Danish Technical University

Energy System Analysis Group

Master Thesis

Modeling of the Norwegian power system and analysis of the power trade in the Nordic countries

Supervisors:

Dr. Kenneth Karlsson

Eng. Maurizio Gargiulo

Prof. Vittorio Verda

Dr. Raffaella Gerboni

Student:

Jacopo Tattini

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Abstract

The purpose of this thesis is to create TIMES-NO, the TIMES model of the Norwegian power system and to establish a hard-link with the existing TIMES-DK model in order to improve the representation of the electrical trade between Norway and Denmark and to assess whether in the future the Norwegian hydropower production can be used by Denmark when the wind is not blowing.

A major effort was put in modeling hydropower, the Norwegian dominant power source.

TIMES-NO can be run both in standalone and hard-linked mode. When TIMES-NO is hard-linked to TIMES-DK the power trade between Norway and Denmark is represented as an endogenous trade process, while when it is in standalone mode all the interconnectors are modelled by means of exogenously defined price criteria.

The baseline scenario was run for TIMES-NO in both standalone and hard-linked mode. The main differences in the two results are commented and explained.

The hard-linked model demonstrated to provide more trustworthy results. Instead in the standalone model a singular trading behaviour was identified and explained.

Finally, the hard-linked model was used to perform sensitivity analyses regarding the water inflow to the Norwegian hydropower stations, the demand evolution and the availability of new interconnections. For each sensitivity analysis it was demonstrated that the model computes a meaningful solution which suggests new structures for the Norwegian power system and various power exchanges with the interconnected countries.

Preface

This thesis represents the end of my student career first in Industrial Engineering at Università degli Studi di Firenze and then in Energy Engineering at Politecnico di Torino, Universidad Politecnica de Madrid and Danish Technical University.

I have written this thesis during winter 2014 at the Department of Energy System Analysis of the Danish Technical University within the program "Thesis abroad on student proposal" financed by Politecnico di Torino.

First of all I want to thank Eng. Maurizio Gargiulo for the continuous and generous availability before, during (and after) the writing of the thesis, for having put me in contact with the Energy System Analysis department at Copenhagen and for having helped me in dealing with TIMES. Beside I want to thank Prof. Kenneth Karlsson for having accepted me in the ESA department, for having been a key figure during my study period in Copenhagen and for the many useful technical advices provided to me.

I also want to thank all the assistant researchers, PhDs and Post Docs of ESA department at DTU for the warm welcoming at my arrival in Copenhagen and for having made me feel as part of their team. In particular many thanks to Cristian, who first engaged with me in the discovery of TIMES model generator and who always kept me informed about the most interesting events and workshops at DTU, to Amalia for revealing some of the secrets of Word and to Giovanni for the "Italian brackets". A special acknowledgment goes to Dr. Olexander Balyk, my co-supervisor in Denmark, who taught me how to use Veda interface and checked for errors and brilliant ideas that have accompanied my thesis work.

Special thanks also go to Nord Pool spot for having given me access to their precious data about the Nordic power market and to the members of the Hydrology department of NVE for the important data about the Norwegian hydropower system provided and for having given me the opportunity to learn Norwegian (unfortunately vainly).

A thousand thanks to Professor Juan Sanchez Inarejo for the two precious and enriching courses he holds at UPM: "Energy planning and sustainable development" and "Simulation of energy scenarios". After dealing with these subjects I decided to specialize in the topic of models and scenarios for energy planning.

To all the class mates of the Master in Management of Energy Markets for having accepted me in the class as if I were Spanish and for having given me the opportunity to learn Spanish studying and laughing together. A special thanks to Nacho Blanco for his crazy and at the same time brilliant idea of going together to Copenhagen for writing the master thesis and afterwards for having suggested me to go to live in Albertslund.

I can't avoid thanking each of my flatmates during my first semester of Erasmus in Madrid for the beautiful time spent together and the profound conversations: "Estuve en Pelayo, no estuve en Madrid!"

Then I want to thank my two super-organized flatmates in Torino, Cocco and Calab, who tried hard to put obstacles to my academic career amusingly. I also want to say thanks to my friends and class mates at Politecnico: Jacopo, Fra and Robbbi for the funny and stressful days spent preparing the assignments and for the deserved and rewarding beers after the exams.

I still have to thank Professor Adriano Milazzo, who first suggested me and encouraged me to choose Energy Engineering as MSc when I was still studying Industrial Engineering. I want to acknowledge all my friends of Engineering Without Borders Firenze for making the last year of study in Industrial Engineering more pleasant and stimulant and for having shared the study and investigation in the field of appropriate technologies.

Of course many thanks go to mom Lella and dad Ric for the emotional, affective, culinary and economical support, for having respected my desire of experiences abroad and for having given me the opportunity to dedicate to the university full-time. To granny Ottavia and grandpa Valerio who would be so proud of having an engineer as grandson, to granny Fiorella and aunt Carla who can finally boast for having an engineer as grandson and to grandpa Basilio who at last will have a most-wanted engineer grandson who, unfortunately, doesn't want to hear of working for the Italian railways company.

Finally many thanks to all my friends in Firenze, Sevilla, Torino, Madrid, Copenhagen and any other place who know they deserve it. In particular to my best friends Gabri and Camme for having been great companions of leisure and for having helped me to become a backpacker engineer.

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Jacopo Tattini

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Chapter 1

Introduction

1.1 Background

From many points of view it is clear that the current energy model based on fossil fuels is no more convenient. First it creates high energy dependence from the politically instable countries where fossil resources are located, thus compromising the security of supply. Then it involves a high cost to the society in order to obtain the increasingly expensive and scarce fuels. And finally it has a deeply negative impact on the environment, being a major responsible of the global warming and of the climate change.

The transition to a sustainable energy model should be based on three principles: economic efficiency, environmental sustainability and security of supply.

Energy planning is the process that allows driving the transition to a sustainable energy system with a holistic and respectful of the three principles described above approach. In fact at the same time it takes into consideration the evolution of the energy demand, the future availability of new technologies and their technical, economical and environmental specifications, the possibility of expanding the transmission grids and of adopting energy efficiency measures.

Due to the high cost of creating a renewable based energy system, it is of primary importance to choose the best option among several possible energy systems and in particular to establish which energy resources is better to employ in the capacity expansion plan, when and where it's better to deploy them and when the non-renewable sources should be phased out.

Such issues can be addressed using optimization methods, which solutions suggest the best strategy for deploying new technologies, their optimal energy production and start of operation, at the same time respecting a great amount of constraints and minimizing the total system cost.

One of the most commonly used tools in energy planning is TIMES, which optimizes an energy system over a long time horizon. In particular TIMES can be used to explore and compare many different scenarios and to assess the effects of different environmental and energy policies on the energy system object of the study.

1.2 Scope

This thesis has been prepared in Copenhagen, at the Danish Technical University (DTU), in the Department of Energy System Analysis under the program "Thesis abroad" of Politecnico di Torino. The thesis work has been included in one of the projects that the department is carrying out: The creation and enhancement of the TIMES model of the Danish energy system, carried out together with the Danish Energy Agency and E4SMA.

At present the model, called TIMES-DK, includes the entire Danish energy system. In the context of the sustainable transition of Denmark it is important to study the role of the interconnections and of the power exchange in the achievement of the environmental targets. At present in the model the interconnections are represented as exogenous trading processes and the power trade is calculated by TIMES by comparing the import/export costs exogenously given to the model with the price of electricity calculated endogenously by the model.
The department is interested in exploring the future electricity exchanges with other countries without using exogenous prices, which are less reliable and to assess if such exchanges can make the achievement of the environmental goals easier.

In fact the Danish Government and those of the other Nordic countries have set very ambitious targets for reducing the greenhouse-gas emissions and for increasing the renewable energy mix. In some cases the goals exceed even those imposed by the EU, as visible in (IEA & NORDEN, 2013). Denmark is committed to produce 100% of its electricity from renewable sources by 2035 and it expects to reach this target mainly by means of wind energy (IEA & NORDEN, 2013). It is therefore of primary importance for Denmark to rely on an energy source with high regulation speed, able to provide real-time balancing energy to use as a backup for the extremely variable wind generation. Hydropower offers the specifications required but unfortunately Denmark doesn’t have almost any hydropower plant nor can build any, due to the geomorphologic characteristics of its territory. The Norwegian power system instead is based on hydropower.

1.3 Purpose

The purpose of this thesis is to create the TIMES model of the Norwegian power system (TIMES-NO) and to create a hard-link with the TIMES-DK model in order to improve the representation of the electrical trade between the two countries and to assess whether in the future the production from the Norwegian hydropower can be used by Denmark when the wind is not blowing.

Since TIMES-NO was hard-linked to that of Denmark one of the interconnections of Denmark has been represented as an endogenous process, which is more reliable, as will be explained later.

The final multiregional model that includes both Denmark and Norway allows exploring the future dynamics of import and export of electricity and is a valuable tool that helps in taking decisions about the Danish power sector considering Denmark not as an isolated country but as part of a wider power system and power market. In fact the final hard-linked model optimizes the electrical systems of the two countries as if they were one single system. Moreover TIMES-NO permits to perform sensitivity analyses assessing the variation of the power exchange in the Nordic countries by varying the evolution of the demand of electricity, the water inflow to the hydroelectric plants and the availability of new interconnections.

A possible future use of the model is to study the most effective and efficient strategies to achieve the programmed targets in terms of emission reduction: TIMES-NO allows evaluating the expansion of interconnections and which technologies should be deployed depending on the scenarios in the two countries.

Furthermore, the model represents a step forward in the analysis of the vision of Norway as the "green battery of Europe" and to analyze what kind of investments are necessary for this vision to become reality (GULLBERG, 2013).

1.4 Structure

This thesis is divided into eight chapters. This first introductory chapter describes the background and the context of the thesis work, the purpose of the thesis and its structure.

Chapter II provides an overview of energy system modeling and of the kinds of energy models existing. Then TIMES model generator is described more in detail, since it is the tool used in this thesis to model the Norwegian power system. Finally there is a brief reminder of the concepts of linear programming and optimization.

Chapter III describes the structure and operation of the Nord Pool, the electricity market of Denmark, Norway and of the other Nordic countries. This chapter was written to explain the economic context in which Denmark and Norway trade power. The roles of the three power markets in which the Nord Pool is divided are presented, the division into bidding areas is explained, the mechanism of formation of different prices in the bidding areas when the interconnectors are congested is analyzed and the benefits of the interconnections are listed.

In Chapter IV TIMES-NO is described. First the structure of TIMES-NO alone and how the hard-link with TIMES-DK was realized are explained. Then the implementation in the model of the energy supply, of the current power generation system, of the domestic power demand, of the future technologies available for power generation, of the electricity transmission grid and of the power exchange is presented. Finally the logic used to model the power exchange with exogenous prices and with endogenous trade process are explained.

Chapter V first describes the baseline scenario and later shows the results obtained running the Norwegian model in both stand alone and hard-linked configuration with the baseline scenario. Then the main differences in the results of the two models are shown and the model validation is presented.

Chapter VI contains the sensitivity analyses on the hard-linked TIMES-NO model performed by running it with various scenarios, regarding different water inflows, power demand projections and availability of new interconnections.

Chapter VII indicates some further improvements of the current model and hopes the addition of the hard-linking of the other Nordic countries.

Chapter VIII contains the conclusions of the thesis.

Chapter **2**

Energy system modeling

2.1 Definition and Purposes

Modelling is a scientific activity that seeks to describe a particular feature of the world, a physical process or a real system in a simplified but also logical and objective way.

Usually models are used when it is impossible or too expensive to create an experiment that would allow researchers to directly measure the results. Even if direct measurement of outcomes from an experiment would be preferable, models are a reliable tool for analyzing the phenomena that take place into the system object of study.

Modelling has a fundamental role in the comprehension and analysis of the behaviour of energy and economic systems. In fact models offer a powerful tool for the assessment of the interaction between the energy sector and the entire economy, in order to analyze how changes in the energy system due either to exogenous interventions of policy makers or to the natural evolution of technologies affect the entire economy.

It is very complicated to take decisions in the energy sector because at the same time many conflicting goals must be pursued and various constraints must be considered. Models can be used to create simplified descriptions of the energy systems and thus allow facing complex problems in a smart and effective way. Therefore such models are a tool commonly used by decision takers and policy makers in problems of optimization, simulation and control.

Models can provide in the long term cost-efficient solutions for the optimal composition and organization of an energy system taking into account a big amount of constraints. They help formulating strategies for the introduction in the market of new technologies and commodities considering the social and environmental implications. Models suggest which technologies should be deployed and which instead should be abandoned in order to meet a certain goal. They allow exploring and determining the economic feasibility of possible energy futures based on different scenarios. Models can be used for comparing the impact of certain energy and environmental policies on the energy systems and for predicting their economic outcomes. They can be used for investigating the causes of policy failures and for determining smart solutions.

2.2 Model generation process

In modelling activities a trade-off between model accuracy, flexibility and manageability should be pursued. In fact, even if adding details improves the model realism, an overly detailed model may be too complex to analyze and control and could give computational time problems; on the other hand, a too simplified model could provide outcomes that are inconsistent with the real world situation object of the study. Therefore it is the modeler's task to identify the most relevant features of a phenomenon in the real world, to establish which aspects can be neglected and which approximations can be made, aiming to get a sufficiently simple and accurate model.

The process that leads to the generation of a model can be summarized in seven key steps:

- Problem definition: the system object of study must be clearly identified and then described in an informal way, may it be graphically or even verbally. In this step the model's purposes and boundaries must be defined
- Observation and data recollection: once identified the object of the study, all the necessary information must be recollected. This part is fundamental, since data relevance deeply influences model's results: even if a model provides a coherent representation of reality, inappropriate input data makes the model's outcomes useless. Moreover data should be recollected and organized rationally
- Model formulation: the system object of study is described in a suitable simplified way by a mathematical programming model using the Operational Research terminology
- Verification: it is necessary to check whether or not the model formulated describes the system accurately. First, the consistency to observed data must be proved: if a model is unable to reproduce the behaviour of the system that it aims to describe, it isn't even reliable to predict future observations. In this case the model shall be modified, verifying it in terms of syntax (the model has been written properly) and semantics (the model really represents the system)
- Solution: once the model has been generated and its consistency verified, an algorithm is required for solving the model and thus for providing a solution oriented to the specified target and consistent with the imposed constraints
- Results: finally the results must be presented, explained and communicated to the rest of the world.

The sequence of steps described above is not linear and it can be interrupted at any point for returning to a previous step. For instance, the critical analysis of the solution may suggest that in the model some important information has been omitted or that there is an error in the formulation of some constraint. This feedback mechanism ensures that whenever an error is detected, it is immediately corrected and then the new proposed solution is analyzed until reaching an acceptable one.

2.3 Classification of energy models

According to the purpose that is intended, many energy models can be used, each one designed to face a particular aspect. The choice of the most appropriate model to use depends, from time to time, on the type of analysis to carry out, on the geographical coverage and on the time horizon. Sometimes, in order to approach the study from its multiple complementary aspects, even a consistent combination of different types of models can be used.

The level of detail for describing the commodities and technologies of an energy system is one of the main differentiating features among energy models and it leads to three major classes: integrated assessment models, macroeconomic models and technology explicit models.

The former class is used to address issues such as long term economic and social impact of the climate change. For this purpose this kind of models are provided of damage functions that correlate climate change with economy. They usually cover the entire global economy and consider a long time horizon. Due to these characteristics, both the macroeconomic model and the energy system description are very simple.

The second class is also defined top-down, due to the fact that it describes the entire energy sector by means of a small amount of equations and variables. The focus is mainly on macroeconomics. Instead, the description of the energy sector loses detail and is less technical: it is represented by production functions that aim to reproduce the dynamics of substitution between the different production factors (labour, capital, resources). Two different types of models are included in this category: macro-econometric models, focused on short to medium term dynamics of adjustment, and general equilibrium models, based on long term equilibrium after adjustments.

The latter class is also defined bottom-up, because a large number of technologies and commodities are used to describe the energy sector. This kind of models aims primarily to provide a technologically rich description of how the energy demand is satisfied. With this aim, existing or under development technologies are carefully characterized along the entire supply chain by means of technical and economical parameters: from raw materials and primary resources extraction and treatment, to conversion processes, then transport and distribution till end-use devices that satisfy the energy services. Some bottom-up models stop their analysis at the final energy step. But including also the end-use devices in the energy system analysis instead allows taking into account the efficiency of the consumption phase.

A typical flow diagram for an energy system is shown in figure 1.

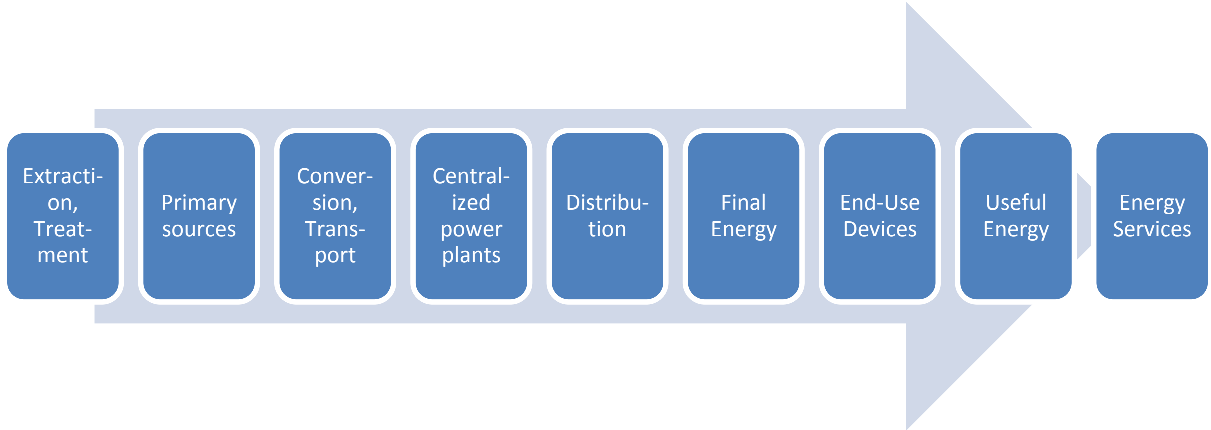


Figure 1: Energy supply chain

On the other hand, in bottom-up models the macroeconomic background remains exogenous and vaguely defined: therefore these models aren't able to consider the energy-economy interactions and thus the effect of technologic evolution on the economic system.

These models are solved calculating a partial equilibrium, which means that the total net surplus is maximized only in the energy sector, while the other economic sectors are not studied (GARGIULO, 2013b).

In order to combine the advantages offered by a careful description of the macroeconomic dynamics with an exhaustive definition of the energy system, it is interesting to link top-down models with bottom-up models. In fact currently great attention is paid by researchers to strengthening the linking between top-down models and bottom-up models.

The concept is that of using the results of a model as input to another model, for instance using the fuel prices given as output by a top-down model as input for a bottom-up model. Then this process is iterated in order to obtain better and more reliable results.

Two kinds of linking are especially studied:

- Hard linking, in which all the information from a bottom-up model are inputs for a top-down model or vice versa
- Soft linking, in which only one or a few results from one model type are input to the other model type.

Still a hard linking between an accurate macroeconomic model and an exact energy system model hasn't been realized, but some soft-linking attempts have been realized, even if usually relative to only one energy sector. Some cases for instances are (MULHOLLAND, 2014) and (COLLINS, 2014).

Although hard and soft linking are still under study, since many years some general equilibrium models include a proper technology disaggregation and a convenient commodities characterization and some partial equilibrium models allow including the effects of some economic dynamics on the energy system.

Examples of this bond are MARKAL and TIMES model generators. MARKAL, for instance, in addition to the possibility of describing in detail an energy system, is also equipped with a macroeconomic part, thus achieving a better integration between macroeconomic evolution and technological development. In TIMES, which represents the evolution of MARKAL, the demand for a commodity is sensitive to the prices of that commodity and at the same time the demand affects commodities' prices. Therefore this model generator represents a useful tool for analyzing the effect of energy-related decisions on the trade of energy commodities. An overview on TIMES model generator is given in the following paragraphs.

2.4 Overview of TIMES

2.4.1 Introduction

TIMES, whose acronym stands for "The integrated MARKAL-EFOM System", is a model generator developed by the Energy Technology Systems Analysis Program (ETSAP), an implementing agreement of IEA (ETSAP, 2005a).

TIMES is a "technology explicit, multi-regional partial equilibrium model generator" (ETSAP, 2005c). It is used for performing local, national or multi-regional energy system analysis and assessments of energy sector dynamics in the middle and long time horizon by maximizing the total surplus (the sum of consumer's and producer's surplus).

Starting from the existing energy technologies, the future available technologies and the availability of primary resources, TIMES determines the operation of the existing equipments, the investment in supplementary capacity or in new technologies and the trade options in order to meet the energy service demand at minimum cost while satisfying the imposed constraints. Therefore TIMES models are extremely suitable for assessing energy and environmental policies and for exploring energy scenarios.

The fact that TIMES is a "technology explicit" model means that energy technologies (defined as any device that produces, transforms, transmits, distributes or uses energy) are deeply described by technical (such as useful life, efficiency, emission factors, capacity and availability factors) and economical (such as investment costs, operation and maintenance costs and variable costs) parameters.

TIMES models are defined multi-regional because in a single model several different regions can be included, each one linked to the other ones by material, energy and financial flows. Since the regions are interconnected, actions and decisions taken in one region affect all the other regions too.

TIMES is said to be a partial equilibrium model because it computes the market equilibrium only in the energy sector: in every period the quantities and prices calculated for the commodities are in equilibrium, which means that for every commodity the quantities produced by suppliers coincide with the quantities demanded by the consumers. Therefore the equilibrium takes place where the supply and demand curves intersect, from which it follows that the market prices are equal to the marginal values in the system. This concept is shown in figure 2:

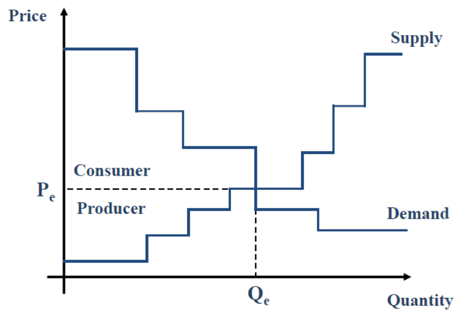


Figure 2: Supply and demand equilibrium (GARGIULO, 2013a)

TIMES assumes competitive markets with perfect foresight: each agent has a perfect knowledge of the market's current and future situation, but alone can't affect the market equilibrium with his actions. This means that the equilibrium is calculated (and therefore that the decisions about investments and operation are taken) in just one step by maximizing the economic surplus over the entire time horizon.

The perfect foresight feature distinguishes TIMES from another widespread partial equilibrium model called BALMOREL, whose inter annual dynamics are myopic (RAVN, 2001). However TIMES flexibility allows switching from perfect foresight to myopic sight, even if the computational time is increased.

The previous assumptions ensure that when supply and demand are in equilibrium the total economical surplus is maximized (or equivalently the net total cost is minimized). Therefore, being the economic total surplus the sum of the consumer's and producer's surplus, it results that TIMES looks for the configuration of the energy system that maximizes the social welfare.

2.4.2 The Reference Energy System

The description of the energy system object of study in TIMES is based on the Reference Energy System (RES), a network diagram that represents the relationship between the main constituents of an energy system, which are:

- Commodities: any good produced, transformed or consumed by technologies. In TIMES they are classified in five groups: energy carriers, material, monetary flows, emissions and energy service
- Technologies (or processes): any equipment that produces, transforms, transmits, distributes or uses commodities. Usually a technology doesn't represent a specific plant, but rather a generic typology of plant. Examples of technologies are mining processes that supply primary resources, conversion processes that transform a commodity into a different one and demand devices that consume commodities
- Commodity flows: the amount of commodity consumed or produced by a certain technology.

Technologies and commodities are represented by nodes (blocs), while commodity flows are the arcs (lines) interconnecting the nodes. An example of RES and of the representation of the main constituents of an energy system is shown in figure 3. As visible from such figure, the typical inputs to bottom-up models are fuel prices, energy service demands and resource availability. Depending on the chain of technologies that compose the energy system the models provide information about energy prices, fuel use, commodity flows, costs and emissions.

Depending on the energy system studied, the RES may cover the whole energy system, showing how primary sources are extracted, then transformed by conversion processes into other commodities, afterward transported and finally consumed by end-use devices. This would make an energy system fully described, but it is not compulsory. In fact the RES and the associated energy system model could just focus on the description of some subsectors of the total energy system.

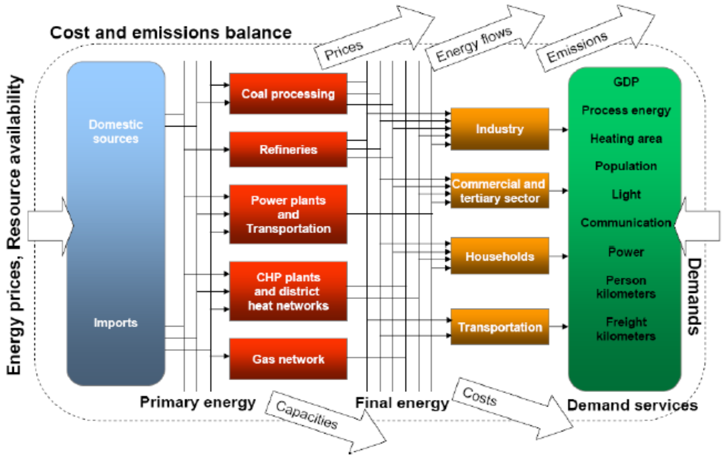


Figure 3: Scheme of Reference Energy System (REMME, 2007)

A TIMES model may include different regions: in this case each region is described by its own RES and the interconnections between the regions are described separately.

2.4.3 Time horizon and time slices

In every TIMES model a time horizon must be indicated. Such time horizon is then divided into various time periods composed by a certain number of years that can also vary from period to period. Usually the first period consists of one single year, of which all the information and values of parameters are known, in order to provide a proper description of the reference scenario and to facilitate the calibration of the model. Then the following time periods have increasing time length.

Time periods can be further subdivided into smaller time periods called time slices. They are used for representing commodities whose characteristics (for instance price, availability, and load) vary sensibly within the year; examples of such commodities are electricity, heat for district heating and wind energy.

2.4.4 Linear programming and optimization

TIMES is not a model by itself but rather a model generator: all TIMES models have the same structure, but according to the data input by the modeler several different models can be generated. The structure of TIMES is built with variables and equations that are derived from the input data. Because of the fact that in TIMES the outputs of a process are linear functions of its inputs and that also non linear functions (such as supply and demand curves) can be represented by a stepped sequence of linear functions, it follows that in TIMES in principle all the equations are linear. This linearity property allows calculating the partial equilibrium as a linear programming problem.

Linear programming problems aim at maximizing or minimizing an objective function linear in the unknowns, at the same time respecting constraints expressed in the form of linear equations and inequalities. The canonical form for linear programming is formulated as follows:

$$\min c^T x$$

$$A x = b$$

$$x \geq 0$$

where c and b are the known coefficients vectors, A is the known coefficients matrix, ^{T} is the transpose operator and x is the vector of decision variables (the unknowns to be determined by the optimization).

The first expression is the objective function, which expresses the criterion to be minimized. The other two expressions are the constraints, which are a set of equations or inequalities containing the decision variables to comply with.

TIMES objective function is represented by the discounted sum of the annual costs of the energy system and must be minimized. First, for every year of the time horizon the sum of the costs occurred in that year is calculated. Then TIMES calculates for every region the total net present value, discounting all the costs of the various years to a selected reference year. They are finally summed into a single cost that is the objective function to be minimized. The mathematical expression of the objective function in TIMES is (ETSAP, 2005b):

$$NPV = \sum_{r=1}^{R} \sum_{y \in YEARS} (1 + d_{r,y})^{REFYR-y} * ANNCOST(r,y)$$

where:

- NPV is the net present value for the total cost of all the regions over all the years
- ANNCOST(r,y) is the total annual cost in region r and year y
- $d_{r,y}$ is the discount rate
- REFYR is the reference year for discounting
- YEARS are all the years over the time horizon for which there are costs, plus past years for which have been defined costs, plus years after the end of time horizon if there are dismantling costs
- R is the set of regions considered in the model.

The main decision variables in the optimization are the activities of the technologies, the investments in new capacity and the flows between the commodities and the processes involved in the energy system object of study.

While minimizing the objective function, TIMES must also satisfy a large number of constraints expressing the physical, technological and economical relationships between the decisions variables and representing the characteristics of the energy system to optimize.

In order to implement such large scale optimization models, TIMES uses GAMS, a high level programming language that allows solving problems with thousands of constraints and variables like those describing energy systems.

In order to manage a TIMES model without inputting and handling data directly in GAMS several tools exist. The most important are the model interfaces VEDA-FE (Front End) and ANSWER for generating, modifying and running a model and VEDA-BE (Back End) and ANSWER for exploring and analysing the model's results.

The model creation process using VEDA is shown in figure 4. The structure and data of the model are input by the modeller to VEDA-FE by means of various Excel workbooks that allow creating, editing and browsing many data in an easy way. VEDA-FE recognises the information contained in the workbooks by means of special key-words and it organizes them in a database.

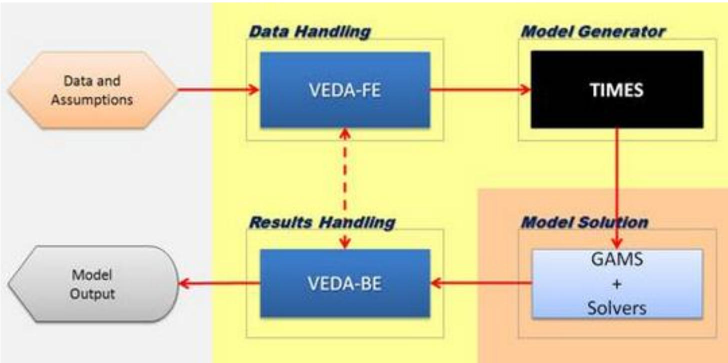


Figure 4: Overview of the VEDA system and TIMES modelling (ETSAP, 2014b)

This database is given as input to the model generator which creates files that are then translated by GAMS into a linear programming matrix containing all the coefficients in a form ready to be associated to the proper variables in the respective equations. The next step is the optimisation: a solver (usually CPLEX or XPRESS) handles the matrix of coefficients and thus finds the optimal solution of the TIMES problem that represents the model. Finally GAMS generates a .vd file that is input to VEDA-BE, the interface that allows handling the results and creating tables and graphs.

2.4.5 Comparison between TIMES and MARKAL

As already said, TIMES isn't the only available tool for carrying on an energy system analysis: also Balmorel, EMPS, MARKAL and many other models exist (CONNOLLY et al., 2009). Models generated using MARKAL and TIMES share the main basic features: both are partial equilibrium, technology explicit, multi-regional models in which the optimization is carried out by maximizing the net total surplus (ETSAP, 2014a). However, TIMES represent the evolutionary replacement of MARKAL, offering a more flexible and easier modelling frame (ETSAP, 2005b).

Primarily TIMES with respect to MARKAL adds the possibility to use flexible time slices for any commodity and process, to create time periods of variable length, to model the building and decommission phase of the facilities and to vintage processes.

All these features allow reaching a better modelling of the real-life processes that take place in the energy system considered, to give a more realistic description of the investment and at the same time to interact with the model in a more flexible way. However, on the other hand it must be considered that the computational time in TIMES is increased with respect to MARKAL.

Chapter **3**

Nord Pool power market

3.1 Overview of the Nord Pool

Nord Pool has been the first electrical energy trading market of the world. Currently it is the world's largest market for trading power and the main marketplace for buying and selling power in the Nordic and Baltic countries. In fact more than 70% of the total power trade in the Nordic regions takes place in the Nord Pool (BJEORNDAL et al., 2012).

The countries in which it operates are illustrated in figure 5.

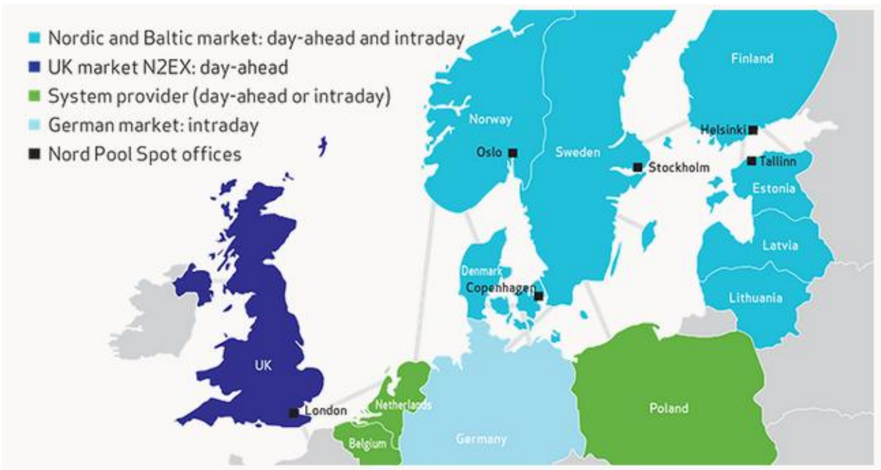


Figure 5: Nord Pool area (NORD POOL, 2015c)

Since the purpose of this thesis is that of modelling in TIMES the interaction and trading dynamics between the Danish and the Norwegian electricity system, in the description of the operation of the Nord Pool market the focus will be kept on the Nordic regions rather than on the Baltic area.

Since the beginning of the ‘90s electricity markets in the North of Europe underwent big changes that led to their liberalization: the state stopped managing both power production and power trading and the free competition principle was introduced (NORD POOL, 2015b).

The Norwegian power market was the first in Europe to be deregulated: in 1991 through the Energy Act (MINISTRY OF PELTROLEUM AND ENERGY, 1990). Later also the power markets in the rest of the other Nordic countries were deregulated. This liberalization process led to the integration of the Nordic countries in one common Nordic wholesale power market, called Nord Pool. Estonia, Lithuania and Latvia liberalized their electricity markets in the late 2000s and afterwards became members of the Nord Pool as well.

The purpose of liberalizing the power market was to encourage the competition between the market agents, so as to increase the efficiency of the entire system: in the short term the increase in efficiency consists in a more intelligent use of the production resources and in the long term in a better development of the electricity system. Liberalization implies higher gains for the producers from the improved efficiency and lower electricity prices for the consumers: therefore this market model serves the society well.

A market based operation of the electricity system ensures that the demand is covered by the cheapest generators, respecting the principle of merit order dispatch. This, together with the fact that producers offer at marginal cost, leads to the system’s highest possible efficiency and competition and therefore to the lowest costs in the long period.

Integrated markets strengthen security of supply and ensure a more efficient use of the energy resources. In fact, the larger the region covered by the market, the more flexible the energy system is, due to the larger available power capacity and therefore higher reserves. Moreover, the higher the number of agents trading, the more liquid and trustworthy the market is. Currently Nord Pool is the largest power market by number of members: 370 companies including power producers, industries and trading company participate (NORD POOL, 2015c).

Nord pool is owned by the Nordic and Baltic transmission system operators (TSOs), as illustrated in figure 6.

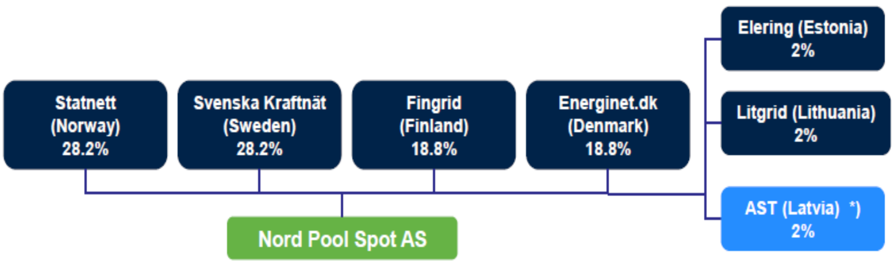


Figure 6: Nord Pool owners (NORD POOL, 2013)

Nord Pool as a company is registered in Norway, so it’s subject to Norwegian laws and authorities. The regulator is the Norwegian Water Resource and Energy Directorate (NVE), which establishes levels of maximum profit for the generators: this ensures certain electricity price stability and above all prevents power prices to rocket.

Regulatory activities in the countries in the Nordic area are carried out by the TSOs in such a way as to ensure the security of supply at the lowest possible cost and at the same time respecting the environment. The TSOs are non-commercial organizations, neutral and independent with regard to the market members (NORD POOL, 2015d). This ensures that regulatory activities are carried forward in accordance with the principles of transparency, equality (all agents have access to equal information) and competition. These principles constitute the prerequisite for a well operating and efficient electricity system.

3.2 The power market

Nord Pool Spot market is a volunteer, one-hour, one-day-ahead, double-auction market. This means that once a day potential sellers submit their offers and prices and simultaneously potential buyers submit their demands and prices for every hour of the day-ahead. Afterwards, by matching the purchase and sale bids the market clearing price and volume is identified: all the sellers who had requested less than the equilibrium price sell and all the buyers who had offered more than the equilibrium price buy at this price.

Since prices and quantities to produce are calculated for the day-ahead, there is a wide time span between the price setting and the delivery of the electricity (36 hours at the most) during which changes concerning production and consumption may occur. Therefore agents are given the possibility to change their position in the market in the intraday market and close to real time in the balancing market.
The temporal sequence of the day-ahead, intraday and balancing market is shown in figure 7.

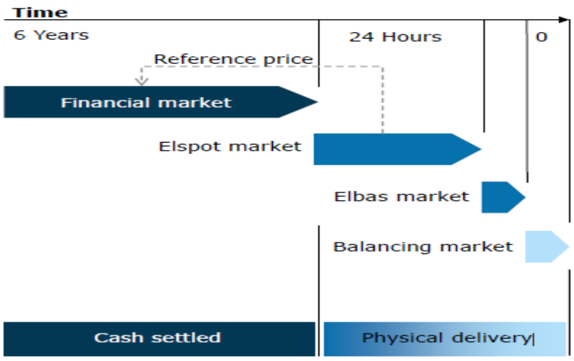


Figure 7: Nord Pool schedule (NORD POOL, 2013)

3.2.1 Day-ahead-market

The day-ahead market, denominated Elspot, is the basis of the Nord Pool market: here trades are mandatory for the market participants. In Elspot the vast majority of electricity is traded, from 36 up to 12 hours before the physical delivery. Participants are mostly power producers, distributors, industries and brokers.
Elspot operates in Norway, Sweden, Finland, Denmark, Estonia, Latvia and Lithuania and currently there are more than 360 agents participating in the Elspot (NORD POOL, 2015a).

Every day buyers assess how much energy they will need the following day, hour by hour and how much they are willing to pay, while sellers decide how much energy they can produce the day after and at what price hour by hour. Then, by 12.00 producers and consumers submit to the Nord Pool the quantities they are willing to buy or sell in each hour of the next day together with the prices. Afterwards all the bids and the offers are grouped together in the aggregated supply curve and the aggregated demand curve.

For every hour of the day the system price is calculated at the intersection of such curves, as is shown in figure 8.

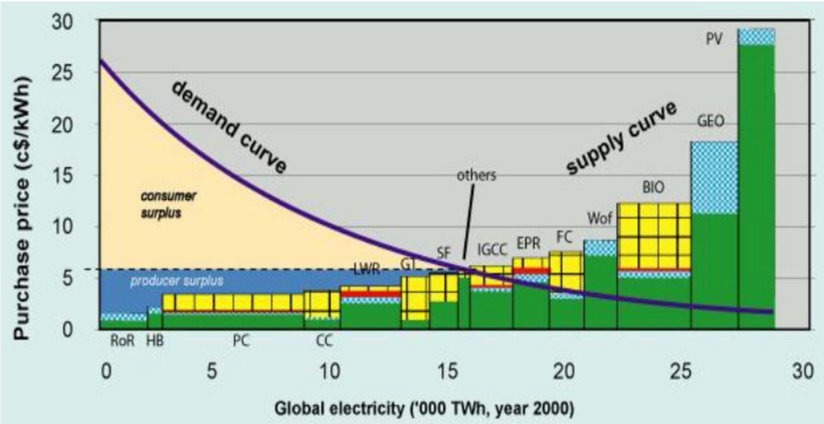


Figure 8: Power demand and supply curves (GARGIULO, 2013a)

Prices represent the marginal cost of the most expensive power generator that needs to be operated to meet the demand every hour. The equilibrium price is valid for all the buyers and sellers whose bids are at the left of the equilibrium point. This trading method is called “equilibrium point trading”.

Every day at 15.00 consumers know how much electricity they are going to be dispatched and producers know how much electricity they are required produce the following day. This timescale also fits to thermal power plants, giving sufficient time to program the production and to verify the technical feasibility of ramping the production up or down.

There are four types of bids at Nord Pool Spot. These are hourly bids for individual hours, which may be accepted only in part, block bids that specify quantities for more hours and have to be accepted or refused as a whole, linked block bids, where the acceptance of one block depends on the acceptance of another and, finally, flexible hourly bids, which are sell bids valid for all the hours but that can be accepted in maximum one hour Pool (NORD POOL, 2015c).

The average Nordic System price in 2013 in Elspot was 38.10 €/MWh (NORDREG, 2014). This represents an increase of 22% with respect to 2012, mainly due to reduced availability of water in the hydro reservoirs.

3.2.2 Intraday market

Even if the majority of the balance between electricity demand and supply is ensured in Elspot market, also an intraday market exists, denominated Elbas (Electricity Balance Adjustment System).

Elbas is a continuous market, which means that power trading occurs every day of the week and every hour of the day up to 60 minutes before the delivery. Here the traded products are one hour long power contracts that have been established in Elspot.

When trading closes on the day-ahead market, the agents can continue exchanging power in Elbas, even if the participation to this market is not obligatory.

Since between the closing of Elspot and the physical power delivery incidents to power plants or to electric grids may occur, Elbas market was conceived for providing to the agents the possibility to fulfil their commitment regarding electricity dispatchment as established by the Elspot clearing before resorting to the balancing markets, whose prices are generally the highest.

Elbas provides direct access to the same countries participating in Elspot but in addition includes Germany, Belgium and the Netherlands.

In 2013 the total volume traded in the intraday market was 6139.2 GWh (NORDREG, 2014), representing about 2% of the overall consumption.

3.2.3 Balancing market

A part from Elspot and Elbas a third electricity market exists, denominated balancing market. This is not part of the Nord Pool exchange, but instead it is managed by the TSOs.

The purpose of such a market is to be able to cope with last minute deviations from forecasted balance between supply and demand: it is activated when it’s too late for agents to bring supply and demand back in balance in Elbas and it can operate up to 15 minutes before delivery.

Minor imbalances are automatically managed by means of frequency reserves, while major imbalances must be handled by means of reserve capacity. In this way the TSO ensures a reliable and sustainable operation of the electricity system.

All the reliable power plants that after the market clearing still have residual available capacity can participate to the market. They submit to the local TSO the quantity of extra power that they are able to generate at short notice at a certain time and its price if the electricity demand rises. They also submit the share of planned production they can stop generating at short notice and its price if the demand decreases.

The balancing market sets a price for upward and downward regulations.

When it is necessary to up regulate, the TSO buys the quantity needed from the generator that offered to produce extra power at the lowest price: he is paid the extra production with the price he asked. When it is necessary to down regulate, the TSO gives the order to reduce the production to the generator that offered to buy the surplus to the TSO at the highest price. In this case the price is paid to the TSO by the producer that reduces the production.

In some cases also consumption can be used for balancing the electricity system.

In 2013 the total volume traded in the balancing market in the Nordic region was 4197.2 GWh (NORDREG, 2014), representing about 1% of the overall consumption.

3.3 Bidding areas

The Nordic and Baltic countries auctioning in the Nord Pool are divided into several bidding areas linked with interconnectors controlled by the TSOs. The partition of the market area in bidding areas is a method for managing the congestion of the electricity grid.

The number of bidding areas in which a country is divided into is established by the local TSO, which makes a trade-off. In fact on one side finer bidding area delimitation ensures that the regional price reflects the condition of the local transmission grid and allows handling transmission grid congestions inside one country without moving the internal limitations to the border; On the other hand rougher bidding area delimitation ensures more competence and more liquidity in the market.

The map of North Europe split in bidding areas is shown in figure 9

Figure 9: Nord Pool bidding areas (NORD POOL, 2015c)

As visible from figure 9 Norway is divided into five bidding areas (denominated by the alphanumeric codes NO1, NO2, NO3, NO4, NO5), Denmark is treated as two bidding areas representing the Western and Eastern parts (called DK1 and DK2 respectively), Sweden is divided in four bidding areas (SE1, SE2, SE3, SE4) while Finland, Estonia, Lithuania and Latvia constitute one bidding area each (FI, EE, LT, LV).

Before the market agents submit their bids to the Nord Pool, the TSOs inform them about the transfer capacity availability between the different areas. This is an important feature of a liberal market because it ensures that all the market members are treated equally and no privileges regarding the allocation of interconnectors' capacity are assigned.

3.4 Area prices

When all the market participants have submitted their bids, the demand and supply of all the bidding zones are aggregated in the two cumulative curves, as shown in figure 10. Then the equilibrium is calculated for the whole market for each hour. The market clearing is realized by the Nord Pool Spot by means of market splitting with implicit auctions: this means that transmission capacity and electricity are not auctioned separately, but instead are combined in one simultaneous auction covering all the bidding regions. In this way the shares of interconnector capacity are implicitly allocated to the market agents in such a way as to optimise the power flow between several bidding areas (NORD POOL, 2014).

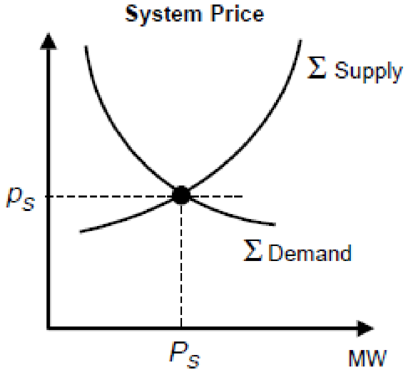


Figure 10: Market clearance without grid transmission restriction (BAKKEN & HAUGSTAD, 2004)

If the transmission capacity limits of the interconnectors imposed by the TSOs are higher than the calculated power flow between the bidding areas, then all the bidding areas are treated as one and there is only one price over the entire market. This is equal to the Nordic System Price (NSP), which is computed from the sale and purchase bids disregarding the available transmission capacity between the bidding areas.

If any of the calculated flows between the bidding areas exceeds the transmission capacity limit, grid congestion occurs and the flows must be adjusted.

Due to bottlenecks in the grid, some bidding areas can assume different prices and thus the market area is divided into price areas, defined as groups of one or more bidding areas with common price.

Whenever a bottleneck occurs, supply and purchase bids are aggregated in purchase and supply curves for every congested bidding area. In order to relieve the congestion the TSO adds in the surplus area a price independent demand equal to the trading capacity of the interconnector between the price areas, thus shifting the demand curve toward right. After that the TSO adds the same volume in the deficit area as a price independent supply, thus shifting the supply curve toward right. This procedure is shown in figure 11.

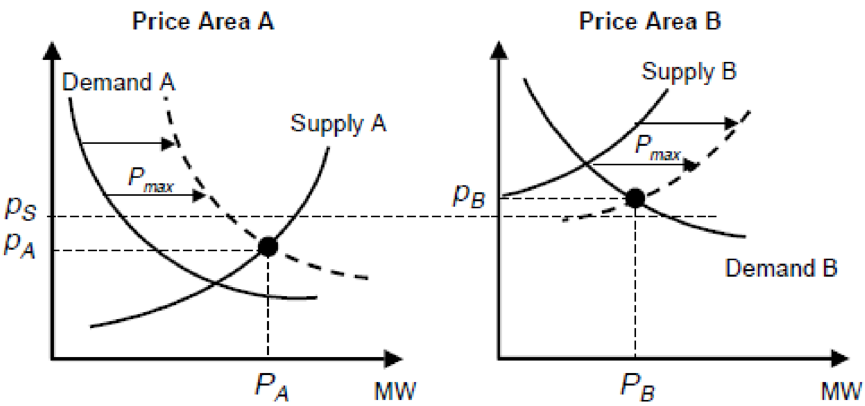


Figure 11: Market clearing with transfer restriction (BAKKEN & HAUGSTAD, 2004)

Compared to the unrestricted system price, using this procedure the TSO manages to decrease the price in the surplus area, thus decreasing the supply and increasing the demand and at the same time manages to increase the price in the deficit area, thus reducing the demand and increasing the supply. Moreover the price difference between the zones is reduced.

Bidding areas delimitation allows identifying the issues concerning the grid capacity and where production lacks. It also helps the TSO reducing the congestion in the grid in the day-ahead market, without having to redispatch or countertrade electricity in the balancing market. Therefore market splitting in bidding areas is an efficient method to handle regional grid congestions.

The number of price areas changes every hour. The minimum number of price areas is one: in this case the system price would be the only price throughout all the bidding areas. Instead the maximum number of price areas is equal to the number of betting areas and it happens when there are bottlenecks between all the bidding areas. In this case the system price is different than those in the price areas.

3.5 Electricity prices

As it has been explained in the previous paragraph, due to bottlenecks in the interconnectors linking neighbouring bidding areas, the Nordic electric system is often divided into areas characterised by different prices.

The average prices in the different bidding areas in 2013 and the difference with respect to 2012 are shown in figure 12.

Spot prices €/MWh	2013	Change from 2012
East Norway (NO1)	37.56	27 %
South West NorwayNO2)	37.33	28 %
Mid Norway (NO3)	38.96	24 %
North Norway (NO4)	38.60	24 %
West Norway (NO5)	37.60	30 %
Sweden Luleå (SE1)	39.19	24 %
Sweden Sundsvall (SE2)	39.19	23 %
Sweden Stockholm (SE3)	39.45	22 %
Sweden Malmö (SE4)	39.93	17 %
Finland (FI)	41.16	12 %
West Denmark (DK1)	38.98	7 %
East Denmark (DK2)	39.61	5 %

Figure 12: Bidding areas average prices in 2013 (NORDREG, 2014)

The largest change in prices from 2012 to 2013 occurred in Norway and Sweden. In fact the bad hydrological situation that characterised 2013 affected strongly these two countries where hydro is a dominant power generation technology.

Prices in the bidding areas reflect the production costs of the generation technologies installed there and the availability of resources for hydro plants and wind mills. In fact some of the main price drivers are:

- Weather: if the temperature is low the demand rises causing an increase of prices. This is especially true in Nord Pool because in the Nordic area, due to the relatively low historical electricity price, many houses are heated electrically
- Ratio between demand and supply
- Interconnectors transmission capacity: congestion creates lock-in-effects
- Status of hydro reservoirs in Norway
- Wind speed in Denmark
- CO_2 credits in the global market: affect the offers of fossil fuelled power plants, which often are the marginal technologies in the supply curve and thus establishing the equilibrium price.

In figure 13 the percentages of the number of hours with equal prices in 2013 are shown.

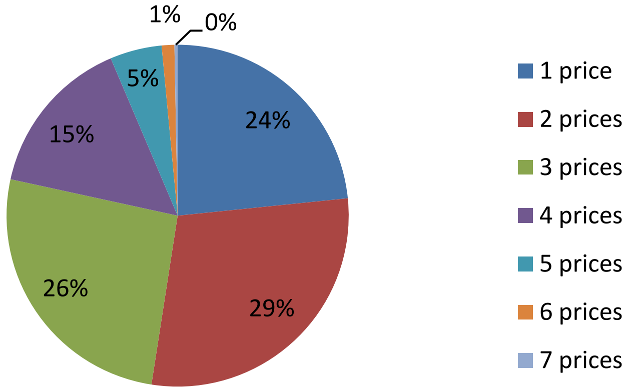


Figure 13: Number of prices share in 2013 (NORDREG, 2014)

As shown in figure 13in 2013 there was one common price over the entire Nordic area for just 23.4% of all the hours. For more than 50% of the year there have been just two prices over the entire Nordic region even if in some rare moments seven different prices existed.

3.6 Interconnectors

In the Nordic area the interconnectors between countries are owned and operated by the TSOs. Interconnectors are a very important component of the electric system, especially in the context of a greater integration of the European electricity market and of a greater share of renewable energies in the national production mix. They represent an essential prerequisite for the successful integration of an increasing volume of variable power sources such as wind in the electricity system. In fact they expand the trading area, allowing excessive wind power or excessive water in the hydro reservoirs to be transported throughout a wider region. In this way the surplus of environmentally friendly energy is not wasted but instead its value is increased, while electricity prices in the regions where it flows decrease.

As already said in the previous paragraphs, the capacity of the domestic interconnectors (those between Nordic countries) is allocated by means of implicit auction in the Elspot market. Trading capacity of external interconnectors (interconnectors between the Nordic region and the neighbouring countries that don't participate in Elspot market) is subject to explicit auction through North-Western-European market coupling.

The map of the internal and external interconnectors between the Nordic and Baltic countries, together with their maximum net transfer capacity is shown in figure 14.

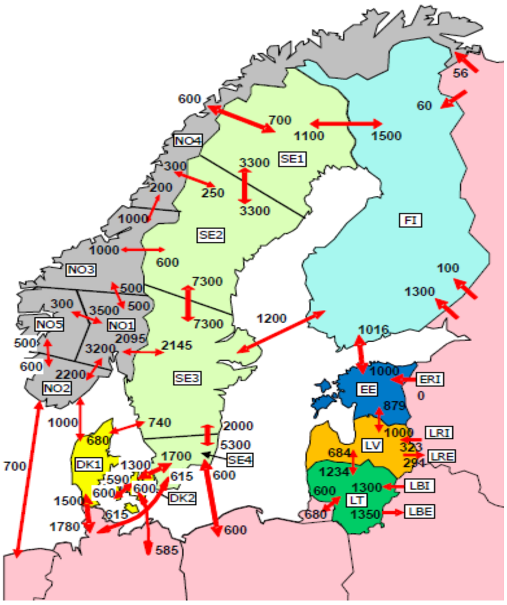


Figure 14: Maximum net transfer capacity in MW, valid from 3rd July 2014 (ENTSOE, 2015)

Interconnectors are especially important in the Nord Pool, since Denmark makes high use of wind energy and according to the Danish Ministry of Climate, Energy and Building (MINISTRY OF CLIMATE ENERGY AND BUILDING & DANISH ENERGY AGENCY, 2012) is intended to increase the share of wind energy in the energy mix. When Danish wind farms generate more power than required, surplus power is often transmitted through the interconnectors to Norway or Sweden, which therefore can draw less from their water reservoirs. When the wind reduces, the Northern hydro power plants increase production, transmitting green power to Denmark.

The cross-border power flow between Nordic countries in 2011, 2012 and 2013 is shown in figure 15. The highest cross-border energy flow in 2013 was that from Sweden to Finland and its value was of almost 13 TWh.

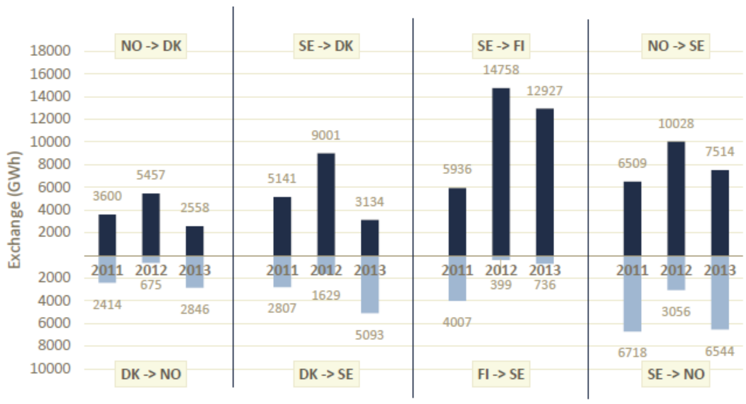


Figure 15: Power flows between Nordic countries in 2011, 2012 and 2013 (NORDREG, 2014)

In October 2013, Thema Consulting Group was commissioned by the Swedish Ministry of Enterprise, Energy and Communications and by the Nordic Council of Ministers a study on prices in the different bidding areas of the Nord Pool (THEMA CONSULTING GROUP, 2013). In particular the study contains an historical analysis of price differences between the Nordic region bidding zones: the data used cover a time span that runs from November 2011 until September 2013. The percentage of hours with the same price is shown in figure 16.

	SE1	SE2	SE3	SE4	NO1	NO2	NO3	NO4	NO5	FI	DK1	DK2
SE1	100.0 %	98.8 %	95.5 %	86.6 %	60.7 %	53.6 %	87.8 %	82.9 %	56.1 %	73.1 %	57.8 %	65.4 %
SE2	98.8 %	100.0 %	96.7 %	87.7 %	61.7 %	54.6 %	86.6 %	81.6 %	57.1 %	73.2 %	58.5 %	66.0 %
SE3	95.5 %	96.7 %	100.0 %	90.0 %	62.3 %	55.0 %	84.2 %	79.7 %	57.6 %	74.5 %	60.8 %	68.1 %
SE4	86.6 %	87.7 %	90.0 %	100.0 %	57.8 %	50.7 %	76.6 %	72.9 %	54.1 %	67.0 %	63.0 %	75.5 %
NO1	60.7 %	61.7 %	62.3 %	57.8 %	100.0 %	89.6 %	58.7 %	56.2 %	86.5 %	47.9 %	44.5 %	46.5 %
NO2	53.6 %	54.6 %	55.0 %	50.7 %	89.6 %	100.0 %	51.8 %	49.3 %	80.0 %	42.7 %	45.0 %	44.4 %
NO3	87.8 %	86.6 %	84.2 %	76.6 %	58.7 %	51.8 %	100.0 %	91.8 %	54.6 %	64.1 %	51.3 %	58.6 %
NO4	82.9 %	81.6 %	79.7 %	72.9 %	56.2 %	49.3 %	91.8 %	100.0 %	52.3 %	61.4 %	48.7 %	56.2 %
NO5	56.1 %	57.1 %	57.6 %	54.1 %	86.5 %	80.0 %	54.6 %	52.3 %	100.0 %	43.7 %	41.6 %	43.2 %
FI	73.1 %	73.2 %	74.5 %	67.0 %	47.9 %	42.7 %	64.1 %	61.4 %	43.7 %	100.0 %	47.9 %	53.6 %
DK1	57.8 %	58.5 %	60.8 %	63.0 %	44.5 %	45.0 %	51.3 %	48.7 %	41.6 %	47.9 %	100.0 %	83.0 %
DK2	65.4 %	66.0 %	68.1 %	75.5 %	46.5 %	44.4 %	58.6 %	56.2 %	43.2 %	53.6 %	83.0 %	100.0 %

Legend: above 95 % · above 90 % · above 80 % · below 80 %

Figure 16: Percentage of hours with the same price from 2011 to 2013 (25)

Since equal prices between two or more bidding areas mean that no congestions are occurring, figure 16 provides information about which interconnectors are most frequently congested. In the three northern zones of Sweden (SE1, SE2, SE3) prices have been very similar for more than 95% of all hours, while prices in SE4 have been equal to those of the others Swedish bidding areas only for about 87% of all hours. Prices in NO3 and NO4 were equal for 92% of hours.

Prices in Denmark and Finland are more rarely equal to those of the other Nordic regions.

During 2013 the most congested interconnections between the Nordic countries were the following (the time of congestion is given as a percentage of the total hour in a year): NO2-DK1 (62.5%), NO1-NO3 (54.5%) and NO1-SE3 (52.1%) (NORDREG, 2014).

Regarding the exchange with the neighbouring countries, in 2013 13.1 TWh were imported and 11 TWh were exported by the Nordic region, thus resulting in a net import of 2.1 TWh. Imports and exports disaggregated into countries are shown in table 1.

Table 1: Power exchange with neighbouring countries in 2013 (TWh)

	Russia	Poland	Netherlands	Estonia	Germany	Total
Export	0	1	4.2	1.5	4.3	11
Import	-4.8	-0.8	-0.2	-0.5	-6.8	-13.1
Net	-4.8	0.2	4	1	-2.5	-2.1

In the last years the NSP has been lower than the electricity price of other European markets. This creates a precondition for making the Nordic countries strong net exporters of clean energy toward Central Europe in the future. This possibility has been deeply studied in (IEA & NORDEN, 2013). According to this study, together with a low electricity price the main driver of such a high export from the Nordic region toward Central Europe is the improvement of the transmission infrastructure. In fact in all the scenarios analyzed in the study, around 40% of the absolute cumulative investment is linked to the electricity transmission network and in particular to the interconnectors linking the Nordic area with Central Europe.

To conclude, investments in increasing the transmission capacity of one interconnector reduce the local bottlenecks probability, but also affect the power flows through the rest of the interconnectors of the system and can increase or decrease bottlenecks in other interconnectors of the system. Therefore the upgrading or creation of new interconnectors is a delicate issue that should be studied and modelled in detail before being realized.

The model of the Norwegian power system described in the next chapter represents a valuable tool that in the future, when integrated with the model of the rest of the Nordic countries, can be used for planning such interconnectors' expansion.

Chapter **4**

TIMES model of the Norwegian power system

4.1 Introduction

In the Nordic power system many generating sources are used, mainly hydro, nuclear, fossil, biomass and wind. In years with average rain and snow fall, hydro is the dominant energy source, accounting normally for more than half of the total generation. Wind currently accounts for only 6%, but the generated power is increasing with a rate of about 20 % or 4 TWh per year.

The breakdown of power generation by sources in 2013 is illustrated in figure 17, which witnesses the high share of renewable in the Nordic system.

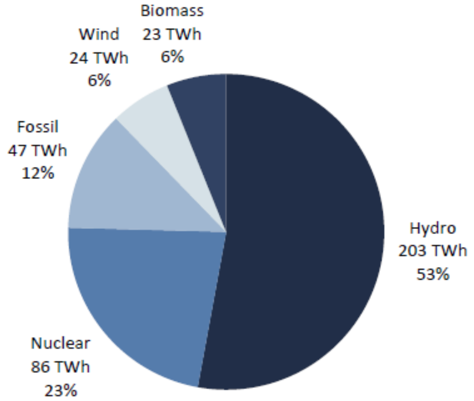


Figure 17: Power generation by power source in the Nordic regions in 2013 (NORDREG, 2014)

The sources indicated in the figure above are not equally distributed between the different Nordic countries, but instead power systems differ greatly from one country to another. In fact in Norway power is produced using almost exclusively hydro, while Sweden and Finland mainly produce power with a mix of nuclear and hydro. Denmark doesn't have any nuclear power plant installed in its territory and makes high use of thermal power plants, but wind power is becoming increasingly important.

In 2013 the total power production in Norway, Sweden, Finland and Denmark was 380 TWh and the total consumption was 380.5 TWh. Such consumption is divided between the four Nordic countries in the following way: Sweden consumed 137.5 TWh, Norway 128.1 TWh, Finland 81.4 TWh and Denmark 34 TWh. The figure below gives an idea of the supply curve in the Nord Pool market and of the equilibrium between demand and supply.

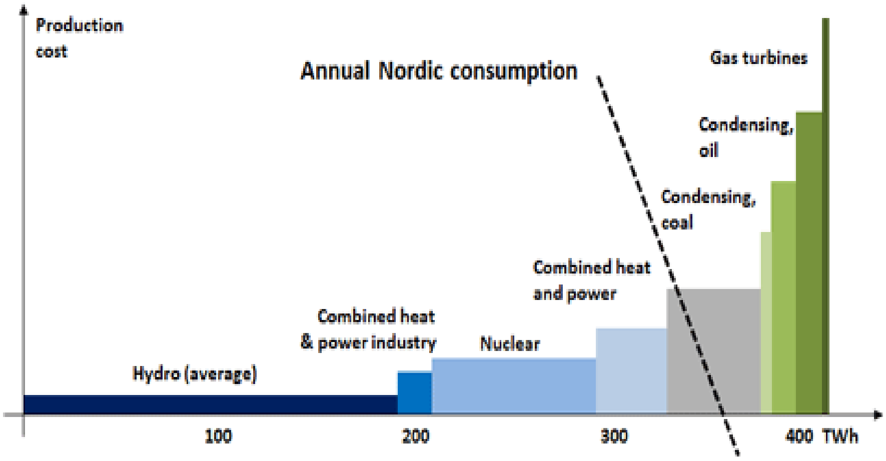


Figure 18: Supply curve in the Nord Pool market

The load isn't constant over the seasons or over the day: it decreases by night and peaks in the early morning and in the afternoon. In the past the highest peaks of the year occurred during winter, when the temperature is lower (the traditional cheap electricity prices in the Nordic countries have made that many homes are heated electrically).

The annual inflow to the hydroelectric reservoirs of the Nordic countries may change up to ±70 TWh from one year to the next. In periods of adequate rainfalls and snowfalls the water level in the reservoirs is kept high, hydro plants can make cheap bids in the spot market (as shown in figure 18) and therefore they access the market clearing and make power prices being low. In case of abundant rain falls, in order to avoid the spillage of water, power is offered in the market at very cheap price. In this situation the power surplus is transmitted from Norway and from the other Nordic countries with high hydropower share to the southern regions. When the water levels in the reservoir are low instead the generation by hydroelectric is substituted by thermal power plants; these plants are shifted toward left in the supply curve, causing a higher market price. In this situation there will be a net power flow from the Southern countries toward the Northern regions.

From what has been said it is clear that in the Nordic countries power prices strongly depend on the rainfall levels and on the availability of interconnectors between countries. Also the possibility of relaying on hydropower as a backup to the unpredictable wind power production depends on the availability of water in hydroelectric reservoirs. About 62% of the total hydropower capacity in the Nordic countries is installed in Norway (NORDREG, 2014), which is also already electrically interconnected with Denmark and is part of the same power market.

In order to explore the future power exchange between Norway and Denmark and to assess the power exchange dynamics in different scenarios a TIMES model describing the Norwegian power system has been created.

The TIMES-Norway model is built in such a way that it can be run both in standalone mode and linked with the pre-existing TIMES model of the Danish energy system created by the Danish Energy Agency, ESA department and E4SMA. This was possible by using a structure for TIMES-Norway model that is consistent with the one of the TIMES-Denmark model.

When the Norwegian model is run in standalone mode all the power trading prices are exogenously given to the model, while instead when the model is run linked with the Danish model the interconnection between these two countries is described as an endogenous trading process and the trading prices are endogenously computed by the model.

Moreover various scenarios have been created in order to perform sensitivity analyses. Some scenarios depict different water inflows to the Norwegian hydro reservoirs and allow assessing how the power exchange between Norway and the interconnected countries varies according to the water availability. Also a scenario with a different power demand projection was generated in order to observe how the demand affects the Norwegian power production and power exchange. Finally the eventuality of not installing the new planned interconnections between Norway and the interconnected countries is explored.

In the following paragraphs the description of the Norwegian TIMES model is given. First its structure is presented and the operation of the hard-link with TIMES-DK is explained. Then the implementation in the model of the energy supply, of the power generation system and of the power demand is described. Afterwards the future technologies available for power generation and the domestic and external power transmission grids are presented. Finally the computation of the power exchange both when it is based on exogenous price criteria and when the power prices are endogenously calculated by the model is explained.

4.2 Model structure

4.2.1 Time slices

In order to run the TIMES model of Norway together with the TIMES model of Denmark, the same time structure must be adopted: so the Norwegian model uses the same as that of the Danish model. In the TIMES model of Denmark each time slice represents a set of hours with similar characteristics:

this implies that the time structure of the model is not in chronological order. This decision was taken by the ESA researchers in order to properly represent intermittent power generation and at the same time minimizing the computational time (GARGIULO et al., 2013).

First the years were divided into the four seasons, then into working day (WD) or not working day (NW) and finally each hour of the year was allocated to one of the following classes, which represent critical combinations of renewable energy production and power demand in Denmark:

- High wind availability, low power demand (A)
- High power demand, low wind availability (B)
- Photovoltaic peak (C)
- Rest of hours (D)

This division ends up with making the time structure of the model divided in 32 time slices. Figure 19 shows the acronyms of the time slices in summer.

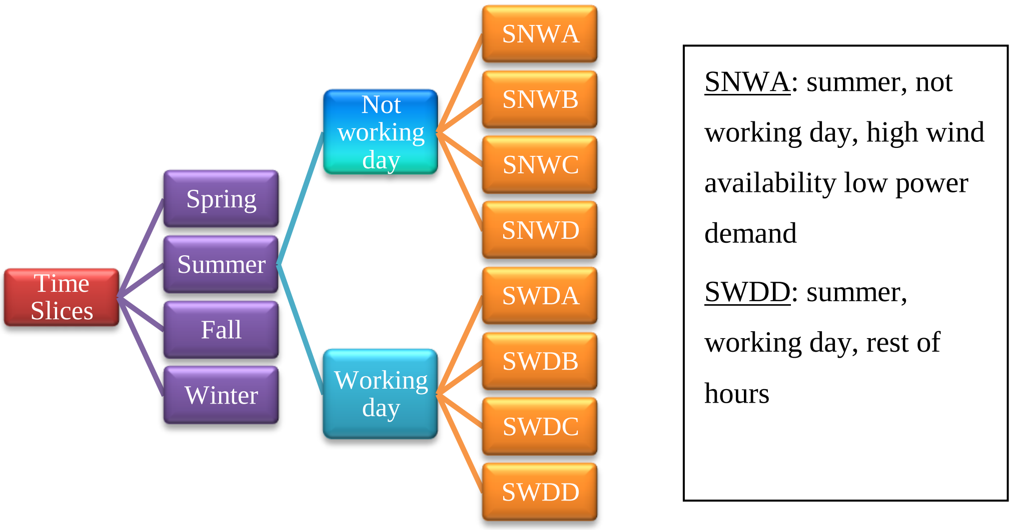


Figure 19: Time structure acronym example

The allocation to the proper class is done using a workbook called “Time Slice Tool”, which groups each hour of the year into 32 time slices by comparing the time profile of the energy content of Danish photovoltaic, wind and demand with some user-established thresholds. A detailed explanation of how “Time Slice Tool” works is given in (LARSEN H. V.).

The 32 time slices group hours that are not in chronological order. Moreover each time slice aggregates different number of hours.

The time structure of the model is described in the workbook called “SysSetting”, which in general contains the settings of the model. Here is declared the division in seasons, working and not working day and in the critical combination A,B,C,D. Moreover though the attribute “YRFR” it is also described the time fraction of each time slice, as visible in the figure below.

Table 2: Year fraction of some time slices

TimeSlice	Attribute	AllRegions
RWDA	YRFR	0.1%
RWDD	YRFR	13.2%
RWDC	YRFR	1.3%
RWDB	YRFR	2.4%
RNWA	YRFR	0.1%
RNWD	YRFR	7.3%

4.2.2 Base year

As for the time slices structure, the same base year (BY) as the Danish TIMES model has been adopted: 2010. This implies that the parameters and characteristics of the energy system described in the model must relate to 2010. For the calibration of the TIMES model of Norway many statistical values were taken from the Norwegian Water Resource and Energy Directorate (NVE). In particular the energy balance and energy production from (NVE, 2010) and (NVE, 2011a), the power demand from (STATNETT, 2015a), the installed capacity sorted by typology from (STATISTICS NORWAY, 2010).

4.2.3 Model periods

Norway TIMES model covers a time period from 2010 to 2050. This time horizon is divided into ten time periods of different duration. In order to calibrate the model the first period includes only 2010, the second period covers three years, the third period covers four years and all the following periods cover five years. The milestone years are: 2010, 2012, 2015, 2020, 2030, 2040 and 2050.

There is also the possibility to run the model with a shorter time horizon, till 2030.

4.2.4 Geographic region

The model describes Norway as one single region. This spatial resolution doesn't allow analysing the power exchange and the bottlenecks inside Norway (which means between the five bidding areas in which Norway in the Nord Pool market is currently divided), nor to catch the differences of hydrology, wind potential and demand among the Norwegian counties. Instead the TIMES model of Norway generated by IFE divides the country in five regions and allows identifying bottlenecks between the five bidding areas (INSTITUTE FOR ENERGY TECHNOLOGY, 2013). Many reasons have led to choose one-region as geographical focus for the model. The main one was that the Norwegian TIMES model was created mainly to be run together with the Danish model, which remains the core and the focus of the analyses. The single-region modelling of Norway is adequate to analyse the global electricity exchange between Norway and the other Nordic countries and the need for new interconnectors, but still keeps the model size manageable. Another important reason was the difficulty to find data related to the single counties: some of this information is held by NVE but are in Norwegian while a lot of information is completely missing so that too many assumptions would have been necessary.

Moreover a linkage between the Norwegian and Danish TIMES models has been realized. The two models can be run at the same time creating a resulting three-region model where Norway, Denmark West and Denmark East are electrically interconnected.

A further improvement of the model would be to model the other two Nordic countries members of the Nord Pool -Sweden and Finland- and to integrate them in a final five-region model.

4.2.5 Interaction with the Danish model

VEDA, the interface used to work with the TIMES model generator, is equipped with a functionality that allows to link more models and to run them together as a single model (KANORS, 2013).

In order to do this a third model denominated “TRADE” was generated. In this model an endogenous trading process between Denmark West and Norway was created, containing all the parameters related to the corresponding interconnector. In “SysSettings” the three regions NOR, DKW and DKE are defined, the same time structure as the other two models is described and all the currencies used in the linked models are listed. In particular the main currency is the Danish Crown 2010, which means that different currencies are converted to this unit. Moreover a workbook that defines the commodity electricity (“ELCC”) was included.

Then in the Norwegian and in the Danish models a scenario workbook was created, denominated “Scen_KILL-ELCC_IMPEXP_DK” in the Norwegian model and “Scen_KILL-ELCC_IMPEXP_NO” in the Danish one. Such scenario resets the activity of the process related to the interconnection between the two countries (“IMPELC-DKW” and “EXPELC-DKW”) in such a way that the trading through that interconnector is not computed twice. The two models can still be run alone simply uncheking this additional scenario.

In order to create the hard linking, from the Case Manager of “TRADE” model the option “Attach another model” was selected and the Norwegian and Danish models were attached. The resulting model is a three-region model that includes Norway, Denmark West and Denmark East and where the interconnection between Norway and Denmark West is represented as an endogenous trading process. A scheme of the final structure of the hard linking is shown in figure 20.

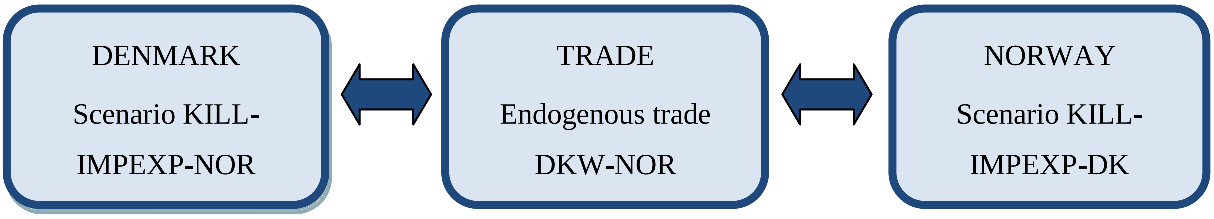


Figure 20: Hard linking between the Norwegian and Danish model

4.2.6 Other settings

The unit used for the capacity of the generating technologies is the MW, while that for the demand technologies and supply technologies is the PJa. The activity of all the processes is expressed in PJ.

The currency of the model is the Norwegian Crown. In case the cost of a technology is expressed in a different currency, this is converted in the Norwegian Crown according to its value in 2010. This is done by means of the currency conversion factors declared in the "SysSettings" workbook and that were computed starting from "Valuta5_2013" workbook (by P. E. Grohnheit). When the Danish and Norwegian models are run together the base currency is the Danish Crown.

The rate used by TIMES to discount all the costs occurred in the various years to the base year 2010 is 4%.

4.3 Energy resource supply

Norway is a country extremely rich of energy resources, especially oil, natural gas and water. In fact it owns the largest reserves of oil and natural gas of Europe and it was estimated that it is the third natural gas exported in the world (U.S. ENERGY INFORMATION AGENCY, 2014). Norway is also a producer of coal, which is extracted in the Svalbard islands. Moreover since the Norwegian coastline is very jagged, the country also has a high potential for the exploitation of wave power. Moreover in the whole Norwegian territory there is a high wind potential.

In TIMES-NO the workbook "VT_NW_SUP" is dedicated to the description of the supply of the primary resources requested by the power plants, which are modelled as commodities. The list of the supply commodities and their relative unit is shown in figure 21.

~FI_Comm						
CSet	Region	CommName	CommDesc	Unit	LimType	CTSLvl
*Commodity Set Membership	Region Name	Commodity Name	Commodity Description	Unit	Sense of the Balance EQN.	Timeslice Level
NRG		COA	Coal	PJ		
		NGA	Natural Gas	PJ		
		WST	Waste	PJ		
		BGA	Biogas	PJ		
		WIN	Wind	PJ		
		HYD	Hydro	PJ		
		HFO	Heavy Fuel Oil	PJ		
		SUPELC	Electricity SUP	PJ		
		WPE	Wood Pellet	PJ		
ENV		SUPCO2	Supply sector CO2	kt		

Figure 21: Supply commodities

As visible from figure 21 the supply commodities described in the model are: natural gas, coal, heavy fuel, biogas, waste, wood pellet, wind and water.

The processes that make these commodities available are only of two kinds: import technologies (“IMP”) and extraction technologies (“MIN”). The proper supply processes have been associated to each commodity in accordance to the Norwegian Energy Balance elaborated by IEA in 2010 (IEA, 2010): coal is both imported and extracted, heavy fuel can only be imported and the other commodities are supplied only by mining processes.

All the supply processes are provided with the mining/import cost, expressed as million of Norwegian Crowns in 2010 per Petajoule. Moreover for every commodity there is the possibility to add constraints regarding the maximum extraction and maximum import per year.

For coal and natural gas the supply cost is that reported by IEA’s Energy Technology Perspective 2012 (IEA, 2012). In the years between those for which the cost is given, the costs are calculated with linear interpolation. The supply cost of natural gas is 10% lower than the one in the report: this has been inspired by the Balmorel model of the Nordic Countries, which makes this assumption based on the fact that Norway is the third natural gas exporter in the world and that it is characterized by so large production volumes that economies of scale are reached.

The cost of fuel oil input in the model is based on a study elaborated in 2014 by Energy Analysis (EA ENERGI ANALYSE, 2013).

The supply cost of biogas input in the model is the total value-chain cost of biogas from liquid waste in 2010 reported in a study about the state of the art of biogas in the Nordic countries (NORDEN, 2010). Since this report doesn’t have any estimation of the future evolution of the cost, it has been assumed that the cost remains constant throughout the entire time horizon of the model, as is done in the Balmorel model of the Nordic countries.

The supply cost of wood pellets is that of bulk pellet described in a study of NVE (NVE, 2011b). Since in this study the future evolution of the cost of wood pellet is not provided, has been assumed that it follows the trend of the cost of wood pellet in Denmark estimated in the report (EA ENERGI ANALYSE, 2013). This decision is due to the fact that in the near future biomass is expected to be traded on a global market and therefore prices are going to be unified all over the world (HEINIMO, 2011).

The evolution of the cost for supplying the energy resources to the power plants from 2010 to 2050 is shown in figure 22. As visible pellet and coal are the cheapest resources all over the time horizon. Also biogas is characterized by cheap prices, while instead natural gas and fuel oil have associated a higher cost, which increases over the time horizon, too.

The cost associated to the mining process of water, waste and wind has been set equal to zero and thus it has not been included in figure 22.

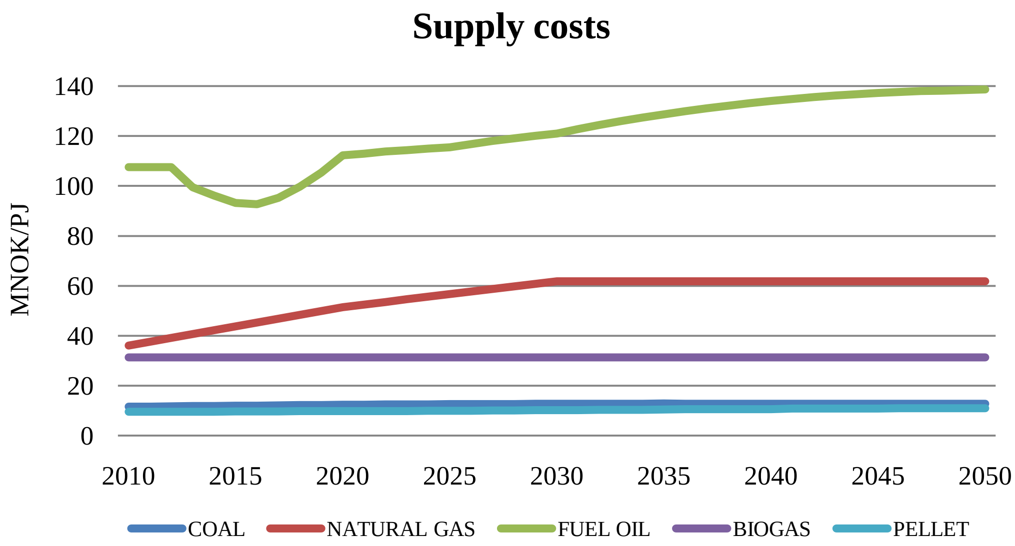


Figure 22: Energy resources supply costs

4.4 Power generation system

In the last ten years the average electricity production in Norway has been about 127 TWh per year (NORWEGIAN MINISTRY OF PETROLEUM AND ENERGY, 2013).

In the base year 2010 the total power production was 124.5 TWh, of which about 118 TWh were produced by hydro, 5.6 TWh by thermal and 895 GWh by wind (NVE, 2010). The share of these three power sources in the total Norwegian power production in 2010 is shown in figure 23.

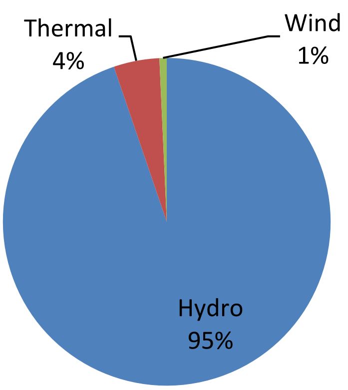


Figure 23: Power production in Norway in 2010

Figure 23 witnesses that in Norway the power generation is based almost entirely on hydropower: Normally the share of hydropower in the total production is 96%, but it depends on the precipitation and on the water inflow to the reservoirs. Figure 23 shows that the production by hydro in 2010 accounted for 94.8 % of the total domestic production, which is less than the average.

In Norway about 50% of the installed capacity for power generation is owned by local authorities, around 30% is owned by the central Government and private companies own about 13%. The ten biggest generation companies control roughly 70 % of the Norwegian average production and around 70% of the installed capacity. These companies are Statnett, Statkraft, Hafslund, Lyse, Agder,BKK, Eidsiva,Skagerak, and Trønderenergi (GONZALEZ et al., 2011).

At the beginning of 2010 in the Norwegian territory there were 810 power stations, which total installed capacity was 31824 MW. Of this capacity 29.944 MW were hydropower plants, 1.455 MW were thermal power plants and 425 MW were wind turbines (STATISTICS NORWAY, 2010).

Since different statistics about the Norwegian power system in 2010 report different values for the same feature, not a single reference was used. In fact it was impossible to find a single reliable source that would provide all the necessary information with the level of detail required by TIMES. Therefore, in order to describe the structure of the power system in the first three milestone years of the model (2010, 2012 and 2015) many references were used according to the availability of information of each one. For the description of the power system in 2015 only sources from 2013 and 2014 have been used, because information relative to 2015 isn't available yet.

The Norwegian power generation system has been described in TIMES in a workbook denominated "VT_NW_ELC": it includes many sheets describing the commodities and the technologies involved in the power generation sector. In the sheets "Tech" the installed capacity of the various technologies in 2010 is described, together with their retirement profile by means of the command "Stock". For all the technology existing in the base year the commodities consumed and the ones generated, the conversion efficiency, the availability factor, the contribution to the power peak, the investment cost (MNOK/MW) (even if it is not used in the computation of the overall system cost), the fixed operation and maintenance cost (called FIXOM and expressed in MNOK/MW) and the variable operation and maintenance cost (called VAROM and expressed in MNOK/PJ) are specified.

The content of the sheet "Tech" with the description of the technologies installed in the base year is shown in table 3. Some attributes are not displayed in order to make the table fit in the page (the complete table is available in the workbook "VT_NW_ELC").

Table 3: Generation technologies in the base year

*TechDesc	Comm-IN	Comm-OUT	EFF	STOCK	STOCK ~2020	STOCK ~2050	FIXOM	VAROM	AFA
*Unit				MW	MW	MW	MNokr/ MW	MNokr/PJ	Factor
Combined cycle GT	ELCNGA	ELCC	0.57	430	430	0	0.41	10.84	0.9
CHP: Back pressure plant	ELCWST	ELCC	0.21	45.8	45.8	0	3.03	10.65	0.86
		HETC							
CHP: Back pressure plant	ELCWPE	ELCC	0.25	2	2	0	0.42	14.95	0.99
		HETC							
Steam condensing turbine	ELCWST	ELCC	0.3	10.65	10.65	0	1.34	7.5	0.86
Steam condensing turbine	ELCCOA	ELCC	0.4	11.06	11.06	0	1.34	12.04	0.9

Steam condensing turbine	ELCHFO	ELCC	0.33	8.02	8.02	0	1.34	10.11	0.9
ICE biogas	ELCBGA	ELCC	0.33	5.66	5.66	0	0.61	8.8	0.9
Gas turbine - fuel oil	ELCHFO	ELCC	0.29	65.3	65.3	0	0.34	11.8	0.92
Gas turbine - natural gas	ELCNGA	ELCC	0.35	300	300	0	0.26	7.56	0.92
Hydro dam plant - Hydro	ELCHYD	ELCC	1	23405	23405	12462	0.97	1.24	1
Hydro run of river - Hydro	ELCHYD	ELCC	1	6539	6539	3482	0.96	1.2	1
Wind turbine (onshore)	ELCWIN	ELCC	1	425	425	425	0.18	4.03	1

In the same workbook and in particular in the sheets "Tech A" and "Tech B" the new installed capacity in 2012 and 2015 is depicted, according to the information about the plants already built and the plants that will become operative by 2015. The new capacity installed between 2011 and 2013 is represented in the model as new installed capacity in 2012, while the new capacity installed between 2013 and 2014 is represented in the model as new installed capacity in 2015.

Since the structure and composition of the Norwegian power system till 2015 is fixed by the statement made, the optimization process in TIMES starts after 2015.

4.4.1 Hydropower

Hydropower is the generation of electricity through the conversion of the kinetic and pressure energy of water. In hydro stations water in generally stored in a reservoir, from which it enters the penstocks (big and highly resistant pipes) that leads it to the hydro turbines. Hydro turbines are the devices that convert the energy of water into mechanical energy and then transfer it to a shaft that drives a generator. Finally water is discharged back into the river without undergoing changes.

The electricity production by hydropower station depends on the available volume of water and on the head, which is the height difference between the water intake and the outlet of the turbines. The volume of water elaborated by the hydropower plant depends on the water inflow and, in case of a reservoir plant, on the regulation of the reservoir.

The water inflow varies from year to year and within the year from season to season (it is higher between late-spring and autumn and it is lower during the winter) depending on the climatic conditions and in particular on the amount of water and snow fall. Such variation can be very large: from 1990 to 2010 the water inflow to the Norwegian hydropower stations has varied in a range of approximately 60 TWh, as visible in figure 24.

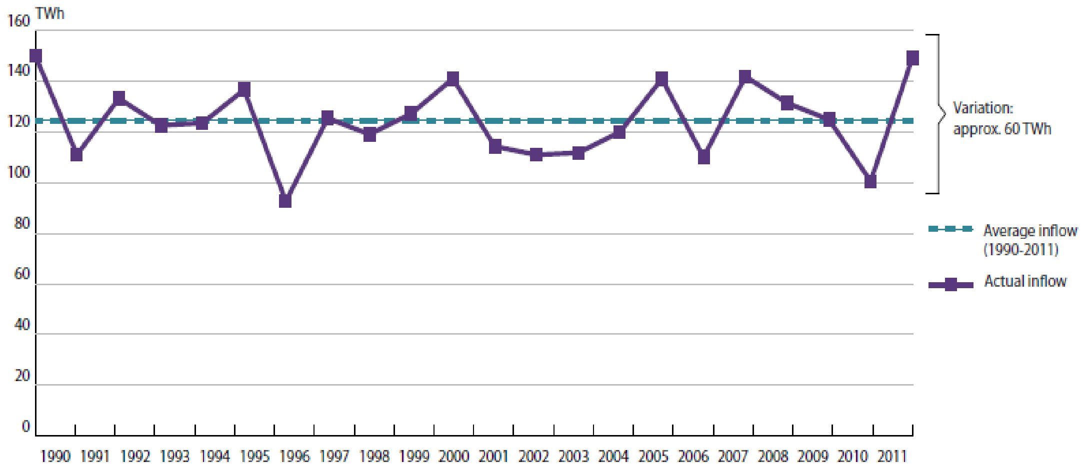


Figure 24: Annual inflow to the Norwegian hydropower system (NORWEGIAN MINISTRY OF PETROLEUM AND ENERGY, 2013)

Norway has the world's largest per capita hydropower production, it is the sixth largest hydropower producer in the world and the largest hydropower producer in Europe (GONZALEZ et al., 2011).

In years with average water inflow the generation from the Norwegian hydropower system is 130 TWh. This amount has been calculated by the Norwegian Ministry of Petroleum and Energy from the installed hydropower capacity and from the expected annual inflow to the hydro plants in a year with average precipitation. Since 1996 the year with the highest production from hydropower was 2000, with a total of 142 TWh, while the lowest production occurred in 2010, with a total generation of only 100.7 TWh, due to the low rainfalls and low snowfalls (NORWEGIAN MINISTRY OF PETROLEUM AND ENERGY, 2013).

The description of hydropower in the TIMES model of Norway has been done with particular accuracy and detail, because it constitutes the spine of the Norwegian electricity system. Since in Norway hydropower plants are essentially reservoir plants (DAM) and run-of-river plants (ROR), in the model all the hydro stations have been grouped into these two major technologic classes, which are operated in different ways.

4.4.1.1 Types of hydropower plants

Run-of-river hydro is a kind of hydroelectric plant with little or no water storage capacity. It doesn't need any land to be flooded, so it is often referred as environmentally friendly. However a small dam is still required to ensure that enough water enters the penstocks connecting with the turbines located downstream.

Since these plants aren't equipped with reservoir, they are subject to the seasonal river flows with very small margins of regulation: water coming from upstream must be converted in power at the moment or must bypass the penstocks. For this reason run-of-river is considered an inflexible and intermittent energy source: the energy output can't be coordinated with the power load but instead the generation varies over the year according to water inflow. It thus produces more power during seasons with high water availability and big river flows (from late spring to autumn, when the ice at high altitude melts) and less power during dry and frozen periods.

Reservoir hydro is characterized by a reservoir upstream of the dam which offers the possibility to regulate the water flow, to secure production in cold seasons and in dry years and to match the generation with the demand. Moreover the reservoir helps to reduce spilling and flood loss, increasing the overall production.

This kind of plant is also very important for the reliability of the electric system: it provides real-time balancing energy thanks to its high regulation speed and low operation cost. Moreover, flexibility makes reservoir hydro a very important technology for compensating the uncertainty due to renewable power generation.

In Norway in 2010 the total reservoir capacity was 62 billion of m^3, which converted by means of the average energy content of water correspond to 84.1 TWh (SINTEF , 2012).

Since 2010 was characterized by low precipitations, at the end of the year the energy content of the reservoirs was only 38.2 TWh, which is a decrease of 18.8 TWh with respect to the levels at the end of previous year.

4.4.1.2 Hydropower capacity

In 2010 in Norway the total installed capacity of hydropower was 29944 MW (NVE, 2010) and 1250 hydro plants were in operation (NVE, 2011a), of both run-of-river and reservoir typology. The distribution of the total power production between power plants of different sizes and their total amount is shown in figure 25.

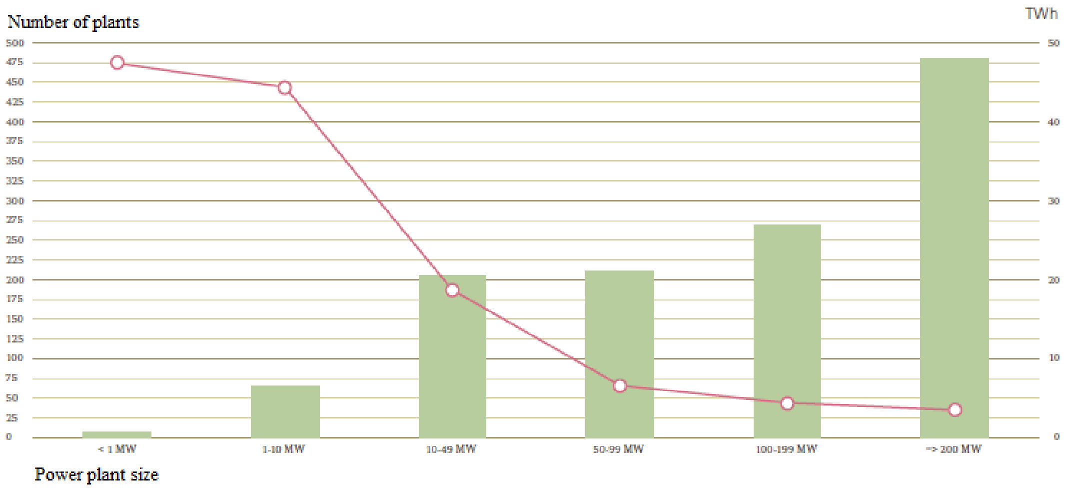


Figure 25: Number of plants and overall average annual production distributed in relation to capacity (NVE, 2011a)

The largest hydropower stations as of 31.12.2010, which together account for about 30 % of the total hydro installed capacity and for 23 % of the average annual hydro generation, are shown in table 4 (NVE, 2010).

Table 4: The largest hydropower stations in Norway as of 12.31.2010

Power Station	County	Max. Capacity (MW)	Mean ann. Production (MW)
Kvilldal	Rogaland	1240	3517
Sima	Hordaland	1120	3441
Tonstad	Vest-Agder	960	4202
Aurland	Sogn og Fjordane	840	2419
Saurdal	Rogaland	640	1300
Rana	Nordland	500	2123
Tokke	Telemark	430	2221
Holen	Aust-Agder	390	805
Tyin	Sogn og Fjordane	374	1398
Svartisen	Nordland	350	1996
Brokke	Aust-Agder	330	1407
Evanger	Hordaland	330	1322
Nedre Vinstra	Oppland	308	1206
Skjomen	Nordland	300	1164
Vinje	Telemark	300	1003
Kobbelv	Nordland	300	733

The total hydropower capacity installed in 2010 in the model is divided in 6539 MW of ROR and 23405 MW of DAM. Even if the total installed capacity of DAM plants is much more than that of ROR plants, these have a greater utilization factor. So the ratio between electricity generated by ROR and DAM is not as low as is the ratio between the installed capacities.

Moreover the new installed capacity of hydropower in 2012 and 2015 has been declared in two specific sheets. In 2012 442 MW of new DAM capacity and 123 MW of new ROR capacity were installed. In 2015 1035 MW of new DAM capacity and 289 MW of new ROR capacity were installed. These data have been taken by Statistics Norway (STATISTICS NORWAY, 2010), but since this source reports only the total installed capacity (DAM plus ROR), the two shares have been calculated according to the two fractions of installed capacity in 2010.

The retirement profile of hydropower stations has been computed from the installed capacity profile and from the hydropower plants lifetime. First, the installed capacity profile was determined using data taken from NVE for the time span 1960-1975 and from Statistics Norway (electricity tables) for the period from 1979 to 2012. The total hydropower installed capacity profile from 1960 to 2010 is shown in figure 26.

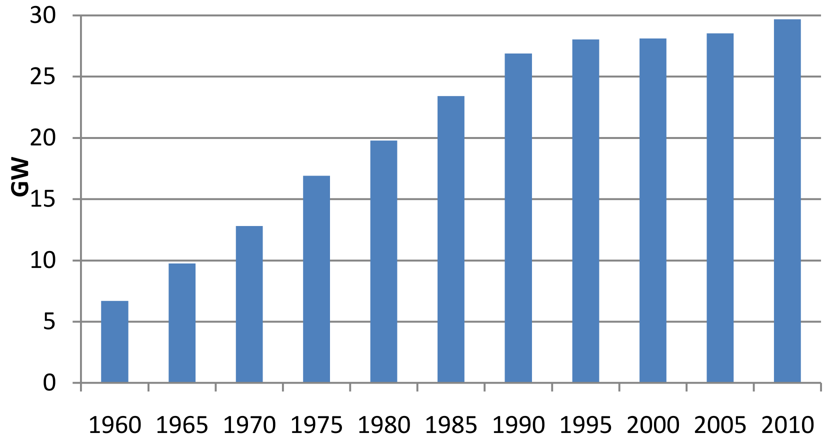


Figure 26: Hydropower installed capacity profile from 1960 to 2010

From this profile the amount of new capacity that had been installed every year from 1960 to 2010 has been calculated. It has been supposed that the same capacity is dismantled after the end of its life time. With the assumption that hydropower plants life time is 75 years, after this time period the hydropower stations that had been installed 75 years before are removed from the total installed capacity. It has been decided to use 75 years as life time for hydropower because the literature about this refers values between 50 and 100 years (IRENA, 2012) (SCHEI et al., 2011). The retirement profile is shown in figure 27 and has been an input to the model in the workbook "VT_NW_ELC" by means of the command "Stock".

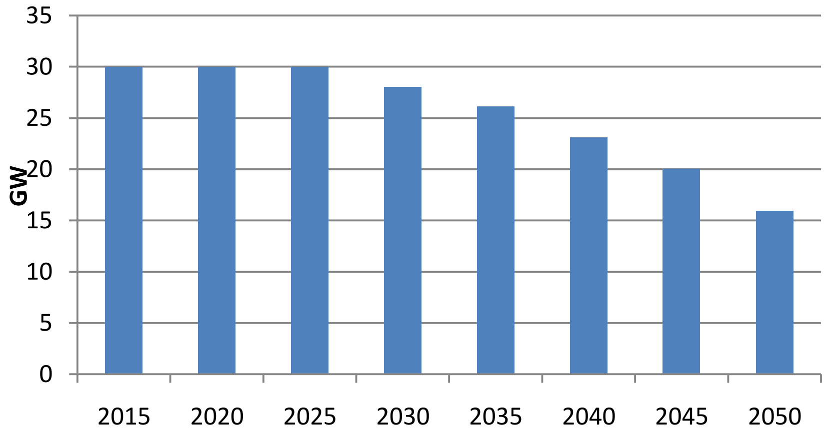


Figure 27: Hydro retirement profile from 2015 to 2050

Having assumed 75 years as hydropower stations lifetime, the oldest plants (those installed in 1950) are decommissioned in 2025. So, from the base year till 2025 the total hydropower installed capacity remains constant.

The division of the total annual capacity reduction between ROR and DAM technologies has been done according to their share of the total installed capacity in 2010 (78% of DAM and 22% of ROR). The values of the attribute "Stock" inserted in the model for DAM and ROR are shown in table 5.

Table 5: Stock attribute for DAM and ROR

Year	2015	2020	2025	2030	2035	2040	2050
Total	29944	29944	29944	28044	26144	23094	15944
DAM	23405	23405	23405	21920	20435	18051	12462
ROR	6539	6539	6539	6124	5709	5043	3482

4.4.1.3 Hydrology and hydropower operation

As already said, water is the commodity needed by hydropower plants to generate electricity. In order to give an adequate representation of hydroelectric power generation, it's of primary importance understanding well the water availability to hydropower stations and more in general the Norwegian hydrologic system.

Water inflow is the volume of water flowing from the catchment area of a river system into the hydroelectric stations. The catchment area is the geographical area that collects the precipitation of a particular river system. Precipitation levels vary strongly depending on the season, the year and the geographical region and the inflow varies proportionally to the precipitations. In general the inflow is higher during the spring thaw, it slightly decreases during summer and then it increases again during autumn due to the high rainfall. During the winter the inflow strongly decreases because the water freezes. This is the general behaviour of the water inflow for the entire Norway, even if slight variations occur from region to region depending on the local climatic and geographic conditions. Most of all precipitations vary strongly from year to year.

Many data about the Norwegian historical water inflow can be found in NVE website (NVE, 2015c).

The average weekly water inflow throughout a normal year is shown together with the average power demand in figure 28 (on the horizontal axis the weeks of the year are represented).

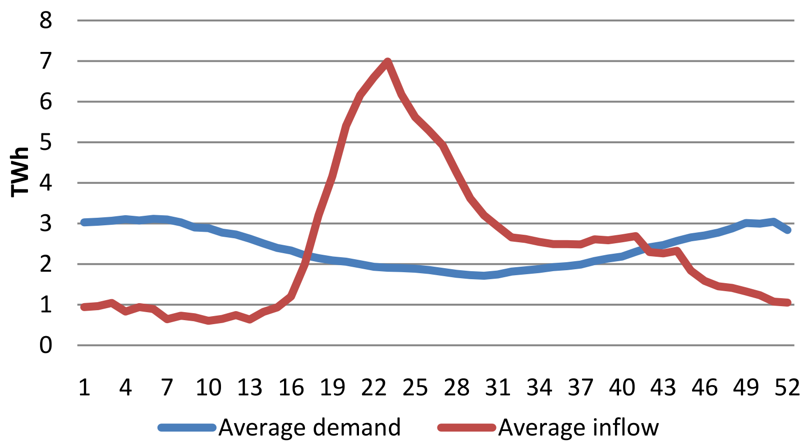


Figure 28: Average historical water inflow and power demand

As visible the two profiles don't match. The power demand doesn't vary strongly between seasons; however it's higher during winter and lower in summer, when the residential and commercial thermal load is almost zero. Instead the water inflow strongly varies over the year, as already explained above.

It results that in winter and early spring the electricity demand is higher than the energy availability due to the water inflow so that production from other sources or power import is required. On the contrary from late spring till late autumn the power demand is lower than the energy availability due to the water inflow and therefore water would be spilled.

In order to reduce the mismatch between power demand and water inflow availability, over the years have been built many hydropower stations equipped with reservoir. In this way a part of the water inflow can be managed in time and hydropower is made a flexible and regulated technology.

In figure 29 the logics of operation of ROR and DAM are illustrated. Run-of-river power stations (in green) can't be regulated, thus the electricity generation throughout the year depends on the water inflow: they produce more between late-spring and autumn and less during the winter. Reservoir hydro plants generation depends on both water inflows through the year and on the allowed changes in the reservoir levels. Normally during the months with more availability (in red) the reservoirs are refilled and the generation is then shifted in winter (in blue), when electricity demand peaks.

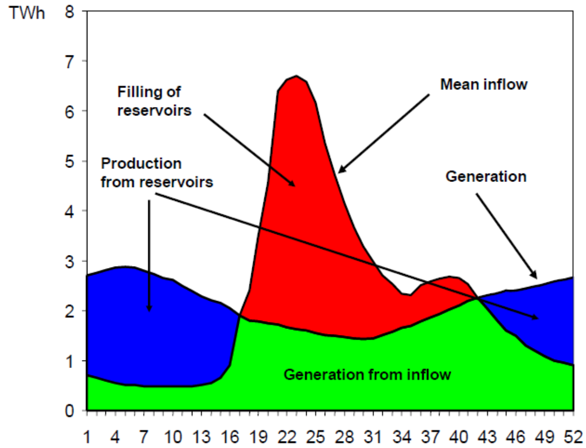


Figure 29: Water inflow and electricity generation from ROR and DAM during one year (FLATBY, 2011)

As a consequence the level of water in the reservoirs isn't kept constant over the year, but it undergoes deep variations. The water level decreases during winter and early springs. Then when the water inflow in the late spring increases due to the high precipitations and to the melting of snow on the mountains the generation from ROR becomes enough to satisfy the power demand and the reservoirs start to be refilled: the level increases during the whole summer and early autumn. In winter, when water is frozen and the power demand increases so that ROR is not able any more to meet the demand the reservoir are discharged and the level decreases again. This trend is explained graphically in figure 30, which shows the variation of Norwegian reservoirs level from 2009 to 2013 expressed in PJ. Moreover the historical minimum and maximum level are shown. As can be seen, levels can vary significantly from one year to another depending on the precipitation. For the 26th week historical data present a difference of even 120.4 PJ.

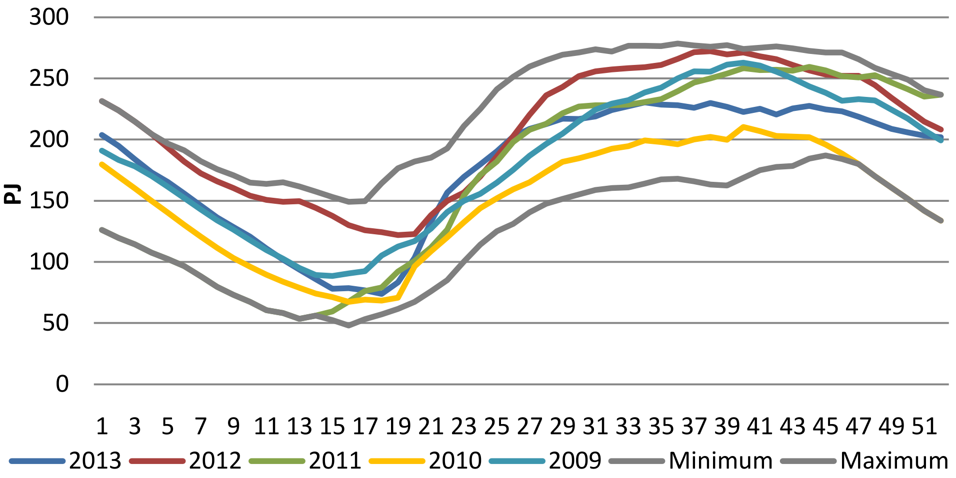


Figure 30: Yearly variation of reservoir levels in Norway

As already said, modeling hydropower in the TIMES model of Norway required a major effort with respect to other power generation forms. In fact, in order to give a proper description of such technology, it was necessary to represent the logics of operation of DAM and ROR hydro and the water inflow availability. The description of how hydropower has been modelled in the Norwegian TIMES model is provided in the following paragraph.

4.4.1.4 Hydropower modeling in TIMES

In TIMES the maximum yearly activity of a process is computed in the following way:

$$ACT = CAP \times AF \times CAP2ACT$$

where ACT is the process activity (which unit in TIMES Norway model is PJ), CAP is the installed capacity of that process (expressed in MW), AF is the availability factor and CAP2ACT is a parameter used to bring the two terms of the equation above to the same unit (in this case it is 0.031536).

From the formula above it follows that in TIMES models a possible way to describe the activity from a process in the various time slices is by defining the availability factor of the plants in the various time slices. Even if this technique allows modelling a complicated feature in an easy way, the definition of the availability factors in every time slice increases the model size. But the implementation of this technique to hydropower modeling is particularly beneficial. In fact since hydropower is a renewable form of power generation and then the efficiency of such type of plants in TIMES models can be set equal to 1, putting a constraint on the output commodity from a process is equivalent to putting it on the input commodity. And the first way allows reducing the computation time of the model, as explained in (INSTITUTE FOR ENERGY TECHNOLOGY, 2013) (LIND et al., 2013).

Therefore in the TIMES model of Norway the production from hydropower (both ROR and reservoir) has been modelled by means of workbooks describing for every time slice the availability factor of the commodity electricity (ELCC) coming out from such plants. This artifice permits modelling hydro generation by describing the power production rather than the water inflow to the hydropower stations. In order to do that it is fundamental to have accurate information about the historical inflow series from which it is possible to trace the hydropower production.

For ROR process the efficiency is set equal to 1 and there isn't any possibility to store water. So power production from ROR is the same as the water inflow (expressed as energy inflow rather than as mass flow rate) that arrives to the plant, except in a few hours when the inflow is higher than the discharge capacity of the hydro turbine. In this case the power production is equal to the maximum output and the excess water is spilled.

For DAM process instead the power generation is set equal to the water inflow only over the entire year, while at time slice level the power production and the water inflow can be different, because this kind of plants has the possibility to store water.

In the TIMES model of Norway the historical inflows series are based on a workbook called "Inflows", elaborated by the Section for Hydro informatics of the Hydrology Department of the Norwegian Water Resource and Energy Directorate (NVE). It contains the weekly total inflow series in GWh to all the Norwegian hydro stations from 1958 to the beginning of 2014. The weekly level of detail for inflow series implies that the water inflow is evenly distributed during a week; this is the same assumption used in the TIMES model of Norway developed by IFE (INSTITUTE FOR ENERGY TECHNOLOGY, 2013).

The weekly water inflow series have been computed by NVE aggregating and converting (from m^3/s to GWh) the data from the HYDARK database elaborated by NVE (2012_15958dgn.zip) (NVE, 2012b). These inflow series are used also by the EMPS model and therefore are reliable and trustworthy (SINTEF, 2011) (SINTEF, 2013) (BAKKEN & HAUGSTAD, 2004).

The weekly average total inflow series applied to the model has been created by assuming as value for every week the average of the historical series for that week. However not all the historical series have been used for the computation, but only those from 1980 to 2014. The reason of this choice is that in the past the total inflow to the hydroelectric stations was lower, because less capacity was installed and therefore less water was caught by the hydro stations. So the very old inflows are no more representative of the actual hydrological situation and even less of the future one.

Then from this total inflow series, the two ROR and DAM inflow series have been computed. For this it has been assumed that the total inflow is divided between ROR and DAM inflows in proportion to the energy that these two technologies generated. Each of the 52 values that compose the total inflow series has been multiplied by two coefficients that represent the share of electric energy generated by ROR and DAM in 2006, for which data were available (LIND et al., 2013). The energy production and the shares of the total annual inflow for the two hydroelectric technologies are shown in table 6.

Table 6: ROR and DAM inflow share

	Energy (PJ)	Inflow Shares
Run of River	37.5	30.3%
Reservoir	86.2	69.7%
Total	123.7	

It has been chosen to use data about energy production instead of installed capacity because in this way also the utilization factors of the two plants, which are quite different, are taken into account.

The resulting DAM and ROR weekly average inflow series are shown in figure 31, where they are overlapped so as to reconstruct the total inflow, too.

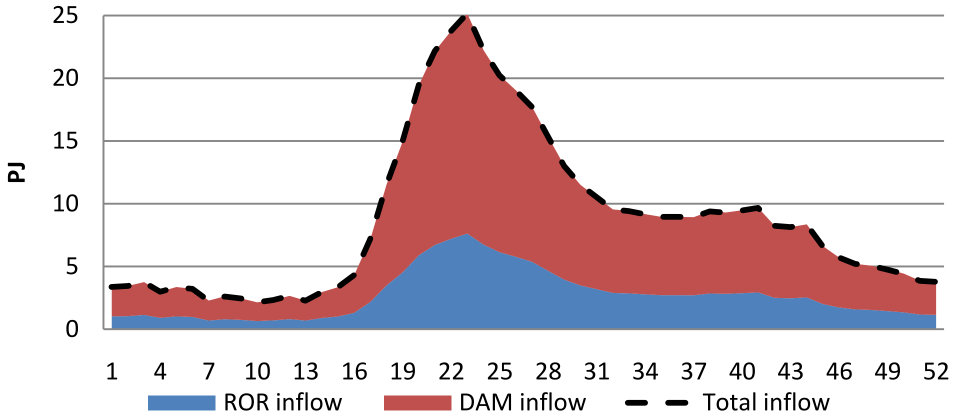


Figure 31: ROR, DAM and total average inflows

As already said, for ROR the profile of the water inflow is the same as the profile of the water outflow and thus of the generated electricity profile. For this reason the ROR average water inflow series has been input to the "Time slice feeder", a workbook that allows allocating time profiles of normalised hourly energy values to the time slices established (GARGIULO et al., 2013). This calculated the availability factor of ROR plants in every time slice. In some time slices in summer the energy content of the inflow to the ROR stations is higher than the maximum power that can be generated. For these time slices the AF has been set equal to 100%: the maximum power can be produced if needed and the water in excess is discharged.

For DAM the computation of the availability factor in each time slice has been harder, because water can be stored and the profile of the water inflow doesn't overlap the profile of the water outflow.

In order to compute the availability factors for DAM (and thus the power generation) it has been considered that reservoir hydro is characterized by very high regulation speed that makes possible to quickly cover the difference between power demand and power generation by ROR. The calculations have been realized for every time slice starting from the difference between power demand plus power losses and production from ROR (that is fixed and strictly depends on the water inflow). Such difference represents the amount of energy that is requested to be produced by DAM, which is the second technology in the merit order curve. Knowing the number of hours included in every time slice it was possible to determine the capacity needed to produce that energy. The ratio between the requested capacity and the total installed capacity gave the availability factors.

Moreover the availability factors were computed for both the base year and the last year of the time horizon, using in the first case the power demand plus transmission losses in 2010 and in the second case the values of 2050. Then the interpolation option between these values has been activated. This implies that as the demand increases over the years, also the production from DAM increases at the same rate, managing to cover the progressively growing difference between demand and generation by ROR. In any case a constraint on the total yearly generation is also set to ensure that the total yearly energy generation by DAM is not higher than the energy content of the total water inflow to DAM stations. This restriction is very strict because in the reality, even if in a drought year the generation by hydropower is lower than the average, still the outflow from hydro reservoirs is higher than the overall inflow trying to reduce the amount of imported energy and relying on higher precipitation in the following year. However it was decided to set this constraint in order to prevent the solver from discharging the reservoirs.

The profile of the DAM power production used in the model, expressed in PJ, is shown in figure 32. In the same figure it is also shown the historical DAM outflow profile. The two profiles are very similar even if they don't overlap. Moreover, the DAM outflow profile used in the model is smooth, which facilitates the determination of the optimal solution.

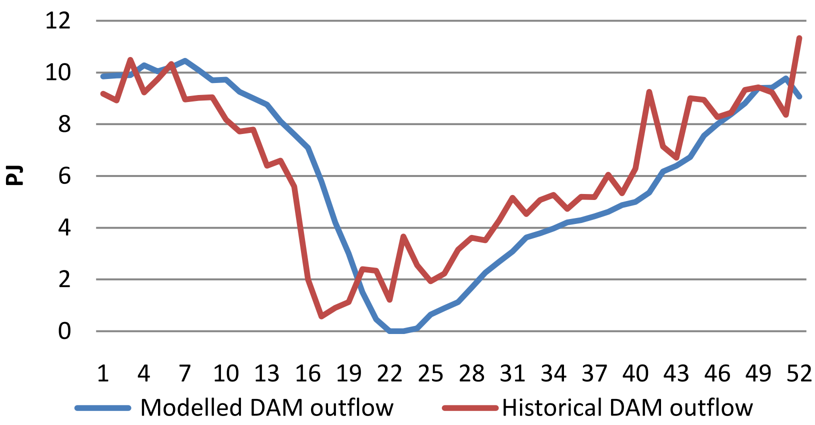


Figure 32: Modelled and historical DAM outflow

In figure 33 the total water inflow to the hydroelectric stations and the outflow from ROR and DAM are shown. The profile of ROR outflow is the same as that of ROR inflow (because this technology can't store water) and it has the same shape as the total inflow but in reduced scale. Instead the outflow from DAM is almost zero in the late spring and early summer, when ROR covers much of the demand: in these periods water is stored in the reservoirs and then it is discharged in winter, early spring and late autumn.

Thanks to the availability of flexible hydropower stations and to the correct operation and integration of the two hydropower technologies, generation from hydro is less dependent from the water inflow and its profile is smooth and almost constant over the year, as visible in figure 33.

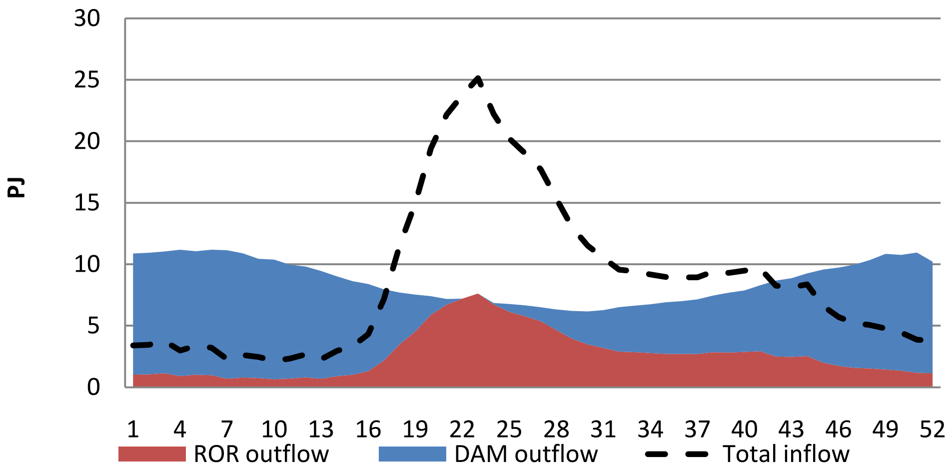


Figure 33: Comparison of hydro outflow and inflow with power demand

As verification that hydropower has been modelled properly, it can be observed that the profiles of the outflow from ROR and DAM, that have been used to compute the availability factors, are the same as those shown in figure 28.

4.4.1.5 Water inflow scenarios

The procedure that has just been explained for the average total inflow series has been applied also to other inflow series. In fact three different water inflow scenarios have been created, denominated "Scen_Average_Inflow", "Scen_Relative-Maximum_Inflow" and "Scen_Relative-Minimum_Inflow". Thanks to these scenarios, the model can be run with different water inflow series so that it is possible to study the power system behaviour in different conditions of rainfall and snowfall. Since water inflow to Norwegian hydroelectric stations is one of the main drivers of the Nord Pool spot price, this feature of the model allows performing interesting sensitivity analyses. Moreover this feature allows assessing how the water availability in Norway affects the power exchange between Norway and the interconnected countries.

The "Average_Inflow" scenario represents the water inflow in a year of normal rainfall. The computation of this inflow series has already been explained in the previous paragraph.

The "Relative-Maximum_Inflow" scenario depicts the water inflow in the wettest historical year. The constraint on the annual maximum power generation by ROR and DAM has been set equal to the total inflow in the wettest historical year, which is 1989. The computation of the availability factors for DAM differs from that of the "Average_Inflow" scenario. In fact in the "Relative-Maximum_Inflow" scenario has been considered that the water availability significantly exceeds the volumes needed to meet the domestic power demand and therefore a substantial share of the total water inflow can be used to produce power for export. So the availability factors were calculated as the difference between the power demand plus the average of the historical power export and the generation by ROR. As for the average scenario, the AFs were computed also for 2050 with the demand in 2050 and the two corresponding values are interpolated.

The “Relative-Minimum_Inflow” scenario defines the water inflow in the driest historical year, which is 1996. In this case the availability factors have been calculated in the same way as in the “Average_Inflow” scenario.

The weighted average AF of the three inflow scenarios are shown in table 7.

Table 7: Weighted average availability factor of inflow scenarios

	Average	Relative Maximum	Relative Minimum
ROR	63%	71%	49%
DAM 2010	46%	51%	50%
DAM 2050	50%	54%	54%

The availability factors for the “Average_Inflow” scenario (ROR and DAM 2010) are fully consistent with the typical values of the Norwegian plants.

In case of high water inflow the availability factors of both DAM and ROR have been set higher than those of the “Average_Inflow” scenario. In this case ROR covers a higher fraction of the total power demand and so less production from DAM is required to meet the demand. The extra water stored in the reservoirs can be used to produce power to export or in the worst case it must be spilled not to exceed the reservoir limits.

In the case of little water availability the AF of ROR plants decrease, because in some moment the water inflow is less than the minimum needed to run the ROR turbine, which therefore can’t work. In order to meet as much demand as possible, the outflow from the reservoir is increased and in fact in this case the AF of DAM is higher than in the “Average_Inflow” scenario. However this higher production is used only for meeting the domestic power demand and not for increasing the export. The presence of constraints on the total energy production assures that the outflow from DAM remains lower or equal than the inflow also in this case.

Each water inflow scenario includes a constraint on the maximum yearly power production. This constraint is imposed separately for DAM and ROR and is equal to the total inflows to ROR and DAM. The values for the three scenarios are shown in table 8 and are expressed in PJ/year.

Table 8: Total inflows in the various inflow scenarios, PJ/year

	Average Inflow	Relative Maximum Inflow	Relative Minimum Inflow
Run of River	138.9	180.4	101.3
Reservoir	319.3	414.6	232.9

Total	458.3	595.0	334.2

Finally, in figure 34 are shown the water inflow series assumed in the three scenarios presented above, where the unit is the Petajoule.

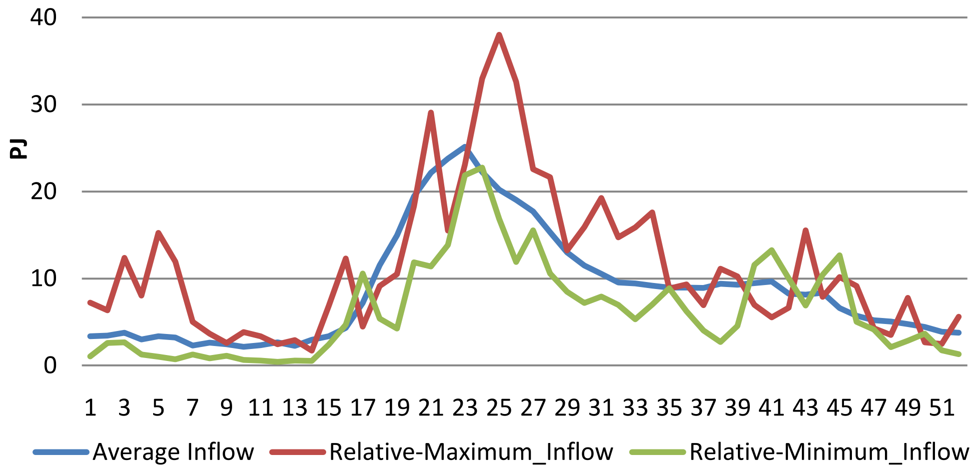


Figure 34: Average, relative maximum and relative minimum total water inflow series

Each of the three inflow scenario workbook created contains two sheets. In the first are listed the AF for ROR and for DAM in every time slice and the interpolation rule, while in the second sheet there are the constraint on the maximum yearly power production from ROR and DAM as in table 8.

4.4.1.6 Costs of hydropower

Hydro power cost can vary considerably, both between different plant kinds and from project to project depending on a big number of factors. In general the cheapest stations have already been developed and nowadays costs are higher. The investment, fixed operation and maintenance and variable operation and maintenance costs were taken from NVE (NVE, 2011b).

The costs of reservoir hydro plants used in the model are those of a high pressure, high fall (>300 m) plant. The reason is that DAM stations are usually characterised by a high water fall rather than by a high water volume. Instead the costs of run of river plants used in the model are those of a low pressure, low fall (<30 m) plant, because usually ROR plants are characterized by a high water volume rather than by a high water fall.

The investment and fixed O&M costs of hydropower plants is easy to determine, but the determination of the variable O&M cost is quite tricky. In fact while the marginal cost is very close to zero, the opportunity cost, which is the foregone opportunity to generate power in another time, might be considerable but is almost impossible to determine. Therefore the values of the variable O&M used in the model are characterized by high grade of uncertainty.

In table 9 the costs applied to the model for the two hydroelectric technologies are shown.

Table 9: ROR and DAM costs

	Run of river	Reservoir
Investment (MNOK10/MW)	12.53	12.69
Fixed O&M (MNOK10/MW)	0.96	0.97
Variable O&M (MNOK10/PJ)	1.20	1.24

4.4.1.7 Hydropower potential

NVE estimated that in 2010 the hydropower potential was about 205 TWh. This is about 66 % more than the currently developed power generation (123.4 TWh), but it can't be developed entirely. In fact 48.6 TWh are protected through nature conservation program under the Nature Diversity Act or have not received the license. In 2010 hydro power plants accounting for an estimated production of 1.4 TWh were under construction, then 2 TWh received the license to be built and there were applications for building other 7 TWh.

The remaining hydropower potential is classified in two groups, totalling 23 TWh: 16.5 TWh from small power plants and 6.5 TWh from new stations with more than 10 MW of installed capacity. These two last classes also include upgrading and expansion (LIND et al., 2013) and (NVE, 2011a).

The division of the total estimated hydropower potential in 2010 in the different classes is shown in the following figure.

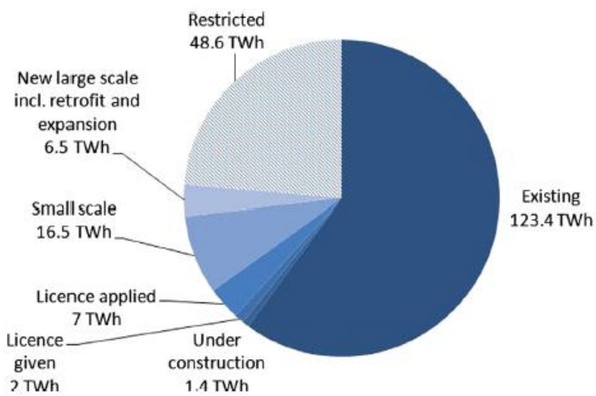


Figure 35: Hydropower potential in Norway 2010

The description of the possible future investments in hydropower implemented in the TIMES model is presented in the chapter "Future technologies available for generation".

4.4.2 Wind power

Wind turbines are devices that convert the kinetic energy of the wind in electrical energy. This energy conversion is realized through a rotor which is invested by a wind stream and that is mechanically connected to a generator. The rotor is located in front of a closed capsule called nacelle, inside which is located the generator and the gear box. The nacelle is mounted on the top of a tower, in order to allow the rotor reaching larger dimension and being invested by wind with higher speed. In fact the power production from a wind turbine is proportional to the third power of the wind speed. Currently wind turbine can generate power when the wind speed at the hub height is in a range between 3 and 25 m/s.

A cluster of wind turbines forms a wind farm. Such wind farms can be installed on the land (on-shore) or lately also on the sea (off-shore). While in Denmark off-shore wind turbines already are a reliable and mature technology, in Norway this technology is still less mature and currently has higher installation and operation cost, although presents greater margins for reducing the costs.

Wind energy is an unpredictable and inflexible energy source: electricity is generated only when the wind blows, which is difficult to be forecasted. Therefore, even if this wind power has zero emissions during operation thus bringing undoubted benefits to the environmental, it complicates the management of the electrical system, which must adopt technologies that deal with the sudden changes of wind generation.

In the Norwegian energy system wind power has so far played a modest role, since it is a relatively new power generation form. The first activities regarding studying and testing wind power date back to the last 1980s, when scientists started mapping wind resources and testing small wind turbines. The interest started arousing in 1997, but a substantial increase in installed capacity occurred only in 2002.

The development of Norwegian wind power capacity and wind energy production from 1997 until 2010 is shown in figure 36. Production is represented with a red line and the unit is the TWh. Capacity is portrayed as blue bars and is given in MW.

The average (not weighted) capacity factor over this time span is 23.8 %, which is quite low considering that the installations are in favourable sites (STATISTICS NORWAY, 2010). In fact the majority of the wind farms installed so far are located along the West coast (NVE, 2014a), which is the zone with the highest wind speed and at the same time characterized by quite mild climatic conditions.

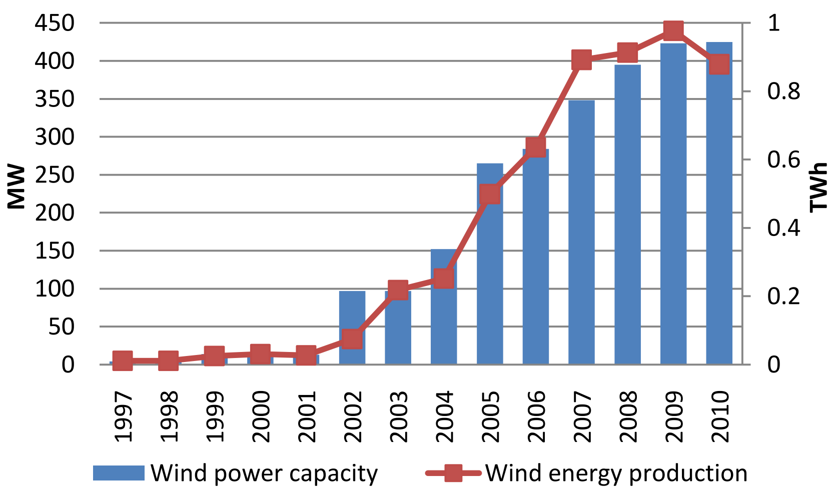


Figure 36: Wind power historical capacity and production

Figure 37 is a map of Norway with the average wind speed: it shows that the area with the highest wind speed is the West coast and the central mountainous zone.

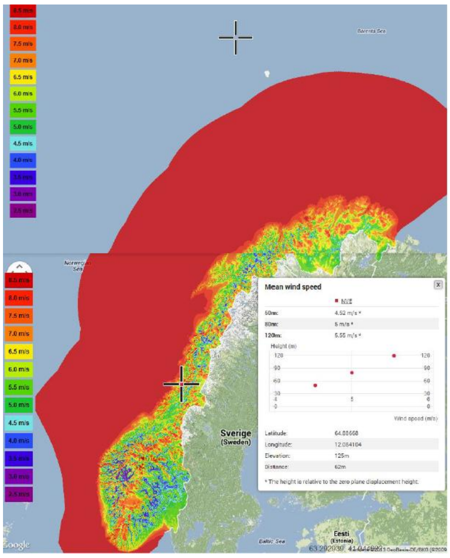


Figure 37: Wind speed map

In Norway the average annual wind speed 50 metres above the ground in well-exposed coastal areas is between 7 and 9 m/s. As a rule of thumb it can be assumed that wind power is feasible in an area with an average wind speed of at least 6.5 m/s (NORWEGIAN MINISTRY OF PETROLEUM AND ENERGY, 2013).

Many maps showing the estimated mean annual wind speed at a height of respectively 50, 80 and 120 meters above ground have been created and are continuously updated by NVE (NVE VINDKRAFT).

4.4.2.1 Wind power capacity

At the end of 2010 on the Norwegian territory there were fourteen wind power farms accounting for 425 MW of installed capacity. The total wind energy production was 879 GWh, which means that the full load hours was 2068 hours, 2.8% less than in 2009. This installed capacity only includes on-shore wind farms. However pilot projects and development of off-shore wind power were already underway in 2010.

In the two specific sheets of the workbook VT_NW_ELC have been declared the new wind power capacities installed in 2012 and in 2015. In 2012 372 MW of new capacity were installed and in 2015 496 MW more. These data have been taken from Statistics Norway (STATISTICS NORWAY, 2010). Also such new installed capacity only includes on-shore plants.

As for hydropower capacity, the retirement profile of wind power has been computed from the installed capacity profile and from the plants life time, which is 20 years (ENERGINET.DK, 2012). The retirement profile is shown in figure 38. It has been input in the model in the workbook “VT_NW_ELC” by means of the command “Stock”.

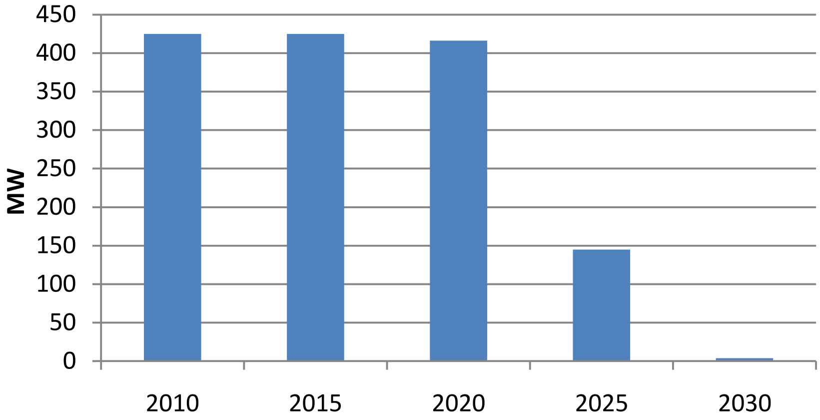


Figure 38: Wind power retirement profile

In 2010 the largest wind farm in Norway was Smola. It is formed by 2 parts: the first was commissioned in 2002 and includes 20 turbines totalling 40 MW of installed capacity and the second part was commissioned in 2005 and comprises 48 turbines, which account for 110.4 MW. So the total installed capacity of the largest Norwegian wind farm is 150.4 MW.

4.4.2.2 Wind power modeling in TIMES

In the Norwegian TIMES model the existing on-shore wind turbines have been represented through a process called "ERWINWON". Wind power has been modelled in the same way as run-of-river hydropower: wind turbines convert the energy content of the wind flow in power in the same moment when the wind is available, without any possibility of storing.

Since wind is a renewable form of energy, in the model the conversion efficiency of wind technologies has been set equal to 1. This means that the profile of the power generated by the wind turbines is the same as that of the energy content of the wind investing the turbines.

In the model the profile of the power generated by the wind turbines has been depicted in the downstream commodity "ELCC" from "ERWINWON", instead of representing the wind profile in the upstream "ELCWIND" commodity. This approach was preferred for the same reasons already explained in the paragraph dedicated to hydropower modelling.

By means of the attribute AF relative to the electricity flowing out from the wind turbine processes, it has been possible to model the activity of the existing wind turbines in every time slice. The computation of the 32 availability factors is based on the historical hourly data about the power generation by wind turbines by NVE (NVE, 2014b) and (NVE, 2014c). In this reference the values of the hourly wind generation from 2002 to 2013 are available.

Since wind power in the last decade has undergone a significant technological development, a study has been realized in Norway which investigated if newer wind farms produce more than elders (HOFSTAD, 2011). The research observed that the capacity factor of Norwegian wind farm has experienced a positive trend: newer wind stations produce for up to 2700 hours per year, in contrast to approximately 2000 hours for the elder plants. This improvement witnesses that wind developers now are finding more appropriate places and more suitable turbines.

In the model the older power production data that don't represent the fast development that has characterized wind power were rejected. In order to represent the state of the art of wind power technologies the wind generation profile has been calculated using only recent data. In particular the wind availability factors have been calculated using only the historical series from 2008 to 2012. Using these data the resulting average hourly wind power production profile aggregated by week is shown in figure 39.

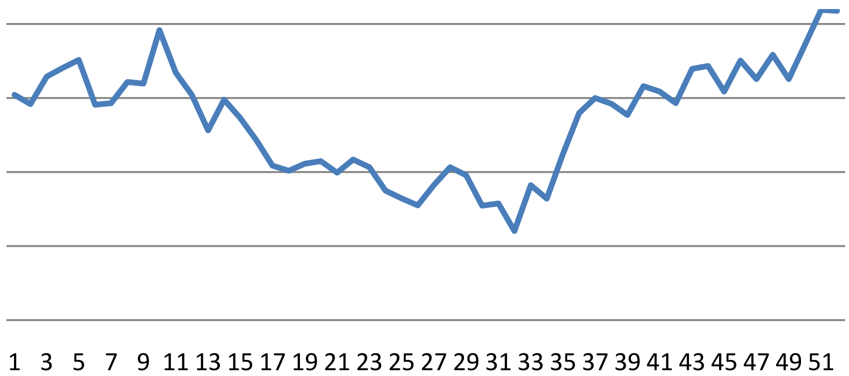


Figure 39: Wind power production profile

As visible, wind power production during summer in the past years has been lower than in other seasons. This profile is also similar to that used for modelling the wind speed during the year in the TIMES model of Norway realized by IFE (INSTITUTE FOR ENERGY TECHNOLOGY, 2013). From the historical series of the generation by wind turbines the average availability factor in every time slice has been calculated. These availability factors have been input in the model through a workbook called "Scenario_Wind_Fraction-Potential". Some of the values of the AF are shown in table 10.

Table 10: Availability factor of wind power technologies

TimeSlice	LimType	Attribute	Year	Cset_Set	Cset_CN	Pset_PN	NOR
RWDA		AF	2010	NRG	ELCC	*WINWON*	18%
RWDD		AF	2010	NRG	ELCC	*WINWON*	24%
RWDC		AF	2010	NRG	ELCC	*WINWON*	24%
RWDB		AF	2010	NRG	ELCC	*WINWON*	24%
RNWA		AF	2010	NRG	ELCC	*WINWON*	20%

The weighted average availability factor is 25.6 %, which is very consistent with the state of the art of the Norwegian wind turbines, but is higher than the values of the availability factor in the past (the weighted average availability factor between 1997 and 2010 is 23.8 %).

In the workbook "Scenario_Wind_Fraction-Potential" have also been input some user constraints whose purpose is to set an upper bound to the yearly power generation from all the set of wind technologies. As shown in table 11, such user constraints are specified for various years and are expressed in PJ.

Table 11: Constraint on wind energy production

UC_N	Pset_PN	Pset_CI	Year	LimType	UC_act	UC_RHSRTS
UC_PotentialOnshore	*WINWON*	ELCWIN	2010	up	1	3.2
	WINWON	ELCWIN	2012	up	1	5.6
	WINWON, *WINWOT*	ELCWIN	2015	up	1	0.0
	WINWON, *WINWOT*	ELCWIN	0	up	1	0.0
			0			5.0
UC_PotentialOffshore	*WINWOFF*	ELCWIN	2030	up	1	0.0
			0			5.0
UC_MaximumFossil	ET*,EC*		2010	up	1	20.2
	ET*,EC*		2012	up	1	12.2

From table 11is visible that the constraint on the maximum generation are not related only to the existing technologies, but also to future available technologies (*WINTOT* and *WINWOFF*) which are presented in paragraph 4.6.2.

The data presented in the table above relative to 2010 and 2012 have been taken from "Statistics Norway" (STATISTICS NORWAY, 2010), while data for 2015 and 2030 are given by (LIND, ROSENBERG, & SELJOM, 2013).

Wind production can suddenly vary and is unpredictable. An appropriate way to depict the stochasticity of its behaviour is to create many scenarios with different wind production profile. However it has been preferred to focus the attention on the variation of power exchange in the Nordic countries (and between Denmark and Norway in particular) depending on the status of the Norwegian reservoirs without introducing any variations in the generation from other technologies. Therefore there is only one scenario describing the wind power production profile.

4.4.2.3 Costs of wind power

The investment, fixed O&M and variable O&M costs relative to existing wind turbines have been taken from NVE (NVE, 2011b). In particular in this report all the O&M costs are attributed to VAROM, while FIXOM is not given. It has been decided to change 75% of wind VAROM to FIXOM. In fact according to Energy.dk (ENERGINET.DK, 2012) the major component of O&M for wind technologies are insurance, repair, service agreement and land rent, which are mainly allocable to FIXOM instead of to VAROM.

The costs described in the workbook "VT_NW_ELC" for 2010 are only relative to on-shore wind turbines. They are shown in table 12.

Table 12: Investment, FIXOM and VAROM costs of wind energy

On-shore wind turbine	
Investment (MNOK10/MW)	13.34
Fixed O&M (MNOK10/MW)	0.15
Variable O&M (MNOK10/PJ)	4.03

It has been assumed that the costs for the wind farms installed between 2011 and 2015 are the same as those relative to 2010 shown in table 12.

The costs associated to off-shore turbines and to the other future available wind turbines are not included in the workbook "VT_NW_ELC" but in the workbook called "Subres_NewTechs_ELC".

4.4.3 Fossil power plants

Fossil fuel power plants are large scale stations that generate power by burning fossil fuels such as fuel oil, natural gas or coal. The chemical energy contained in the fuel is converted in a boiler or in a combustion chamber in thermal energy which is later converted in mechanical energy by means of a turbine, whose rotation is transmitted to an electrical generator.

In Norway the vast majority of fossil power production is done with natural gas. The three largest gas-fired power plants are Kårstø Power Station, Mongstad Power Station and the power plant on Melkøya island (NORWEGIAN MINISTRY OF PETROLEUM AND ENERGY, 2013).

Kårstø Power Station is a combined cycle power plant placed in the homonym industrial site. It was opened in 2007, being the first commercial fossil fuelled power plant in Norway. Its installed capacity is 430 MW and is dedicated only to power generation since the area is inhabited and there isn't any need for district heating and heat generation.

Mongstad power plant is a combined heat and power gas-fired plant that became operative in 2010. It was built in the context of collaboration between DONG Energy and Statoil. It serves as energy supplier for the refinery located nearby and has an installed capacity of 280 MW of electricity and 350 MW of heat. The plant was built in order to anticipate the greater future demand for electricity: during the first years of operation it was not operated with a high utilization factor (STATOIL, 2014).

On the island of Melkøya a gas-fired combined heat and power plant of 215 MW for electricity generation and 167 MW for heat is located. It was completed in 2007 and was built in order to meet the energy demand of the LNG plant on the island

Moreover in Tjeldbergodden and Nyhamna there are two gas turbines of 150 MW each owned by Statnett.

All the previously mentioned plants have been built in recent times in order to have highly efficient available power generation that can be started at short notice in case of water shortage. Beside these power plants of relatively great installed capacity there are other smaller ones that are fuelled with other fossil fuels: coal and fuel oil.

4.4.3.1 Fossil capacity

In the model the total fossil installed capacity described for 2010 is 1309 MW. This is composed by 495 MW of gas-fuelled combined heat and power, 430 MW of natural combined cycles, 11 MW of coal-fuelled and 8 MW of fuel oil-fuelled steam turbines, 65.3 MW of fuel oil-fuelled and 300 MW of natural-gas fuelled gas turbines. The share of the different fossil technologies is shown in figure 40.

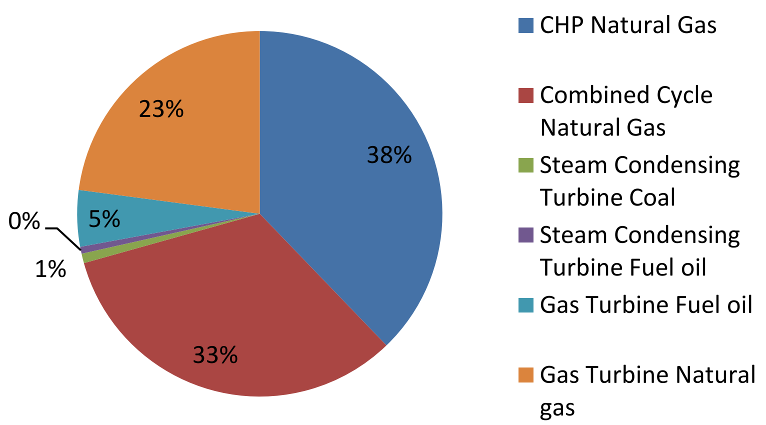


Figure 40: Fossil technologies installed capacity share

By means of the attribute "Stock" in the model the retirement profile of the fossil technologies is described: starting from the date of installation of the power plants and from their lifespan it was possible to determine when they will be dismantled (or need to be reconverted/renovated) (NVE, 2011b) (ENERGINET.DK, 2012).

The efficiency values and the availability factors for the fossil power plants were mainly taken from the RAMSES database. This is a database that includes the description of more than 1200 existing and possible new technologies for Denmark, Norway, Finland and Sweden. It has been used for the description of Denmark power system in the Danish TIMES model, too.

When some data were missing (for instance for combined cycle, coal, and natural gas fuelled gas turbine) they were taken from (NVE, 2011b) or (ENERGINET.DK, 2012).

The efficiency and availability factor for the CHP with natural gas and for the combined cycle are the same as those of the corresponding technologies in the Danish TIMES model.

4.4.3.2 Costs

The investment, FIXOM and VAROM costs of the technologies were calculated from the values reported in a study by NVE about the costs of the energy technologies in Norway in 2011 (NVE, 2011b). When the cost of a certain technology is given for two different capacities, the cost associated with such technology in the model is determined by interpolating or extrapolating these values.

The cost of the 8 MW fuel oil steam turbines wasn't found, so it has been assumed that its investment and FIXOM costs are the same as the coal steam turbine and the VAROM has been calculated doing a proportion with the VAROM of the fuel oil gas turbine and the efficiencies of the two technologies.

In this report the costs are expressed in millions of Norwegian Crown in 2011 and have been converted in millions of Norwegian Crown in 2010.

4.4.4 Biopower plants

The term biopower refers to the production of electricity through the conversion of biomass, bio-fuels, livestock waste, sewage sludge and other organic waste. Combustion is the typical way to produce power from solid bio-fuels: the heat released by the combustion is used to produce steam that moves a steam turbine connected to an electric generator. For sludge fractions biogas production is common, which is associated with power generation in a gas engine.

Even if waste shouldn't be considered a bio-fuel, it has been decided to describe the status of waste incineration in this paragraph, since other reports do the same (NORSK ENERGY, 2011) (NVE, 2011b).

In Norway the share of bio power on the total electricity generation is quite low if compared with that of the other Nordic countries. Nevertheless there are some power and CHP plants fuelled with biomass, waste and biogas. In particular in Norway the use of wood from the forest industry and thinning has been common.

The total installed capacity for biopower in 2010 in Norway was 146.2 MW and is distributed as visible in figure 41.

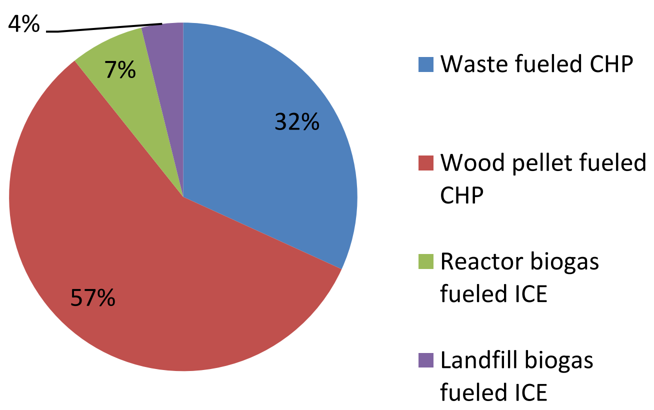


Figure 41: Biopower technologies installed capacity share

The two following paragraphs describe how biopower plants have been implemented in the model. They have been divided in two classes: power plants that generate power burning solid bio-fuels and power plants that produce power burning gaseous fuels.

4.4.4.1 Biopower by solid fuels

Steam turbines for power generation from solid bio-fuels or from waste are installed in pulp and paper industry, waste incineration and other biopower industry. The total installed capacity in 2010 was 130.5 MW.

The data about biopower by solid fuels that have been inserted in the Norwegian TIMES model mostly come from a study prepared by Norsk Energy for Enova SF (NORSK ENERGY, 2011). It describes the state of the art of the use of biomass, sludge and municipal solid waste for energy production in 2011 and presents new possibilities to exploit them until 2020.

In the Norwegian paper factory “Södra Cell Tofte” two wood pellets fuelled steam turbines are installed: one of 40 MW and another one of 10 MW capacities. These turbines were installed in order to exploit a steam surplus that otherwise wouldn’t have been used: the steam for power generation can therefore be considered free.

Other three turbines accounting in total for 32 MW are installed in three paper factories (Norske Skog Saugbrugs, Norske Skog Skogn and Norske Skog Follum). They were built about forty years ago and they receive an incentive even if they are not operated because they serve as reserve production in dry years. In 2009 they didn’t produce electricity at all.

All the mentioned plants installed in pulp and paper industries also produce heat.

In 2010 in the Norwegian territory eight waste incineration power plants were installed, for a total capacity of 46.5 MW. In all of them the power generation is performed using steam turbines. Most of the plants also supply heat for district heating.

In 2012 a waste incineration plant with 38 MW of installed capacity was built. It has been described in the model in the sheet relative to the new technologies in 2012.

Regarding biopower plants outside the pulp and paper industry and outside waste incinerations, in 2010 there was only one biopower plant for solid bio-fuels. In particular it burns wood pellets and has an installed capacity of 2 MW. It has a very high utilization factor: 8000 hours per year.

In the model all the CHP plants fuelled by wood pellets have been aggregated in one plant with total installed capacity of 84 MW. The availability factor of 0.9 and the efficiency of 0.29 were taken from (ENERGINET.DK, 2012) and are relative to a medium sized steam turbine fuelled by woodchips. The costs associated to such technology were given by (NVE, 2011b). The authors warn that the estimates are provided with quite high degree of uncertainty: the investment costs can vary strongly if fuel storage or fuel handling device is needed. Also the quality of the fuel burnt strongly affects the design of the plant and thus the final installation cost.

For the waste incinerator plants the efficiency of 0.21 and the availability factor of 0.86 were taken from RAMSES database (LARSEN H. , 2014). The costs instead were calculated from (NVE, 2011b).

4.4.4.2 Biopower by gaseous fuels

Internal combustion engine plants that produce power from gaseous bio-fuels in Norway are installed in landfills and in sludge treatment plants.

By means of 85 landfill gas extraction plants about 25% of the gas annually generated in the landfill is collected. Furthermore about 60% of such collected quantity is used for energy purposes. The conversion takes place in internal combustion engines whose installed capacity in 2010 was estimated to be 10 MW (VALJORD, K.; SOLLESNESS, G., 2009).

In 2010 there were 29 biogas plants in Norway (AVFALL NORGE, 2010). In particular there were 23 sludge treatment plants, 1 plant for the treatment of sludge and food waste, 5 plants for the treatment of food waste and two plants for the treatment of sludge which can also receive food waste. In addition there are some little biogas plants in farms, which are not accounted in the statistics.

In 2009 such biogas plants produced 33 million Sm^3 of biogas, which is used for various purposes. The relative distribution is shown in figure 42.

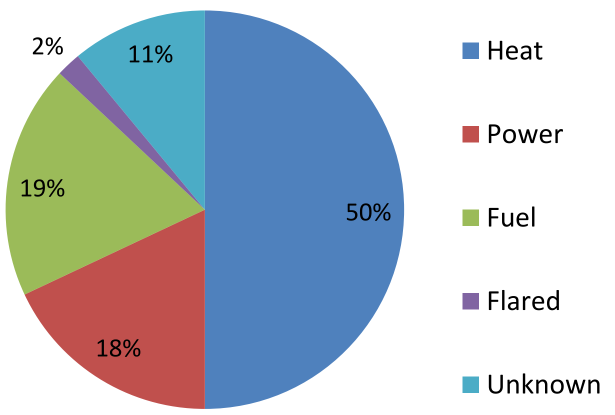


Figure 42: Utilization of biogas from reactor

As visible from the figure above the majority of biogas is used for heating purposes. The power generation from biogas from reactor is realized in nine biogas plants equipped with internal combustion engine, whose total installed capacity is 5.66 MW.

From what has been explained in this paragraph it results that the total installed capacity of internal combustion engine for the power conversion of biogas is 15.66 MW. The efficiency of 0.33 and the availability factor of 0.9 were given by RAMSES database. The costs were taken from (NVE, 2011b). Since the costs for internal combustion engines burning biogas weren't reported, it has been assumed that the investment and FIXOM costs are the same as those of Diesel internal combustion engine. The VAROM cost instead was taken from an equivalent plant in the Danish TIMES model.

4.5 Power consumption

In 2010 the Norwegian domestic gross consumption of electricity was 132 TWh (NVE, 2010) that, by removing the distribution losses and the energy industry self-consumption, leads to a final consumption of 114.7 TWh (NORDEN & IEA, 2013).

The total power demand has been split in four energy sectors: residential, industrial, transport and commercial (that includes agriculture and fishing too). The contributions of these sectors to the total final power demand in the base year are described in figure 43. As shown, the transport contribution to the total consumption is almost negligible and the highest share is associated to industry (NORDEN & IEA, 2013).

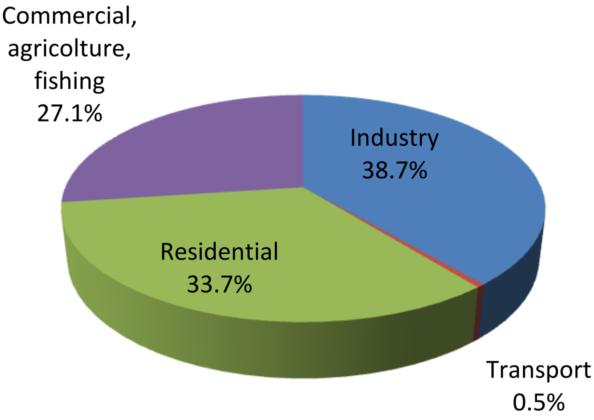


Figure 43: Final consumption per sector in 2010

4.5.1 Structure

In the TIMES models the demand for energy services is given exogenously. In fact in the Norwegian TIMES model a workbook called “VT_NW_DEM” has been created for describing the final power demand in Norway in 2010. In order to model the power demand of the energy sectors considered four commodities are used: one relative to industry (DINDELC), one to transport (DTRAELC), one to the residential sector (DRESELC) and one to the commercial sector (DCOMELC). These commodities, which are flowing out of four processes denominated “Demand Technologies”, together with the associated demands are shown in table 13.

Since the efficiency associated to these processes is equal to one, they work as dummy processes linking the demand commodities with the power commodity ELCC and thus representing the fulfilment of the energy service.

Table 13: Demand commodities

CommName	Region	DEMAND
*Unit		PJ
DINDELC	NOR	160

DTRAELC	NOR	2
DRESELC	NOR	139
DCOMELC	NOR	112

4.5.2 Projections

TIMES is a demand-driven model generator which computes the optimal investments to meet the present and future demand. So the projections of energy demand are an essential feature of policy analyses, because they deeply influence the need for new installed capacity and the future energy system in general. Since long-term energy demand projections are affected by high uncertainty, various scenarios concerning power demand should be created in order to perform sensitivity analysis and to illustrate the impact of different demand evolution trends on the energy system, as suggested by (ROSENBERG et al., 2013). Such sensitivity analysis has been realized and its results are described in paragraph 6.1

In the demand workbook “VT_NW_DEM” only the power demand in 2010 has been described. Separately two scenario workbooks with the demand projections have been created, which are called “Scen_DEM_FR-PROJ-2DS” and “Scen_DEM_FR-PROJ-4DS”. In this way the model can be run with two different trends of the power demand in the various sectors until 2050.

The trends are those of the 4°C increase and 2°C increase scenarios elaborated by the NETP report (NORDEN & IEA, 2013) and are shown in figure 44.

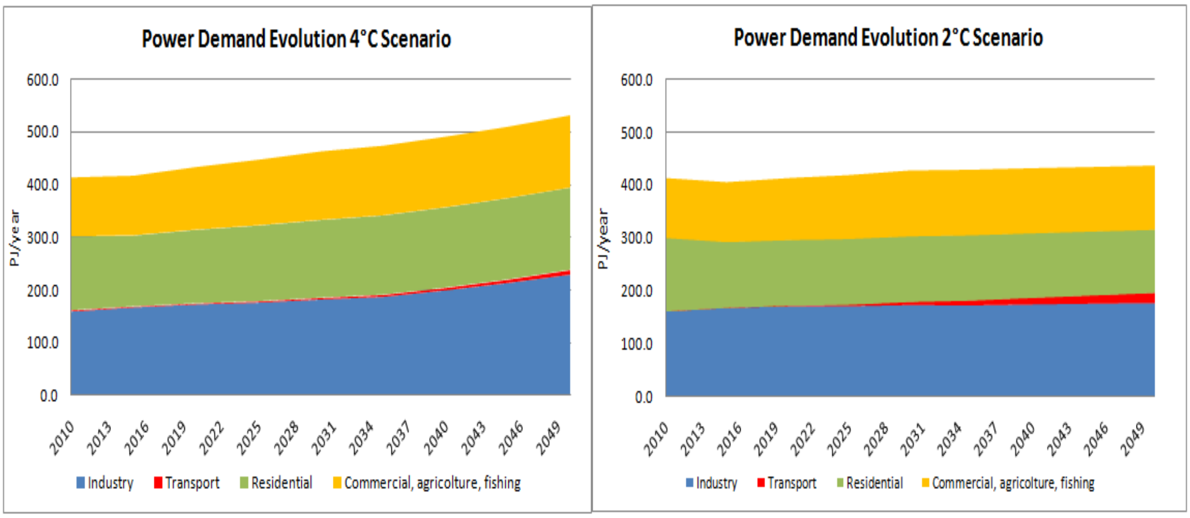


Figure 44: 4°C and 2°C increase power demand scenarios

According to the 4°C increase scenario the total final consumption is assumed to rise of 30% in 2050 with respect to 2010. In particular all the energy sectors are characterized by an increase of the power demand. However the highest increase is observed in the transport sector, for which the demand increases more than three times between 2010 and 2050. Anyway its share in the total demand in 2050 still accounts for only 2%, as shown in figure 45.

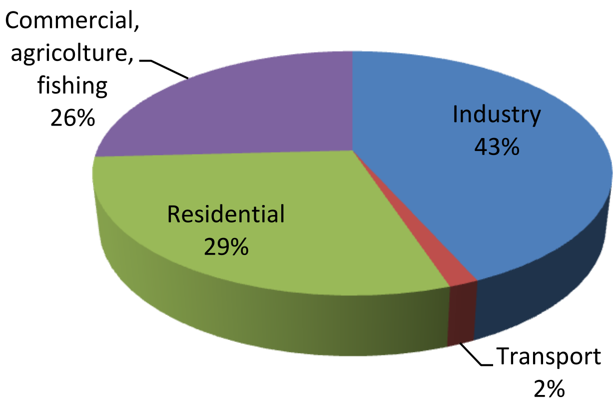


Figure 45: 4°C increase scenario's final consumption per sector in 2050

Instead in the 2°C increase scenario the total demand is assumed to rise of only 6% in 2050 with respect to 2010. Also in this case the highest increase is represented by the transport sector, which increases more than nine times throughout the time horizon considered and thus reaching 5% of the total consumption in 2050. The modest demand increase in this scenario is believed to be due to a decrease of 14% of the consumption of the residential sector and to the fact that the increase in all the other sectors remains modest.

The contribution of the different sectors to the final consumption in 2050 according to the 2°C increase scenario is shown in figure 46.

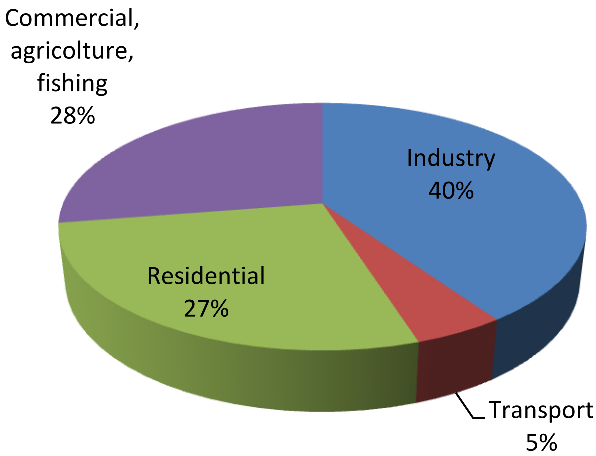


Figure 46: 2°C increase scenario's final consumption per sector in 2050

4.5.3 Load profile

The power demand isn't constant over the day or over the year but instead is characterized by a strong variation, with a maximum during winter when the temperatures are lower. With the purpose of catching this variation, a description of the load profile has been included in the TIMES model of Norway in the scenario workbooks that also describe the demand projection. Using the attribute

“COM-FR” (fraction of the total demand) it has been possible to associate a share of the total annual power demand to each one of the 32 time slices.

A part of the definition of the load profile in the model is shown in table 14, taken from the workbook “Scen_DEM_FR-PROJ”.

Table 14: Demand Fraction

TimeSlice	Attribute	Year	Cset_SET	Cset_CN	NOR
RWDA	COM_FR	2010	DEM	D*ELC	0.0009
RWDD	COM_FR	2010	DEM	D*ELC	0.1299
RWDC	COM_FR	2010	DEM	D*ELC	0.0144
RWDB	COM_FR	2010	DEM	D*ELC	0.0257
RNWA	COM_FR	2010	DEM	D*ELC	0.0005
RNWD	COM_FR	2010	DEM	D*ELC	0.0716

The shares of total demand associated to the various time slices have been calculated from the historical data of the power consumption from 2006 to 2013 provided by Statnett (STATNETT, 2015a). First of all, for every hour of the year the average between all the historical demands has been calculated. Then these 8760 values have been input to the “Time slice feeder”, which gave as output the energy content of the total demand in every time slice and these are the 32 demand-fraction values.

The annual profile of the demand of electricity input to the model is shown in figure 47, where the unit is the PJ.

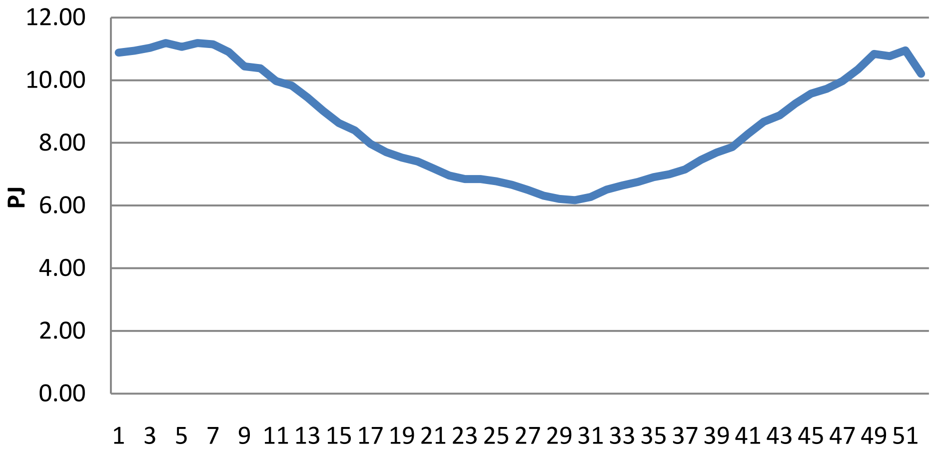


Figure 47: Power demand yearly load profile

4.6 Future technologies available for generation

In TIMES models the main decision variable is the capacity to be installed in order to meet the demand. Until 2015 the existing or under construction plants are described and fixed in the workbook “VT_NW_ELC”, so that the solver is limited to determine the optimal use of the installed plants in terms of activity (electric energy production, in PJ). On the contrary, from 2015 on TIMES must determine which technologies to install to ensure that the electricity demand is satisfied in each time slice.

In the TIMES model of Norway the electricity demand has been represented as inelastic, which means that it must be met without limitations neither of cost nor of system efficiency. In order to ensure that the demand is met throughout the time horizon, from 2015 the solver both selects the optimal technology mix for replacing and/or complementing the existing stock and quantifies the optimal use of the already existing and new-installed plants.

The solver establishes which new technologies to install by selecting from the “SubRes_NewTechs-ELCnor” workbook. This is a list of future available power plants technologies described by technological, environmental and economical parameters. The format of this workbook is very similar to that of the base year workbook, but it presents some extra attributes needed to better characterize the investment: INVCOST (investment cost, which is divided in many annual payments over the lifetime of the plant), START (year when the technology becomes commercially available), ILED (year it takes to build the technology)

The technologies considered in “SubRES_NewTechs-ELCnor” are those suggested in (LIND, ROSENBERG, & SELJOM, 2013). This set of new available processes doesn’t include any nuclear, coal or fuel-oil power plants and future investments in natural gas fuelled power plants are possible only if equipped with carbon capture and storage (CCS).

The technologies taken into account for future investments are presented in table 15, together with the respective potential and investment cost in 2015 and 2030.

Table 15: Overview of future available technologies, potential and investment cost

Technology	Potential (PJ)	Investment (MNOK10/MW)
Year	2030, 2050	2030, 2050
Gas turbine combined cycle with CCS	Unlim.	10.7
Waste to energy CHP	Historical	26.4
Wind turbine large on-shore	64.1	9.7
Wind turbine medium on-shore		12.1
Wind turbine off-shore	82.4	20.3
New DAM hydro	7.2	12.6
New ROR hydro	43.2	12.1
Expanded and upgraded DAM hydro	18.6	8.6
Expanded and upgraded ROR hydro	8.1	5.1
Decommissioned and rebuilt DAM hydro	Inflow	12.6
Decommissioned and rebuilt ROR hydro		12.1

Data describing these future available technologies have been taken from various sources, which are presented each time.

The following paragraphs contain a brief presentation of the technologies listed in table 15.

4.6.1 Future hydropower plants

Hydropower is a mature technology and therefore the description of future available hydroelectric plants in the model is based more on the division of the total hydropower potential between classes than on the technological and economical improvements.

Future hydroelectric technologies are divided in three main classes:

- New hydro plants
- Expanded and upgraded hydro plants
- Decommissioned and rebuilt hydro plants.

These classes are further divided between ROR and DAM technologies.

Due to technological maturity of hydropower, the margins of cost reduction and technological improvement are minimal. In fact in the model the FIXOM and VAROM costs of future ROR and DAM plants have been set equal to the respective costs in the base year, which means that O&M cost reduction is assumed to be zero. The investment costs were assumed to be equal to those of "New hydropower" in (LIND et al., 2013) for all the years of the time horizon of the model, which are only slightly lower than the investment costs in the base year.

New hydro plants (both ROR and DAM) start being available for investment in 2015 and it takes two years to build a new ROR station and three years to build a new DAM station.

For the new DAM and ROR hydro plants a constraint has been imposed on the yearly maximum activity (PJ) by means of the attribute "ACT_BND". Such constraint has been set equal to the estimates of hydropower potential elaborated by NVE in 2010 (see figure 35). In particular the allocation of the total potential to DAM and ROR was done using the data provided by (LIND, ROSENBERG, & SELJOM, 2013).

Expanded and upgraded hydro plants represent the increase of capacity and thus of power generation due to the enhancement of the machinery and electrical components of the hydro stations. In the model two upgrading processes have been implemented: one for DAM and one for ROR, both available from 2015. For this technology the construction time is one year.

The constraint on the maximum yearly power generation was set equal to the data provided in (LIND et al., 2013).

Expanded and upgraded hydro plants have associated an investment cost that is lower than the one for the other future hydro technologies. In fact according to (NVE, 2011b) the investment cost related to the construction of the facility accounts for 68% of the total cost of DAM and 42% of the total cost of ROR. So for the two kinds of plant these percentages were discounted from the total cost giving a lower investment cost.

Decommissioned and rebuilt hydro plants were implemented in the model in order to take into account that once a hydro plant ends its lifetime, instead of just stopping producing power in that location a new hydro plant can be built. In fact even if it will be necessary to build a new dam, a new facility, new machineries and electrical generators all hydraulic works for the collection and management of water are already present and it is not necessary to carry out a feasibility study to known that a plant in that location is rentable.

This class of plants start to be available in 2026, year in which the first existing plants are decommissioned according to the retirement profile created. The construction time for this process is two years for both ROR and DAM.

This type of plants doesn't have associated any "ACT_BND" kind constraints, but instead the sum of its power generation with that by the existing hydro stations must be lower than the water inflow (table 9). In fact this kind of plants is built in a location where a power plant was already located and therefore the overall water inflow is not increasing. On the contrary for the other future available hydropower plants a new installation also implies that a greater flow of water is captured. For this class of hydro plants it would have been reasonable also to set for every milestone year a constraint on the maximum new installed capacity lower or equal than the decommissioned capacity in the same year. However it was preferred to set the restriction on the energy generation since it's less strict.

The generation by all the previously described hydro technologies is modelled using the same availability factors of the existing hydro stations. This means that the solver will determine the optimal new DAM and ROR capacity to install in such a way that the total generation from these technologies doesn't exceed the activity constraints imposed and always keeping in consideration that the generation profile is the same as the already existing hydro technologies.

4.6.2 Future wind turbines

Nowadays wind energy is considered to have a high potential in Norway and to play an important role in the future Norwegian power system. In this context it is important to have a reasoned idea of the expected contribution from wind power, with the aim to carry on an adequate plan for the deployment of this technology. For this reason NVE has been creating various statistics collecting plenty of data on wind power generation, on wind farms availability and capacity factors and on wind (HOFSTAD, 2011) (VINDTEKNIKK, 2015) (NVE, 2013) (NVE, 2009).

Future wind turbines available for investment are first divided in two groups: on-shore and off-shore turbines. Then onshore turbines are classified in large turbines and medium turbines. Both these categories are further divided into several technologies that have gradually lower investment cost and higher lifetime, but which become available gradually later in the future (the first class of on-shore wind turbines becomes available in 2015), as visible in table 16 taken from "SubRES_NewTechs-ELCnor".

Table 16: Future available wind technologies

TechName	*TechDesc	START	INVCOST	LIFE
ERWINWON115N	Wind Turbines Onshore - Large 15	2015	13.0	20
ERWINWOT120N	Wind Turbines Onshore - Large 20	2020	12.3	20
ERWINWOT130N	Wind Turbines Onshore - Large 30	2030	12.0	25
ERWINWOT150N	Wind Turbines Onshore - Large 50	2050	11.3	30
ERWINWON215N	Wind Turbines Onshore - Medium 15	2015	15.0	20
ERWINWOT220N	Wind Turbines Onshore - Medium 20	2020	14.1	20
ERWINWOT230N	Wind Turbines Onshore - Medium 30	2030	13.8	25
ERWINWOT250N	Wind Turbines Onshore - Medium 50	2050	13.0	30
ERWINWOFF530N	Wind Turbines Offshore 30	2030	20.1	25
ERWINWOFF550N	Wind Turbines Offshore 50	2050	19.0	30

The description of the availability factors of future available wind technologies in Norway attempts to share the same grade of optimism adopted in the Danish model. This was done in order to prevent the model to suggest installing new wind turbines only in one region just because the assumptions on technological development for that region are more optimistic.

The values for the availability factors of future available wind turbines were taken from the Balmorel model of the Nordic Regions (File Geogr.inc, 2004). In particular these availability factors are the estimates related to the turbines installed in the Southern part of Norway, where the highest amount of wind farms is currently located (THEWINDPOWER.NET). The values are shown in table 17.

Table 17: Future wind turbines AF

Wind turbine cathegory	Weighted average AF
Existing	26%
Onshore Large	46%
Onshore Medium	39%
Offshore	48%

These coefficients have been normalized with the availability factors of the existing wind turbines (see table 10), thus determining an availability factor for every time slice also for future wind technologies. This corresponds to assuming that in the future the full load hours of wind turbines will increase but that the wind power production profile will remain the same as the historical one. While this is a good approximation for future on-shore wind turbines, it is not for off-shore ones. However no off-shore wind turbines are currently installed in Norway and then it wasn't possible to have data about the power production profile. A further improvement of the model would be reached by using two different power production profiles for the two technologies, even if this would increase the model size.

In the model the wind power future maximum potential has been specified, too. Since such potential is not imposed on individual technologies but on the set of all the wind turbines (already in stock, to be installed in the future, on-shore and off-shore) it had to be written as a user constraint. So the restriction on the future maximum potential was not included in the "SubRES_NewTechs-ELCnor" workbook but instead in the scenario file "Scenario_Wind_Fraction-Potential". The restrictions imposed on the future wind generation are shown in table 11.

Even if the estimated wind power potential in Norway seems to be high, the severe weather conditions characterized by snow and ice can pose obstacles in the exploitation of this electricity generation form and are difficult to estimate.

The investment cost in 2015 has been taken from (LIND et al., 2013). In particular the lower bound value was associated to large wind turbines (which name in the model is "ERWINWON115N") and the upper bound value was associated to the medium wind turbines (which name in the model is "ERWINWON215N"). Then for both large and medium turbines the investment costs reduce throughout the time horizon following the investment cost reduction profile of wind turbines in the Danish TIMES model.

The FIXOM and VAROM costs are the same for each technology and are equal to those in the base year.

Off-shore wind turbines become available in 2030, according to (LIND, ROSENBERG, & SELJOM, 2013). The investment cost in the starting year has been taken from the same table (the cathegory "Near shore" has been considered), while the cost in 2050 has been calculated supposing that the cost reduction profile is the same as that in the Danish TIMES model.

Construction time was set equal to one year for on-shore and to two years for off-shore wind turbines. Lifetime increases over the time horizon for both technologies: for on-shore it is 20 years in 2015 and 30 years in 2050, for off-shore it is 25 years in 2030 and 30 years in 2050 (ENERGINET.DK, 2012)).

4.6.3 Combined cycle with CCCS

Norway has established the environmental target of becoming carbon neutral by 2050 and, in the short-term, it aims to have a renewable energy share of 67.5% by 2020 (IEA, 2012). In accordance with these goals on the Norwegian territory it is forbidden to build natural gas based power plants if they are not equipped with CCS. CCS in general indicates all those processes that aim to the reduction of the concentration of CO_2 in the exhaust gases of a plant.

For ten years some companies, agencies and universities have been carrying on research projects on CCS and have created CCS pilot plants. Some CO_2 capture systems at small scale are already available, too. They can be divided in three groups: post-combustion capture, pre-combustion capture and oxy-fuel combustion (ENERGINET.DK, 2012).

Combined cycle gas with CCS is implemented in the model as a process called "ETNGACCYCCS1N".

According to (TZIMAS, 2009) power plants equipped with CO_2 capture device will be available from 2015, while Zero emission platform claims that base versions of power plants with CO_2 capture represent current technology choices but that CCS will become commercially available only by 2020 (ZERO EMISSION PLATFORM, 2011). In the model 2020 has been set as the starting year. To the construction time the value of 4 years was assigned, to the plants lifetime 20 years and to the plant efficiency 46% (TZIMAS, 2009).

Concerning the costs of CCS technologies, the literature only reports estimates, because mature and optimised plants with CCS are not available yet. For this reason there is high uncertainty regarding this information.

For natural gas based combined cycle plants with CCS (NGCC-CCS) some estimations of the investment cost reported in the literature are shown in figure 48.

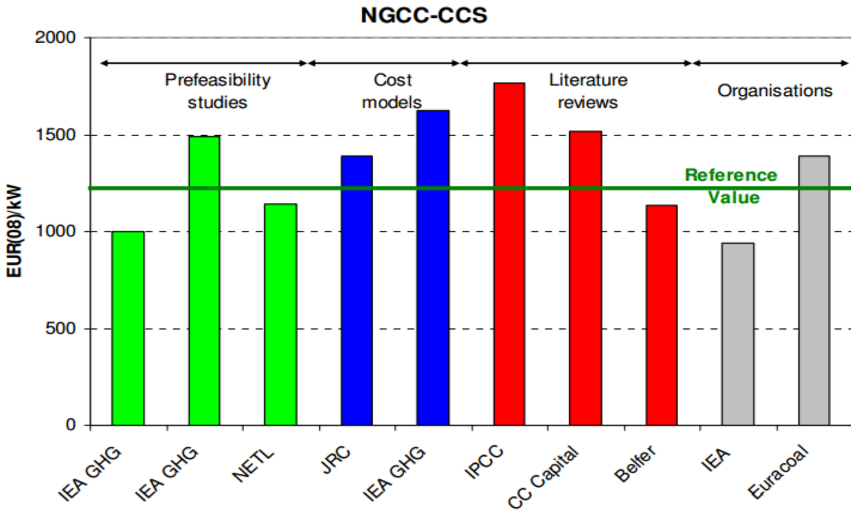


Figure 48: NGCC-CCS Investment costs of different literature sources (TZIMAS, 2009)

The estimates in figure 48 vary widely. In the model the investment cost has been set equal to the reference value represented in the figure 48with a green line: 1.3 M€2008/MW, which is converted in the reference currency by means of the conversion table located in the workbook “SysSettings”.

On the contrary in the literature the values reported for FIXOM and VAROM costs for NGCC-CCS are quite similar. In the model these two costs have been set equal to the reference values proposed by (TZIMAS, 2009): FIXOM is equal to 0.038 M€2008/MW and VAROM to 3.24 M€2008/PJ.

Since no data were found about future development of these parameters, in the model it has been assumed that the parameters remain constant also in 2030 and 2050.

4.6.4 Future waste to energy CHP

The name of the process associated to this technology in TIMES is “ECWSTGEEXC1N”.

Since waste to energy CHP is already available, the starting time has been set equal to 2015. To the plant lifetime has been assigned a value of 20 years and to the construction time 4 years. The efficiency was supposed to increase, from 24% in 2015 to 26 % in 2050 (ENERGINET.DK, 2012).

Since no data about the future development of costs in Norway were found, the costs in the future have been set equal to the costs in the base year.

Many other plants that are believed to play an important role in the future power system could have been added to the list of technologies in the "SubRes_NewTechs-ELCnor" workbook, for instance tidal, biomass, wave and hydrogen. However it has been decided not to include other plants in the list of the future available technologies because they are not important in the context of this thesis, which rather aims to evaluate whether it is worth increasing the installed capacity of the Norwegian hydropower.

4.7 Electricity transmission and power exchange

The Norwegian power system is characterized by being strongly interconnected with the neighbouring countries. Moreover Statnett, the Norwegian TSO, in collaboration with the TSOs of other European countries is planning to increase the number of interconnections. New and existing interconnectors are making the Nordic power market more integrated with the European one. Power can be transmitted between different countries thus offering balancing services between areas with low and high prices. Also the fact that the power systems differ from country to country ensures that if one country is facing energy shortage electricity can however been imported by another country without problems of energy availability. In fact interconnections increase the security of supply.

The integration of the national electric grids by means of interconnectors is driven by the EU's policy which aims to improve the security of supply, to mitigate climate change, to support competition in the power sector and to increase the overall efficiency of the electric system (SVENSKA KRAFTNAT & STATNATT, 2010).

This chapter presents the Norwegian power distribution system, the current and planned interconnectors' capacities, the historical prices in the different countries and in the bidding areas that have been used in order to model the international electricity exchange using exogenous trade processes and the logic of operation of the endogenous trading.

4.7.1 Electricity distribution

In the TIMES model of Norway the national distribution grid hasn't been described with particular detail. In fact since the geographical resolution of Norway is national, it was not interesting to describe in the model the power distribution lines between different bidding areas.

In the model the power distribution grid has been taken into account by describing its losses, which imply that the power plants in stock must produce more power than just the electricity demand, because a part of the production is to compensate the losses.

The distribution losses have been modelled by means of the attribute “COM_IE” (power distribution efficiency) in the “SysSettings” workbook. The value associated to this attribute is 0.921. It was calculated as the average of the ratios between the distribution losses and the total power consumption from 2008 to 2012 (U.S. ENERGY INFORMATION ADMINISTRATION, 2015) and is consistent with the value used in the Norwegian TIMES model by IFE (INSTITUTE FOR ENERGY TECHNOLOGY, 2013).

4.7.2 Existing interconnectors

In 2010 Norway was electrically interconnected to Sweden, Denmark, Netherland, Finland and Russia. The total existing transmission capacity summed up to 5450 MW. This value is almost two times higher than the goal established by the Meeting of Barcelona of 2002 which states to have interconnection capacity totalling at least 10% of the installed capacity (EUROPEAN COMMISSION, 2002).

In figure 49 the already existing and the future planned interconnectors between Norway and the neighbouring countries are shown.

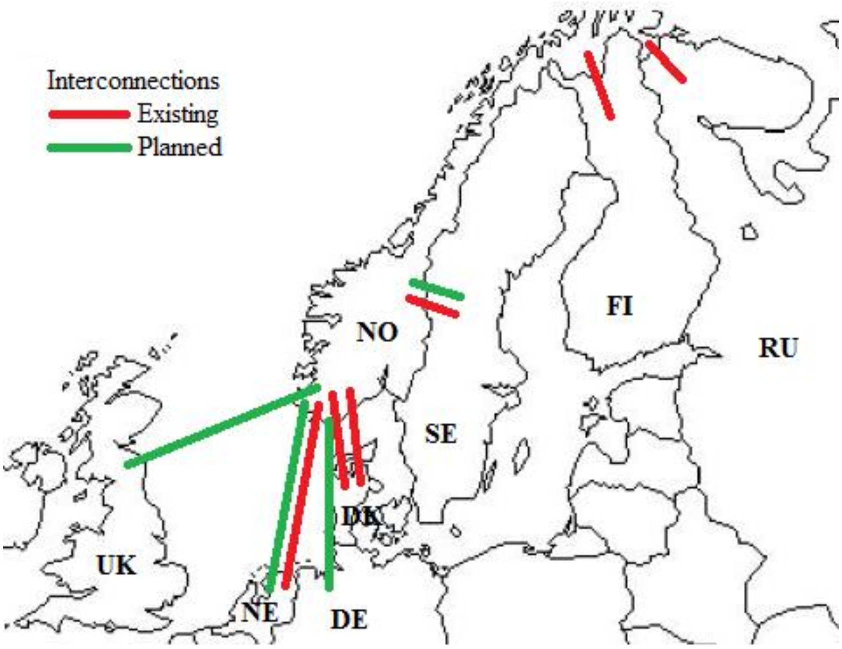


Figure 49: Existing and planned interconnectors between Norway and the neighbouring countries

Such interconnectors represent an alternative way to fulfil the power demand in an efficient way: instead of starting an expensive plant in the peak hours or instead of using water stored in the reservoirs in periods of drought, power can be imported from the surrounding country which in that moment are producing power at cheaper cost

The Danish and Norwegian electricity systems are interconnected by means of the Skagerrak transmission system, owned by the TSOs Statnett in Norway and Energynet.dk in Denmark.

Until 2010 the interconnection between these two countries was realized by means of three submarine HVDC cables passing through the channel of Skagerrak, for a total transmission capacity of 940 MW. At the end of 2014 a fourth cable called SK4 with a transmission capacity of 700 MW has become operative. In this way the total transmission capacity between Norway and Denmark currently accounts for 1700 MW (STATNETT, 2015C) (ABB, 2015)

The technology employed for the interconnection between Norway and Denmark is called HVDC (high-voltage direct current) and offers many advantages. First of all it can prevent the transmission of faults and synchronization problems between the two electric grids. It is also characterized by minimal transmission losses: they are 30-50% less than comparable alternating current overhead lines.

The interconnection between Sweden and Norway is very strong and is realized by means of eight interconnectors: in the Southern bidding area (NO1), in the central bidding area (NO3) and in the Northern bidding area (NO4), as visible in Figure 14.

Norway is electrically interconnected to the Netherlands by means of NorNed, a 580 kilometres long HVDC submarine power cable. This is owned by Stattnet and the Dutch system operator TenneT. NorNed has the record of world’s largest power cable.

NorNed is a bipolar HVDC cable of 700 MW of transmission capacity. The installation started in the beginning of 2006 and it took until 2007 to finish the work. It became operative in May 2008.

At the beginning the capacity of the interconnector was managed through explicit auction, then, since 2011, an implicit auction system was set.

Moreover Norway is interconnected with Russia and Finland through one interconnector for each country. With these countries the transmission capacity is quite small: 100 MW with Finland and 50 MW with Russia. In particular the interconnection with Russia allows Norway only to import electricity.

Table 18 summarizes the current exchange capacities between Norway and the interconnected countries (where the unit is the MW) and the starting year set in the model.

Table 18: Current exchange capacities between countries (MW)

	Denmark	Sweden	Finland	Netherlands	Russia	Denmark (SK4)
Import	1000	3600	100	700	50	700
Export	1000	3600	70	700	0	700
Start	2010	2010	2010	2010	2010	2015

In the model the existing interconnectors have been declared in a workbook called “SubRES_ELC-IMPEXP”. The interconnectors are represented as import and export processes that can exchange the commodity electricity (ELCC) with the outside of the borders of the system. Each interconnector in the model has associated parameters defining the lifetime, the starting year of operation, the efficiency and the availability factor. For all the interconnectors the lifetime has been set equal to 50 years, as in the Danish TIMES model, the efficiency to 0.97, as in the TIMES model of Norway created by IFE (LIND et al., 2013) and the availability factor to 0.92.

Except Skagerrak IV all the interconnectors described above already existed in the base year and therefore in the model 2010 was set as starting year of operation. Instead the process associated to the interconnector Skagerrak IV has 2015 as starting year.

The description of the transmission capacity in the model was declared in another SubRes workbook called "SubRES_ELC-IMPEXP_Trans". The capacity was input in the model in the form of a restriction on the maximum annual activity, using the attribute "CAP_BND". In order to remain consistent with the Danish TIMES model, the constraints were not given for the installed power but for the energy associated to one year of operation with the available transmission capacity. In particular these constraints were specified for many years and not interpolated.

4.7.3 Future interconnectors

Apart from the existing interconnectors described above Statnett is currently designing with the TSOs of the other European countries new interconnections that will increase the integration of the power markets.

Stattnet and TenneT are currently working on the installation of a subsea cable called NorGer, which will connect the Norwegian and German power electricity grids. The investment decision was taken in 2014 and the two system operators aim to complete the project by 2018 (STATNETT, 2015b). The total transmission capacity between Norway and Germany is going to be 1400 MW.

Other power grid interconnection projects are still at the design stage or are waiting for receiving the licence. These projects foresee that in the next years Norway will be also interconnected with England and that the interconnections with Sweden and the Netherlands will be reinforced.

From the collaboration of Statnett and National Grid was born the project of a submarine cable connecting the United Kingdom and Norway, called NSN. The connection points are going to be Kvilldal on the Norwegian side and Blyth on the British side. The transmission capacity of this interconnection is planned to be 1400 MW. The project obtained the licence in May 2013.

The new interconnection between Norway and the United Kingdom will be available in 2020 (STATNETT, 2010).

Statnett and TenneT are planning to create a second linking between the Norwegian and Dutch grid systems. The future interconnection will be called NorNed2 and its transmission capacity will be 700 MW. However it was planned that it will become operative not in the close future but instead in 2030.

Finally, Statnett and Svenska Kraftnat are going to strongly reinforce the already tight interconnection between Sweden and Norway. The project consists in the creation of new interconnections accounting in total for a transmission capacity of 1400 MW that will become operative in 2020. In the Norwegian TIMES model realized by IFE the capacity of the future interconnection between Sweden and Norway was considered to be much higher: in particular in this model three new different lines of 1400 MW each are considered. However the Nowegian National Plan for the next generation power grid of 2013 states that only one of this three lines will actually be built (in the North of Norway) (STATNETT, 2010). So it was preferred to rely on this information and in the model the new planned transmission capacity is set equal to only 1400 MW.

Currently there isn't any project regarding the improvement of the interconnection with Finland and Russia. In particular Statnett cooperated for several years with the Russian power company Inter-RAO on the development of a new interconnection between Skogfoss in Finnmark and Nikel on the Kola Peninsula in Russia. It was decided to wait for the shut-down of the two nuclear reactors in the Kola Peninsula before creating the new linking. Such shut-down is scheduled for 2018 but meanwhile the two companies are not carrying out the project. However Statnett still assesses that higher import from Russia is beneficial for the security of supply and is economically convenient, due to the very cheap power prices in the Kola Peninsula (STATNETT, 2010).

Table 19 summarizes the description of the planned and under construction interconnections between Norway and the other countries as they have been input in the model. As for the existing interconnectors, also these planned and under construction interconnectors have been described in the workbook "SubRES_ELC-IMPEXP". The associated life time, efficiency and availability factor are the same as the existing interconnectors.

Table 19: Planned and under construction interconnections

State	Connection	Capacity (MW)	Investment Cost (kNOK10/MW)	FIXOM Cost (kNOK10/MW)	Start
Under construction	Germany (NordLink)	1400	7000	33	2018
Planned	UK (NSN)	1400	15591	36	2020
Planned	Sweden	1400	900	9	2020
Planned	Netherlands (NorNed 2)	700	13800	32	2030

As visible from table 19 for the future interconnectors were also collected data about the investment and FIXOM costs (STATNETT, 2010). At present these costs are not input in the model. In fact it is assumed that all the above presented planned and under construction interconnectors are going to be built. However, by inputting these costs in the model it would be possible to investigate if it is more convenient to install new transmission lines or to invest in new generation capacity. Moreover the solver would determine the optimal transmission capacity to install between the various countries.

However it was not decided to perform this kind of assessment but instead to analyze as a sensitivity analysis how to reorganize the power system if the planned interconnectors are not built.

The capacity of the planned and under construction interconnectors has been described in the workbook "SubRES_ELC-IMPEXP_Trans" in the same way as the existing interconnectors.

4.7.4 Exogenous trading

The exchange flows between Norway and the neighbouring countries are based on price related criteria exogenously defined in the model. In fact for some reference years and for all the interconnected countries, in the model the costs of import and export have been described. The power exchange is calculated by TIMES by doing a comparison between the import/export costs and the price of electricity endogenously calculated by the model: if the electricity price is higher than the import cost then Norway will import, while if the electricity price in Norway is lower than the export cost then Norway will export.

The import and export costs used by TIMES for the determination of the exchange flows are exogenously given and have been calculated, as suggested by (JOHNSEN, 2011), starting from the historical power prices in the various countries by Nord Pool, from the forward prices by Nasdaq and from the future prices forecasted by Energinet.dk.

The procedure for obtaining the costs of import and export is explained in detail below: first the trading price profiles were calculated for the base year and then the projections for the future prices were computed.

For the Nordic countries the trading price profile has been calculated from the prices of the power market in 2010. Nord Pool kindly provided a temporary access to their FTP that contains all the hourly historical series for the power prices in the various bidding areas. In this way for the Nordic countries the hourly prices in 2010 were used. For the Nordic countries that are divided in more bidding areas, the hourly prices were calculated as the average between the values in the bidding areas. The historical series with hourly resolution was then given to the "Time slice feeder" thus obtaining a power price for every time slice, which is the price profile.

The trading price profile for the United Kingdom was obtained from the hourly power prices of the N2ex power market (given by Nord Pool). Since the interconnection between Norway and UK is planned to be built in 2020, it was decided to base the associated power price profile on data as close as possible to the planned data: in fact the power prices in 2014 instead of 2010 were used. The same procedure explained for the Nordic countries was used in order to obtain a power price for every time slice.

For Germany the power price profile is the same as the one used in the Danish model. The hourly prices of the European Power Exchange market were used in this case. But since data in 2010 were not available (it was required to pay a fee), the power prices in 2011 were used.

Unfortunately it wasn't possible to find the power prices in 2010 with hourly resolution neither for the Netherlands nor for Russia. For the Netherlands the price profile was calculated from the monthly average price in 2010 by APX, the local power spot market (APX GROUP, 2015). In this case it has been considered that the average monthly price is constant throughout the whole month, thus creating a series that was then given in input to the "Time slice feeder" which returned a power price for every time slice.

For Russia the time resolution of the power prices data used for the computation of the price profile is even worse, because it is at half-year level. In the Russian power market there is not a single power price, but nodal pricing model is adopted. Therefore the power price by ATC for the province of Murmansk, the one where is located the interconnector with Norway, has been used (ATSENERGO, 2015). Power prices in the region of Murmansk have traditionally been low, due to the presence of two nuclear reactors and many hydropower plants. Even if the trading price profile for Russia is based on data with very low time resolution, it must be considered that the interconnection between Norway and Russia is unidirectional and that the transmission capacity is of only 50 MW. Therefore the error introduced by this approximation doesn't affect strongly the solution.

In all the cases the prices were not given in NOK2010 a currency conversion was realized in such a way as to have the prices in that currency.

The power price profiles described above calculated starting from the hourly power prices in 2010 have been used also for the future price profiles. In fact these have been calculated by multiplying the price profile in the base year for some coefficients that estimate the evolution of the power prices in the future. The computation of such coefficients was realized using the historical data from Nord Pool and APX, the forward prices from Nasdaq and the future price estimated by Energinet.dk. All these data were elaborated is such a way as to determine a projection for the power prices from 2014 to 2035.

The historical power price from 2010 to 2014 for all the countries interconnected to Norway were used as starting point for the price projection. The hourly price series provided by Nord Pool were used to calculate, for every country, the average power price from 2010 to 2014. For Russia it has been assumed that the average price is constant over this time span and equal to the average price calculated for the power price profile in the base year. All the prices were then converted in the main currency, NOK2010.

For the years 2015 and 2016 the forward prices by Nasdaq were used. Since such prices were available neither for Finland nor for Russia, for these countries in these two years the average power price was obtained by interpolation between the historical data and the future price forecasted (described below).

The estimates of the future power prices from 2020 to 2035 were taken from Energinet.dk and have been simulated with the BID model (better investment decision) (ENERGINET.DK, 2013). Since these estimates are not available for Finland and Russia, for these two countries the future price estimates are instead based on (ROSENBERG et al., 2013).

These three groups of price data have been arranged into a table from 2014 until 2035. The data for the missing years (between 2017 and 2020) were determined by interpolation from the known data. From the explained table figure 50 was obtained, which shows the estimated projection for the average prices in the countries connected to Norway from 2015 to 2035.

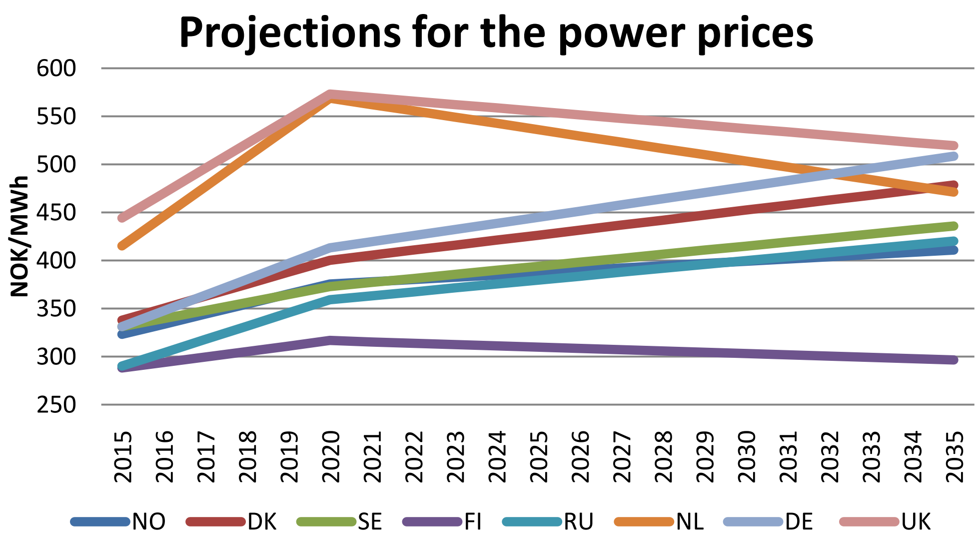


Figure 50: Projections for the power prices from 2015 to 2035

As visible from figure 50, the lowest power price in 2050 is estimated to be that of Finland and the highest that of the United Kingdom. The prices of Russia and Sweden at the beginning of the time horizon are lower or coincident with those of Norway while in 2050 the prices of Norway become lower than these. Only Finland is believed to have lower prices than Norway. All the other interconnected countries have during the entire time horizon higher power prices than the Norwegian ones.

Since the projections before and after 2020 are based on different references the trend is not constant, but a discontinuity exists in 2020. Being based on forecasts, all the projections are affected by uncertainty. In particular future prices for Russia are dubious: in fact prices in Murmansk region have traditionally been low and generally lower than the other nodal prices in Russia, but the probable creation of a joint Russian power market would make prices become homogeneous and then prices in Murmansk would become much higher than in the past.

Finally, from the price projections described above the coefficients used to compute the price profiles in 2015, 2018, 2020 and 2035 have been calculated. For every country by dividing its average estimated price in 2015 by its average price in the base year a coefficient representing the future price evolution was obtained. The same computation was done also for 2018, 2020 and 2035. By multiplying such coefficients by the power price profiles in the base year the future power price profiles were obtained.

Once calculated all these prices it was possible to declare in the model the import and export costs. For every country and for every time slice the import cost was set equal to its power price, while instead the export cost was set equal to 99% of the import cost. It was decided to use this method in order to maintain consistency with the Danish TIMES model.

The description of the import and export costs for the various countries, for the various years and for the various time slices was input in the model in the workbook "SubRES_ELC-IMPEXP_Trans". An extract of the exogenous import and exports costs between Denmark and Norway as they have been input in the model is shown in tables 20 and 21.

Table 20: Impost costs from Denmark in 2010

TimeSlice	Attribute	Year	NOR	Pset_PN	CURR
RWDA	COST	2010	34	IMPELC-DKW	MNOK10
RWDD	COST	2010	91	IMPELC-DKW	MNOK10
RWDC	COST	2010	100	IMPELC-DKW	MNOK10
RWDB	COST	2010	104	IMPELC-DKW	MNOK10

Table 21: Export costs to Denmark in 2010

TimeSlice	Attribute	Year	NOR	Pset_PN	CURR
RWDA	COST	2010	34	EXPELC-DKW	MNOK10
RWDD	COST	2010	90	EXPELC-DKW	MNOK10
RWDC	COST	2010	99	EXPELC-DKW	MNOK10
RWDB	COST	2010	103	EXPELC-DKW	MNOK10

With this exogenous definition of the power trade, TIMES in every year and in every time slice compares the endogenously calculated equilibrium price with the cost of importing and exporting from the interconnected countries.

If the equilibrium price is higher than the import cost the model will import power as long as the new equilibrium price becomes equal to the import cost or as long as all the transmission lines are congested. First power will be imported by the countries with associated the lowest import cost and so on, respecting the principles of the power market.

On the contrary if the endogenously calculated equilibrium price is lower than the export cost, the model will start exporting. In fact in the trading equation in TIMES the export cost is negative and therefore all the exports make the objective function reduce. First Norway will export to the countries with the highest export cost, because in this way higher revenue is obtained and then to the countries with gradually lower price. Then it will stop exporting when the new equilibrium price will become equal to the export cost or when all the transmission lines are congested.

This way of exogenous modelling the power trading creates a problem that will be now only introduced and better explained when commenting the results of the model. In fact if in the model there is at least one interconnector with associated and import cost lower than the export cost of another interconnector the model will consider cost-effective to import as much as possible from the country with low import cost and to export to another country with higher export cost. This is due to the fact that in the objective function the costs of export are negative and that therefore the solver aims to maximize them in order to minimize the objective function.

This feature causes that when power trading is modelled exogenously and more than one trading process is represented, it is impossible to investigate the import and export power amount necessary just for meeting the domestic demand and not to spill water and wind in excess. In fact Norway imports a power flow only in order to export it to more expensive countries thus gaining the difference between the two costs.

But since the power exchanges are calculated depending on the power prices, which are exogenously input in the model and affected by high uncertainty because they are forecasts for the future, it follows that such analysis is not highly reliable. For this reason it is recommended to explore the future power exchanges also modelling the power trading processes endogenously and then to compare the results obtained with the two methods.

4.7.5 Endogenous trading

As already explained in paragraph 4.2.5, the Norwegian TIMES model can be run together with the Danish model. When this configuration is adopted, the power exchange between Norway and Denmark is modelled by means of an endogenous trade process, while the other interconnectors are still represented as import/export processes and their exchange flows are determined on the basis of the price related criteria explained in paragraph 4.7.4.

An endogenous trade process differs from an exogenous one because the power exchange flows is not based on exogenously defined price related criteria, but instead the trading price is determined by the model itself.

In order not to compute the trading through the interconnector between Norway and Denmark twice, the associated exogenous trade process can be deactivated just by checking the two scenarios ”Scen_KILL-ELCC_IMPEXP_DK” in the Norwegian model and ”Scen_KILL-ELCC_IMPEXP_NO” in the Danish one.

The definition of the endogenous trading process between the two regions NOR and DKW of the three-region model was done in the “TRADE” model by means of the electricity trade matrix. Since power can flow in both directions, in particular the bi-lateral electricity trade matrix was used. It is shown in table 22, where exporters are by rows and importers by columns.

Table 22: Table 23: Bi-lateral electricity trade matrix

~TradeLinks

ELCC	NOR	DKW	DKE
NOR		1	
DKW	1		
DKE			

This trade matrix is used by VEDA-FE to automatically create the endogenous trade process called "TB_ELCC_NOR_DKW". This process is recognized by TIMES as an IRE process, which means an endogenous trade process. The same way was also used in the Danish TIMES model for describing the interconnection between DKW and DKE.

The technical description of this interconnection is realized in a scenario trade file called "ScenTrade_trade", which contains the availability factor (0.92), the efficiency (0.97) and the CAP_BND constraints for 2010 (1000 MW) and for 2015 (1700 MW), when also the fourth cable becomes operative.

Chapter **5**

Results of the model

This chapter consists in the presentation and discussion of the results obtained running the baseline scenario of the Norwegian power system implemented in the TIMES model.

First the results from the run of the Norwegian TIMES model alone will be presented. In this case, called Exogenous Baseline Scenario (EXBS), the trading processes are modelled as exogenous processes (as explained in paragraph 4.7.4). Then the results obtained running the hard-linked three-region model that comprises Denmark-East, Denmark-West and Norway together, which is called Endogenous Baseline Scenario (ENBS), will be presented. In this case the trade process between Norway and Denmark-West is implemented as an endogenous trade process (as explained in paragraph 4.7.5).

The most remarkable differences between the results obtained running ENBS and ENBS are described and discussed together with the explanation of the advantages and the disadvantages offered by the two different models.

For both the Baseline Scenarios it was considered that the demand in the future will evolve according to the trend defined in the “Scen_DEM_FR-PROJ-2DS” scenario (described in paragraph 4.5.2), that the water availability to the Norwegian hydropower stations is as in a year of normal rainfall, as described in the “Average_Inflow” scenario (described in paragraph 4.4.1.5) and that all the planned interconnections will come into operation as scheduled.

5.1 Exogenous baseline scenario

In this scenario the cost of the optimized Norwegian power system in the time horizon between 2010 and 2050 is 642987 MNOK.

In the exogenous baseline scenario the solver decides not to install any new capacity. In fact the increase in capacity visible in figure 51 for the years 2012 and 2015 is not optimized, but instead it is due to the fact that in the workbook "VT_NW_ELC" new ROR, DAM, thermal and wind capacity (equal to the values given from the statistics) is forced to be built by means of the attribute "Stock".

After 2025 the total installed power generation capacity decreases due to the retirement profile exogenously described in the model. From 2040 only hydropower stations remain available for power generation because the entire thermal and wind capacity existing in the base year will be retired.

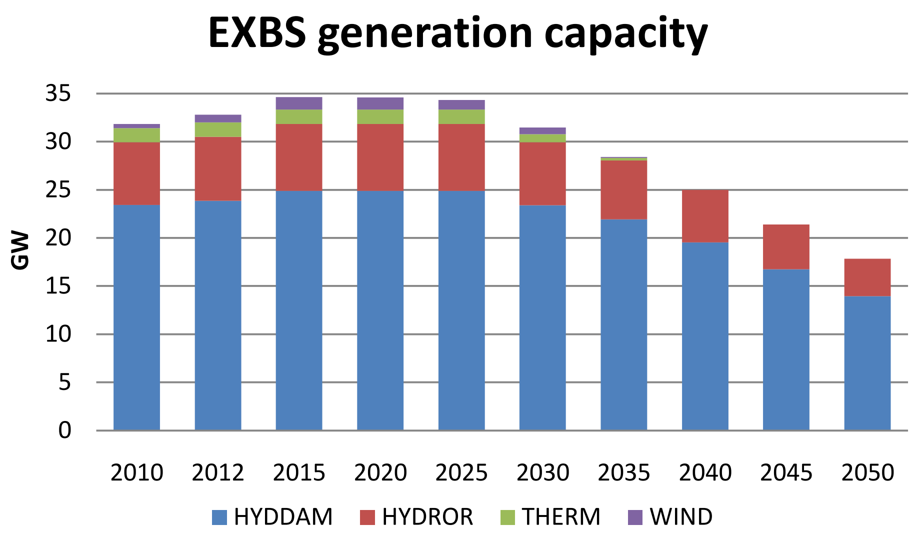


Figure 51: EXBS power generation capacity

Also the trend of the Norwegian power generation calculated by the model is characterized by a decrease over the time horizon, as visible from figure 52.

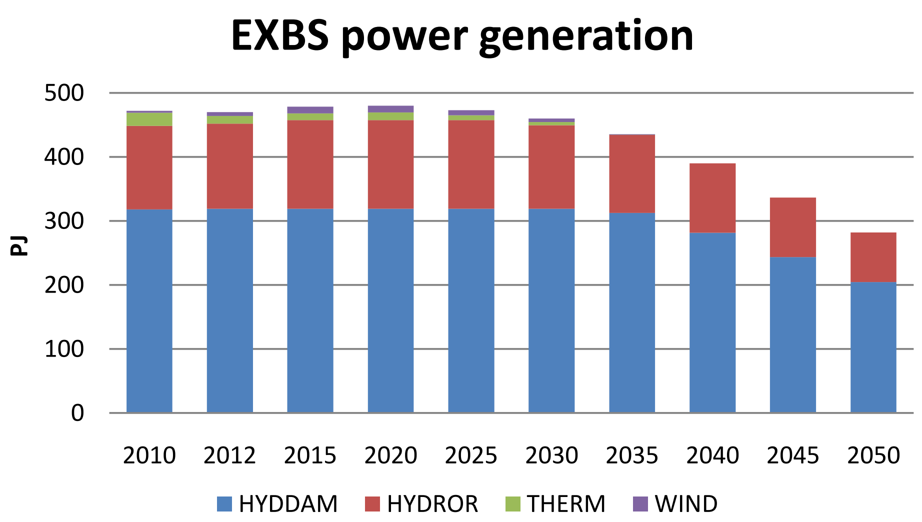


Figure 52: EXBS power generation

From 2035 almost no thermal nor wind capacity will be available for power generation any more. So the solver claims that it is more convenient to import power from the neighbouring countries rather than producing it in Norway, perhaps because new installed power plants wouldn't work for a number of hours high enough to justify the investment cost.

ROR and DAM hydro plants have the lowest VAROM costs of all the available power plants and in fact they are operated during the entire time horizon: it is more convenient to operate them than to import electricity. However the power generation by such plants still decreases, because of the fact that some installed capacity over the time horizon is retired.

Since the trend of the demand of electricity in the "Scen_DEM_FR-PROJ-2DS" scenario is quite constant while the power generation profile is characterized by a marked reduction, a gradually increasing amount of import power is required to meet the demand, as shown in figure 53. On the other side the power export in a first moment increases and then from 2030 starts reducing, due to the retirement of some of the previously existing generation technologies.

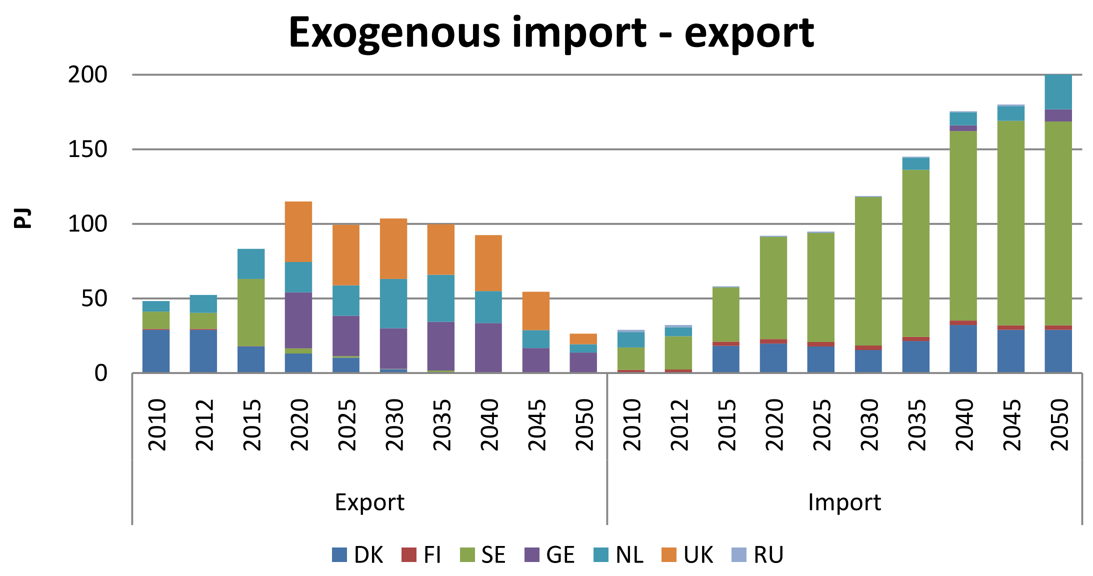


Figure 53: EXBS import and export

If we focus the attention on the power trade between Norway and Denmark it can be observed that in the first two milestone years Norway is a net exporter to Denmark, while from 2015 on the exports from Norway start reducing and the import start increasing thus leading Norway to become a net importer of electricity from Denmark. In particular from 2045 Norway stops exporting power to Denmark.

Concerning the other countries interconnected to Norway, from figure 53 it results that:

- Finland is a net exporter over the whole time horizon, due to the fact that its power prices are the lowest. However the interconnection with this country is very small, so that this import doesn't count so much in absolute terms

- Sweden is a net exporter toward Norway over the entire time period. In particular, since the interconnection with this country is very tight, Sweden plays an important role also in absolute terms regarding the Norwegian imports
- Since prices in Germany are quite high, Norway imports from Germany only a very small amount of power, only in 2040 and 2050. From 2020, when this interconnection becomes available, Germany starts importing a lot of power from Norway
- The Netherlands on average are characterized by higher power prices than Norway and therefore, apart in the base year, this country is always a net importer from Norway
- The United Kingdom is the country characterized by the highest power price and therefore it is the last option for importing for Norway. For this reason Norway never imports from the UK but instead from 2020, when the interconnection becomes operative, power starts flowing from Norway to the UK.

Observing the imports and exports at time slice level it can be realized that some interconnections are frequently congested. This means that if more transmission capacity would be available, the solver would probably suggest to import and export even more power through those interconnectors. In particular the interconnection from Finland to Norway is often congested from 2020 to 2050, the interconnection from Sweden to Norway from 2040 to 2050 and the one from Norway to the United Kingdom between 2020 and 2030.

As already mentioned in paragraph 4.7.4, such very high imports from Finland and Sweden are due to the fact that the solver considers rentable for Norway to import as much as possible from these countries, which have associated the lowest import prices, in order to directly export to the United Kingdom, which has very high export price, thus gaining the difference between the two costs. In fact the power imported by Norway is not just what would serve to cover the demand, but much more.

Norway behaves as a “power-bridge” between the other Scandinavian countries, characterized by the lowest electricity prices and the other interconnected countries. This behaviour of the model is well suited to Denmark but not to Norway. In fact Denmark is really a bridge between the Scandinavian countries (Norway included) and the rest of Europe, because sometimes Denmark is characterized in the same hour by a large power flow in import and the same power flow in export.

Another clue that these results aren’t very reliable is given by the fact that from 2030 on Norway becomes a net importer of electricity, as visible in figure 54. In fact this result doesn’t fit with the future power prices exogenously given to the model shown in figure 50. Norway is characterized by the second lowest electricity prices and therefore it is expected that in the model behaves as a net exporter and not as an importer. But instead in the exogenous baseline scenario, even if an optimistic power demand trend is considered, the power prices become so high that it is more convenient to import rather than to internally produce power and even more than producing for exporting.

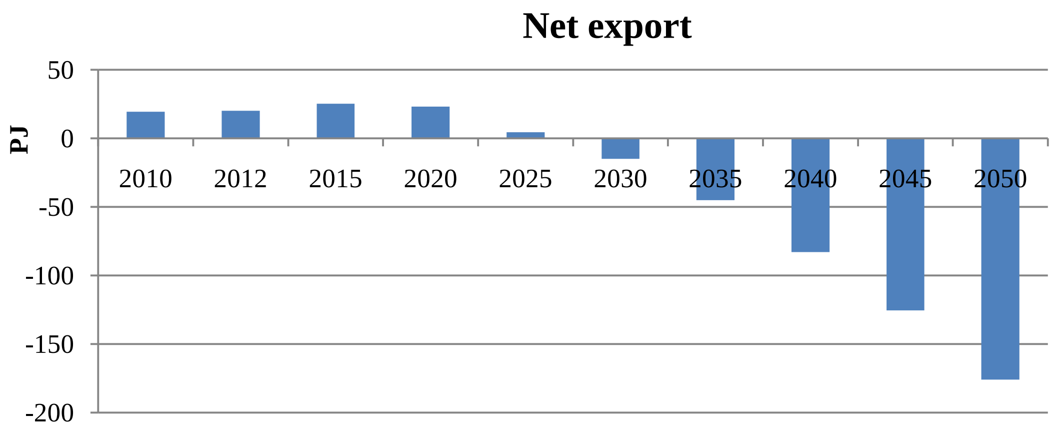


Figure 54: Norwegian net export

Apparently the future power prices exogenously input in the model (calculated as explained in paragraph 4.7.4) are too low and therefore the future power prices calculated in the model are anyhow too high.

An evidence of the fact that the exogenous prices are too low can be found in the fact that the coefficients multiplied to the prices of Sweden in 2010 in order to obtain an estimate of the prices in 2035 are lower than one, which means that power prices in Sweden in 2035 are estimated to be lower than those in 2010. It is hard to assume that these prices are plausible. In fact even if the power prices in 2010 were very high due to drought, a similar situation could occur again in the future and it would add to a plausible increase of the price of the primary fossil resources.

Therefore it looks more likely that the exogenous trade prices input in the model are too low rather than that the prices calculated endogenously by the model are too high.

5.2 Endogenous baseline scenario

In the endogenous baseline scenario the TIMES model of Norway is run together with the one of Denmark by activating the hard-linking described in paragraph 4.2.5. The scenarios for the Norwegian model have already been explained at the beginning of this chapter, while the scenarios for the Danish model are those contained in the case ”TIMES-DK_WLP-NFE”: Danish taxes are not taken into consideration and the bounds on the emission of carbon dioxide are deactivated.

In the Endogenous Baseline Scenario the cost of the optimized Norwegian power system in the time horizon between 2010 and 2050 is 2343472 MNOK. This is the overall system cost and it is related to Denmark-West, Denmark-East and Norway. The cost of the Norwegian power system alone instead is of 680920 MNOK.

In this baseline scenario the solver suggests to install new capacity more than just the one that is exogenously forced to be built. In fact, as visible in figure 55, 405 MW of new ROR capacity are installed in 2025, other 193 MW in 2045 and 6.7 GW more in 2050. Wind turbines are also intensively installed at the end of the time horizon: In particular new 2.1 GW are built in 2045 and 2.3 GW in 2050.

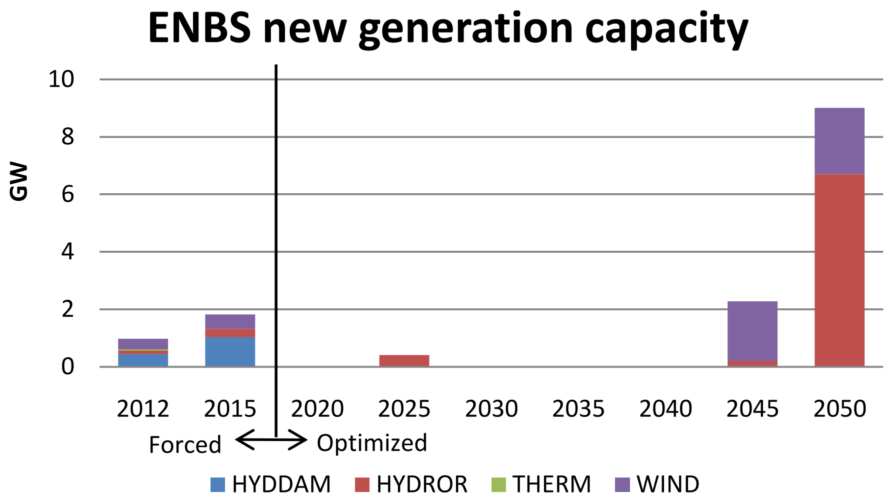


Figure 55: ENBS new generation capacity

As a consequence of these investments, even if some plants are retired, the total installed capacity of ROR and WIND increases over the time horizon, as visible in figure 56 (where the ordinate axis has been shifted up so as to allow a better view of the new installed capacity). Instead the installed capacity of DAM reduces despite remaining the most widespread plant in Norway and thermal plants disappear from 2040.

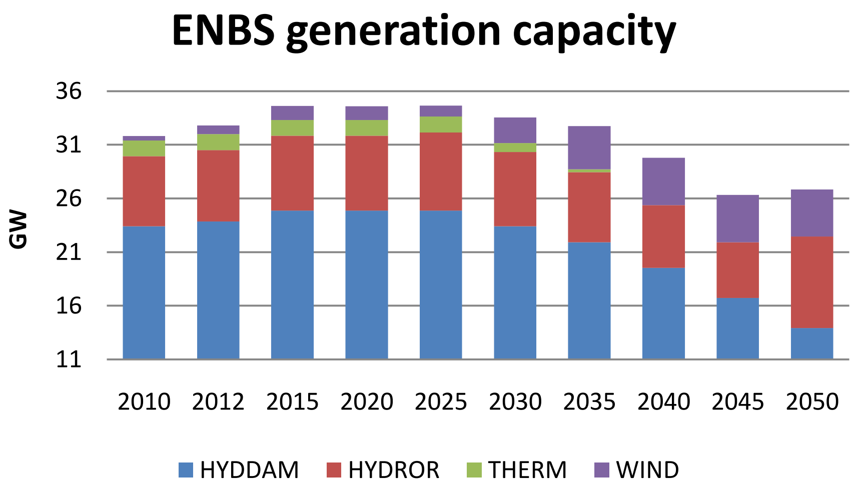


Figure 56: ENBS power generation capacity

Due to these new investments in new power generation facilities also the structure of the power generation changes, as visible from figure 57. In general in ENBS the power generation is higher than in EXBS. It increases till 2035 and then starts reducing, due to the retirement of DAM plants which are not built again. At the end of the time horizon the total power generation becomes lower than in the base year, but the difference is much smaller than in EXBS. At first sight it is visible that while in the base year the power generation is prevalently from DAM and ROR, the share of WIND power increases over the whole time period till covering a share of 16% in 2050.

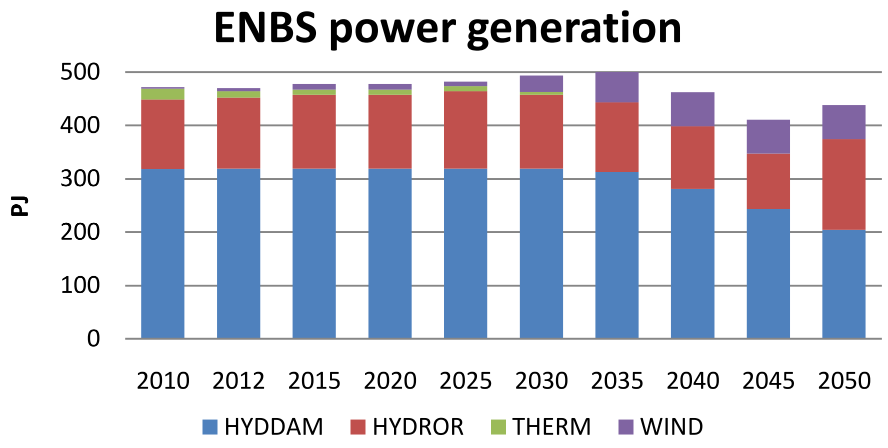


Figure 57: ENBS power generation

From the previous figures it is clear that in this scenario the solver suggests to install new capacity and thus to internally generate more power than in the base year. However imports are still required to meet the demand and they are characterized by a gradual increase over the time horizon. Except in 2025 and in 2030 imports are lower than in EXBS.

As shown in figure 58 the exports increase till 2035 and then decrease, due to the fact that part of the installed power capacity is then retired and that therefore less plants are available for generating and even for exporting.

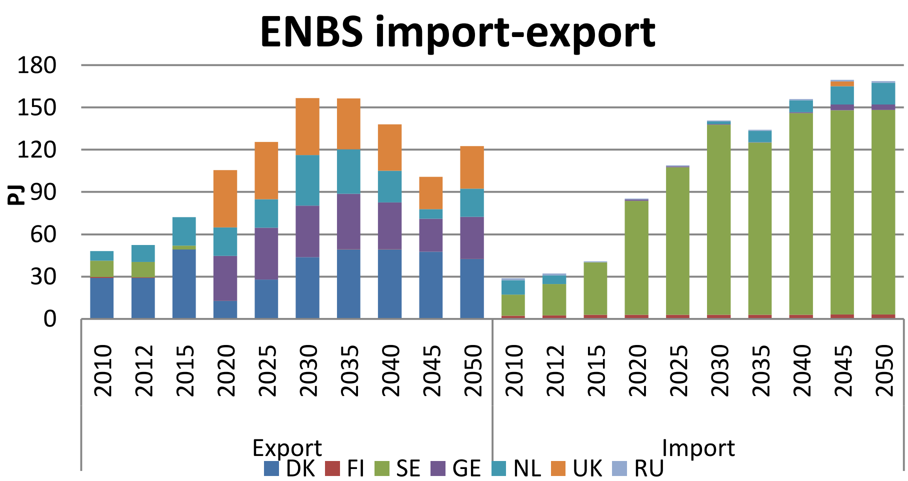


Figure 58: ENBS import and export

Focusing on the power trade between Norway and Denmark it is evident that Denmark is a net importer from Norway over the entire time period. In fact almost no power is ever imported by Norway, while in every milestone year Denmark imports great amounts of power from Norway. This export is characterized by a reduction in 2020, probably due to the fact that the interconnection with the UK becomes operative and that exporting to the UK is even more convenient than to Denmark. But later this export increases again, perhaps because a new cheap investment that makes the export to Denmark convenient becomes available. Finally the export reaches a plateau in 2035.

Figure 59 shows for every time slice in 2050 the power prices endogenously calculated by the model for Norway and for Denmark, together with the net export from Norway. It is evident that for this baseline scenario in 2050 the power prices in Norway are almost always lower than those in Denmark and consequently the power flow direction is prevalently from NOR to DKW. Even when the Danish power price is the lowest, the export from Denmark is very limited.

The time slices associated with the lowest prices in Denmark are those ending in A: in fact these time slices are characterized by high wind and low demand (see paragraph 4.2.1). On the contrary the time slices with the highest Danish power prices are those ending in B (high demand, low wind).

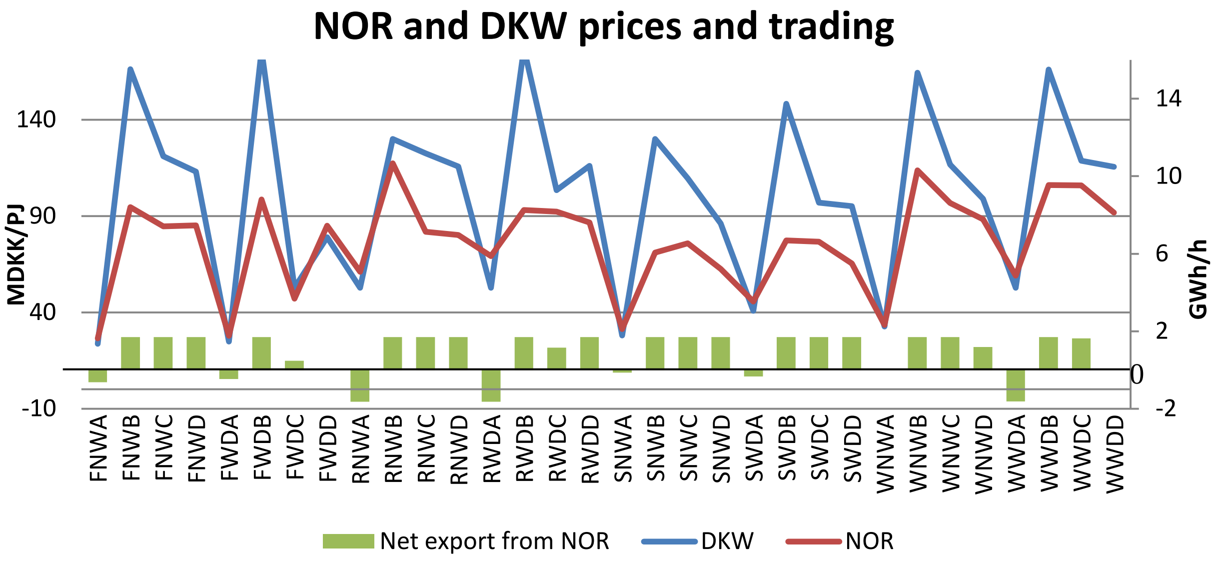


Figure 59: Power prices in NOR and DKW and relative trading

Regarding the other neighbouring countries, from figure 58results that:

- Finland is a net exporter over the whole time horizon but its import count very little in absolute terms
- Sweden is the main exporter to Norway and almost exclusive in absolute terms
- When the interconnection with Germany becomes available, this country starts importing a big amount of power from Norway
- The Netherlands are a net importer from Norway except in the base year and in 2045
- The United Kingdom is a net importer from Norway from 2020 when the interconnection becomes operative till the end of the time period.

Concluding, in ENBS Norway is a net power exporter until 2040, while after this year it becomes a net importer. In particular the results obtained in ENBS with the interconnection between DKW and NOR modelled as an endogenous trade process are very different with respect to the exogenous representation of the trade processes employed in EXBS. In fact according to ENBS Norway is a net exporter to Denmark (as expected from the estimated future prices of figure 50) while according to EXBS Norway is a net importer from this country.

In ENBS the cost of the Norwegian power system is higher than that in EXBS. This is due to the fact that the endogenous prices calculated by the model for Denmark are such that it is not cost-effective for Norway to import from Denmark in order to export the same amount to another country characterized by high export prices as instead is done in EXBS. Apparently it isn’t economically viable or it isn’t technically feasible to import from other countries with cheap prices for exporting to countries with high export prices or however such trade is less profitable than in the case EXBS. Moreover in the majority of the time slices it is more convenient to produce power in Norway and to export it to Denmark rather than producing it directly in Denmark. Despite these Norwegian exports count as negative in the objective function associated to the Norwegian power system, it is still required that Norway invests in new generation capacity (as shown in figure 55), which supposes an increase of the objective function.

From the comparison of the results of the two baseline scenario, it is possible to draw a first conclusion: in energy models the endogenous description of the trading processes gives more trustworthy results than those obtained with exogenous modeling. In fact it can happen, like has just been verified for Denmark, that the prices exogenously input in the model are not consistent. Moreover creating a hard-link between two or more models gives the possibility to do analysis considering various scenarios not in a country at a time but also in two or more countries at the same time. For instance it is possible to study the optimal configuration of the power system considering high availability of water in Norway and little availability of wind in Denmark and the opposite case. This way of modeling also allows assessing where it is best to install the future available technologies between two different countries. But for this assessment it is very important that the description of the parameters for the two countries shares the same degree of optimism.

Finally, it is of great interest to study the role of the rest of the Nordic countries in the model when their associated trading processes are modelled as endogenous. Perhaps also for Finland and Sweden the prices calculated endogenously would be much higher than those exogenously given in this model in EXBS. It is even possible, as for Denmark, that their power prices endogenously computed are higher than the endogenous prices of Norway. This would make of Sweden and Finland a net importer from Norway instead of a net exporter.

However in order to perform this assessment it is also necessary to model the entire power system of the other Nordic countries, as has been done for Norway in this thesis work.

5.3 Calibration

The calibration of a model is the phase in which it is verified that the parameters input in the model are suitable and that the optimized variables fit with the statistical values. This phase is important for the validation of the model: if the solution given by the model is similar to the statistical values it is likely that also the solution for the future is reliable.

In order to check that the TIMES model of the Norwegian power system is well calibrated, the solution for 2010 and 2012 has been compared with the historical data for the same years provided by (NVE, 2010) and by (NVE, 2012a).

For 2010 the hydro generation optimized by the model is higher than the historical value. This is due to the fact that 2010 was a dry year and less water was available for energy production. But in the model the water inflow is constant over the years and equal to the average historical values and therefore the model can’t catch the higher or lower water availability in a single year. Since according to the model the water availability in 2010 is the same as all the other days, the total export optimized by the solver is higher than the real value and the total import optimized by the solver is lower than the statistical value for that year.

On the contrary 2012 was a very wet year and therefore the hydro generation optimized by the solver for this year is lower than the statistical values. The computed total import is higher than the real value and the computed total export is lower than the real value.

In both 2010 and 2012 the generation from wind and thermal power plants is very well calibrated. Therefore the differences in export and import are only due to the fact that in the model it is always considered an average water inflow.

If the average statistical values for 2010 and 2012 are compared with the average results of the model for the same years, it results that the model is well calibrated, as visible in table 23.

Table 23: Model calibration

	Hydro	**Wind**	**Thermal**	**Import**	**Export**
Historical average	469.5	4.4	16.2	33.9	52.4
Model average	450.3	4.4	16.2	30.5	50.2

Chapter **6**

Sensitivity analyses

This chapter consists in the presentation and examination of the sensitivity analyses that have been realized. The purpose of such sensitivity analyses is that of studying the variation of the optimal solution changing the input parameters or changing assumptions. In fact sensitivity analyses allow to explore and compare different possible futures and to evaluate which are the optimal decisions to take depending on different possible situations.

VEDA-FE allows performing sensitivity analysis in a very easy way: just checking the scenarios that want to be run and unchecking those which are not necessary.

All the sensitivity analyses presented in this chapter were performed for the hard-linked Danish-Norwegian TIMES model, since this is the one that for the baseline scenario gave more trustworthy results. They have been performed considering the following cases:

- Case with 4DS demand increase
- Case with relative maximum water availability
- Case with relative minimum water availability
- Case with no new interconnections

For each of these cases the results are discussed pointing out the main differences with respect to the endogenous baseline scenario.

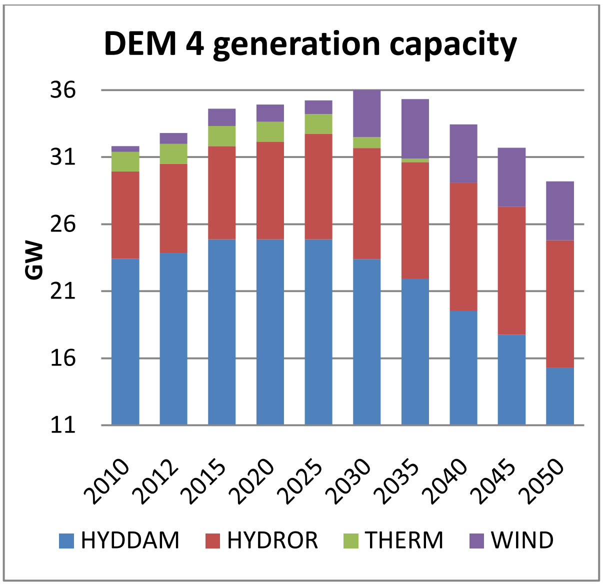
6.1 Case with 4DS increase

This sensitivity analysis was performed to see what happens to the Norwegian power system if Norway does not realize the energy efficiency measures required to have a demand profile as that considered in ENBS. In fact in this case we consider that the demand for electricity increases in a less optimistic way, which is according to the "Scen_DEM_FR-PROJ-4DS" scenario described in paragraph 4.5.2.

In the following paragraph the acronym DEM4 will be used to refer to the case with "Scen_DEM_FR-PROJ-4DS" as demand projection.

As expected, the cost of the Norwegian power system increases due to the increase in electricity demand, assuming a value of 721304.3, which represents an increase of 6% with respect to ENBS. But it is interesting to observe that also the prices in Denmark increase, of 1.2 % in DKW and of 0.4% in DKE. The fact that the increase in DKW is higher than in DKE can be explained by the fact that Norway is directly interconnected to this bidding region and that since more power is required to meet the Norwegian demand, fewer remains available to be exported to Denmark. Then Denmark has to produce on its own or to import from other more expensive countries an amount of power that instead in ENBS was imported from Norway.

From figure 60 results that the Norwegian generation capacity is affected by the power demand. In fact when the model is run with 4DS as trend for the demand it is necessary to meet a higher electricity demand, thus the solver now suggests installing more capacity. The new capacity is not only ROR and WIND as it was in ENBS, but also DAM. In particular the new capacity amounts to 6.2 GW of ROR, 4.4 GW of WIND and 1.4 GW of DAM.



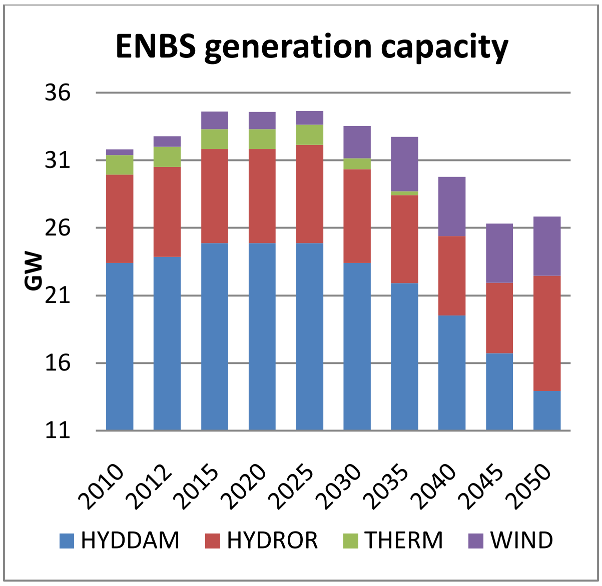


Figure 60: DEM 4 and ENBS generation capacity comparison

As a consequence of the investments in new capacity the total generation capacity installed in Norway increases till 2030. Afterwards it gradually reduces, even if investments in new capacity still take place.

By comparing the generation capacity in DEM4 and ENBS cases it appears that the total installed capacity in DEM4 is always higher than in ENBS. The wider difference occurs in 2045 and amounts to 5.4 GW.

Proportionally to the increase in generation capacity, also the power generation increases in order to meet the higher demand that characterizes the "Scen_DEM_FR-PROJ-4DS" scenario. Till 2020 the power generation in DEM4 is the same as in ENBS, later it increases till reaching a maximum in 2035 equal to 550.4 PJ and then starts decreasing till producing 478.2 PJ in 2050.

A consequence of the higher demand projection is that, even if the total installed capacity increases, less power is available for exports: all the years except 2045 are characterized by less export than in ENBS (for 2010 and 2012 the exports are the same as in ENBS, as should be in a well calibrated model), as visible from figures 61. The reason is probably that in some time slices in which in ENBS was convenient to export from Norway, in DEM4 the domestic demand has increased and there isn't enough excess of water so as to produce also power for export. And on the other hand it is not convenient either to produce power for exporting with any of the other plants available in the future.

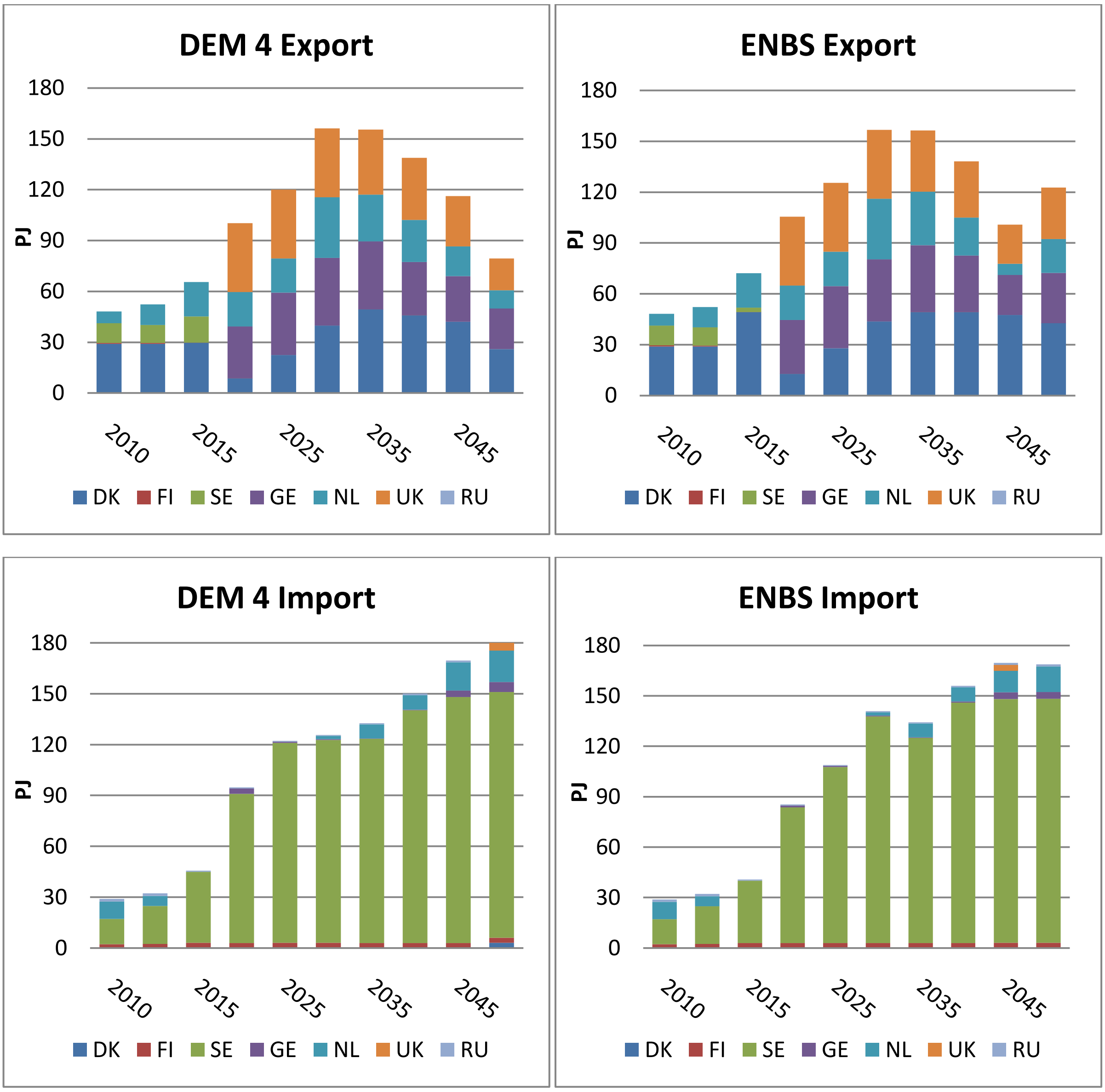


Figure 61: DEM4 and ENBS import and export comparison

Except from 2030 to 2040, the imports in DEM4 are characterized by an increase. Due to the increased demand in fact there are more time slices in which it is more cost-effective to import rather than to operate an expensive plant. The widest difference between the import in DEM4 and ENBS occurs in 2050. In fact in this year Norway has to import from the United Kingdom, which is characterized by very high import prices.

The most remarkable reduction of export is toward Denmark. Since this interconnection is modelled in a different way than the others because it is represented as an endogenous trading process, it is likely to believe that once the other interconnections are modelled in this way also their export flow would reduce.

The export to Finland isn’t affected by the change in the demand, while that to Finland is only characterized by a peak in 2015. The export to Germany and to the Netherlands in some years is higher and in some is lower than in ENBS. The export to the UK is the same from 2020 to 2030, then it increases but in 2050 it strongly reduces.

Concerning the imports, Norway in DEM4 imports more from all the countries except from Russia and Finland for which the trade doesn’t change because the interconnections were already all congested in ENBS. The imports from Netherlands increase from 2040, while those from Germany increase a little bit but are still almost insignificant in absolute terms. The imports from Sweden at the beginning increase with a higher rate and then become lower than in ENBS.

Concluding, this sensitivity analysis shows that the demand of electricity affects the power system and that some measures must be taken in order to meet a higher demand. The required measures basically consist in the installation of new capacity, which entails an additional cost to the system. From the analysis of the imports and exports in DEM4 and from the comparison with the values of ENBS it results that the new installed capacity is mainly used for fulfilling the higher demand.

6.2 Case with relative maximum water availability

This sensitivity analysis has been carried out in order to analyze how a high water inflow to the Norwegian hydroelectric plants affects the power generation and the electricity trade with the interconnected countries. In order to perform such analysis the scenario representing the water inflow in the wettest historical year was used, called “Relative-Maximum_Inflow” (described in paragraph 4.4.1.5). This scenario is characterized by higher availability factors for hydropower plants and by more relaxed bounds on the maximum annual hydropower generation. Therefore in this case, that in the rest of the paragraph will be called with the acronym RELMAX, ROR and DAM can produce more power.

As expected, the cost of the Norwegian power system decreases, assuming a value of 642987 MNOK, which represents a reduction of about 6% compared to ENBS. Moreover also the cost of the Danish power system is affected by the higher water availability in Norway: the total cost in DKW decreases of 0.8% and in DKE of 0.3%. In fact a higher water inflow reaches the catchment area of the Norwegian hydro stations, so that these can produce more power. And since the ROR and DAM prices are the lowest of the merit curve, Denmark can import power at cheaper price, thus decreasing its system cost.

Regarding the power capacity, the solver does not consider cost-effective to install new capacity, but rather increases the production from ROR and DAM. As visible in figure 62, until 2030 the power generation in RELMAX is higher than that in ENBS. Afterwards the power generation begins to decrease, due to the retirement of old power stations and it becomes lower than in ENBS, where instead new capacity is built.

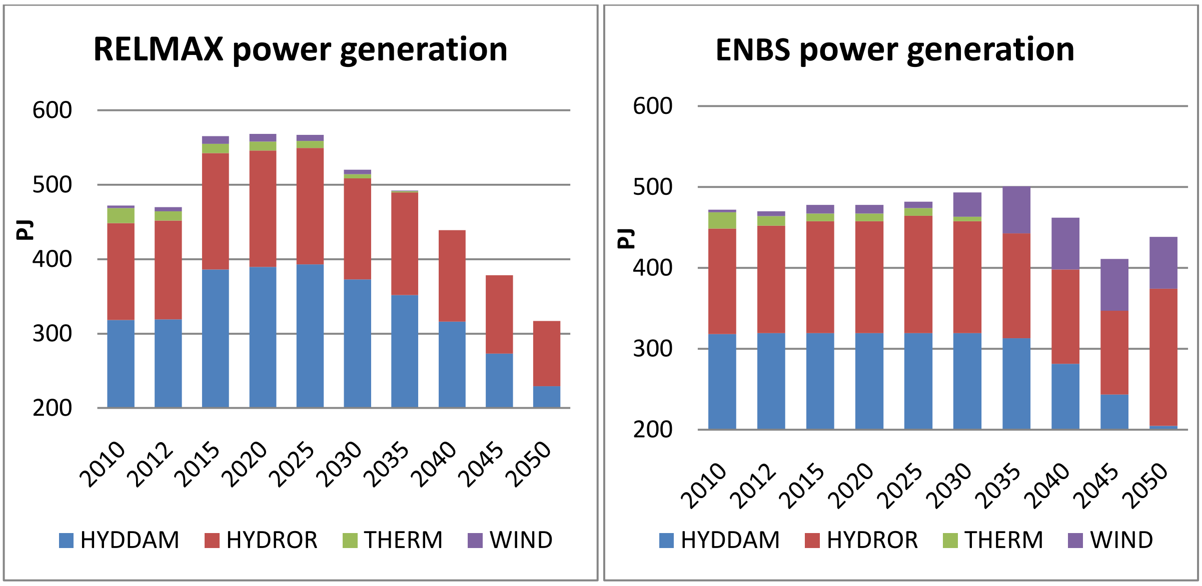
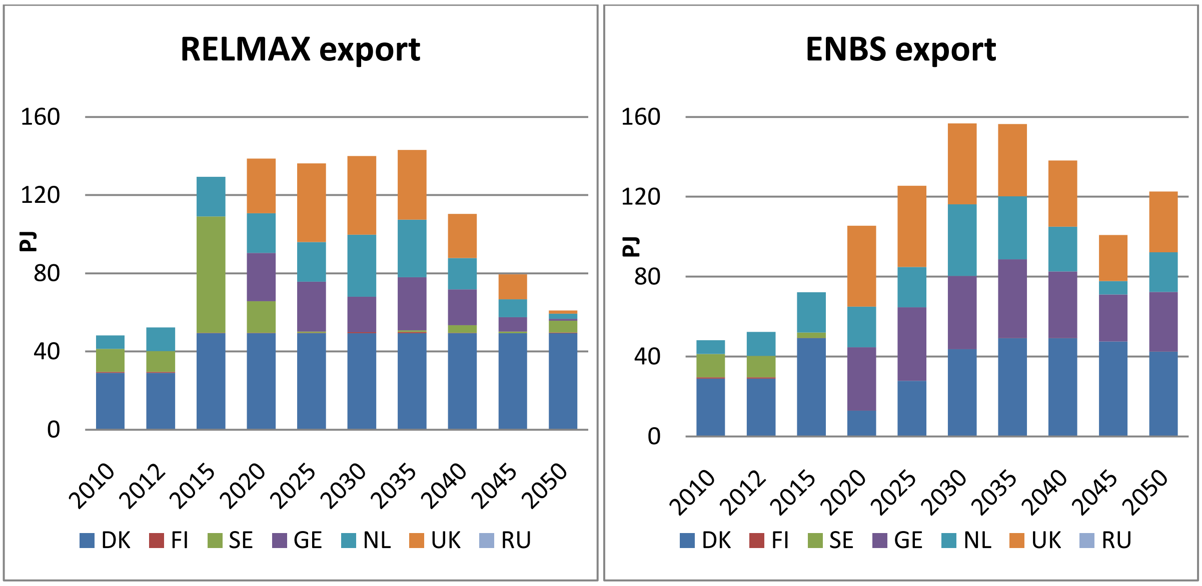


Figure 62: RELMAX and ENBS power generation comparison

The higher water availability and the resulting higher hydropower generation at the beginning is even higher than the domestic demand of electricity, so that a significant share is exported.

As shown in figure 63, as a consequence of higher water availability until 2025 the exports increase, while after 2030 the power generation permitted by the remaining installed capacity is limited, so that the exports reduce until returning to the levels of the base year in 2050.



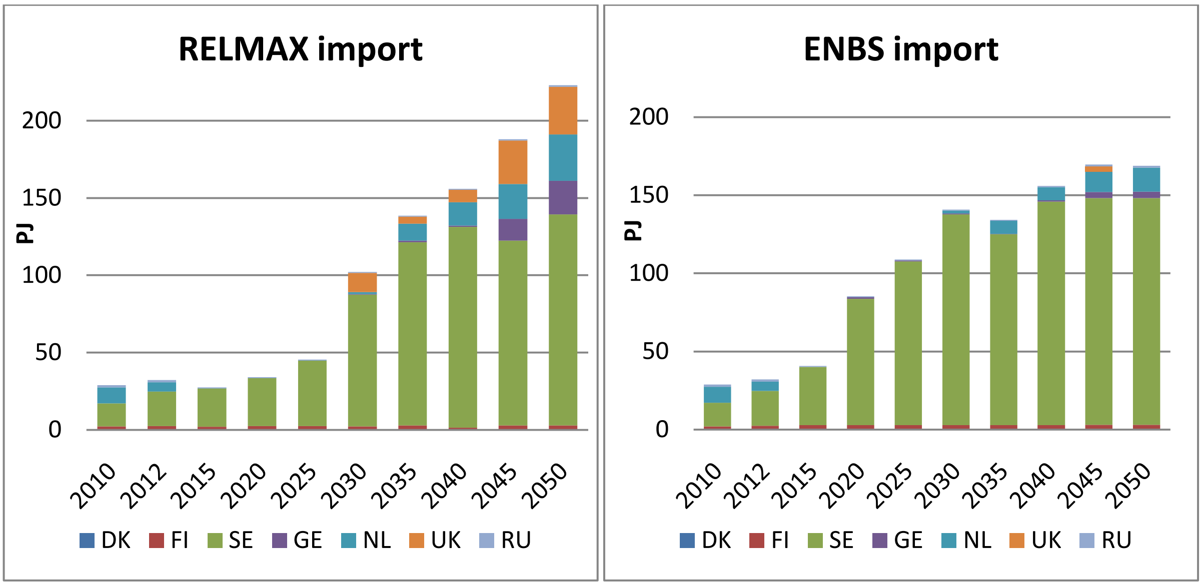


Figure 63: RELMAX and ENBS import and export comparison

The increase of the exports that characterizes the first years is mainly due to Sweden and Denmark. Then from 2025 the exports to Denmark remain constant and very similar to the values calculated in ENBS. The exports toward all the other countries instead reduce.

Regarding the imports, until 2025 Norway imports a very small quantity of energy and only from Sweden, Russia and Finland, the three cheapest exporters. Perhaps such imports are not used for meeting the domestic demand but in order to export them to other more expensive countries according to the trick explained in paragraph 5.1.

From 2030, when the power generation starts decreasing and it becomes lower than the demand, the imports begin to increase and power starts to be bought also from countries with higher import price. Even the United Kingdom exports large quantities of energy to Norway in 2045 despite its very high import costs.

The high exports that distinguish this analysis in the first years represent a significant income which is reflected in the reduction of the objective function. Even if from 2035 Norway has to import large amounts of power to meet its demand, however the total cost of the system is still lower than in ENBS. Moreover the imported energy is not only the cheap one from Sweden, but all the countries increase their exports to Norway (except Finland and Russia, whose lines were already almost congested in ENBS) and become net exporters.

Since the increased availability of water is enough to cover the domestic demand for a longer period, the necessity of new installed capacity for meeting the domestic demand starts later. But the solver states that it is not convenient to install so late new generators, nor to install new plants before and use them at the beginning only for exporting. This is also due to the fact that the time horizon considered in the model is of forty years only: the result would be different considering a longer horizon. In the first period Norway already exports a lot, so that it wouldn't be possible to export enough to make new plants cost-effective.

Concluding, this sensitivity analysis shows that the water availability in Norway affects the power system, even if no investments in new generation capacity are worth realizing. The high water inflow makes the stock existing in the base year sufficient and reduces the total system cost. The higher hydropower generation that characterizes the first years is used for increasing the exports, but later more power is needed to be imported since no more capacity was installed.

6.3 Case with relative minimum water availability

The purpose of this sensitivity analysis is to analyze how Norway will reorganize its power system and how the power trade with the neighbouring countries will vary in case the water inflow to the hydropower plants decreases with respect to the historical average values.

For this analysis the scenario “Relative-Minimum_Inflow” (described in paragraph 4.4.1.5) representing the water inflow in 1996, which was the driest historical year, was used. In this scenario the availability factors for ROR are lower than in the average inflow scenario. In fact in some periods the water inflow to the hydropower plants is lower than the minimum threshold that allows producing power, so that the water bypasses the turbines. The availability factors of DAM are higher than in the average inflow scenario, because these plants try to cover a greater portion of the demand and to balance the lower production from ROR. However the constraint on the total annual power production is lower than in the average scenario for both ROR and DAM: this assures that even if the plants are available for production for more time, the total power production over the year decreases. This restriction is suitable for ROR but not as much for DAM. In fact in drought years the production from DAM increases so that Norway doesn’t need to import excessively and so that the power prices don’t increase too much. This balancing is done only if the climatic forecasts foresee that the next year will not be drought again, otherwise the water level in the reservoirs would decrease too much. But in the scenario “Relative-Minimum_Inflow” it is assumed that the reduction of inflow applies to all the years and thus for avoiding the emptying of the reservoirs was imposed that the maximum production over the year must be lower than or equal to the total inflow.

The definition of this scenario makes that both DAM and ROR can produce less power than in the average case and then Norway will need to increase the production from other sources or to increase the imports in order to meet the demand. In the rest of the paragraph this case will be called RELMIN.

Due to the reduced availability of water and the resulting reduced hydropower production, Norway has to generate power using other more expensive technologies and thus the system cost increases. In particular it assumes a value of 784072, which is an increase of 15% compared to ENBS. The water shortage in Norway also strongly affects DKW, which total system cost increases of 7.5%, while it is not reflected that much in the cost of DKE, which only increase by 1.2%.

The reduced productivity of ROR and DAM plants makes that in this scenario the installed hydro capacity is not enough for producing the greatest share of the power demand as in ENBS and therefore it is required to install a great amount of new capacity. In particular the investments are mainly in wind power because hydropower is less rentable, although in 2025 a substantial investment in ROR is done.

The existing generation and transmission capacity would be enough for meeting the demand in the first years, but then it would be necessary to import big amounts of energy and also from very expensive countries, which implies a high cost on the system. Therefore the solver computes that it is more cost-effective to start increasing the capacity as soon as possible and already in 2020 the wind turbines denominated "ERWINWOT120N" are installed even if they are the least performing of their category, because they are the first to become available in the market.

Since more capacity is installed over the years the total installed capacity in Norway in RELMIN is always higher than in ENBS, as visible in figure 64.

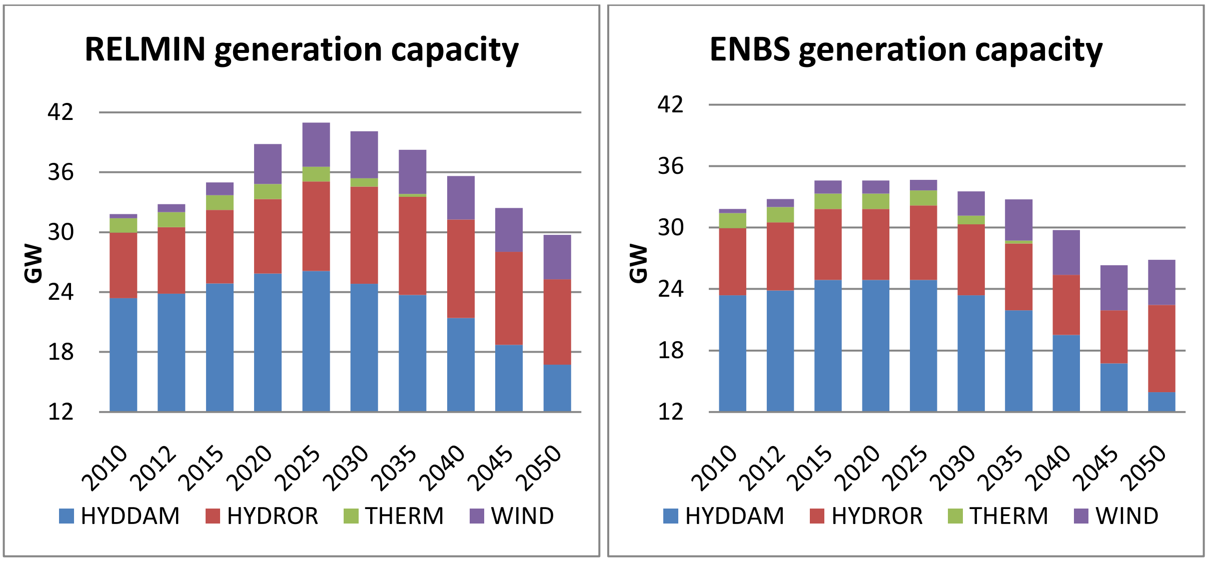


Figure 64: RELMIN and ENBS generation capacity comparison

Regarding the power generation, for 2010 and 2012 it has been considered that the hydropower plants receive a historical average water inflow and thus they produce as in ENBS. Then from 2015 on the hydropower plants receive a lower inflow as described in "Relative-Minimum_Inflow" and in fact until 2025 the power generation is much lower than in ENBS as visible from figure 65. Then from 2020 a lot of new capacity starts to be installed and thus the energy generation raises, reaching levels slightly lower than those in ENBS. Much of such new capacity does not end its life time during the time horizon of the model and thus the power generation from 2040 onwards becomes higher than in ENBS, where instead a lot of capacity is retired from 2040.

The reduced productivity of hydropower is counterbalanced by an increment of production from wind power, which reaches its maximum potential of 64.1 PJ (LIND et al., 2013) already in 2030 and since then remains constant. Due to the massive investment made in 2025, the production of ROR is higher than in ENBS until 2045, although this implies the use of more capacity. Instead generation from DAM always remains lower than in ENBS.

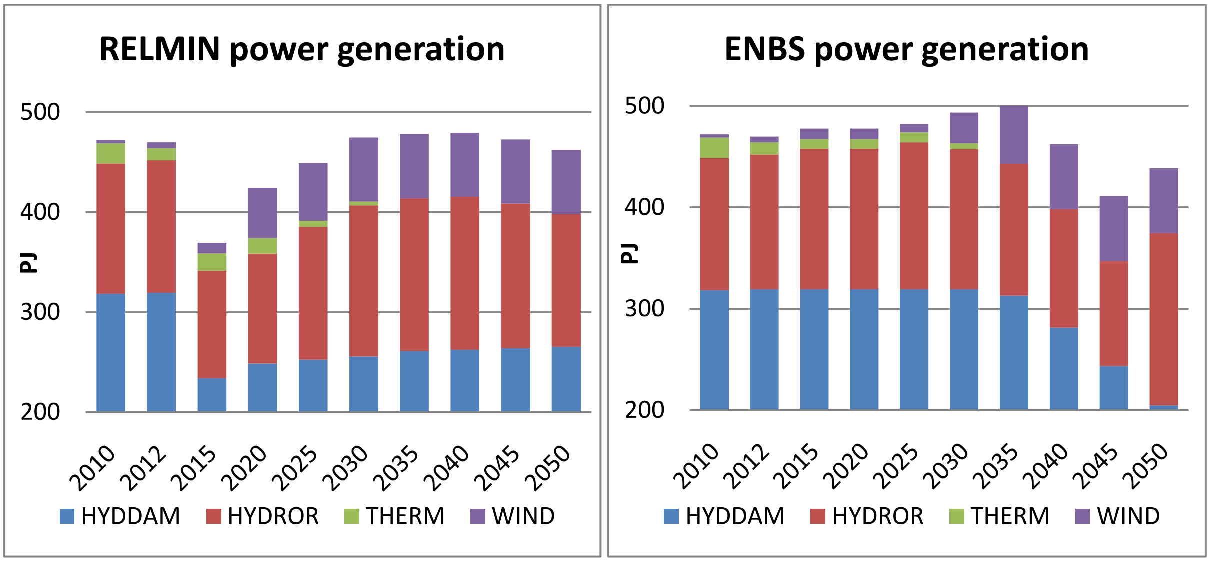


Figure 65: RELMIN and ENBS power generation comparison

In this case the power export in 2015 is much lower than in ENBS. In fact the existing capacity is not enough for producing a lot of electricity to be exported. It is not convenient to install new capacity already from 2015 for exporting, because the technologies available in that year are still very expensive. In 2015 power is exported only to Sweden and to the Netherlands, because the planned interconnections are not available yet and it is not convenient to export to Finland and Denmark. In fact it is interesting to observe that with the minimum inflow scenario the endogenously calculated electricity prices in 2015 are lower in Denmark than in Norway. Then after new capacity is built the power prices in Norway decrease and power starts to be exported also to Denmark, even if the traded volumes are strongly reduced with respect to ENBS.

The exports to Germany in a first moment are lower than in ENBS, but from 2040, when the installed capacity exceeds levels in ENBS, it becomes greater. The exports to the Netherlands and to the United Kingdom in a first moment are not affected by the drought (mainly because these countries have the highest import price so that they are the firsts to which Norway exports), but after 2040 these increase, for the same reasons explained for Germany.

The overall effect of the reduction in water inflow is that the exports decrease in a first time and then increase after new capacity is installed, thus bringing the export profile in the years to be more levelled.

Regarding the imports, at first sight from figure 66 is visible that until 2025 these are higher for RELMIN than for ENBS, while after 2025 the situation changes thus bringing the imports profile in the years to be more levelled.

Focusing on the import from Denmark, in 2015 this is very high. Also the import from Sweden increases in 2015. The reason is that Norwegian capacity is not enough for meeting the domestic demand but it is not cost-effective either to install one of the very expensive technologies available from 2015, because later they would not be competitive and would no longer be used. Therefore the only way for fulfilling the demand is increasing a lot the imports. In particular such imports are higher than in ENBS until 2025 because it is only in 2020 and 2025 that significant investments in new capacity are done. However Norway continues

importing from Denmark for the entire time horizon considered in the model. The imports from Finland are not affected, since in every case this country is the first from which Norway imports. Also those from Russia are only slightly affected: they are higher than in ENBS until 2025 and then the contrary. The same variation happens also for the imports from the Netherlands and Germany, but in a more visible way.
Finally, the biggest difference in import with respect to ENBS regards Sweden, from which in a first time Norway imports more and then from 2030 less.

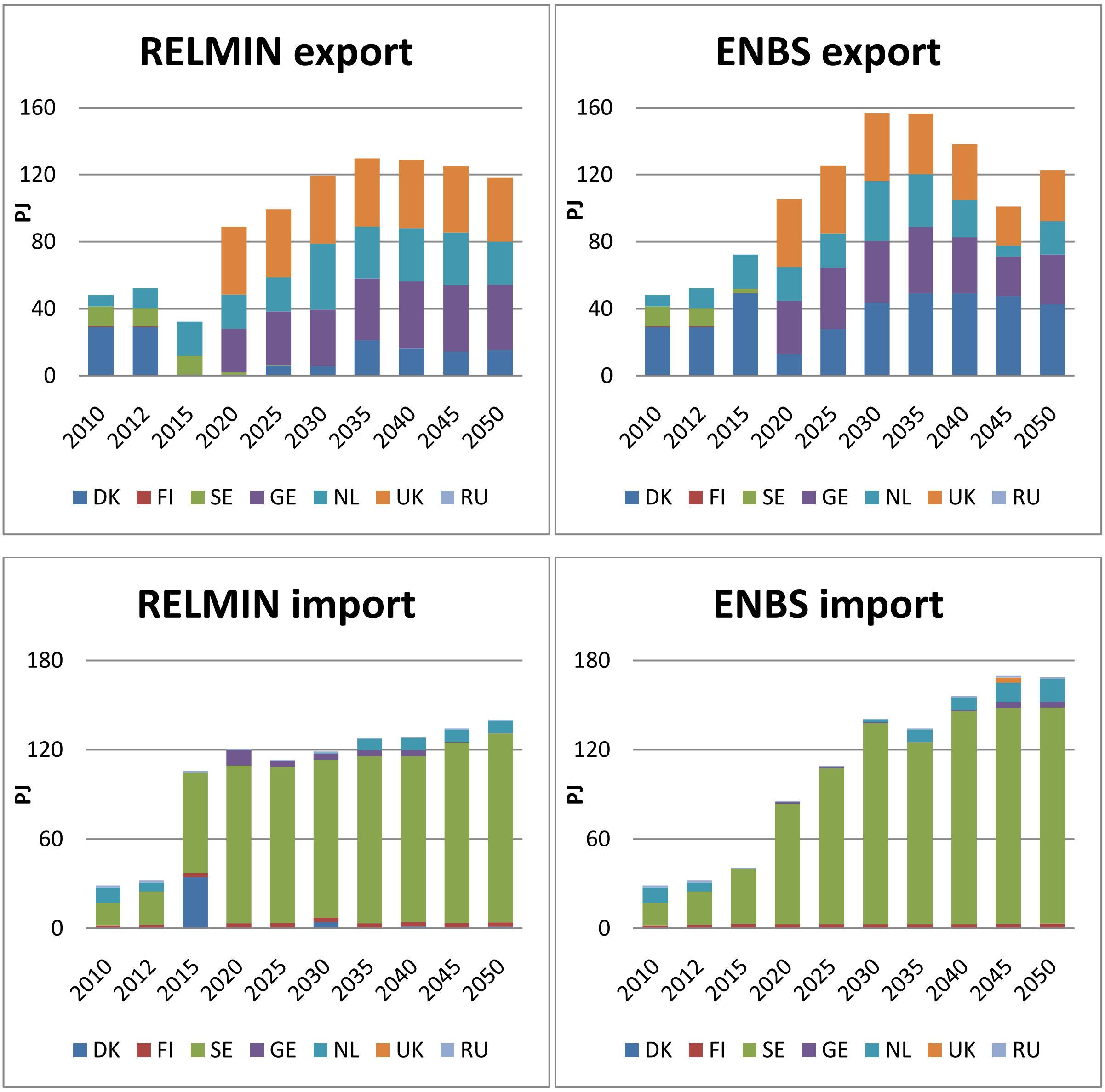


Figure 66: RELMIN and ENBS import and export comparison

Concluding, the overall effect of the reduced water inflow to the Norwegian hydropower plants is an increase of the system cost and the necessity to install new capacity. Since the solver computes that it is not cost-effective to install such new capacity already in 2015 due to the initial high cost of the available technologies, until 2025 the imports from the neighbouring countries increase and the exports decrease.

Then, being more capacity available for power production fewer imports are needed and more power is exported, thus avoiding that the objective function increases too much.

6.4 Case with no new interconnections

This sensitivity analysis was performed in order to investigate how the non-creation of the new planned transmission lines affects the electrical system. In order to perform such analysis a scenario called "Zero_New_Exchange" was run together with the other workbooks of ENBS. This scenario forces the power flow through the interconnections planned for the future to be equal to zero. Since the interconnections don't have associated any installation or FIXOM cost, a constraint forcing the power flow through these interconnections to be zero is equivalent to a constraint forcing not to install these interconnections.

The interconnections which import and export were set equal to zero in "Zero_New_Exchange" are all those that are currently still in the planning or pending license stage. They are the new interconnections with Sweden (of 1400 MW) and with the Netherlands (NorNed2, of 700 MW) and the interconnection with the United Kingdom (of 1400 MW). All the previously existing interconnections, Skagerrak4 with Denmark, which has already been activated and NordLink with Germany, which is already under construction, have not been changed in this scenario analysis.

In this paragraph when referring to the case without the planned interconnections the acronym NONINT is used.

In NONINT the cost of the Norwegian power system increases, assuming a value of 693686 MNOK, which represents an increase of about 2% compared to ENBS. Regarding the cost of the Danish power system, only DKW is affected by the non-realization of the planned interconnections and very slightly, of only 1%. In fact the interconnections between Norway and Denmark aren't modified in this sensitivity analysis.

This result is in line with the economical theory of the interconnections, which claims that interconnections make the power system more efficient, reduce the need for reserves and increase the competence bringing it to transnational scale.

From figure 67 results that the Norwegian generation capacity is affected by the reduction of the transmission capacity. In fact from 2020 the solver starts installing more capacity than in ENBS, due to the fact the planned interconnections don't become operative and therefore less energy can be imported. The power generation before 2020 isn't affected because the planned interconnections would become operative only from 2020. However, since TIMES assumes perfect foresight, it might be possible that it considers cost-effective installing new generation capacity from the beginning predicting that in the future less energy can be imported.

The widest difference in total installed capacity between NONINT and ENBS occurs in 2045 and amounts to 2.2 GW, quite much less than the total reduction in transmission capacity.

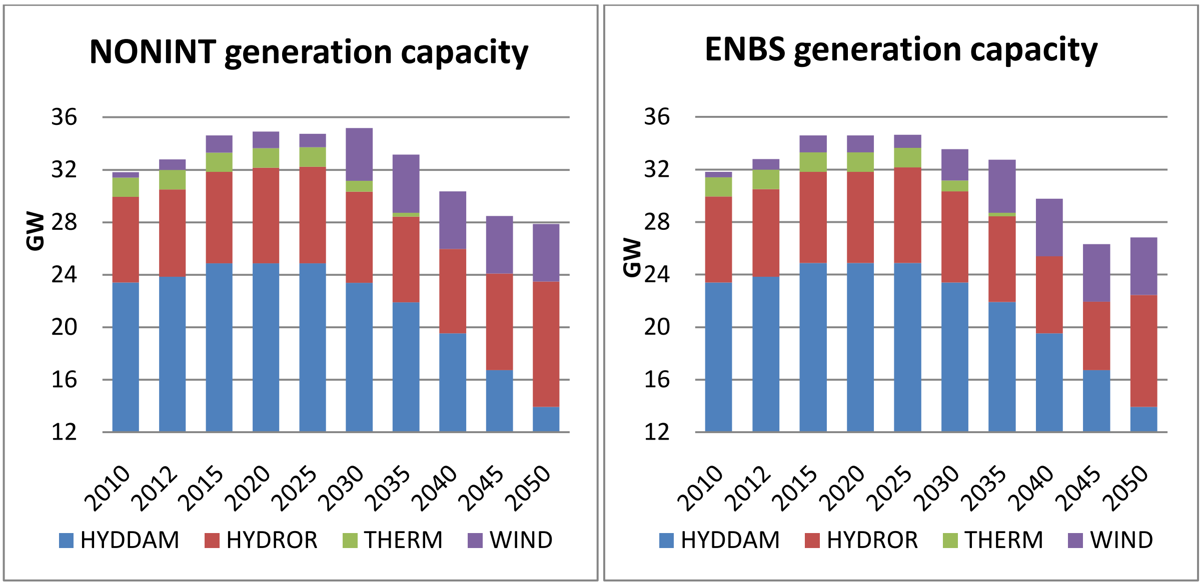
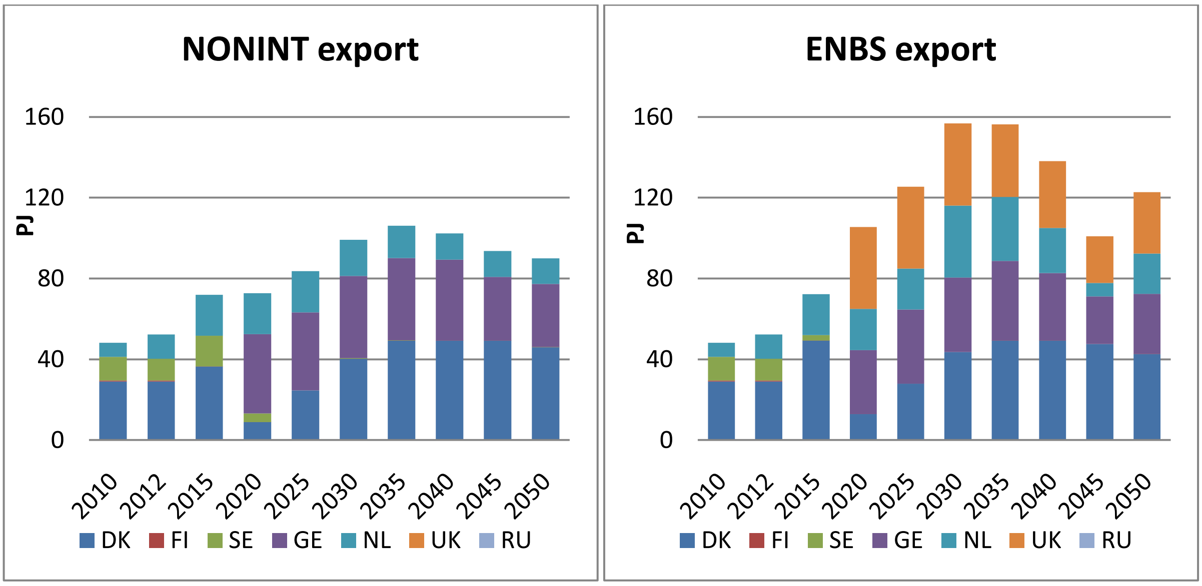


Figure 67: NONINT and ENBS generation capacity comparison

The trend of the power generation in NONINT has the same profile as that of the capacity and therefore isn't shown. Instead it is interesting to observe from figure 68 how the imports and exports change in this sensibility analysis.

The exports are lower every year, mainly because the interconnection with the UK lacks. But in some years this lack is compensated by an increase of export to other countries, in particular to Germany and to Sweden. In particular the exports to Sweden increase even if the new interconnector with this country is not built, although very little. The exports to the Netherlands reduce, mainly after the year in which the planned interconnection was expected to come into operation. Also the export to Denmark decreases.

The changes in the exports described above cause that their profile is smoother over the time horizon.



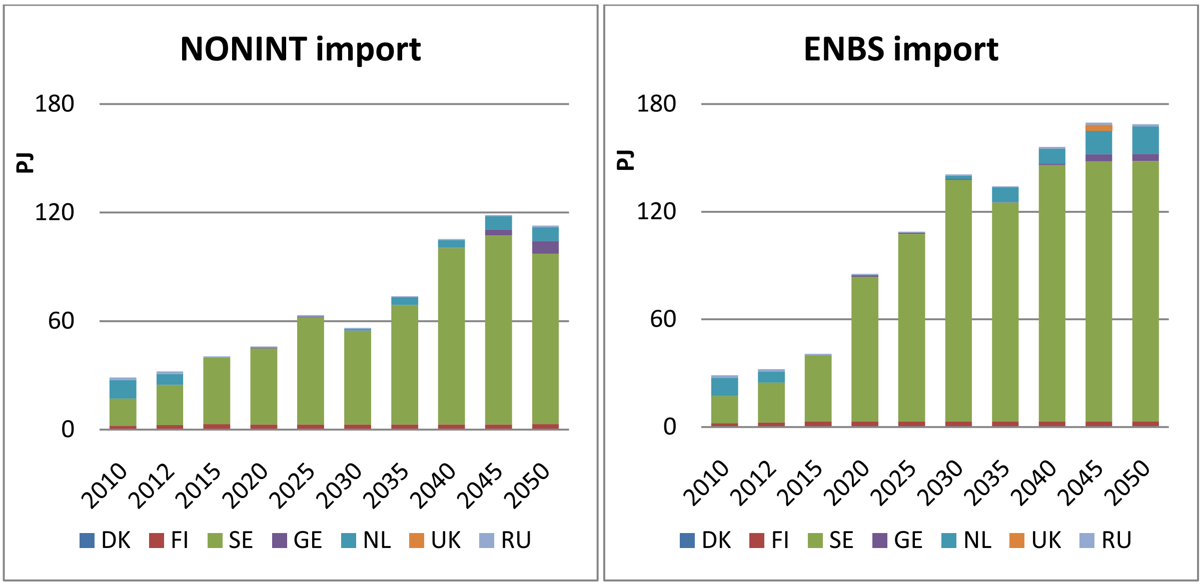


Figure 68: NONINT and ENBS import and export comparison

Also the imports are characterized by a reduction with respect to ENBS and mainly such reduction is due to the lack of the new planned interconnection with Sweden. Also the imports from the other countries in general scale down, but in absolute terms such reduction is very little.

The fact that the highest difference in the total installed capacity between NONINT and ENBS is lower than the total reduction in transmission capacity is a first evidence of the importing-for-exporting trick. Not all the imports are used for meeting the domestic demand, otherwise the decrease of transmission capacity would be offset by the installation of a similar amount of generation capacity, while this is sensibly lower.

Another clue is given by the fact that the imports from Sweden decrease much more than for the mere fact the new line is not built. In fact since it is not possible to export to the United Kingdom, it is not as cost effective as in ENBS to import more power just for directly exporting it to another country.

Chapter 7

Further developments

The Norwegian TIMES model is well calibrated and at present it can be used for exploring the future Norwegian power system. Moreover it enables to perform sensitivity analyses assessing the variation of the Norwegian power generation and the power exchange between the Nordic countries by varying the evolution of the demand of electricity, the water inflow to the hydroelectric plants and the availability of new interconnections. However, there is still room for improvement.

First, but not in order of importance, it would be desirable to have more data about off-shore wind turbines. In fact in the model it was assumed that the generation profile of this technology is the same as that of on-shore wind turbines. This approximation may be replaced by real data once these turbines will begin to come into operation along the Norwegian coast.

Then it would be better to have the historical prices in the Netherlands and in Russia with a higher time resolution, even hourly as for the Nordic countries. In fact, even if for Russia the error introduced by this lower resolution doesn’t strongly affect the results, since this interconnection is only 50 MW, for the Netherlands it does, due to the fact that the interconnection is quite strong.

It would be also desirable to have more recent data on the production of ROR and DAM, so as to allocate the total inflow to these two technologies taking into account the state of the art of their production instead of old data.

It would be interesting to model the reservoir-hydro plants as a storage process, as done in the TIMES model of Norway realized by IFE (LIND et al., 2013). In the current TIMES-NO this way of representing the reservoir hydro plants wasn’t adopted because it doesn’t fit very well to the time frame used, which is not in chronological order and because it would make the computation time longer. Moreover, modeling the reservoir as a storage process would not allow to optimize its operation endogenously, since this functionality is not implemented in TIMES (ETSAP, 2005b), but it would remain necessary to exogenously define for each time slice if the storage has to recharge or to discharge.

Reservoir-hydro is a particular technology, which thanks to its high regulation speed can modulate its generation depending on the price in the electricity market, aiming to the maximization of the profit. It should be further investigated how to better represent in TIMES this logic of operation without relying on historical data.

The most interesting improvement to the current model would be given by the implementation in the same model of the electrical systems of the other Nordic countries. The resulting five-region model would represent a more reliable tool for the exploration of the future power exchange between the Nordic countries and perhaps it could prevent the trick of importing-for-exporting from occurring. Even if such behaviour would continue, the result would be more trustworthy and representative of the reality, because the power prices of all the Nordic countries and not only those of Denmark and Norway would be endogenously computed by TIMES. Furthermore, the creation of hard links between all the Nordic countries allows better studying the interrelationships between the countries and how an energy policy implemented in one country impacts the power systems of the interconnected countries. Finally, with such model it would be possible to assess whether or not the environmental targets established for 2020, 2035 and 2050 can be met in a more effective way by optimizing the power systems of all the Nordic countries at the same time.

Chapter **8**

Conclusions

This thesis work has brought to the creation of a TIMES model of the Norwegian power system. Such model, called TIMES-NO, has implemented the Norwegian energy supply system, power production system, electricity transmission system, power demand and the future technologies available for power generation. A major effort in the implementation of the power system was that of modelling hydropower. The correct representation of the availability factors and the determination of the exact future potential of such technology are essential factors in this analysis.

TIMES-NO has demonstrated to be well calibrated and a valuable tool for exploring the future evolution of the Norwegian power system and the power exchange dynamics in different scenarios.

Thanks to the formation of a hard link with the pre-existing TIMES-DK model, the model can be run both standalone and hard-linked. This second option allows studying the power trade between Norway and Denmark in a more reliable way. In fact the hard-link give the possibility to model the power trade between these two countries as an endogenous process and no more according to exogenously defined price criteria. But also when the two models are hard-linked the interconnections with the neighbouring countries are still represented as exogenous processes.

The baseline scenario was run for TIMES-NO in both standalone and hard-linked mode. In the two cases the results were different. In fact when TIMES-NO is run alone the solver suggests not to install new capacity but just to rely on the imports from the other countries to meet the domestic demand. Therefore Norway behaves as a net importer from all the interconnected countries and also from Denmark.

Instead when TIME-NO is hard-linked to TIMES-DK the solver recommends to install a lot of new capacity and Norway behaves as a net exporter to Denmark. This second result looks more trustworthy and in line with other models and forecasts (LIND, 2014).

The reason of such profound difference in the results of TIMES-NO standalone and hard-linked was further investigated. First it was concluded that in the standalone case the power prices exogenously set for Denmark for the future are too low and that therefore the endogenous representation of the power trade is more reliable, since it eliminates the problem of consistency of exogenous prices.

Moreover it was observed that another problem occurs when interconnectors are modelled with exogenous prices. In fact when in the model there is at least one interconnector with associated an import cost lower than the export cost of at least another interconnector, the solver starts importing as much as possible from the cheaper interconnector and to directly export the same amount trough the more expensive interconnector. In this way the modelled country behaves as a “power bridge” that simply gains the difference between the two exogenous costs. Therefore this kind of modelling doesn’t allow assessing the import strictly necessary for meeting the domestic demand and the exports of domestically produced power.

For this reason it is recommended to explore in TIMES the future power exchanges between countries representing the power trade with endogenous processes, even if this implies the necessity to model the entire power system of the countries.

Finally, TIMES-NO hard-linked to TIMES-DK was used to perform sensitivity analyses. For this purpose four different scenarios were created, regarding higher and lower water inflow to the Norwegian hydro plants, higher demand projection and lack of new interconnections. For all the sensitivity analyses it was demonstrated that the model reacts computing a different and meaningful solution which suggests new structures for the Norwegian power system and various power exchanges with the interconnected countries.

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