation) and nuclear (41.5%). The remaining 15.5% is covered by wind, biomass, coal, natural gas and oil. Finally, Germany has a very diversified energy system. The biggest shares are generated by lignite (26.8%), coal (21.5%), nuclear (16.2%), wind (10.7%), natural gas (10.2%), sun (5.6%), hydro (3.5%) and smaller percentages of biogas, municipal waste, biomass and oil.

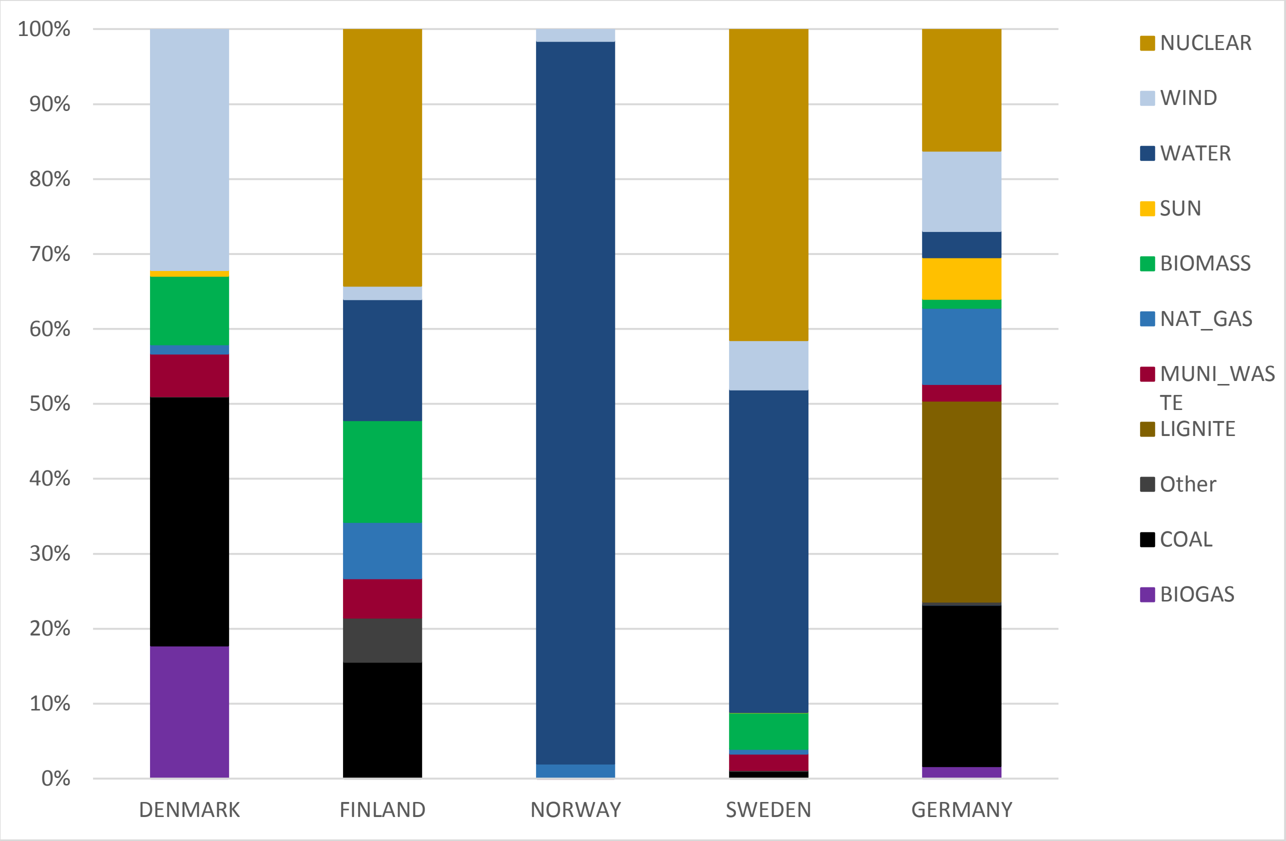

Figure 13: Annual electricity generation by fuel in 2013 for the different countries in percentage.

In 2030, Denmark's energy system is changed, due to investments in RE. As it can be observed from the figure below, no coal is used for the generation of electricity. Wind and biomass are the basic fuel sources participating by 53.6% and 38% respectively in the annual electricity generation. Sun is increased to 2.6% while biogas is reduced to 1.4%. Finland is now using almost 20% more nuclear and almost 8% more wind. The use of water and municipal waste are slightly decreased, while the coal presents the biggest decrease (from 15.6% to 3.8%). Biomass is slightly increased and no oil is used by 2030. Norway's energy system is still dependant mainly on hydro (86.6% of the annual electricity generation) although it is reduced by 10%, while the wind is increased to 10.6%. A small increase is observed also to the use of municipal waste and biomass, while the use of natural gas is reduced to 0.9%. In Sweden, less hydro and nuclear energy are used, while wind and biomass present an increase to 11% and 10% respectively. The coal is almost eliminated and used only by 0.5%. As far as it concerns Germany, lignite is decreased by 7.4%, natural gas by 7.3% and coal by 5.9%. Wind experience the biggest increase, having the biggest share in the annual electricity generation (38.1%). Also, the use of sun is increased to 10% along with a small increase in the use of biomass and biogas. Nuclear energy is phasing out following the national plans, i.e. decommission of all the nuclear reactors by 2022 and no oil is used. In the Appendix, the actual numbers for the annual electricity generation by fuel are included.

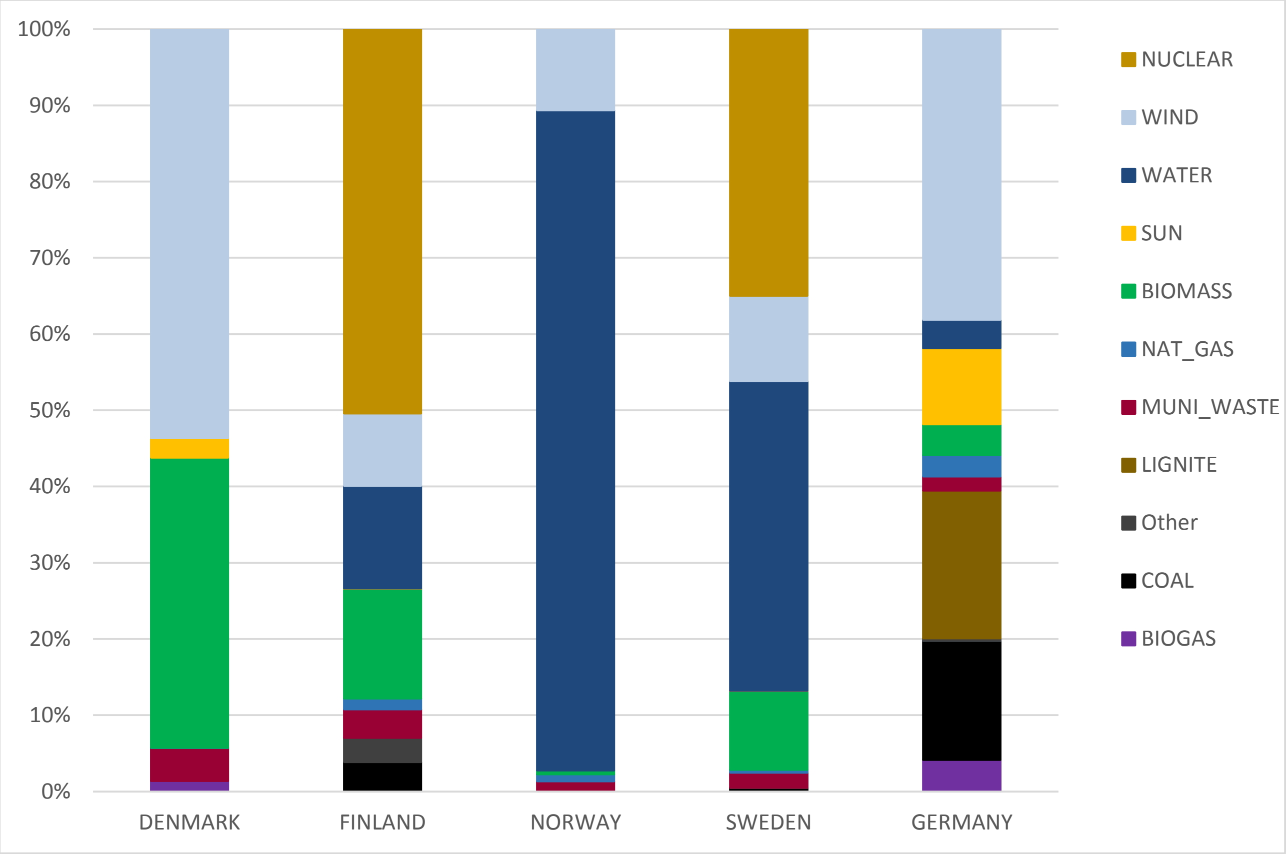

Figure 14: Annual electricity generation by fuel for the scenario RE 2030 for the different countries in percentage.

Summing up, in 2030 Denmark has the largest share of REs with wind and solar accounting to more than 55% of the total generation, Finland's energy system is based on thermal production by nuclear power, Norway is dominated by hydropower, in Sweden hydro and nuclear are the main energy sources and Germany's energy generation is based on wind and fossil fuels.

Consequently, the scenario for 2030 concerning the RE deployment in the different countries lead to an increasing share of RE in the generation mix. The RE generation in 2030 is increased by 25% and it accounts for the 65% of the total generation (see figure 15). In particular, the Nordic countries remain dominated by the hydropower while a 15% of the total generation is based on wind and sun power and the rest on thermal power production from biomass and nuclear. For Germany, 60% of the total generation is based on RE and the rest 40% is generated from fossil fuels.

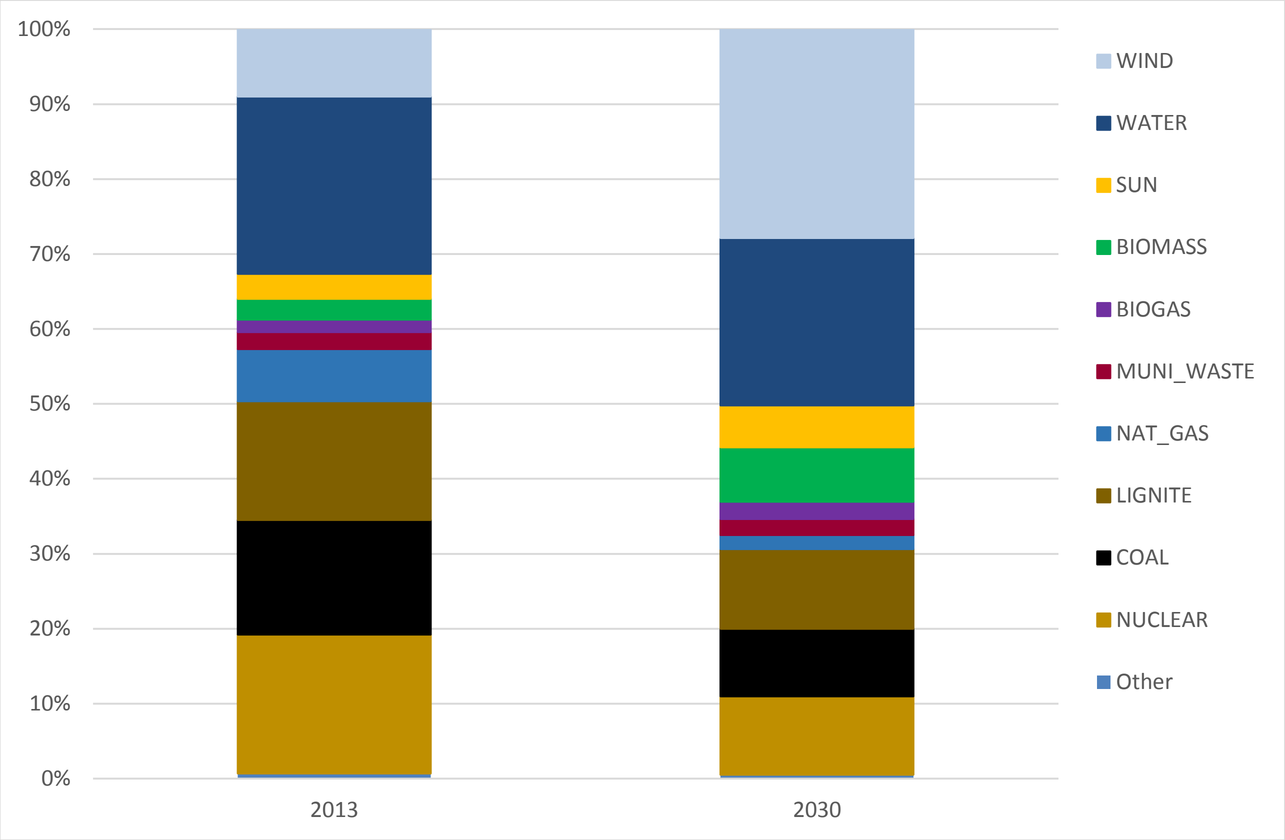

Figure 15: Generation mix for 2013 and 2030 for the Nordic countries and Germany.

Total costs

In this section, the total system costs for the different countries for 2013 and 2030 are presented. The included costs are investment costs, operation and maintenance cost, fuel and CO_2-costs. The value of CO_2 emissions is set on the model based on IEAs New Policy Scenario from the World Energy Outlook 2013. As it can be observed from the following table, the total costs per countries are increased through the years and this is attributed mainly on the investment costs to new generation technologies. However, the fuel costs are decreased for Denmark, Finland, Norway and Germany due to the increase of fluctuated Res, i.e. wind, solar and hydro. On the other hand, the fuel costs are increased in Sweden, due to the increased use of biomass and in particular wood. CO_2 costs are increased due to the increase in the CO_2 price from 4.9 €/ton in 2013 to 26 €/ton in 2030.

	2013	**2030**
DENMARK	**5023**	**5698**
Capital Cost (m€)	2271	2967
Fixed O&M (m€)	691	1111
Fuel Cost (m€)	1993	1578
CO2 Tax (m€)	68	43
FINLAND	**4879**	**5004**
Capital Cost (m€)	2748	3015
Fixed O&M (m€)	1078	928
Fuel Cost (m€)	946	780

CO2 Tax (m€)	107	282
NORWAY	**5464**	**6623**
Capital Cost (m€)	4220	5145
Fixed O&M (m€)	1066	1357
Fuel Cost (m€)	171	80
CO2 Tax (m€)	8	40
SWEDEN	**8900**	**8952**
Capital Cost (m€)	6103	5987
Fixed O&M (m€)	2024	1764
Fuel Cost (m€)	732	1077
CO2 Tax (m€)	41	125
GERMANY	**53810**	**64309**
Capital Cost (m€)	32464	41161
Fixed O&M (m€)	8011	9839
Fuel Cost (m€)	11668	8067
CO2 Tax (m€)	1666	5243
Total	**78076**	**90587**

Table 14: Total system costs in m€ per country for 2013 and 2030.

Electricity Prices

As it is expected, different electricity prices are observed based on the available generation technologies and on the RE deployment. As it can be seen from the table below, Northern Scandinavia presents lower electricity prices than Southern Scandinavia and Germany, mainly due to the big amounts of hydropower generated there compared to the thermal dominated systems in Continental Europe. Although it would be expected that the electricity prices will be reduced by 2030 due to the bigger deployment of REs and since wind generation is increased and it has low marginal cost (near zero operating costs) in the merit order rank. However, this is not the case as the prices increase. Even though a lot of electricity is generated by wind power, still the thermal power plants have to supply a part of the demand. The short-run marginal costs of the power plants, which are the price that the plants require to cover the operating expenses, are the ones, which determine the electricity price. In addition, electricity is sold, starting with the lowest cost and progressing to those with higher costs, until the demand is met. The most expensive power plant required to meet the demand are the ones who determine the electricity price on the spot market. So in cases where a peak in the demand occurs, it will be covered by the expensive power plants i.e. the ones operating with coal and natural gas, and as a result high electricity prices will be set by them. It should be noted also that electricity prices depend on the assumption inputted in Balmorel about fuel prices and CO_2 prices. In 2013 the CO_2 price of 4.9 €/ton is used, while in 2030 the price of 26 €/ton is used for the simulations.

€/MWh	2013	2030
DENMARK		
DK_E	39.10	49.05
DK_W	37.71	49.13
FINLAND		
FI_R	38.83	45.29
NORWAY		
NO_M	37.00	47.64
NO_MW	36.17	47.68
NO_N	36.97	37.13
NO_SE	37.15	48.70
NO_SW	36.82	49.74
SWEDEN		
SE_M	37.28	46.38
SE_N1	37.09	45.57
SE_N2	37.11	45.99
SE_S	37.86	46.43
GERMANY		
DE_CS	39.77	54.50
DE_ME	39.73	54.45
DE_NE	39.72	54.40
DE_NW	39.76	54.45

Table 15: Electricity prices in €/MWh per regions in 2013 and 2030.

In the next figure, the duration curves of electricity prices for some of the countries' regions are presented. The duration curves illustrate the hours with a price above a certain level. The different variations in both demand and generation from the various energy sources affect the electricity prices. In 2030, where more REs are integrated in the energy system more hours with lower and even negative prices (in Germany and Denmark) can be observed. Also, more variations in the prices are observed in 2030 compared to the ones in 2013. Norway followed by Sweden have the fewest hours with very low prices in the low end of the curve due to the hydro dominated energy system. Moreover, the high peaks of the electricity prices are decreased in 2030.

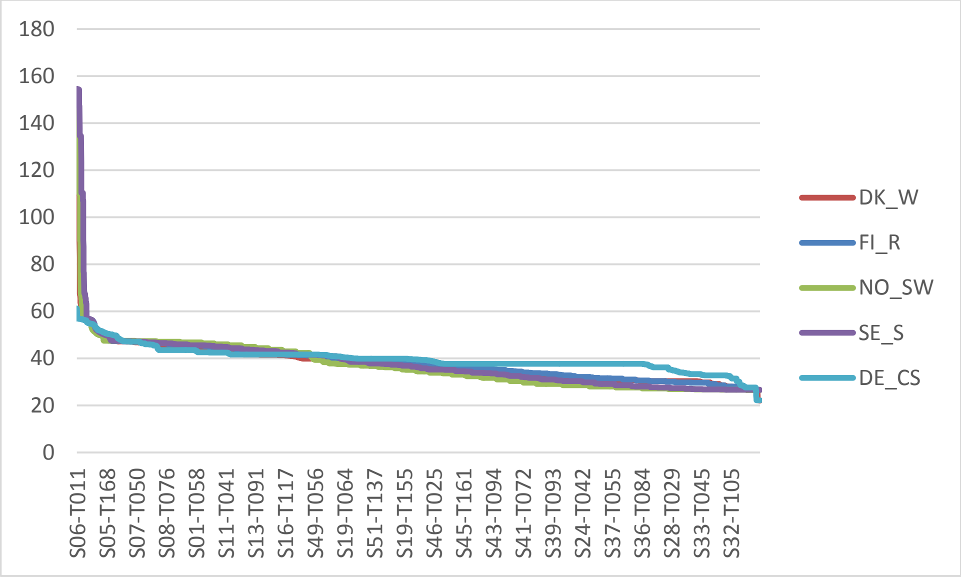

Figure 16: Duration curve for electricity prices per country in 2013.

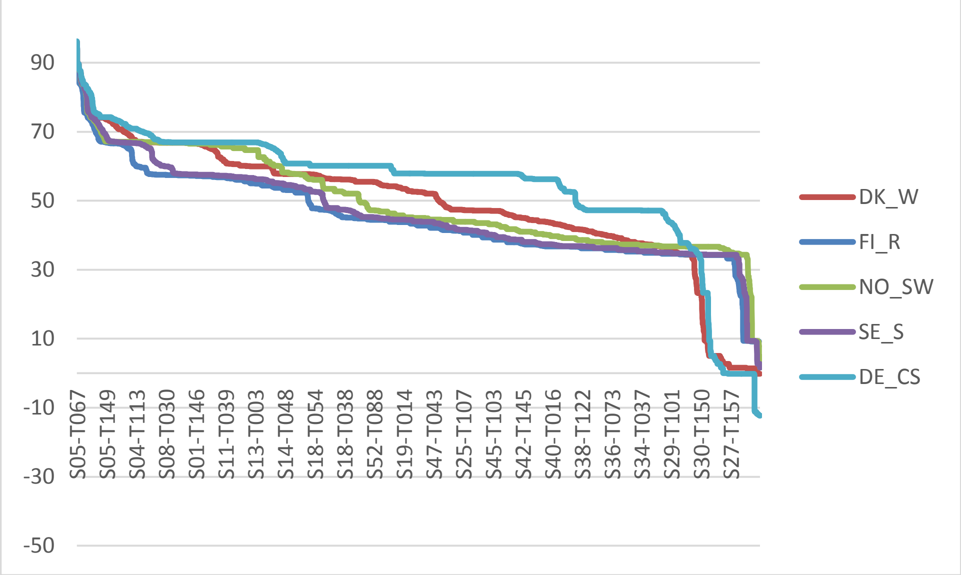

Figure 17: Duration curve for electricity prices per country in 2030.

CO_2 Annual Emissions

In the table below the CO_2 emissions are presented for 2013 and 2030, for all the researched countries for the reference 2013 and RE 2030 without unit commitment. As it can be seen, for all the countries the CO_2 emissions are reduced. This is expected due to the bigger penetration of RE sources and particularly wind and sun. The biggest reduction is noticed in Denmark with 88% decrease in 2030, while the least occurs in Norway with only 4.5% decrease, since this country's energy system is already based in hydro generation.

Sum of kton

	2013	2030
DENMARK	13,714	1,631
FINLAND	21,562	10,716
NORWAY	1,591	1,519
SWEDEN	8,191	4,753
GERMANY	336,226	199,345

Table 16: CO_2 Annual Emissions for the reference 2013 and 2030 when UC is not applied.

System operation

As mentioned before the simulations in these two scenarios do not include any system operation requirements or restrictions such as or minimum must-run capacity for different generating technologies or minimum online time for thermal power plants or start up/shut down costs. However, the energy balance is fulfilled at all times.

The integration of more RE in the energy systems creates challenges in the way they operate. If more RE continue to be added to the energy systems while the existent requirements and the operation of the energy system remains the same, then the number of hours with excess electricity generation will be increased and the value of the additional variable RE will be reduced.

In the figure to follow, the operation of German energy system for two weeks in winter and two in summer is illustrated, as an example of the challenges that the energy system face. The light blue and yellow show the electricity generation from wind and solar power respectively. The black line represents the electricity prices, while the red dotted one shows the electricity demand.

As it can be seen from the figure below, in end of week 36 and the week 37 high penetration of wind occurs while the thermal power plants do not generate any power. At these hours, electricity prices are very low and even negative. As a result it can be assumed that high generation of wind energy results into low electricity prices. Also at the same weeks, i.e. during summer when the demand is lower in the Nordic countries, more imports are observed in Germany. It is expected that if unit commitment is introduced to the model i.e. a must-run level for dispatchable generation in terms of minimum generation level in operating thermal capacity (GW) at all times is inputted in the model, this would lead to increasing curtailment of variable RES-E. This fact indicate the challenge to increase the flexibility of the grid, in order to increase the deployment of variable REs.

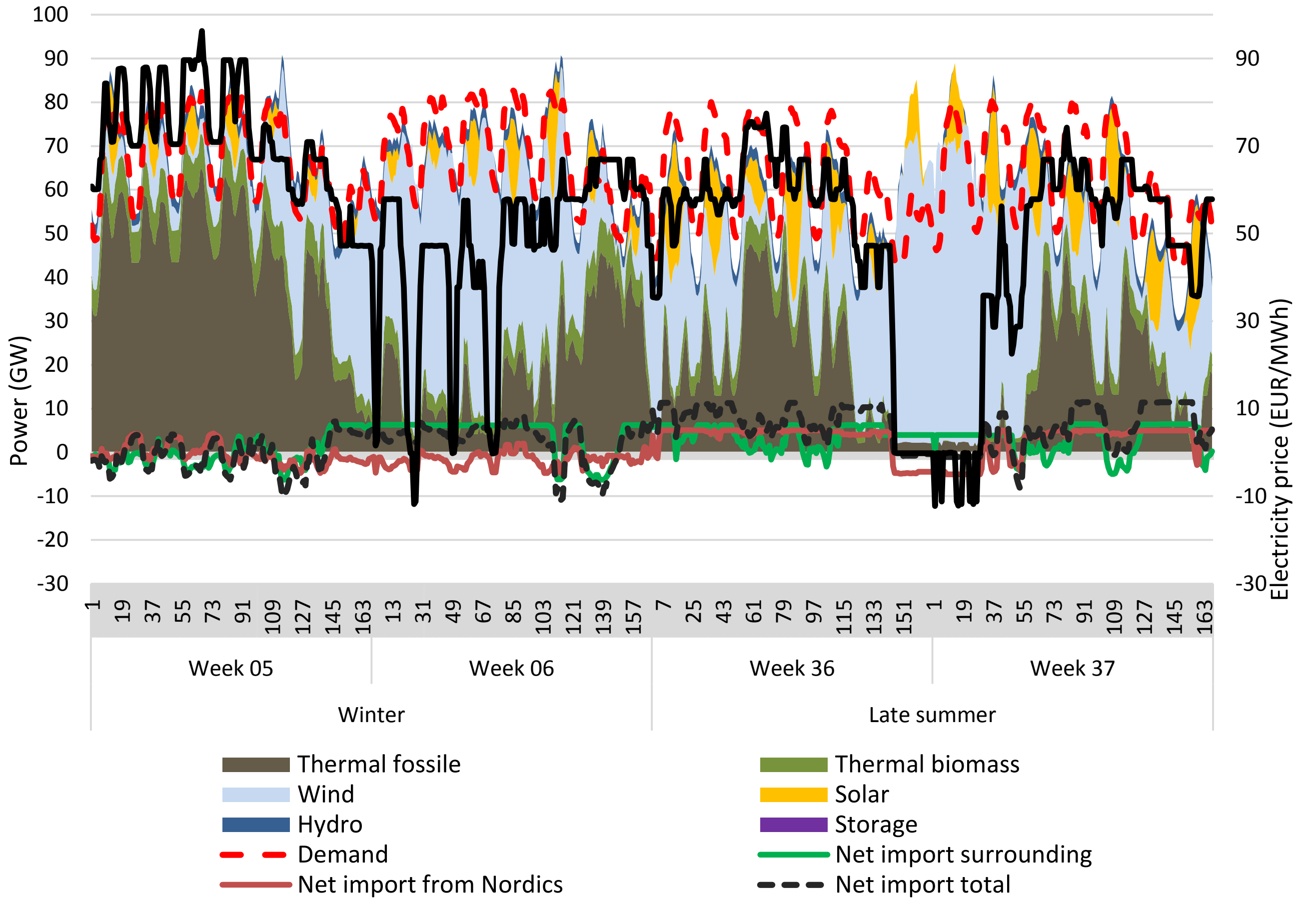

Figure 18: Operation of the German power system for two weeks in winter and two in summer in 2030.

7.3 Reference 2013 and RE 2030 with UC

Annual electricity generation

Comparing the reference 2013 with and without unit commitment, minor changes in the electricity generation are observed for all the countries except of Denmark. The fuel mix is changed as in the run with unit commitment almost 10% more wind power is generated, 15% more natural gas is used, 5% less coal, 5% less biomass and 16% less biogas. These changes can be justified if it is taken into account the fact that, single cycle gas turbines using natural gas as fuel have the least starting up costs and minimum up and down time, followed by steam turbines using biomass as fuel, while CCGT have bigger starting costs and that is why less biogas is consumed. In addition the total electricity generation in 2013 for Denmark is less when UC is used in the model. From the table below it can be seen, that with UC, Denmark exports less electricity than without UC.

Year	**2013**						
Sum of MWh							
From:	**To:**						
DENMARK	**DENMARK**	**FINLAND**	**NORWAY**	**SWEDEN**	**GERMANY**	**HOLLAND**	**Total**
No UC	0		-1,277,889	-2,880,539	6,700,306		2,541,878
UC	0		-974,286	-2,376,380	3,898,196		547,530
FINLAND							
No UC				-13,292,246			-13,292,246
UC				-12,620,488			-12,620,488
NORWAY							
No UC	1,277,889		0	1,737,719		3862535	6,878,143
UC	974,286		0	593,460		3049086	4,616,832
SWEDEN							
No UC	2,880,539	13292246	-1,737,719	0	1,126,791		15,561,858
UC	2,376,380	12620488	-593,460	0	461,402		14,864,810
GERMANY							
No UC	-6,700,306			-1,126,791	0	20798704	12,971,607
UC	-3,898,196			-461,402	0	19365307	15,005,708

Table 17: Exports/imports in MWh for 2013 with and without UC.

For 2030, the changes in the generation mix are minor in most cases less than 1%. In Denmark, less electricity is generated from biogas and biomass, and more from natural gas (1.5% more) and wind (0.5%) in comparison to the non UC run in 2030. Finland generates less electricity from coal and biomass and more from natural gas. In addition, Norway generates less electricity from biomass and more from wind and more from natural gas as well. Sweden also follows the same pattern with natural gas and generates less wind and a bit more nuclear. Finally, Germany generates more electricity from natural gas and less from biogas, coal, lignite and wind, water and sun. As mentioned before natural gas turbines are cheaper in the start up cost and that is why they are used more. In total, 18% more electricity is generated from natural gas in the UC run for 2030. Furthermore ,the imports presents some differences with the Nordic countries exporting less electricity in the UC run and Germany importing less in the same run.

Year	**2030**						
Sum of MWh	**To:**						
From:	**DENMARK**	**FINLAND**	**NORWAY**	**SWEDEN**	**GERMANY**	**HOLLAND**	**Total**
DENMARK							
No UC	0		-814,457	-5,713,128	13,676,239	623,393	7,772,046
UC	0		-611,471	-4,980,330	11,946,925	550,345	6,905,469
FINLAND							
No UC				4,393,803			4,393,803
UC				4,358,254			4,358,254
NORWAY							
No UC	814,457		0	-6,233,858	3,836,517	598,260	-984,624
UC	611,471		0	-6,038,853	3,598,105	487,084	-1,342,192
SWEDEN							
No UC	5,713,128	-4,393,803	6,233,858	0	2,617,604		10,170,786
UC	4,980,330	-4,358,254	6,038,853	0	2,225,701		8,886,629
GERMANY							
No UC	-13,676,239		-3,836,517	-2,617,604	0	-22,858,312	-42,988,671

UC	-11,946,925		-3,598,105	-2,225,701	0	-21,910,663	-39,681,395

Table 18: Exports/imports in MWh for 2030 with and without UC.

Total cost

The total system costs for the UC run are presented in the following table. Although a new cost is added which concerns the start-ups of the different power plants, the differences of the total system costs with and without UC are mainly attributed to the fuel costs and the CO_2 cost. The capital costs and the O&M are the same for the two runs. The total costs for 2030 are increased by 0.8% compared to the non UC run.

	2013	**2030**
DENMARK	**4165**	**5640**
Capital Cost (m€)	2271	2967
Fixed O&M (m€)	691	1111
Fuel Cost (m€)	1105	1502
CO2 Tax (m€)	88	54
Start-up costs (m€)	10	7
FINLAND	**4951**	**5018**
Capital Cost (m€)	2748	3015
Fixed O&M (m€)	1078	928
Fuel Cost (m€)	1003	788
CO2 Tax (m€)	114	285
Start-up costs (m€)	8	2
NORWAY	**5472**	**6639**
Capital Cost (m€)	4220	5145
Fixed O&M (m€)	1066	1357
Fuel Cost (m€)	178	94
CO2 Tax (m€)	8	42
Start-up costs (m€)	0.43	0.44
SWEDEN	**8919**	**8976**
Capital Cost (m€)	6103	5987
Fixed O&M (m€)	2024	1764
Fuel Cost (m€)	747	1091
CO2 Tax (m€)	41	128
Start-up costs (m€)	3	6
GERMANY	**54325**	**65094**
Capital Cost (m€)	32464	41161
Fixed O&M (m€)	8011	9839
Fuel Cost (m€)	12031	8415
CO2 Tax (m€)	1703	5331
Start-up costs (m€)	117	349
Total	**77833**	**91368**

Table 19: Total system costs in m€ per country for 2013 and 2030 for the UC run.

Concerning the number of start-ups, they are decreased from 2013 to 2030 only for Denmark, while for Sweden and Germany a bid increase in observed, attributed mainly to the gas turbines, which have low start-up costs for both countries. However, start-ups costs as mentioned before are quite lower compared to the other costs and they are not considered the ones that make the difference in the total ones when applying a unit commitment run.

No. of start-ups	2013	2030
DENMARK	3813	909
FINLAND	243	245
NORWAY	6	17
SWEDEN	386	2070
GERMANY	40226	90177

Table 20: No. of start-ups in 2013 and 2030 for the UC run.

Electricity prices

In the next table, the electricity prices for the UC run are presented. For this scenario also, Scandinavia has lower electricity prices than Germany for 2030, which can be explained by the big amounts of hydropower generated in Norway and Sweden compared to the thermal dominated systems in Continental Europe. Comparing this scenario with the one without UC, it can be observed that all the different regions have higher electricity prices when UC is applied.

€/MWh	2013	2030
DENMARK		
DK_E	41.90	52.52
DK_W	38.99	49.62
FINLAND		
FI_R	41.26	45.63
NORWAY		
NO_M	38.47	48.00
NO_MW	37.41	48.03
NO_N	38.44	37.25
NO_SE	38.62	49.04
NO_SW	37.83	50.04
SWEDEN		
SE_M	39.16	46.80
SE_N1	38.84	45.92
SE_N2	38.89	46.35
SE_S	40.13	46.90
GERMANY		
DE_CS	39.65	55.33
DE_ME	39.61	55.27
DE_NE	39.61	55.22
DE_NW	39.65	55.27

Table 21: Electricity prices in €/MWh per regions in 2013 and 2030 for the UC run.

The next two figures show the duration curves for the electricity prices in 2013 and 2030. Due to more RE integration in the energy system more hours with lower and even negative prices (in Germany and in

Denmark) can be observed. Moreover, in 2013 very high peaks are observed for all the countries, higher than 2030 and than the run without the UC applied in Balmorel and no hours with negative prices. However, in 2013 the peaks are dropping but remaining bigger than the non UC run and negative prices are observed for Germany and Denmark. The hours with negative prices in Germany are more in the UC run but the actual prices are lower, while in Denmark the hours are fewer in the UC run but the prices are the same. It should be noted that less fluctuations are noticed in the prices when UC is applied.

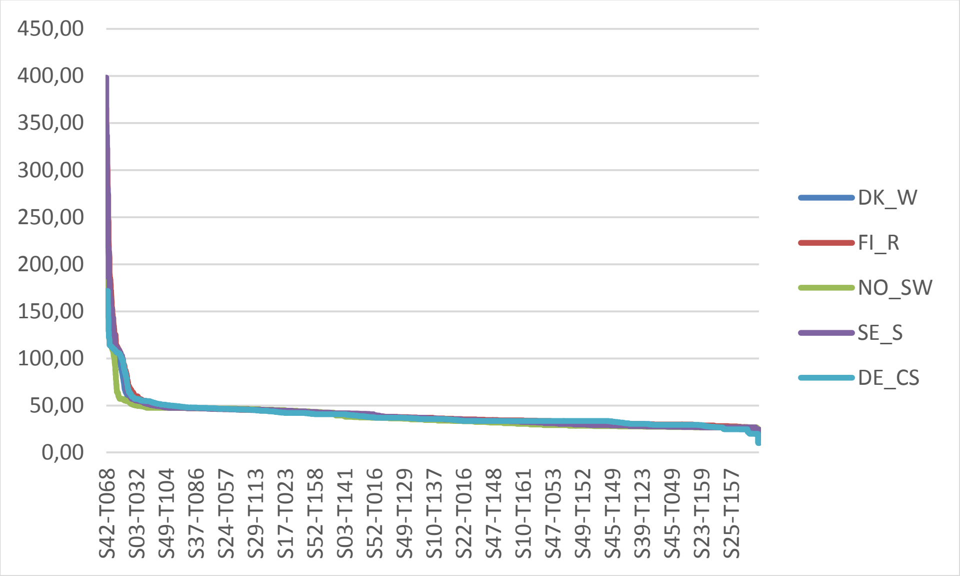

Figure 19: Duration curve for electricity prices per country in 2013 when UC is applied.

Figure 20: Duration curve for electricity prices per country in 2030 when UC is applied.

CO_2 Annual Emissions

As it can be seen from the table below, the CO_2 emissions follow the same trend for this simulation with UC as well, i.e. reduced for all the countries. Moreover, Denmark presents again the biggest decrease in the emissions (88%) and Norway the least (2%).

Sum of kton

	2013	2030
DENMARK	16,971	2,051
FINLAND	22,978	10,852
NORWAY	1,643	1,609
SWEDEN	8,326	4,875
GERMANY	343,568	202,692

Table 22: CO_2 Annual Emissions for the reference 2013 and 2030 when UC is not applied.

From the following figures, it can be observed that the CO_2 emissions in the countries are increasing when the UC is applied in the model. This is due to the increased fuel consumption related to the CO_2 emissions[12], see table 23.

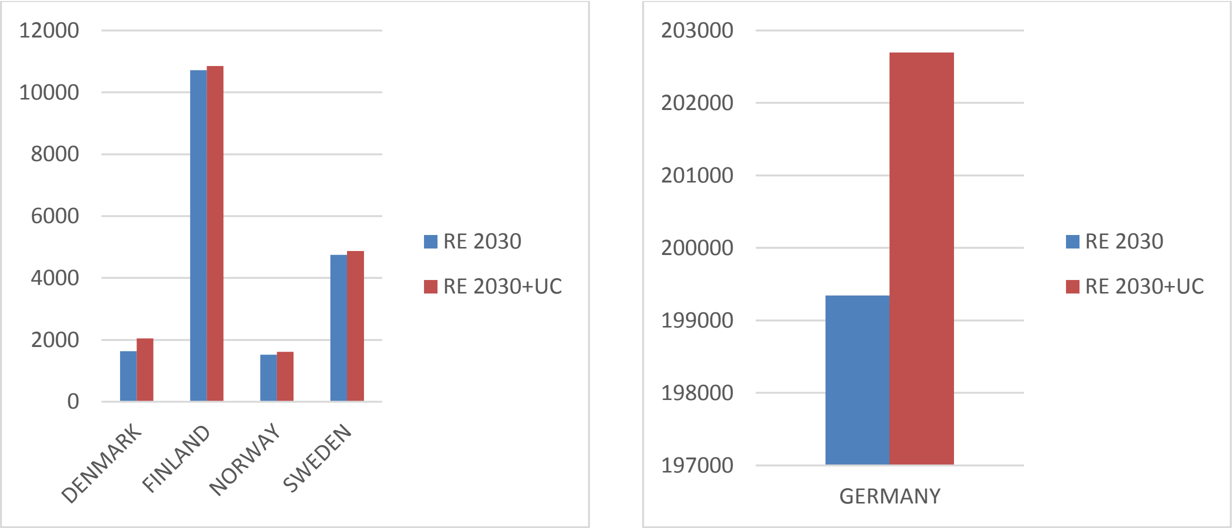

Figure 21: CO_2 emissions in 2030 for the scenarios RE 2030 and RE 2030+UC.

Sum of PJ

	RE 2030	RE 2030+UC
DENMARK	41.86	49.12
FINLAND	150.74	152.25
NORWAY	36.21	37.81
SWEDEN	108.68	110.66
GERMANY	2206.35	2248.89

Table 23: Fuel related to CO_2 emissions, consumption in 2030 with and without UC.

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[12] The fuels, which in the model have data with CO_2 emissions (kg/GJ) are coal, lignite, oil, municipal waste, natural gas and peat.

System Operation

As mentioned before in this simulation system operation requirements and restrictions such as or minimum must-run capacity for different generating technologies, minimum online time for thermal power plants and start-up/shut down costs are included. In the next figure, the operation of German energy system for the exact two weeks that are also illustrated in figure 18 for the non UC run can be seen.

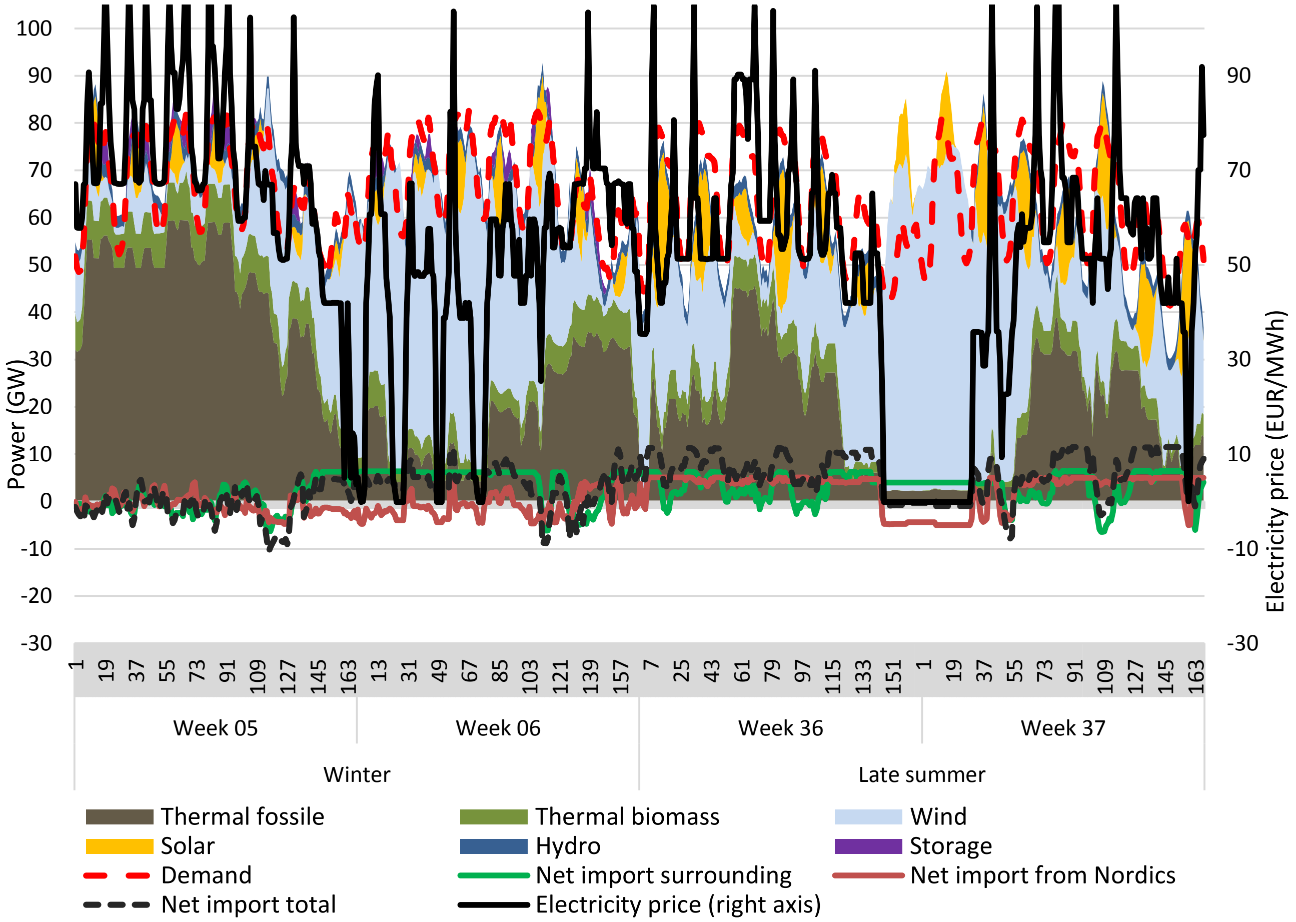


Figure 22: Operation of the German power system for two weeks in winter and two in summer in 2030 for the UC run.

Comparing the two figures (18 and 22), the basic differences are the high peaks in the electricity prices and the fewer negative prices, when the wind has the biggest share in the electricity generation. Furthermore, it can be observed a difference in the operation of the thermal power, both the ones that run with biomass and fossil fuels. For instance in the late week 6, the thermal power plants operate in a more stable way, i.e. presenting less peaks and operate more hours than in the non UC run.

7.4 RE 2030 + EVs

Annual electricity generation

For the scenario where EVs are implemented in the model, the changes in the energy mix are almost unnoticeable in comparison to RE 2030 sceario. For Denmark, the use of biomass, natural gas and wind are increased. In Finland, the extra demand is supplied by coal, natural gas and hydro. The use wind is decreased by almost 0.4%. In Norway, hydro is the main fuel used to produce electricity and in this scenario is increased by 0.5%, while the generation from wind is remaining almost the same. For Sweden, the extra demand for EVs is supplied by hydro, which is increased by 2%. Wind, nuclear and waste experience a small decrease. Finally, for Germany coal, lignite and natural gas are the ones that increase in order to supply the EVs, while wind and sun are decreasing by 1.6% and 0.4% respectively.

As it can be observed from the table below the total electricity generation is increased as expected in order to cover the extra demand to supply the EVs.

Year	**2030**	
	RE 2030	**RE 2030 + EVs**
DENMARK	47,797,815	48,564,576
FINLAND	93,804,821	94,579,585
NORWAY	138,150,040	143,270,533
SWEDEN	149,525,095	153,771,938
GERMANY	528,421,276	550,533,545

Table 24: Total electricity generation in MWh for the RE 2030 and RE 2030 + EVs scenarios.

When the unit commitment is applied, the total electricity generation is decreased for Denmark, Norway and Sweden while it is increased for Finland and Germany. In addition, the mix of the fuels used for the electricity generation is also different. For Denmark, 79,8228 MWh are generated from natural gas in the unit commitment run instead of the 26,566 MWh in the non UC run, the generation from biogas is decreased from 68,5831 MWh to 64,264 MWh, while the generation from biomass and wind is slightly decreased. For Finland, the difference in the generation between the two simulations is attributed to the decrease of coal, nuclear and biomass and the increase of natural gas and wind. In Norway, the natural gas turbines are generating more electricity along with the steam turbine using biomass as a fuel, while the hydro production is slightly decreased. Also, Sweden generates more electricity from natural gas, biomass and nuclear, while the hydro production is reduced. Finally, Germany used more coal, lignite, natural gas, a bit more wind and sun and less water and biogas to generate electricity.

	RE 2030 + EVs	**RE 2030 + EVs + UC**
DENMARK	48,564,576	47,762,116
FINLAND	94,579,585	94,839,206
NORWAY	143,270,533	142,089,822
SWEDEN	153,771,938	152,700,789
GERMANY	550,533,545	560,838,358

Table 25: Total electricity generation in MWh for the EVs scenarios without and with UC.

The next table presents the imports/exports from one country to another for the two different simulations in 2030. Denmark, Norway and Sweden export less, while Finland is exporting more to Sweden, when the UC is applied. Germany is the only country, which is only importing, but it is importing less in the UC run.

Year	**2030**						
Sum of MWh	**TO:**						
FROM:	**DENMARK**	**FINLAND**	**NORWAY**	**SWEDEN**	**GERMANY**	**HOLLAND**	**Total**
DENMARK							
NO UC	0		-1,459,564	-6,056,654	14,625,173	601,221	7,710,176
UC	0		-11,33,741	-5,305,896	12,877,933	463,939	6,902,235
FINLAND							
NO UC		0		3,018,572			3,018,572
UC		0		3,277,869			3,277,869
NORWAY							
NO UC	1,459,564		0	-4,551,477	4,545,827	742,179	2,196,093
UC	1,133,741		0	-4,868,411	4,156,561	590,956	1,012,847
SWEDEN							
NO UC	6,056,654	-3,018,572	4,551,477	0	2,749,466		10,339,024
UC	5,305,896	-3,277,869	4,868,411	0	2,378,536		9,274,973
GERMANY							
NO UC	-14,625,173		-4,545,827	-2,749,466	0	-24,936,977	-46,857,444
UC	-12,877,933		-4,156,561	-2,378,536	0	-23,787,353	-43,200,383

Table 26: Exports/imports in MWh for 2030 with and without UC when extra demand for EVs is implemented in the model.

Total cost

Since the electricity demand for this scenario is increased no comparison can be made concerning the costs with the baseline scenario for 2030 (RE 2030). However, they are going to be presented in order to be compared with the next scenarios to follow. No transportation costs are included in the project. The capital and the O&M costs are the same with the other scenarios.

For all the countries, except of Denmark, the UC simulation is more costly but this is basically due to the fuel costs and not to the introduction of the start-up costs, as more fossil fuels and mainly natural gas is used more.

	RE 2030 + EVS	**RE 2030 + EVs + UC**
DENMARK	**5722**	**5660**
Capital Cost (m€)	2967	2967
Fixed O&M (m€)	1111	1111
Fuel Cost (m€)	1602	1522
CO2 Tax (m€)	43	54
Start-up costs (m€)		6
FINLAND	**5016**	**5031**
Capital Cost (m€)	3015	3015
Fixed O&M (m€)	928	928
Fuel Cost (m€)	788	798
CO2 Tax (m€)	284	288
Start-up costs (m€)		2
NORWAY	**6626**	**6641**
Capital Cost (m€)	5145	5145

Fixed O&M (m€)	1357	1357
Fuel Cost (m€)	83	95
CO2 Tax (m€)	40	43
Start-up costs (m€)		0.4
SWEDEN	**8966**	**8997**
Capital Cost (m€)	5987	5987
Fixed O&M (m€)	1764	1764
Fuel Cost (m€)	1089	1109
CO2 Tax (m€)	127	131
Start-up costs (m€)		7
GERMANY	**65594**	**66398**
Capital Cost (m€)	41161	41161
Fixed O&M (m€)	9839	9839
Fuel Cost (m€)	8858	9188
CO2 Tax (m€)	5737	5866
Start-up costs (m€)		345
Total	**91923**	**92726**

Table 27: Total system costs in m€ per country 2030 for the non UC and UC run.

In the table below, the number of start-ups are shown for the two UC scenarios in 2030 with and without EVs. As it can be seen, the start-ups are reduced only for Germany when the EVs are introduced to the model. Actually the mix of the power plants that operate is different, but the biggest difference in the number of start-ups is made due to the reduction of the operation of the expensive stream turbines and the increase in the number of gas turbines committed to the grid.

No. start-ups

	RE 2030 + EVs + UC	RE 2030 + UC
DENMARK	909	909
FINLAND	281	245
NORWAY	19	17
SWEDEN	2187	2070
GERMANY	87654	90177

Table 28: Number of start-ups for the two UC scenarios in 2030 with and without EVs.

Electricity prices

The electricity prices increase when the EVs are implemented and they increase even further with the UC simulations, with Finland, Sweden and Norway having the lower prices. However, the duration curve without UC follows the exact trend with the one without the implementation of EVs. In the case of UC, very high prices are observed, especially in Sweden where it reaches 368.89 €/MWh.

Year	2030	
Sum of €/MWh		
	NO UC	UC
DENMARK		
DK_E	51	55
DK_E_EV	51	55
DK_W	51	51
DK_W_EV	51	52
FINLAND		
FI_R	46	47
FI_R_EV	47	47
NORWAY		
NO_M	48	49
NO_M_EV	48	49
NO_MW	48	49
NO_MW_EV	48	49
NO_N	38	38
NO_N_EV	38	38
NO_SE	49	50
NO_SE_EV	49	50
NO_SW	50	51
NO_SW_EV	50	51
SWEDEN		
SE_M	47	48
SE_M_EV	48	48
SE_N1	47	47
SE_N1_EV	47	47
SE_N2	47	48
SE_N2_EV	47	48
SE_S	48	48
SE_S_EV	48	48
GERMANY		
DE_CS	57	57
DE_CS_EV	57	58
DE_ME	57	57
DE_ME_EV	57	57
DE_NE	57	57
DE_NE_EV	57	57
DE_NW	57	57
DE_NW_EV	57	57

Table 29: Electricity prices in €/MWh per regions in 2030 for the non UC and UC run.

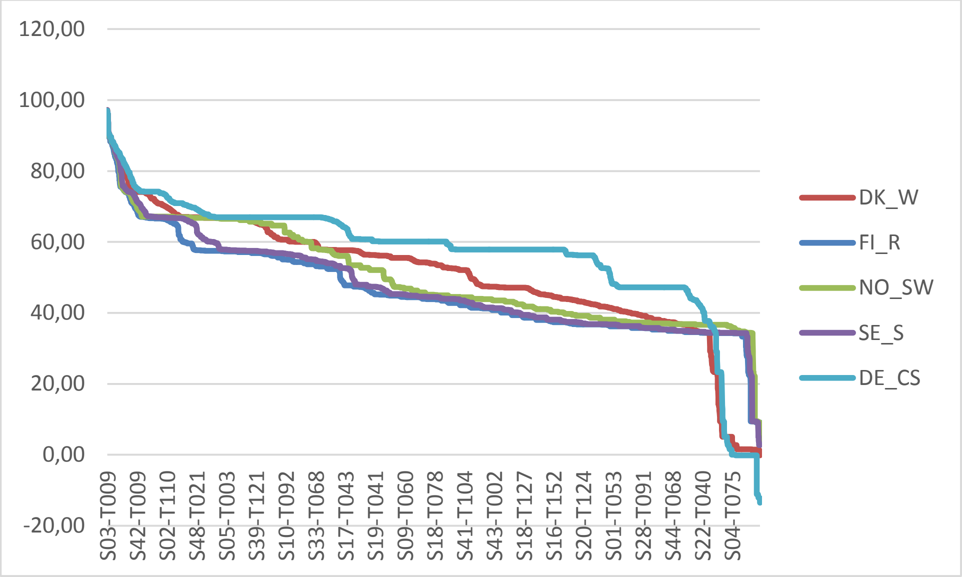


Figure 23: Duration curve for electricity prices per country in 2030.

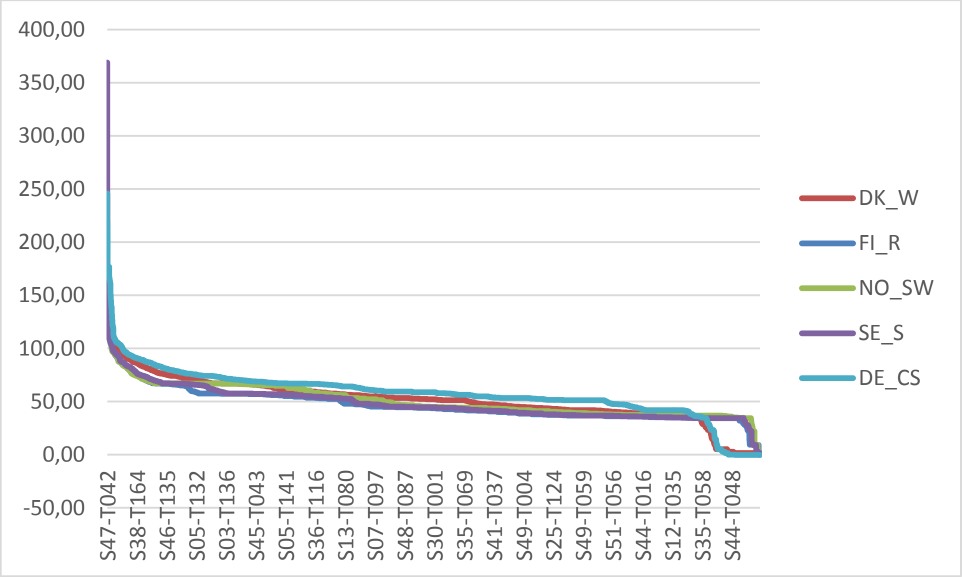


Figure 24: Duration curve for electricity prices per country in 2030 when UC is applied.

CO2 Annual Emissions

In the table to follow, the CO_2 emission for the EVs scenarios with and without UC are presented. As it can be observed when UC is applied, the emissions are increasing. This can be attributed to the increased fuel (associated with CO_2 emission) consumption in the UC run (see table 31).

Sum of kton

	RE 2030 + EVs	RE 2030 + EVs + UC
DENMARK	1,627	2,059
FINLAND	10,811	10,955
NORWAY	1,534	1,620
SWEDEN	4,811	4,974
GERMANY	218,134	223,026

Table 30: CO_2 Annual Emissions for 2030 for all the scenarios with and without UC.

Sum of PJ

	RE 2030	RE 2030 + EVs	RE 2030 + UC	RE 2030 + EVs + UC
DENMARK	41.86	41.81	49.12	49.27
FINLAND	150.74	151.88	152.25	153.51
NORWAY	36.21	36.49	37.81	37.99
SWEDEN	108.68	109.32	110.66	111.99
GERMANY	2206.35	2405.54	2248.89	2462.25

Table 31: Fuel related to CO_2 emissions, consumption in 2030 for all the scenarios with and without UC.

System Operation

As it can be seen from the figure 23 below for the simulation without UC, in the hours with high penetration of wind electricity prices are very low and for a few hours (47hours) they are negative. As a result it can be assumed that high generation of wind energy results into low electricity prices. When the UC is applied the hours with negative prices are decreased (37 hours) but high peaks in the prices occur especially when thermal plants generate the biggest share of the electricity demand. Furthermore, as mentioned before the power plants operate in a more stable way in the UC run.

In the case that the two following figures are compared with the respective ones for the RE 2030 scenario, the differences are associated to the electricity prices, where in the RE 2030 more hours with negative prices (54 hours) occur and the also have lower values.

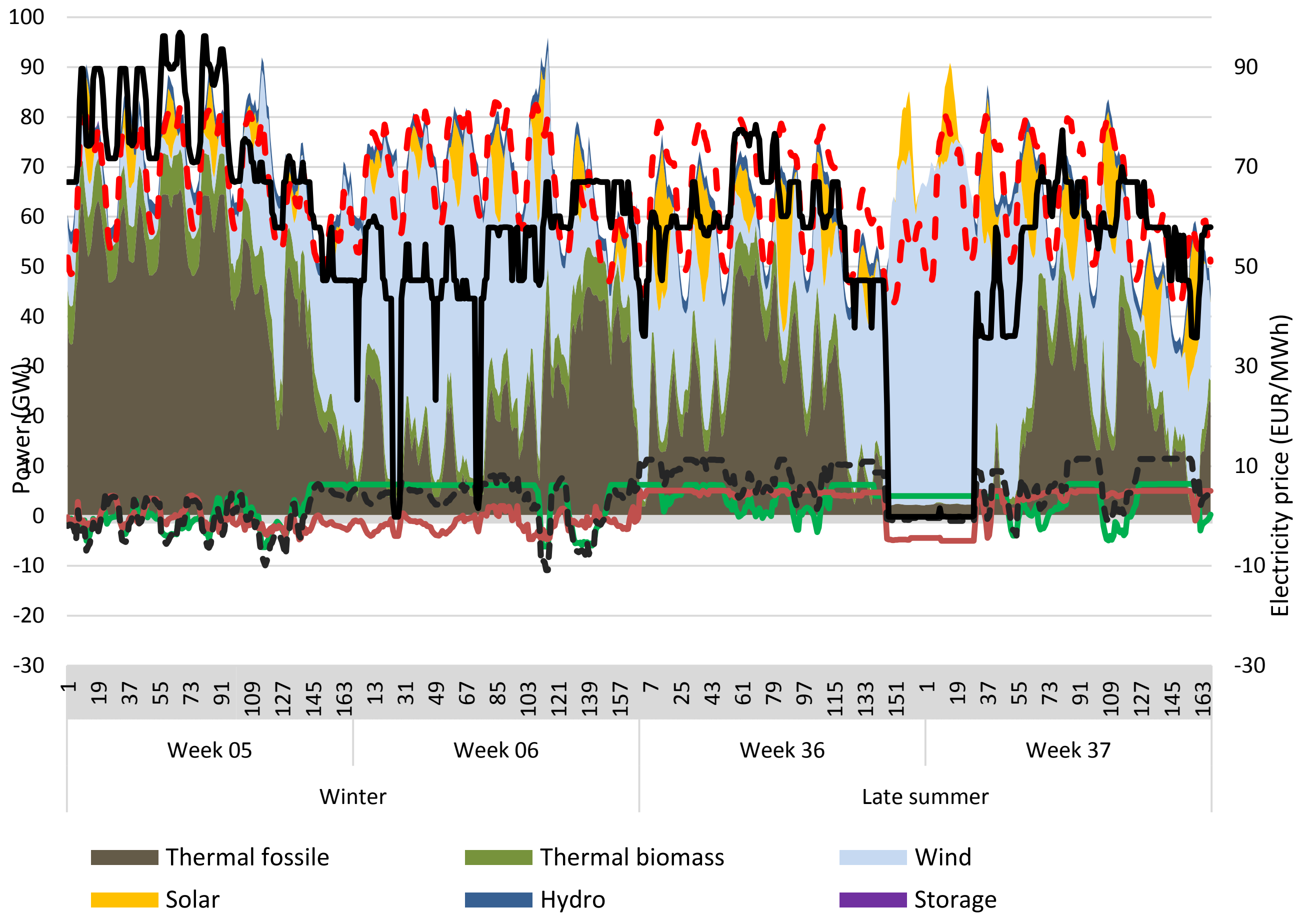


Figure 25: Operation of the German power system for two weeks in winter and two in summer in 2030, for the EVs scenario.

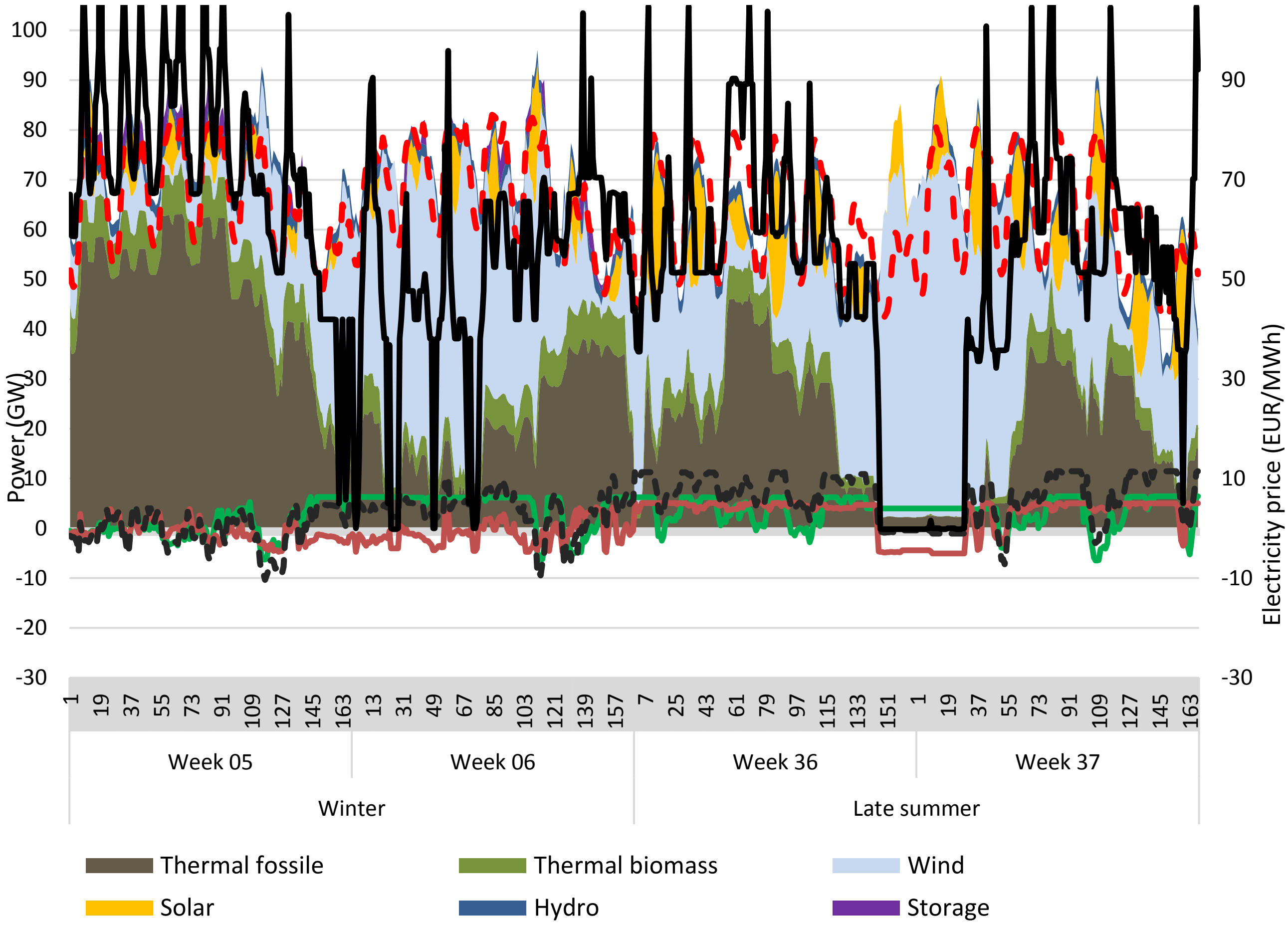


Figure 26: Operation of the German power system for two weeks in winter and two in summer in 2030, for the EVs scenario and UC.

8 Discussion

In this chapter a discussion is drawn around the most important results for this thesis. Firstly, the two scenarios (RE 2030 and RE 2030 + EVs) without UC are going to be discussed and compared. Afterwards, a comparison of them is going to be presented when the UC is applied. Finally, for each scenario the most significant results are going to be presented in order to draw some conclusion about the UC.

	NON - UC	UC
RE 2030	↕ ↔	↕
RE 2030 + EVs	↔	

Table 32: Presents the structure of this chapter. The arrows represent the comparison between the scenarios.

RE 2030 vs RE 2030+EVs

The annual electricity generation for all the countries when EVs are taken into account is increased by 33TWh, since the annual electricity demand is also increased by 37TWh in order to cover the needs for the EVs. The interesting thing is that the fuel mix remains almost the same, i.e. in Denmark's biggest share in the electricity generation is held by wind, Finland's by nuclear, Norway's by water, Sweden's by water and nuclear and Germany's by wind and fossil fuels (coal and lignite). However, the additional demand for the EVs is covered by natural gas (2.6TWh more) and coal and lignite (17TWh more). An increase is noticed also in the electricity generation by water (9.56TWh more), biomass (1.7TWh more) and wind (447GWh more). The annual electricity prices when EVs are applied in the model are higher for all the countries, which is due to the use of more fossil fuels. In the scenario with the EVs, the CO_2 emissions are increasing due to the increase in the consumption of fuels associated with the emissions, while this is not the case for Denmark where the emissions are dropping by 4kton, as the fuel consumption is also dropping (see table 30).

RE 2030+UC vs RE 2030+EVs +UC

When UC is enabled for the same scenarios, in the generation mix the same trends are noticed, i.e. increase in the generation in order for the additional demand to be covered. The fuels used in this case also is natural gas (2.3TWh more in the RE 2030 + EVs + UC scenario compared to RE 2030 + UC), coal and lignite (18.7TWh more), water (9.2 TWh more), biomass (1.5TWh more) and wind (528GWh more). It is a fact also that the number of start-ups is decreased only for Germany when EVs are introduced to the model (see table 28). Comparing the electricity prices, higher peaks are noticed for the scenario with EVs for all the countries, due to the electricity generation from natural gas in these specific hours. For example, in Sweden as it can be seen from the figure above, in week 5 high generation from natural gas is observed (2104MWh) and at the same time the price reaches the amount of 220.87€/MWh. The generation from coal is more constant and that is the reason why it is concluded that prices are driven by natural gas. Concerning the CO_2 emissions, they are increasing for the EVs scenario for all the countries, since the fuel consumption associated with CO_2 emissions is increased.

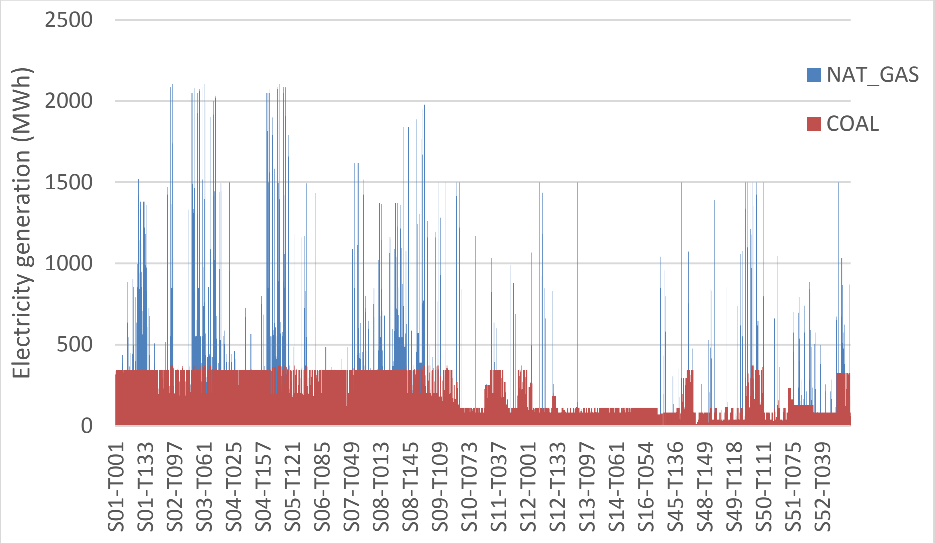


Figure 27: Electricity generation by fuel in MWh during the year 2030 for Sweden for the scenario RE 2030+EVs+UC.

The total costs for the above two comparisons cannot be compared due to the fact that additional demand is implemented for the scenarios with EVs.

RE 2030 vs RE 2030+UC

In the UC run, more electricity is generating in total mainly from fossil fuels, biomass, wind and slightly more from sun, due to more use of fossil fuels as the power plants operate in a an inflexible way with partial loads introduced. However, the annual electricity generation is decreased all the countries except of Germany. In addition, less electricity is exported from Denmark, Finland and Sweden, while Germany imports less and Sweden exports and imports less, As mentioned in the subchapter 7.3, the total costs are increased in the UC run, but not because of the introduced new data of start-up costs but due to the increased fuel and CO_2 costs. In the UC run, the annual electricity prices in the different regions are higher. Moreover, high peaks are noticed for a few hours and also the negative prices can be observed for more hours in Germany (443 hours in the UC run, 415 in the non UC run), while the actual prices are not so low (-0.28€/MWh in the UC run, -12.28€/MWh in the non UC run (see figure 28). However, In Denmark less hours with negative prices are observed in the UC run (24hours Vs 37hours in the non UC), but the actual prices are the same (-0.16€/MWh).

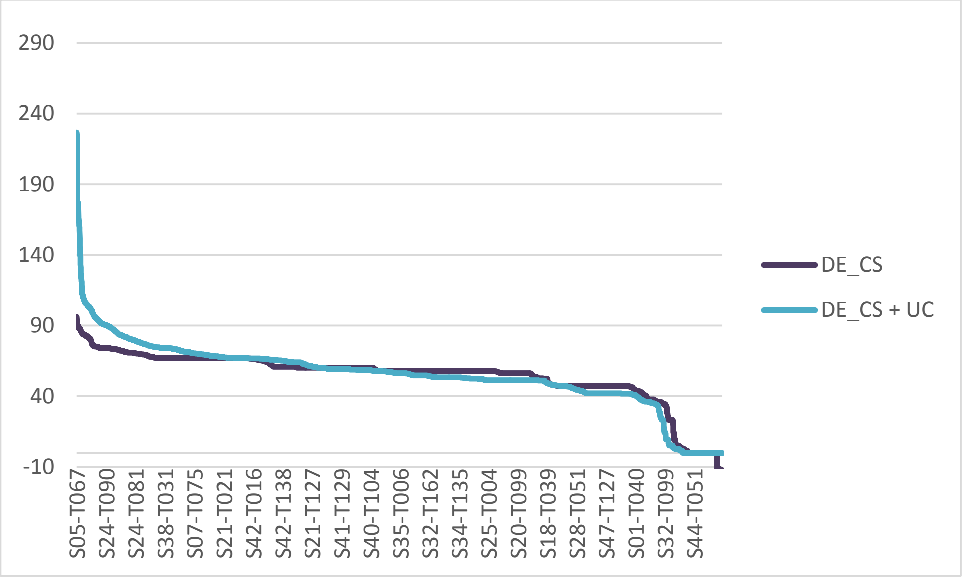


Figure 28: Duration curve for electricity prices in central South Germany, with and witout UC. (The light blue line represents the prices with UC)

In the figure below, is presented the operation German system for weeks 5, 37, 47 and 51 for the scenario without UC. In weeks 5 and 47 high prices are observed and in weeks 37 and 51 negative prices occur. As it can be concluded negative prices occur when there is high electricity generation from wind and the thermal power plants do not operate. But, in the case of UC for the same weeks, high peaks are observed when the thermal power plants operate. In the table below, the electricity generation by fuels is presented for Germany in week 51 hour 103 with low electricity price and hour 110 with high prices. In the hour with the high electricity price, the electricity generated from fossil fuels is increased in comparison with the hour with low electricity price.

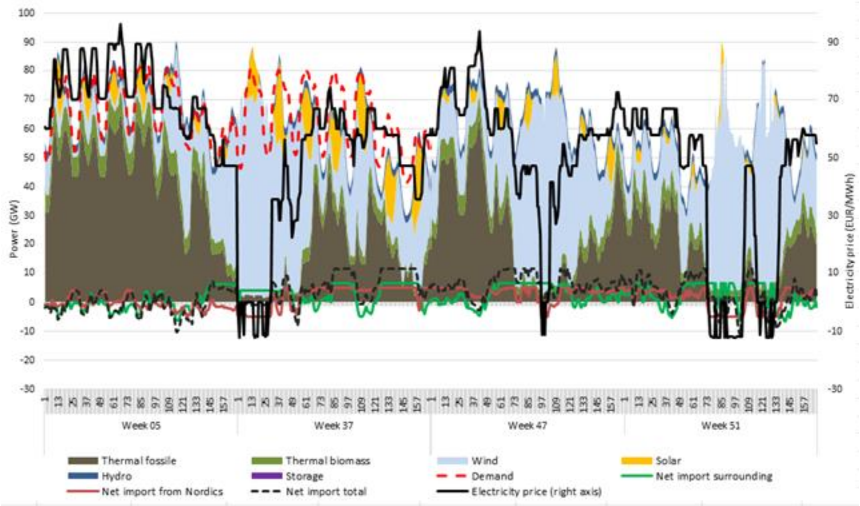


Figure 29: Operation of the German power system for two weeks with high and low prices in 2030.

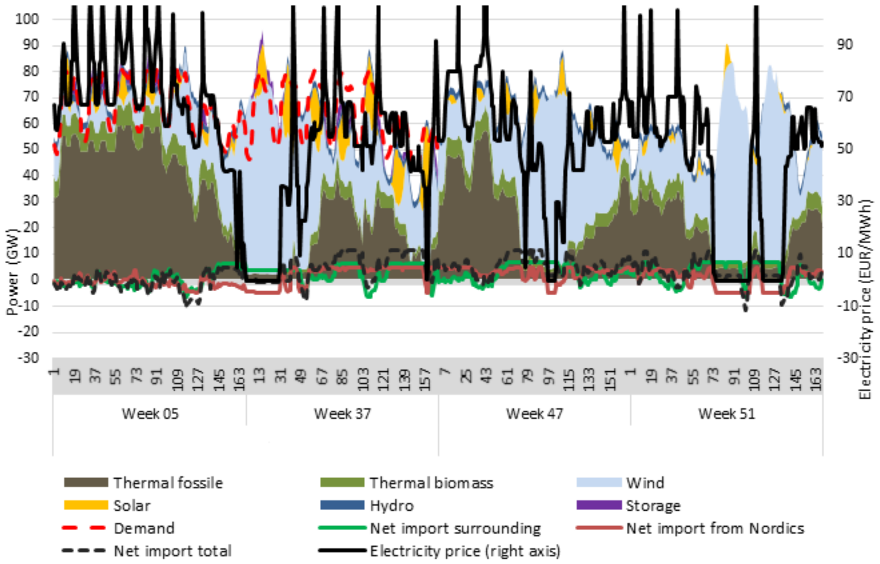


Figure 30: Operation of the German power system for two weeks with high and low prices in 2030 when UC is applied.

		Sum of MWh					
	El prices €/MWh	**COAL**	**LIGNITE**	**NAT_GAS**	**BIOMASS**	**SUN**	**WIND**
GERMANY							
RE 2030							
S51-T103	-11.8	114.01	1217.75	64.95	2165.21		49285.23
S51-T110	47.2	2635.81	8796.76	2854.81	2299.35	2958.23	24981.30
RE 2030 + UC							
S51-T103	-0.16	2754.64	1217.75	64.95	2331.97		54397.14
S51-T110	115.4	2785.52	2467.59	6269.42	2303.34	2958.23	24981.30

Table 33: Electricity generation and prices for two hours in Germany.

RE 2030+EVs vs RE 2030+EVs +UC

Like in the scenario without the EVs, in this case more electricity is generated in the UC from fossil fuels, biomass, wind and slightly more from sun. However, the annual electricity generation is decreased for Denmark, Norway and Sweden, which as a result export less. Finland, with an increased electricity generation in the UC run, is exporting more to Sweden, Germany is the only country, which is s only importing, but it is importing less in the UC run. Moreover, the total costs are increased, but not due to the introduction of the start-up costs, but mainly to the fuel costs and CO_2 costs, since more fossil fuels are used, when UC is implemented. Following the same trend that the scenarios without EVs follow, the electricity prices are higher in the UC run with high peaks and less negative ones, mainly attributed as explained above to the different operation of power plants when UC is applied and the higher generation of electricity from fossil fuels in the hours with high prices.

It should be noted also that higher deployment of wind and solar is observed in the scenario with EVs are implemented and UC commitment is not used (see table 34). This is expected due to the fact that in the EVs scenario additional demand needs to be covered and the power plants operate in a flexible way, since no start-up costs, partial load and minimum up and down time are introduced in the model.

Year	2030				
	DENMARK	NORWAY	SWEDEN	FINLAND	GERMANY
Solar Power Curtailment (GWh)					**41**
RE 2030 + EVs					11
RE 2030					29
Wind Curtailment (GWh)					
RE 2030 + EVs	1.422	136			503
RE 2030	1.853	151			504
RE 2030 + EVs + UC	1.682	136			
RE 2030 + UC	2.195	151			

Table 34: Solar and wind curtailment in GWh for the different scenarios in each country. The blanc spaces imply that no curtailment occurs in these cases.

9 Conclusion

This study is analysing the future German and the Nordics energy systems with and without the Balmorel's option of unit commitment. These countries have adopted policies to integrate more fluctuating RE and as a result, challenges in the operation of the thermal power plants will be created. Different scenarios are formulated in order to examine the interpretation of the energy systems. The simulations without the unit commitment represent more flexible power plants, while the ones with unit commitment add restrictions in the operation of power plants in order to represent a closest to reality operation.

In order to address the issue of the modelling with and without constraints in the operation of energy systems with high integration of RE, a literature study is carried out to find information about the policies of the researched countries. The energy model Balmorel is used to simulate the energy systems and through the different scenarios the following research question is going to be answered:

"What are the differences when energy systems with high penetration of fluctuating renewable energy sources are modelled with and without unit commitment?"

From the simulations, it was noted that the fuel mix to generate electricity is changed. More fossil fuels (especially natural gas), biomass and wind is used when UC is applied. That can be explained by the fact that restrictions such as the start-up costs and minimum up and down time are added to the model. As a result, some of the units with low variable costs are not contributing in the generation, due to their high start-up costs, i.e. the model will start the operation of a gas turbine with high variable cost for a few hours instead of starting up a large coal fired power plant with low variable costs, as it costs more to start it up.

Moreover, the total costs are increased when UC is applied, to some extent due to the additional start-up costs but mainly due to the raised fuel and CO_2 costs, since more fossil fuels are consumed. Also, the CO_2 emissions are increased in the UC run, which is attributed in the fact that more fuel associated with these emissions are consumed. Another difference is noted to the electricity prices, which in the case of UC are increased and present high peaks, due to the operation of the expensive power plants, as explained in the paragraph above. Finally, when the UC is applied more curtailment in the wind is noticed in the Nordic countries. In the non UC simulation, where no restrictions are added, the power plants operate in a more flexible way, since the model can start them up and shut down without taking into account any minimum up and down time and since no partial loads are considered, and consequently bigger deployment of wind is noticed.

To sum up, from this study, the author's opinion concluded to the fact that the closest to reality interpretation of the energy systems is modelling them without using the Balmorel's option of unit commitment, although the power plants operate actually with constraints and restrictions when UC is applied to the model. This is argued due to the fact that the high peaks in electricity prices in the UC run such as 398 €/MWh in south Sweden in 2013, have not been noticed so far in the Nord Pool market and also the number of start-ups for some of the power plants are not realistic. For instance, a gas turbine in central south Germany has 2840 start ups per year, which means around 8 start ups in a day, which means that it starts up every three hours.

However, it should not be assumed that the UC should not be used at all in similar projects, since the power plants operate closest to the current market conditions when it is applied. Nevertheless, it should be kept in mind that it is probable until 2030, the market to be reformed. In addition, the data for start-up costs, efficiencies and minimum up and down time is representative of the current conditions and there is a probability that power plants in the future will be improved and all the data about them will be changed.

Further suggestions proposed to expand this research, could be a stakeholders analysis including interviews with key actors concerning the improvement of the operation of the power plants and gams language programmers to evolve the mathematical equations in order for the model to provide a closest to reality operation of the energy systems. In addition, it should be taken into account from the model that when UC is applied to Balmorel then the O&M costs should be reduced, since they include some of the costs associated with the start-up costs which are additional implemented in Balmorel and also a variable could be introduced to the model so that the O&M costs are increased through the years and the efficiencies are decreased and not stay constant throughout all the simulations.

References

ABB. (2015). *Baltic cable*. Retrieved from new.abb.com: http://new.abb.com/systems/hvdc/references/baltic-cable

ABB. (2015, 4 8). *SwePol Link*. Retrieved from new.abb.com: http://new.abb.com/systems/hvdc/references/swepol-link

AGEB. (2013). *Auswertungstabellen zur Energiebilanz Deutschland.* Berlin.

Agora. (2014, 10 16). *Germany's Clean Energy Transition: What is energiewende?* Retrieved from www.agora-energiewende.org: http://www.agora-energiewende.org/topics/the-energiewende/germanys-clean-energy-transition-what-is-the-energiewende/

Agora Energiewende. (2014). *Negative Strompreise: Ursachen und Wirkungen.* Berlin.

Antikainen, M. (2015, 4 8). *EVE – the Finnish electric vehicle programme – including a co-Nordic dimension.* Retrieved from www.iea.org: https://www.iea.org/media/workshops/2013/egrdmobility/Antikainen.pdf

Balmorel. (2015, 26 February). *Projects*. Retrieved from Balmorel, Energy System Model: http://www.eabalmorel.dk/index.php?option=com_content&view=category&layout=blog&id=10&Itemid=17

Bryman, A. (2012). *Social Research Methods.*

Compassion in world farming. (2015, 4 10). *Factory farming intensifies climate change, releasing vast volumes of greenhouse gases.* Retrieved from http://www.ciwf.org.uk/: http://www.ciwf.org.uk/factory-farming/environmental-damage/climate-change-in-detail/?gclid=CNz3wcLa68QCFYgLcwodRowAMw

Curran, S. J., Wagner, R. M., Graves, R. L., Keller, M., & Green, J. B. (2014). *Well-to-wheel analysis of direct and indirect use of natural gas in passenger vehicles.* Elsevier Ltd.

Danish Energy Agency. (2012). *Energy Statistics 2012.* Copenhagen: Danish Energy Agency.

Danish Energy Agency. (2015, 4 7). *Test scheme for electric vehicles*. Retrieved from www.ens.dk: http://www.ens.dk/en/climate-co2/test-scheme-electric-vehicles

Danish Energy Agency. (December 2012). *Energy Policy in Denmark.* Danish Energy Agency.

Danish Energy Agency. (February 2014). *Energy Statistics 2012.* Copenhagen: Danish Energy Agency.

Dragoon, K., & Papaefthymiou, G. (2015). *Power System Flexibility Strategic Roadmap: Preparing power systems to supply reliable power from variable energy resources.* Berlin: European Copper Institute.

Ea Energy Analyses. (2011). *CO2 emissions from future passenger cars in the Nordic countries.* Copenhagen.

Ea Energy Analyses. (n.d.). Balmorel Introduction. Copenhagen.

Ea Energy Analyses. (n.d.). Balmorel Introduction: Unit Commitment. Copenhagen.

Ea Energy Analyses. (n.d.). *Balmorel Map.* Copenhagen.

Ea Energy Analyses; DTU. (2013). *Analysis and projections of biomass fuel prices.* Copenhagen.

Elbilsupphandling.se. (2015, 4 8). *Sweden a perfect country for EVs*. Retrieved from Elbilsupphandling.se: http://www.elbilsupphandling.se/en/sweden-a-perfect-country-for-evs/

Energi Styrelsen . (Januar 2007). *Basisfremskrivningen til CO2-kvoteallokeringsplanen for 2008-12 og regeringens energistrategi: En visionær dansk energipolitik.*

Energinet.dk. (2009). *Efficient utilisation of wind power in Denmark.* Fredericia: Energinet.dk.

Energinet.dk. (2014, January 15). *2013 was a record-setting year for Danish wind power*. Retrieved from Energinet.dk: http://www.energinet.dk/EN/El/Nyheder/Sider/2013-var-et-rekordaar-for-dansk-vindkraft.aspx

Energinet.dk. (2015, 4 7). *Electricity interconnections*. Retrieved from www.energinet.dk: http://www.energinet.dk/EN/ANLAEG-OG-PROJEKTER/Generelt-om-elanlaeg/Sider/Elforbindelser-til-udlandet.aspx

Energinet.dk. (2015, 4 10). *The Nordic Power System*. Retrieved from www.energinet.dk: http://www.energinet.dk/EN/OM-OS/Sider/Det-nordiske-elsystem.aspx

Energinet.dk. (April 2013). *Energinet.dk's analysis assumptions 2013-2035.* Energinet.dk.

Energinet.dk. (September 2014). *Energinet dk's analyseforudsætninger 2014-2035.* Energinet.dk.

Energinet.dk. (September 2014). *Energinet dk's analyseforudsætninger 2014-2035.* Fredericia: Energinet.dk.

Energinet.dk; Energistyrelsen. (May 2012). *Technology Data for Energy Plants.*

European Commission. (2010). *Energy Trends 2030.* Belgium: European Commission.

European Commission. (2013). *EU Energy in figures.* Luxembourg: Publication Office of European commission.

European Commission. (2015, 4 11). *Eurostats: Statistics explained*. Retrieved from ec.europa.eu: http://ec.europa.eu/eurostat/statistics-explained/index.php/Passenger_transport_statistics

European Commission. (2015, 4 7). *Renewable energy*. Retrieved from http://ec.europa.eu/: http://ec.europa.eu/energy/en/topics/renewable-energy

European Commission. (October 2008). *Interconnecting Europe.* Luxembourg: EU.

European Commission. (October 2014). *Progress towards achieving the Kyoto and EU 2020 objectives.*

European Network for Transmission System Operators for electricity (ENTSO-E). (2014). *Ten Year Network Development Plan.*

European Network of Transmission Systems Operator for Electricity (ENSO-E). (2015, 4 11). *Who Is ENTSO-E?* Retrieved from www.entsoe.eu: https://www.entsoe.eu/about-entso-e/Pages/default.aspx

European Network of Transmission Systems Operator for Electricity (ENTSO-E). (2014). *Ten Year Network Development Plan (TYNDP).* ENTSO-E.

Federal Ministry of Environment, Nature Conservation and Nuclear Safety. (October 2011). *The Federal Government's energy concept of 2010.* Berlin: Federal Ministry of Environment, Nature Conservation and Nuclear Safety.

Fingrid. (2015, 4 8). *Nordic power system and interconnections with other systems*. Retrieved from www.fingrid.fi: http://www.fingrid.fi/en/powersystem/general%20description/Nordic%20power%20system%20and%20interconnections%20with%20other%20systems/Pages/default.aspx

Finnish Energy Industries. (2015, 4 8). *Electricity Generation*. Retrieved from energia.fi: http://energia.fi/en/energy-and-environment/electricity-generation

Flybjerg, B. (2006). *Five misunderstandings about case studies.* Qualitative Inquiry.

Forward, E., Glitman, K., & Roberts, D. (2013). *An Assessment of Level 1 and Level 2 Electric Vehicle Charging Efficiency.* Vermont: Vermont Energy Investment Corporation .

Friedmann, J. (1987). *Two centuries of planning theory: an overview. In: Planning in the Public Domain: From Knowledge to Action.* New Jersey: Princeton University Press.

German Federal Ministry for Economic Affairs and Energy. (August 2014). *Renewable Energy Act (EEG).* German Federal Ministry for Economic Affairs and Energy.

Grohnheit, P. E. (March 2001). *Balmorel - Data and Calibration.*

Grohnheit, P. E., & Larsen, H. V. (March 2001). *Balmorel - Data and Calibration.*

Hedegaard, K. (September 2013). *Wind power integration with heat pumps,heat storages, and electric vehicles.* Risø : DTU Management Engineering.

Hedegaard, Karsten; Ravn, Hans; Juul, Nina; Meibom, Peter. (2012). *Effects of electric vehicles on power systems in Northern Europe.* Elsevier Ltd.

Herbst, A., Toro, F., Reitze, F., & Jochem, E. (2012). Introduction to Energy Systems Modelling. *Swiss Journal of Economics and Statistics, Vol. 148*, 111-135.

Hvelplund, F. (2005). *Cognition and change. Theories of adequate recognition and technological change in energy examples from 1974 2001.* Aalborg: Aalborg University: Department for development and planning.

Indus Institute of Technology and Engineering. (2015, 4 20). *Interconnected grid system*. Retrieved from https://iiteeeestudents.wordpress.com: https://iiteeeestudents.wordpress.com/2011/11/14/interconnected-grid-system/

International Energy Agency (IEA). (2011). *Energy Policies of IEA countries: Denmark.* Paris: IEA.

International Energy Agency (IEA). (2011). *Energy Policies of IEA Countries: Norway.* Paris: IEA.

International Energy Agency (IEA). (2012). *Emergency report of IEA Countries: Germany.* IEA.

International Energy Agency (IEA). (2013). *Energy Policies of IEA Countries: Finland.* Paris: IEA.

International Energy Agency (IEA). (2013). *Energy Policies of IEA Countries: Germany.* Paris: IEA.

International Energy Agency (IEA). (2013). *Energy Policies of IEA Countries: Sweden.* Paris: IEA.

International Energy Agency (IEA). (2013). *World Energy Outlook: New Policies Scenario.* Paris: IEA.

Kempton, W., & Tomic´, J. (November 2004). *Vehicle-to-grid power implementation: From stabilizing the grid to supporting large-scale renewable energy.* Elsevier B.V.

Kiviluoma, J., & Meibom, P. (2011). *Methodology for modelling plug-in electric vehicles in the power system and cost estimates for a system with either smart or dumb electric vehicles.* Elsevier Ltd.

Lund, H. (2010). *Renewable Energy Systems: The choice and modelling of 100% renewable solutions.* Elsevier.

Lund, H., & Kempton, W. (March 2008). *Integration of renewable energy into the transport and electricity sectors through V2G.* Elsevier Ltd.

Lund, R., & Mathiesen, B. V. (2015). *Large combined heat and power plants in sustainable energy systems.* Copenhagen: Elsevier Ltd.

Mathiesen, B. V., & Lund, H. (2009). *Comparative analyses of seven technologies to facilitate the integration of fluctuating renewable energy sources.* IET Power Gen.

Mathiesen, B., Lund, H., Connolly, D., Wenzel, H., Ostergaard, P., Moller, B., . . . Hvelplund, F. (February 2015). *Smart Energy Systems for coherent 100% renewable energy and transport solutions.*

matter2energy.wordpress.com. (2013, February 22). *Wells to wheels: electric car efficiency* . Retrieved from matter2energy.wordpress.com: https://matter2energy.wordpress.com/2013/02/22/wells-to-wheels-electric-car-efficiency/

Ministry of Climate, Energy and Buildings. (April 2013). *Energy Policy Report.* Ministry of Climate, Energy and Buildings.

Ministry of the Environment and Ministry of Enterprise, Energy and Communications. (2009). *An integrated climate and energy policy.* Stockholm.

Moulson, G. (2015, 4 9). *German government: 1 million electric cars by 2020*. Retrieved from http://abcnews.go.com/: http://abcnews.go.com/Business/german-government-million-electric-cars-2020/story?id=8364933

Muller, J., Remmen, A., & Christensen, P. (1984). *Society technologies: the technology community.* Herning.

Muranen Lauri Finish Energy Industry. (2012). *Finish Energy Policy.* Helsinki: Finish Energy Industries.

Nicolosi, M. (2010). *Wind power integration and power system flexibility.* Koln.

Norsk Elbilforening. (2015, 4 8). *The Norwegian Electric Vehicle Association*. Retrieved from www.elbil.no: http://www.elbil.no/elbilforeningen/english-please/717-the-norwegian-electric-vehicle-association

Organisation for Economic Co-operation and Development (OECD). (2015, 4 7). *About OECD*. Retrieved from OECD: http://oecd.org/about/

Poul Erik Grohnheit, H. V. (March 2001). *Balmorel - Data and Calibration.*

Ravn, F. H. (March 2001). *Theoritical Background.*

Ravn, F. H. (September 2011). *Balmorel Model Structure.*

Shah, S. D., Woolsey, J., Lodal, J., & Tonachel, L. (2009). *Plug-In Electric Vehicles.* Washington: The Brooklin Institute.

Swedish Energy Agency. (February 2014). *Kontrollstation 2015.*

Swedish Energy Agency. (October 2014). *Checkpoint 2015.* Swedish Energy Agency.

Technical Research Center of Finland VTT. (2012). *Low Carbon Finland 2050.* VTT.

teslaliving.net. (2015, 4 20). *Measuring EV charging efficiency*. Retrieved from teslaliving.net: http://teslaliving.net/2014/07/07/measuring-ev-charging-efficiency/

The Danish Partenership for Hydrogen and Fuel Cells. (2015, 4 7). *The Current Energy Network*. Retrieved from www.hydrogennet.dk: http://www.hydrogennet.dk/energisystemetidag0/

Tikkanen, S., & Ornberg, S. (2012). *The development of finnish electric mobility.* Helsinki.

United Nations. (2015, 4 7). *Kyoto Protocol*. Retrieved from http://unfccc.int/: http://unfccc.int/kyoto_protocol/items/2830.php

Unruh, G. C. (2000). *Understanding carbon lock-in.* Madrid: elsevier.

Unruh, G. C. (2002). *Escaping carbon lock-in.* Madrid: Elsevier.

Vuola, L., & Lindgren, J. (2015, 3 2). *Is an Electric Vehicle Boom About to Take Off in Finland?* Retrieved from Castren and Snellman: http://castrenblog.com/2015/03/02/is-an-electric-vehicle-boom-about-to-take-off-in-finland/

Wellington, J., & Szczerbinski, M. (2007). *Research Methods for the Social Sciences.* London: Continuum International Publishing Group.

World nucler news. (2013, May 23). *IEA praises nuclear's role in Finnish policy*. Retrieved from http://www.world-nuclear-news.org/: http://www.world-nuclear-news.org/np-key_role_for_nuclear_in_finnish_energy_policy-2305134.html

World Wide Fund (WWF). (2015, 4 10). *What causes climate change?* Retrieved from http://wwf.panda.org/: http://wwf.panda.org/about_our_earth/aboutcc/cause/?gclid=COr_t8Pa68QCFUHicgod1VwAOw

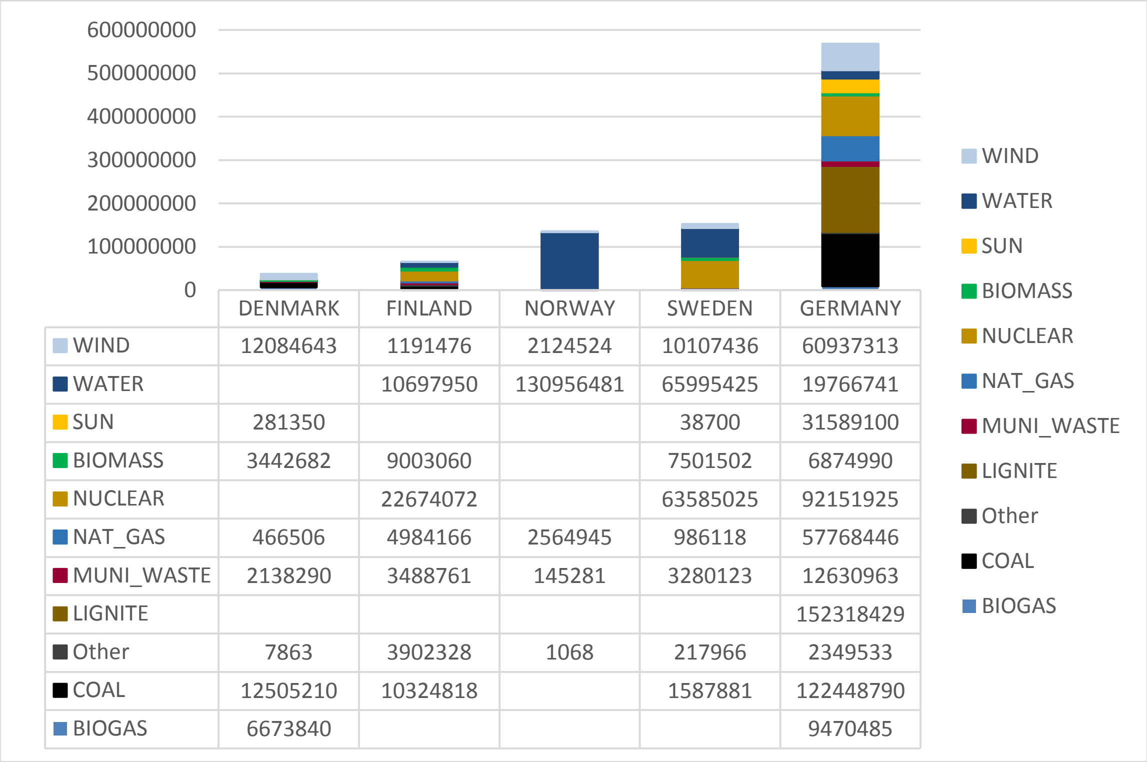
Worldwatch Institute. (2015, 4 9). *Germany Boosts Electric Vehicle Development*. Retrieved from http://www.worldwatch.org/: http://www.worldwatch.org/node/6251

Wright, B. (28 May 2013). *A review of Unit Commitment.*

Yin, R. (2009). *Case Study Research: Design and Methods.* Los Angeles: Sage.

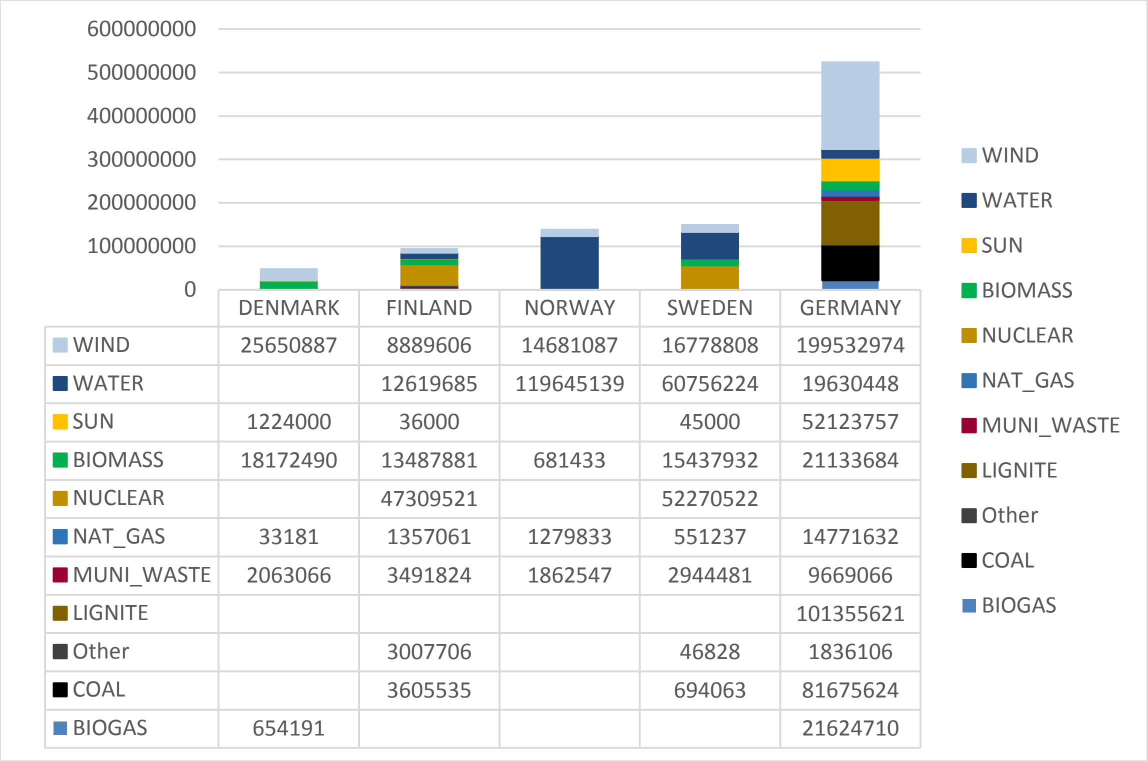
Appendix

A Annual Electricity generation for the different scenarios



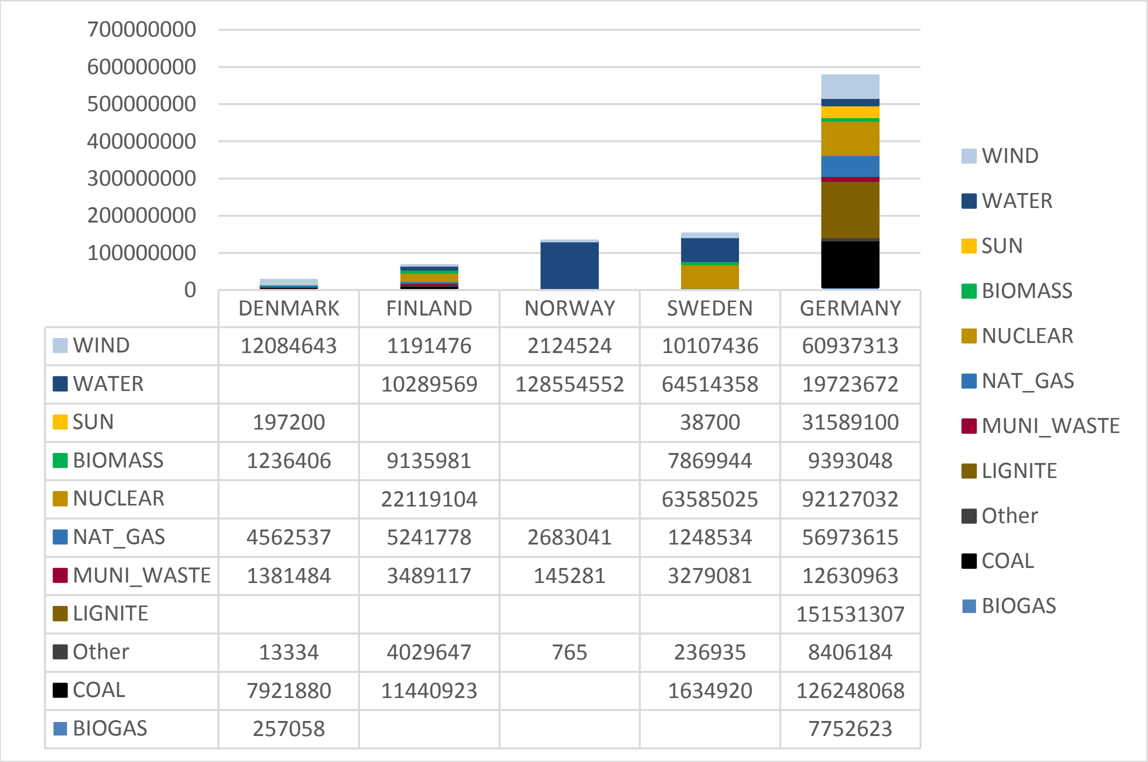
	DENMARK	FINLAND	NORWAY	SWEDEN	GERMANY
WIND	12084643	1191476	2124524	10107436	60937313
WATER		10697950	130956481	65995425	19766741
SUN	281350			38700	31589100
BIOMASS	3442682	9003060		7501502	6874990
NUCLEAR		22674072		63585025	92151925
NAT_GAS	466506	4984166	2564945	986118	57768446
MUNI_WASTE	2138290	3488761	145281	3280123	12630963
LIGNITE					152318429
Other	7863	3902328	1068	217966	2349533
COAL	12505210	10324818		1587881	122448790
BIOGAS	6673840				9470485

Figure 31: Annual Electricity generation for the Reference 2013 scenario in MWh.



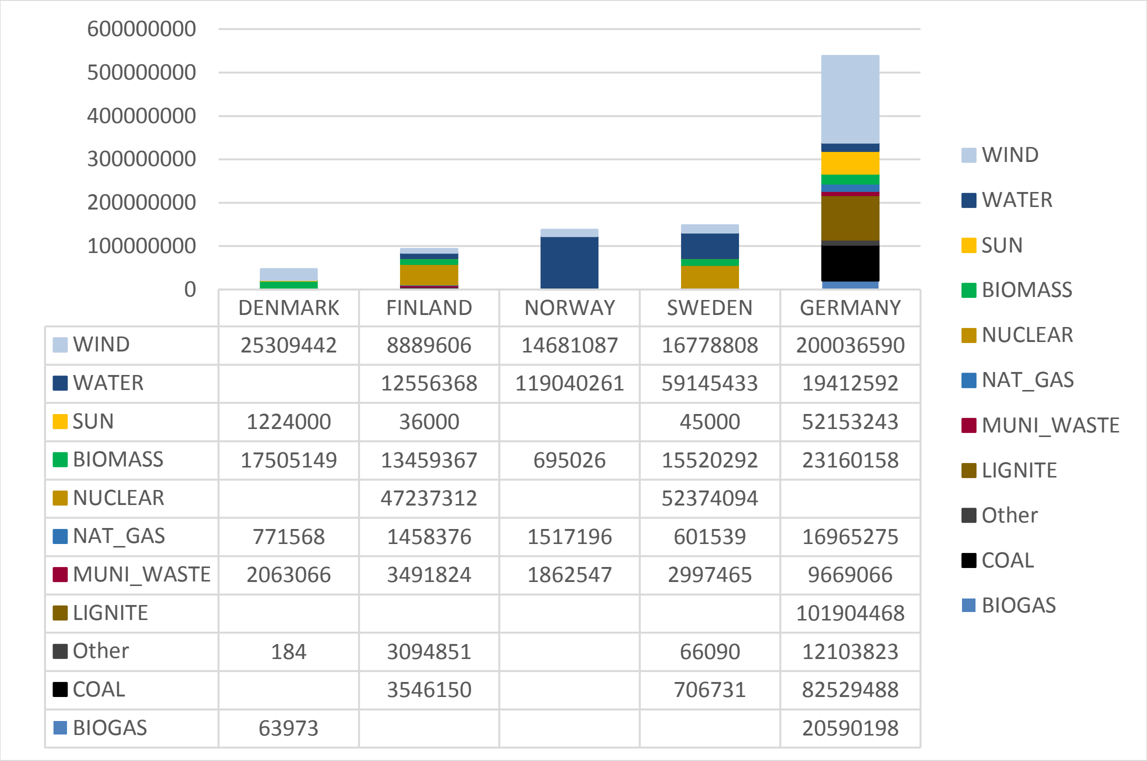
	DENMARK	FINLAND	NORWAY	SWEDEN	GERMANY
WIND	25650887	8889606	14681087	16778808	199532974
WATER		12619685	119645139	60756224	19630448
SUN	1224000	36000		45000	52123757
BIOMASS	18172490	13487881	681433	15437932	21133684
NUCLEAR		47309521		52270522	
NAT_GAS	33181	1357061	1279833	551237	14771632
MUNI_WASTE	2063066	3491824	1862547	2944481	9669066
LIGNITE					101355621
Other		3007706		46828	1836106
COAL		3605535		694063	81675624
BIOGAS	654191				21624710

Figure 32: Annual Electricity generation for the RE 2030 scenario in MWh.



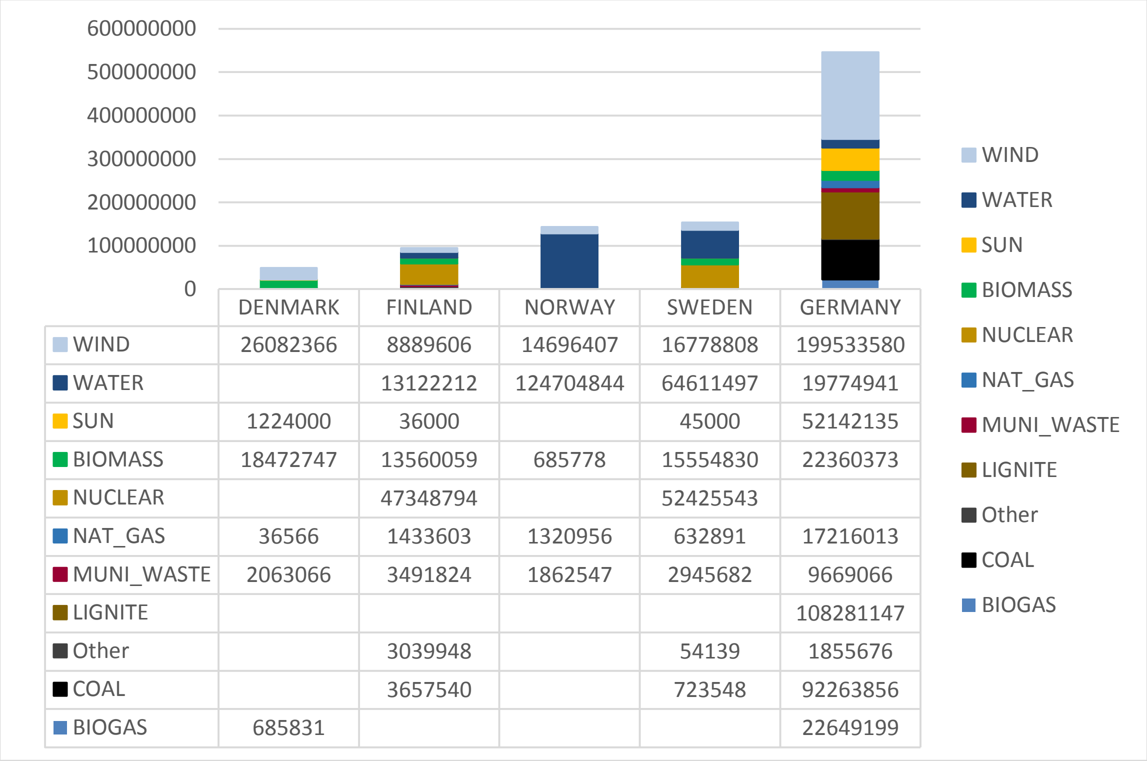
	DENMARK	FINLAND	NORWAY	SWEDEN	GERMANY
WIND	12084643	1191476	2124524	10107436	60937313
WATER		10289569	128554552	64514358	19723672
SUN	197200			38700	31589100
BIOMASS	1236406	9135981		7869944	9393048
NUCLEAR		22119104		63585025	92127032
NAT_GAS	4562537	5241778	2683041	1248534	56973615
MUNI_WASTE	1381484	3489117	145281	3279081	12630963
LIGNITE					151531307
Other	13334	4029647	765	236935	8406184
COAL	7921880	11440923		1634920	126248068
BIOGAS	257058				7752623

Figure 33: Annual Electricity generation for the Reference 2013 + UC scenario in MWh.



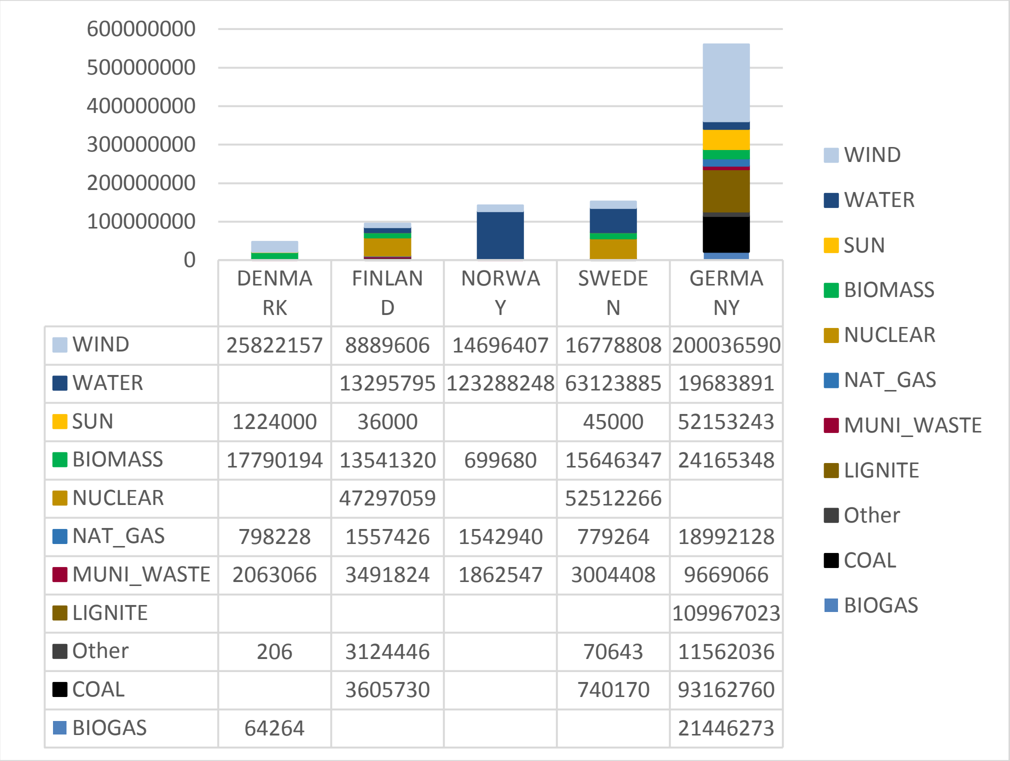
	DENMARK	FINLAND	NORWAY	SWEDEN	GERMANY
WIND	25309442	8889606	14681087	16778808	200036590
WATER		12556368	119040261	59145433	19412592
SUN	1224000	36000		45000	52153243
BIOMASS	17505149	13459367	695026	15520292	23160158
NUCLEAR		47237312		52374094	
NAT_GAS	771568	1458376	1517196	601539	16965275
MUNI_WASTE	2063066	3491824	1862547	2997465	9669066
LIGNITE					101904468
Other	184	3094851		66090	12103823
COAL		3546150		706731	82529488
BIOGAS	63973				20590198

Figure 34: Annual Electricity generation for the RE 2030 + UC scenario in MWh.



	DENMARK	FINLAND	NORWAY	SWEDEN	GERMANY
WIND	26082366	8889606	14696407	16778808	199533580
WATER		13122212	124704844	64611497	19774941
SUN	1224000	36000		45000	52142135
BIOMASS	18472747	13560059	685778	15554830	22360373
NUCLEAR		47348794		52425543	
NAT_GAS	36566	1433603	1320956	632891	17216013
MUNI_WASTE	2063066	3491824	1862547	2945682	9669066
LIGNITE					108281147
Other		3039948		54139	1855676
COAL		3657540		723548	92263856
BIOGAS	685831				22649199

Figure 35: Annual Electricity generation for the RE 2030 + EVs scenario in MWh.



	DENMARK	FINLAND	NORWAY	SWEDEN	GERMANY
WIND	25822157	8889606	14696407	16778808	200036590
WATER		13295795	123288248	63123885	19683891
SUN	1224000	36000		45000	52153243
BIOMASS	17790194	13541320	699680	15646347	24165348
NUCLEAR		47297059		52512266	
NAT_GAS	798228	1557426	1542940	779264	18992128
MUNI_WASTE	2063066	3491824	1862547	3004408	9669066
LIGNITE					109967023
Other	206	3124446		70643	11562036
COAL		3605730		740170	93162760
BIOGAS	64264				21446273

Figure 36: Annual Electricity generation for the RE 2030 + EVs + UC scenario in MWh.