Flexible international exchanges: a possible solution for large – scale wind power integration within the future power system

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Preface

This graduation project is dedicated to my father.

Furthermore, I would like to thank the rest of my family for giving me the chance to study for these two years in the Netherlands, in TU Delft, namely Dimitris, Charoula, Georgina.

Apart from my close family members, there are some people that I would like also to thank for helping me completing successfully this project:

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I wish you all, best of luck and success in any future endeavour

Konstantinos Ntotas

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NOMENCLATURE

RES: Renewable Energy Sources
TSO: Transmission System Operator
W-UCTE: Union for the Coordination of Transmission of Electricity Western Part
UC-ED: Unit Commitment and Economic Dispatch
LOLP: Loss of Load Probability
ENS: Energy-Not-Served

1. Introduction

Whilst, still in the end of the 19th century, a famous inventor and scientist (Thomas Edison) during a public demonstration of his incandescent light bulb, was stating that "we will make electricity so cheap that only the rich will burn candles". In the start of the 21st century, marketers and engineers are trying to accomplish that with various ways, in a whole new environment of a deregulated, almost privatized electricity market. From the end of 1960s, when the development of the power system demanded the construction of significant infrastructure and the replacement of old and inefficient tortuous equipment, till the present days where renewable energy sources (RES) integration and market's adaptation to new mechanisms, alter the traditional picture of system's operation, power systems have always experienced a transition.

This report will focus on one important aspect of this transitional wave towards the future, which is the current issue of large-scale wind integration within the power system. More specifically, the approach aims to illustrate the significance that international exchange can play in wind power's integration and it will be assisted by a computational tool, PowrSym3, which is a production cost simulation model capable of high levels of optimization. In order to achieve this, a relevant model of the power system seen from a high perspective will be constructed and the system's response to different levels of wind penetration will be measured mainly in terms of (un)-used wind energy, system operating costs and emission levels. However at first, the relation of these factors with the large-scale wind integration must be highlighted.

1.1 Basics of power system operation

One of the main characteristics of electricity in power systems is its non-storability. Power system operation is governed by this principle; for each point in time, the generated energy in the system should exactly match the demand [1]. Due to daily load variations, the coordinated control of the generators' outputs is mandatory for balancing total generation to the total load, so as the system frequency does not deviate from the nominal operating frequency (50 or 60 Hz). Because of this tenuous balance between supply and demand, the monetary value of electricity also changes continually with time over a day and over the year for most systems[2]. Therefore, for the involved parties, the economic operation of the system under these conditions is significant to return a profit on the invested capital.

Unit commitment (UC), which has a high influence on power system economics, refers to the computational procedure for making decisions in advance, upon which generators to start up and when to connect them to the grid, along with the sequence in which the operating units should be shut down and for how long. Unit commitment is a complex problem which combines data and information on fuel prices, generators' or transmission lines' maintenance schedules, ramp rates, idle periods, start-up and shut-down costs. The next step, after unit commitment has been decided, is the economic dispatch (ED), the process in which the system load is corresponded to the total generation output of the committed units such, that the total operating costs are minimized. UC-ED mostly refers to the economic operation of the system, bound by technical limitations.

Currently, due to the introduction of new generation technologies such as wind and solar energy and the liberalization of energy markets, the future challenges appear to be already quite different than before. In addition, the need for complying with environmental limitations under the shadow of global warming but also the wish for energy savings and sustainable production, increase even more the complexity of the power system operation. Under this spectrum, UC-ED scheduling gains high importance, since most of the impacts of recent developments can be mitigated with an optimum UC-ED schedule.

Renewable Energy Sources (RES)

The operation of the system based on fossil fuels has three important drawbacks. The first is the realization that the fossil fuels are not abundant and they are decreasing steadily, while demand is increasing. The second is that the stocks of fossil fuels (especially oil and gas) are not distributed equally between countries. This leads to energy dependency of especially the western-world countries and may result in political instability. The third disadvantage is that the age-long use of fossil-fuels is significantly affecting the environment and has given rise to the now widely known greenhouse effect. From the start of the 21st century especially, governments all over the world and specifically in the EU, sensitized and promoted the terms of sustainability and "green" energy into the power system. Thus, the transitional wave towards the future power systems would be based on two main pillars: sustainable development and integration of renewable energy sources (RES) within the system. What the contemporary society is experiencing is this transition which undoubtedly has not yet entirely occurred.

One of the main drivers on the direction of the future power system is the integration of especially, wind energy. Most of the scenarios refer to a highly sustainable energy future with wind energy acquiring a large percentage in the total generation. Therefore, the analysis should also include this dimension, separately (section 1.2).

Liberalization of Electricity Markets

Within European Union (EU), electricity markets used to be a monopoly in each member - state until recently. This was mainly due to the idea that electricity is a top priority commodity, which cannot be susceptible to competitive market's forces. Likewise, the nature of electricity is such that cannot be stored efficiently for now, causing therefore a need for immediate transmission after the generation, through the grid, to the consumption. These two basic limitations along with the high investment costs have mostly been the brake for any private initiative until the end of the 1980s. At that point, the EU officials, facing the increased competition in many industrial sectors and the effect of globalization, they decided to promote the liberalization of the electricity markets in each member state, taking under consideration the sufficient technical experience and the up-to-date evolved technology.

Consequently, their long-term target was the formation of a unique, interconnected and robust energy market.

While, generation and distribution of electricity was let in markets competition, after the liberalization, power balancing, transport of electricity and the facilitation of the market were guaranteed by an impartial party, the Transmission System Operator (T.S.O.). Nonetheless, the activation of independent eligible companies in a regulated power market model has posed new questions and has formulated new needs. Furthermore, the transition from a monopolistic energy market model to a competitive, partially regulated model, revealed contingencies but also chances that were not evident at first glance. After all, it was expected from the early days of liberalization, that the modern concepts of selling energy as an independent producer or buying energy as a distributor or a simple consumer would apparently influence the market and its mechanisms. In this fast changing business environment, the involved companies must be ready to face the challenges and to facilitate innovations that keep them update, sustainable and efficient.

1.2 Influence of wind power on the system

Present Status of Wind Energy

The re-emergence of the wind as a significant future source of the world's energy must rank as one of the significant developments of the late 20th century [3]. Governmental and business organizations all over the world have been supporting on-shore wind projects since many years, expecting to benefit in the long run in terms of economical profit and environmental compliance. Consequently, from *Figure 1* it can be easily concluded that wind energy will continue to increase and to acquire finally a higher share in the total electricity generation. In 2008 the total installed wind power capacity on-shore and off-shore is over 100GW, of which 75 GW are installed in Europe.

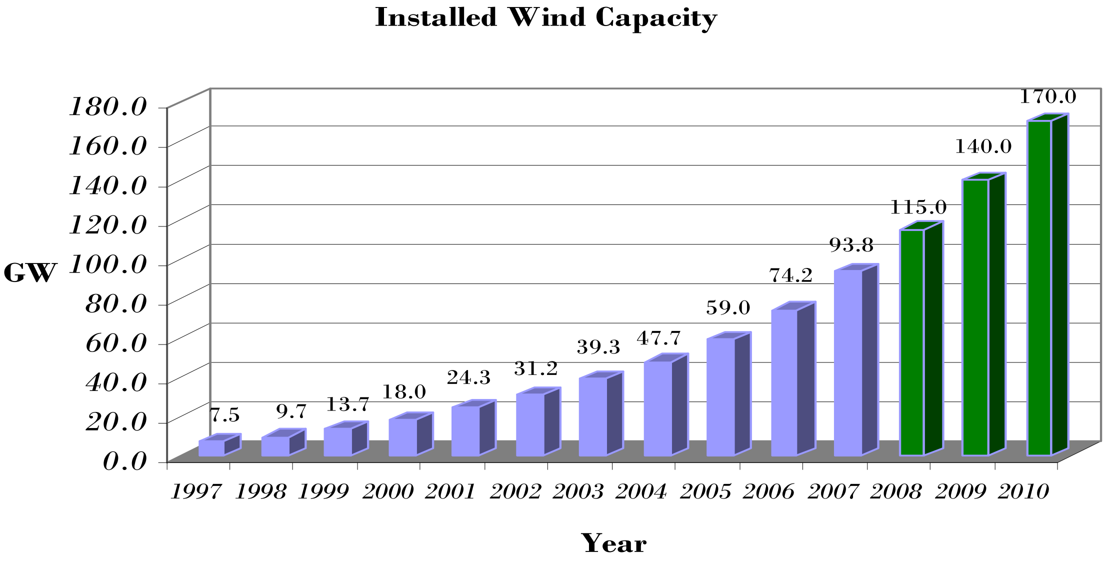


Figure 1: Installed wind capacity worldwide till 2007 and prediction until 2010 [4]

Figure 2: Onshore wind power in MW installed in Europe by end of 2007 [5]

The present status of wind energy in Europe is depicted in *Figure 2*. The leading countries are Germany and Spain with 22 and 15 GW of installed wind capacity respectively, with Denmark, Italy and United Kingdom following. The Netherlands is at the seventh position, but this may change in the future, since the country has a high potential for wind, especially on the northern coast, to the North Sea. More specifically, the government of Holland is considering a target of 6 GW of additional off-shore wind power for 2020, promising this way a more sustainable future for the country, which is powered at the moment mainly by fossil fuels [6], [7] and is dependent on imports. Such target for wind power will influence the operation of the rest of the system, bringing about a number of challenges.

Large-Scale Wind Integration in the Power System

The large-scale integration of wind power within the system on the one hand can be highly beneficial in terms of fuel cost and emission savings, but on the other hand may cause problems of both technical and economic nature that need to be addressed before the complete realization and application of the plan. The impacts of wind on power systems, which can be roughly divided into local and system-wide impacts [8], are mainly due to the stochastic nature of wind as a resource. The local impacts of wind, which are principally dependent on the turbine type and the characteristics of the local grid, will not be of concern in the particular study, since the effects become less noticeable when the (electrical) distance from the source increases [9]. On the contrary, the system-wide impacts, which are closely related to the variability and limited predictability of the wind, will be presented here.

Technical Impacts

In *Figure 3* a concentrated picture of all the technical impacts is shown. As one can notice, the impacts comprise different time-scales and various distances from the source in an effort to demonstrate all possible repercussions of large-scale wind integration. Apart from the effects of wind power into power balancing and unit commitment, large-scale wind integration affects a number of parameters such as adequacy of power or grid, system stability and congestion management.

More specifically, adequacy of power refers to the total supply available to cover peak load situations. In order to make an accurate assessment, maintenance schedules plus system load must be known, and the criteria used for the evaluation include the loss of load probability (LOLP) or the loss of energy expectation (LOEE). However, the inability of knowing the exact wind pattern leaves the system planner with limited knowledge about the total generation available for a given period especially for a market design of 12-36 hours ahead, clearance time.

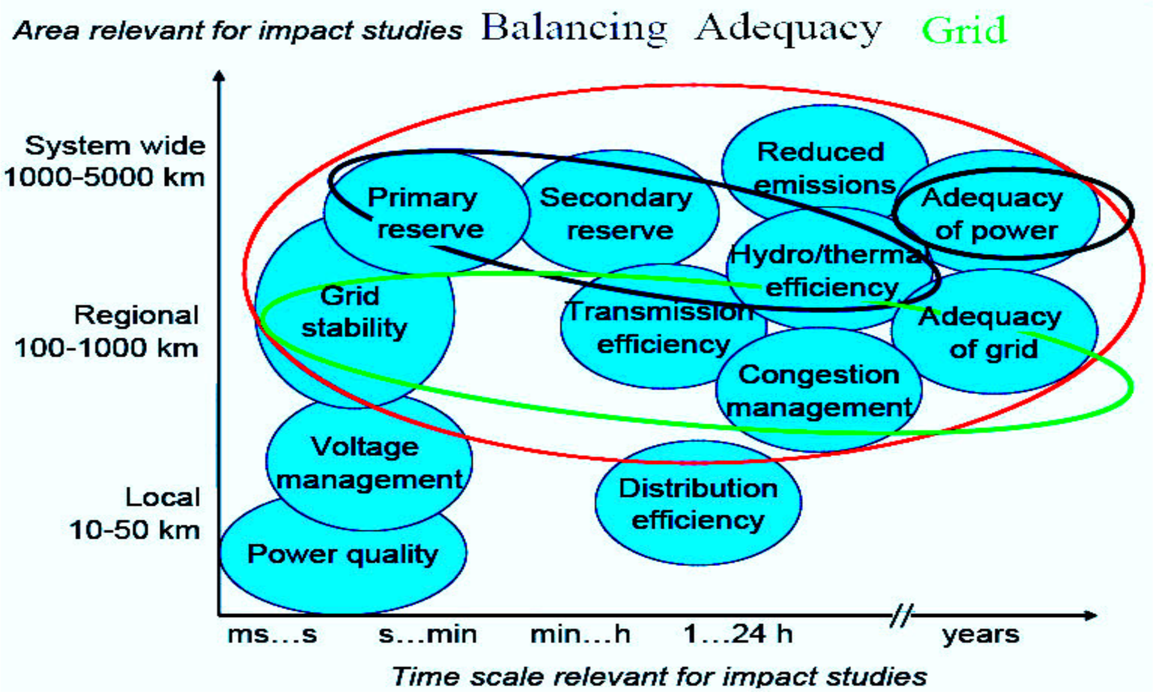


Figure 3: Technical impacts of large-scale wind integration [11]

The power system's, transient stability from the wind power point of view is mainly dependent on the wind turbine type and its capability to operate well during grid fault conditions. Even if the effect of wind power in this parameter is mostly local, given a large amount of wind turbines (especially concentrated in one geographic region), the impact of large-scale wind power can affect the total system's stability with important consequences for the reliable and secure delivery of power. Therefore, wind farms should be equipped with control properties similar to the thermal stations.

The impacts of wind power on transmission, depend on the location of wind farms relative to the load and the correlation between wind power production of different areas or/and load consumption [11]. Thus, increasing wind power penetration can affect possible bottleneck situations. Namely, in a study about the integration solutions for wind energy [12], an important correlation between the Dutch and the German wind (0.73) has been pointed out. This means that during periods of low load and high wind (minimum-load situation), interconnection capacity between the two countries may not be fully available for exchanges due to similar minimum load issues on both sides of the border, resulting in wasted wind energy.

Apart from the effects of wind power into adequacy of power or grid, system stability and congestion management, large-scale wind integration significantly affects power balancing and unit commitment, which are of main concern in this study. Power system balancing and economic unit scheduling are two processes which are carefully planned and at the same time quite sensitive to abrupt changes of generation (unplanned generator outage) or load. Two of the most important considerations are that the generation can be controlled and that load can be predicted very well. However, the integration of large-scale wind power means that an uncontrollable, with limited predictability resource must enter the well structured equation of power balance.

Power Balancing & Unit Commitment

The technical impacts of wind in power balancing and especially in unit commitment and economic dispatch (UC-ED) are of main concern for this research and therefore they will be studied in more detail.

In general, for dealing with mismatches between generation and load, power reserves are set on hold by operating, generation units at reduced output and consequently at lower efficiencies such, that they will be able to re-adjust fast (within seconds) their generation capacity if a disturbance occurs, in order to restore a temporary power balance equilibrium – primary control. Spinning reserves are next used (secondary control) to reinstate the frequency to its nominal equilibrium value. The tertiary control refers then to the economical distribution of system's loads to the various on-line units (ED). However, the best set of available units to supply the system load along with the desired reserves is already pre-decided by the unit commitment (UC) [1]. UC-ED even if they are subject to load variations or unexpected generator trips, they can be well enough predicted in the traditional power system and therefore relatively accurately planned.

Wind patterns, however are unpredictable and they may be described as the addition of two meteorological phenomena: the macro-scale variations and the micro-scale turbulences [10]. On the one hand, macro-scale fluctuations can result by night and day, by season or by unexpected variations of the wind's speed and direction. The amplitude of these fluctuations is high enough to have an impact on energy planning. On the other hand, micro-scale turbulences comprise much shorter time scale (seconds to minutes), which may have an influence on the adequacy of primary reserves. Yet, as it was proved in [13], [14], even at very high levels of wind penetration, effects of wind power at primary reserves level are negligible compared to load fluctuations for instance.

As the capacity of installed wind increases, the undesired disturbances are transmitted into the grid, resulting in significant power fluctuations and uncertainty about the energy volumes. Since, ordinarily, the supply-demand balance is maintained by conventional generation, the stochastic nature of wind induces conspicuous uncertainty in the planning especially of spinning reserves. Namely, with the presence of wind for longer time periods, the amount of conventional generation used for system balancing is reduced. Thus, UC-ED are affected, as the existence of wind energy reduces the output and/or the operating hours of conventional generation units, while these units are crucial for the compensation of the wind power's variability and limited predictability [9]. If the fluctuations in wind power production are not appropriately (fast and reliably) smoothed by thermal stations, adverse situations cannot be excluded. Therefore, the system planner has to find an optimum balance between keeping sufficient reserves to confront wind's variability and operating the total system with as low CO_2 emissions as possible in the most economic fashion.

In periods when the load is low – especially at night – the wind is high and the conventional units cannot reduce adequately their output for various reasons (deployment obligations etc), the aggregate of total supply can exceed the demand. Under such minimum-load situations, wind-powered production needs to be curtailed at one extent to avoid more problems [7]. The question that arises refers to which level of wind penetration the power system can operate in a safe and reliable fashion, while the incoming wind power is completely integrated. The result of a relative study [7] with fixed import levels is depicted in *Figure 4* for the Netherlands, where as the wind penetration increases, in turn results in significant waste of available wind energy. In the course of this study, *Figure 4* will be reproduced and verified with the suggested methodology, where international exchange will not be fixed but dependent on the specific characteristics of the system in each time-step.

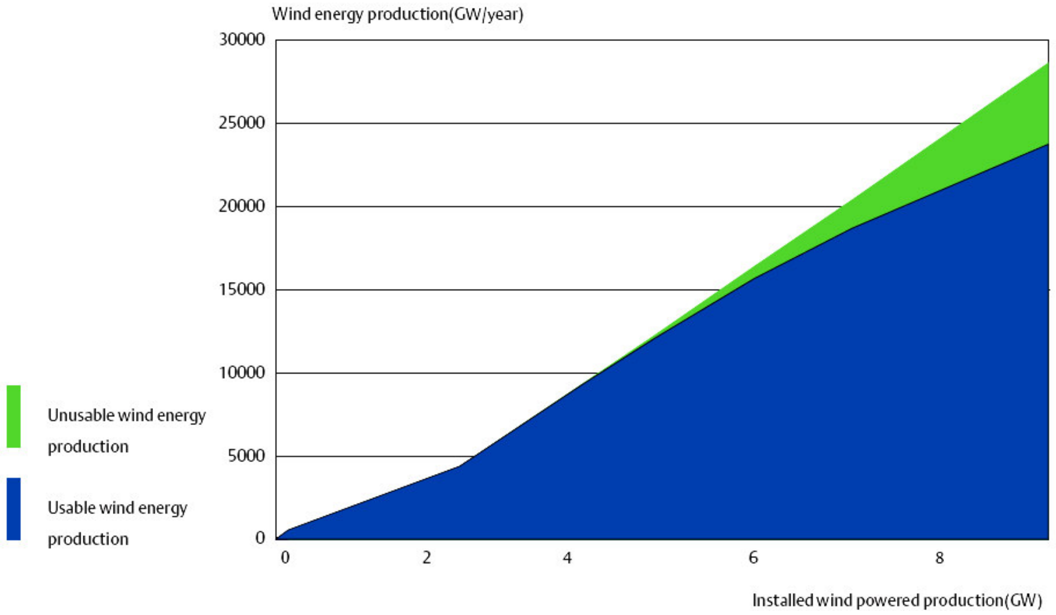


Figure 4: (Un)-usable wind energy production as a function of the installed wind-powered production capacity [7]

Summary

In general, the operation of the power system with high penetration of stochastic energy sources, especially wind, is quite different then previously. The traditional algorithms are based on deterministic approaches mainly and the advent of more wind power asks a solely probabilistic view. Therefore, generation expansion, system operational planning and stability studies have to be redefined under the prism of uncertainty [15]. Otherwise, the calculations and predictions will always lack accuracy and in some particular cases depending on the focus they might be either depreciated or overestimated.

Economic Impacts

Aside from the apparent technical implications of integrating wind energy in large-scale within the power system, economics are also of importance, especially, because the wind-produced MWh has a low marginal cost in the electricity market. Likewise, it can be induced that the market design has also an influence in the way that wind energy is participating in the daily transactions. The dimensions of the market, along with the generation mix, the market gate closure time (after this the international exchange schedules are fixed), the geographic position and the flexibility of the conventional generation units (ramp rates, minimum power levels etc.) are of concern in the spectrum of economic integration of wind energy.

In spot markets with 12-36 hours ahead, gate closure time, the bids including wind power are cleared for the 12-36 hours ahead, horizon. For conventional generation, apart from some less frequent unplanned outages, the planning is much easier than for wind power, which is susceptible to an intermittent source, as the wind. Hence, the inevitable forecast error bears the power producer with the cost of regulation in the ancillary services market, which can vary from low to high values depending on which generation technologies are used. In systems with available hydro power the cost is relatively lower, whereas in systems where regulation is performed with combined-cycle gas turbines (CCGT), the cost for regulation is significantly higher. Moreover, from an international exchange perspective, a large forecast error prevents a suitable and precise scheduling of import – export energy volumes.

It has been found in various studies [9], [12], [16], that if the market clearance moves from 12-36 h ahead to 3 h, the forecast error can be mitigated significantly and if moved to 1 hour ahead (almost real-time), forecast error is very close to zero. Thus, total system operating costs are minimized and international link capacities can be highly utilized. However, this is an ideal situation, which still does not yet widely exists, apart from some after-sales markets in Sweden and Finland with continuous trade [16].

Especially for systems that include large hydro reservoirs, such as Norway and Sweden, high wind penetration can have an additional repercussion. Since, wind is a resource with a low level of marginal cost, and the compensation for its irregularities is performed by hydro units with also low price, it can be observed that the marginal cost of the total system is decreasing significantly, and can reach almost zero in windy periods [17]. This, in turn affects mostly the condensing power plants, but also the combined heat and power (CHP) units, which are operated less. In a situation like this, the nuclear is usually the marginal power and furthermore low prices make the future or contemporary

investments in electricity generation not profitable, since the revenues are significantly diminished.
Therefore, due to market's operational characteristics, condensing plants with low capital costs and high operational costs are needed as marginal plants to guarantee a price level at the spot market that is profitable for new investments [17].

1.3 Interconnections as an integration option for wind power

After having presented the negative impacts of integrating large-scale wind power within the power system, it is important to suggest some solutions that mitigate wind's effects. In accordance with the technical and economical impacts, the issue of wasted wind, due to minimum-load problems and insufficient reserves can be tackled by the installation of large-scale energy storage facilities. However, according to a related study [12], the key for wind power integration, especially at high penetration levels, is international exchange. Namely, instead of commissioning new, costly energy storage projects, such as CAES (compressed air energy storage) and pumped hydro storage (surface or underground – PAC, UPAC respectively), priority should be given to national interconnections especially with areas with lower average marginal costs, which for example is the case for the Netherlands and Norway. In second level, it can be induced that interconnections operate similarly to energy storage, since instead of storing the excessive wind to use it at times of high demand, national links, transfer it to other markets that can integrate the additional energy volumes. Moreover, at low wind periods, interconnections can offer a channel to significant energy reserves from different trans-areas. Consequently, the three main advantages of national interconnections can be summarized in the following:

a. They give access to neighboring trans-areas which can offer valuable power in times of excessive demand, which contributes even more into the security of energy supply.
b. If price difference due to generation mix or different load patterns is present between neighboring power systems, interconnections can increase the overall benefit in terms of operation cost and emissions savings. However, when interconnections become stronger the additional gains become progressively less important [18].
c. Connecting together all participants across a transmission system makes it feasible to select the cheapest generation available in the system – taking into account transmission losses and transmission capacity limits – irrespective of plant's location [19]. Moreover, a robust interconnected electricity network forms the basis of sound competition between large electricity producers [7].

1.4 Research Objective and Thesis Outline

Focus

The simulation model for the North-Western part of the W-UCTE system developed by TU Delft and TenneT TSO will be extended to include the Nordel system. On the one hand, this increases complexity but on the other enables a more global view and opens up new possibilities for model validation. If seen from, the perspective of investigating possible grid extensions from the Netherlands to Norway (NorNed2) or Denmark (COBRA), investigation of the technical and economic aspects is only possible by developing such models. Moreover, the differences between the fossil-fuel based Western-European system and the hydro-power based Scandinavian system provide interesting opportunities for research. In this master's thesis project, power system simulation studies will be performed in order to quantify the benefits of coupling the North-Western part of the W-UCTE system and the Scandinavian Nordel system. The simulations will be conducted using the existing probabilistic, chronological, multi-area production cost simulation tool PowrSym3. The optimization in PowrSym3 has the objective of minimum total system costs, using inter-area exchanges in order to minimize differences in marginal costs between areas, which in turn depend on the marginal generation technologies of each area. The generating unit database already contains representative models for the areas the Netherlands, Belgium, France, Germany and the United Kingdom, and needs further extension to capture the special characteristics of the Nordic power system and the new operation areas.

Research Objective

"To develop a model that can simulate the physical and market coupling between the systems of W-UCTE and Nordel such that the impact of international exchange in the large-scale wind power integration will be investigated "

In order to achieve this, the sub-objectives that need to be met are:

- Development of representative models for the Scandinavian areas Norway, Sweden, Finland and Denmark (East - West) including interconnections between these areas and with W-UCTE.
- Development of an annual hydro allocation method for the scheduling of reservoirs of hydro-power generating units. More details will be given in section 4.
- Simulation of all areas focusing on the NorNed link and reporting of technical (area exchanges, system reliability), economical (total system cost) and environmental (emissions, wind power integration) aspects.
- Additional simulations to evaluate different integration scenarios (NorNed 2, BritNo, and Gas Power in Norway) and other crucial limitations such as reservoir state (high, medium, low inflow in Norway), or various reservoir handling methods.

The existing database of PowrSym3 previously applied by TU Delft and a database developed for TenneT TSO and made available by TenneT are used for the development of thermal and hydropower units in the Scandinavian system. Installed capacities will be based on adequacy forecasts made by W-UCTE, Nordel, ETSO and TenneT for the year 2014. The annual hydro optimization methodology will be built using historical reservoir level information, market price data and load data. These data are obtained from Nord Pool.

Thesis Outline

In chapter 2, a standard unit commitment problem and the tool used for the study will be presented along with a brief presentation of the data already included in the database. Furthermore, in chapter 3 a thorough analysis of the Nordic power system will be demonstrated initially, including the discussion about the Nordic wind power. Consequently, the steps taken for the model development will be described. Within chapter 4, the PowrSym3 build-in weekly optimization will be introduced along with the discussion upon long-range hydro scheduling and consequently the suggested optimization - allocation methods. In chapter 5, the final characteristics of the simulations will be presented, and furthermore the choice of the selected scenarios for the final simulations will be illustrated. In the 6th chapter, the results of the simulations will be processed accordingly and a sensitivity analysis will be carried out to assess the performance of the model. Finally, in chapter 7, the conclusions of the research will be presented, along with the recommendations for future work.

2. Simulation Model & Existing Database

2.1 Standard Unit Commitment (UC) problem formulation

A problem that must be frequently solved by an electrical utility is to economically determine a schedule of which units will be used to cover the forecasted demand while respecting the operating constraints such as spinning reserve requirements, over a short time horizon. This problem is known as the unit commitment and a short representation of this will be presented here.

Assuming a perfectly-operating energy market the objective function that has to be minimized while taking into account all technical constraints is:

Minimize the total generating cost:

$$\sum_{t=1}^{T}\sum_{i=1}^{N}\left\{C_i(p_i^t)+S_i\right\}*u_i^t \quad (1)$$

t = 1, ….T: number of time intervals;
i = 1,…..N: number of generation units;
S_i = start-up costs
p_i^t = power output of unit I in time interval t
C_i = operating costs of unit i
U_i^t= 1 if unit is on for time t and 0 if unit is off for time t

Subject to the following constraints:

Covering the load:

$$\begin{gathered} P^{t}_{Load} = \sum_{i=1}^{N}(p_i^t * u_i^t) + ENS_{slack} \\ ENS_{slack} \geq 0 \end{gathered} \quad (2)$$

Satisfying power generation limits:

$$u_i^t * p^{\min}_i \leq p_i^t \leq u_i^t * p^{\max}_i \quad (3)$$

Meeting ramp rate constraints:

$$abs(p^{t+1}_i - p_i^t) \leq r_i * 1 \quad (4)$$

Meeting spinning reserves requirements:

$$\begin{gathered} P_{spin,res} \leq \sum_{i=1}^{N}(p^{\max}_i - p_i^t) * u_i^t + Spin,\mathrm{Re}s^{t}_{slack} \\ Spin,\mathrm{Re}s^{t}_{slack} \geq 0 \end{gathered} \quad (5)$$

And finally minimum up- and down-time constraints:

$$u_i^t = \left\{ \begin{matrix} 1..if...1 \le x_i^{t-1} \le t_i^{on} \\ 0.if\ -1 \ge x_i^t \ge -t_i^{off} \\ free:0.or.1 \end{matrix} \right\} \qquad (6)$$

X_i^t= number of hours unit i has been on/off at time t
t_i^{on}, t_i^{off} = minimum up- and down-times

In the previous equations, Xs are the state transition variables:

The state transitions are:
$X_i^{t+1} = X_i^t + 1$ if $U_i^t = 1$ and $U_i^{t+1} = 1$
$X_i^{t+1} = X_i^t - 1$ if $U_i^t = 0$ and $U_i^{t+1} = 0$
$X_i^{t+1} = 1$ if $U_i^t = 0$ and $U_i^{t+1} = 1$
$X_i^{t+1} = -1$ if $U_i^t = 1$ and $U_i^{t+1} = 0$

The output of the unit commitment problem yields values for the two decision variables: $\left\langle u_i^t, p_i^t \right\rangle$, that is the on-off status of all units and their power output for all time periods of the study.

As it is evident solving the unit commitment problem, demands an iterative process, where all the constraints are re-evaluated at each time step. For the traditional power system, the solution of the unit commitment problem is a straightforward concept, which takes into account controllable sources such as conventional generation units.

Currently, the prevailing concept is that the transition to the future power systems will be based on two main pillars: the integration of RES and especially wind, along with the sustainable development, which is related to high fuel utilization, lowering of emissions, optimum maintenance schedules and overall consumption decrease. However, all the previous concepts apply an additional complexity upon the already complex issues of optimizing the unit commitment and economic dispatch (UC-ED) schedules. Moreover, UC and ED, even if they are interrelated, they comprise different time frames (UC: once or twice per day, ED: throughout the day) and different procedures. Before the integration of stochastic generation and prior to the market influence, unit commitment decisions were relatively easy to take; UC was almost fixed, except for some cases of unexpected, generator outages or demand variations that needed re-assessment. Nonetheless, the integration of wind power and the liberalization of electricity markets, add more uncertainties (market prices, wind forecast) in the optimization problem of UC-ED.

In order to investigate the previously mentioned issues, PowrSym3 will be used in this thesis. PowrSym in its newer version (PowrSym3) is a multi-area, multi-fuel, chronological generation cost simulation tool for electrical power systems including combined heat and power, energy storage and energy limited fuel contracts [20], which was developed from the 1980s onwards by Operation Simulation Associates, Inc. and the former Dutch utility SEP with support from the Tennessee Valley Authority, U.S. PowrSym3 is a powerful simulation tool, with high capabilities in UC-ED scheduling, which closely matches the objectives of this study. The main reason for using PowrSym3 in this study is that it is an existing tool, procured along with a database with validated models for the existing conventional generation in the Netherlands, by the Dutch TSO, TenneT [9]. More information about PowrSym3 will be presented in Appendix B.

2.2 Existing Database

The input at the start of this research was the generation unit database of the W-UCTE system. The database among others comprised validated models of the largest seventy power (more than 60 MW) generating units and models for sixteen heat areas in the Netherlands. Apart from this, which was the basis for the initial development of PowrSym's database, it also included wind power characteristics (wind power and forecasts), hydro energy and hydro storage models. Moreover, the database included thermal power unit models to represent generating units planned to be installed in the Netherlands, along with aggregated models for nuclear, coal, natural gas and hydro units in neighbouring systems as well as interconnections between the Netherlands and these systems. The models for these units are based on best-practice unit data and expert knowledge made available by TenneT TSO and they will be presented in more detail in section 2.4.

IYR	IWK	N1	N2	N3	N4	AID	A1	X1	CLASS	COMMENT
…	…	…	…	…	…	…	…	…	………	……………
…	…	…	…	…	…	…	…	…	………	……………

Table 1: Organization of the database records

The database includes initially approximately 6,500 records, which define the various models' attributes (thermal generation units, system load, wind power, heat load, CHP units, hydro energy and energy storage units). It is organised in ACCESS, using the data format shown in *Table 1*. Each record consists of a single line, in which, IYR and IWK represent the year and week respectively the record applies to. N1 to N4 identifiers usually are used to identify unit numbers and week applicability. AID is the parameter name, A1 the generating unit or area name and X1 is the parameter's value. Then, CLASS is used to cluster certain records, thus forming a specific simulation's set-up or scenario (adjustments of transmission capacities, addition of interconnections or of installed capacities, sensitivity analysis etc). When exporting the database from ACCESS, a CLASS can be ticked on or off and saved as a simulation input file. A data exchange interface implemented in ACCESS produces the ASCII-file used as input for the calculations. This process allows the user to develop consistent data input files, guaranteeing reliable simulation results, which can be compared between scenarios. The development of consistent scenarios in the database can be done very efficiently and exporting the scenarios requires little time and effort. Some of the various models attributes will be presented here:

Thermal Generating Units

The existing database contains models for all the range of conventional generation technologies for various fuels such as coal, natural gas, oil and uranium. Each technology is modelled in clusters of records that define the operational characteristics of each power plant. The types of thermal power plants modelled are: combined-cycle-gas units (CCGT), combined-heat-power units (CCGT CHP), nuclear units, coal or lignite condensing power plants and oil & gas turbine units. The most important technical parameters defined within the model for conventional generation units are presented below [9]:

- Minimum up- and down- time: the continuous commitment or de-commitment periods due to technical constraints, such as temperature-related aspects.
- Commitment and dispatch status: The commitment types of thermal generating units are must-run or economic operation, and separate types exist for pumped storage, hydro power and wind power since these are separately taken into account in the optimisation of UC–ED. The dispatch status for all units is economic operation, which refers to choosing an optimal operating point (MW output) for each unit to minimize total system costs.
- Ramp rate: Ramp rates specify the maximum rate-of-change [MW/h] of a generating unit's power output. For this study this value is ranging depending on the generation technology from 1.5 – 3 %/ of installed capacity per minute [9].
- Operating costs: The operating costs of generation units comprise fixed operating costs and variable operating costs (fixed start-up costs, and variable fuel costs and emissions costs).
- Emission levels: CO_2, SO_2 and NO_x emissions are included as fixed coefficients on a fuel energy content base (ton/GJ).
- Heat rate levels for CHP: This is the constraint which is associated with the technical operational area of these units (power P, heat H) and an example is given in *Figure 5.* All, CHP units power-heat characteristic is located within the shaded trapezium,

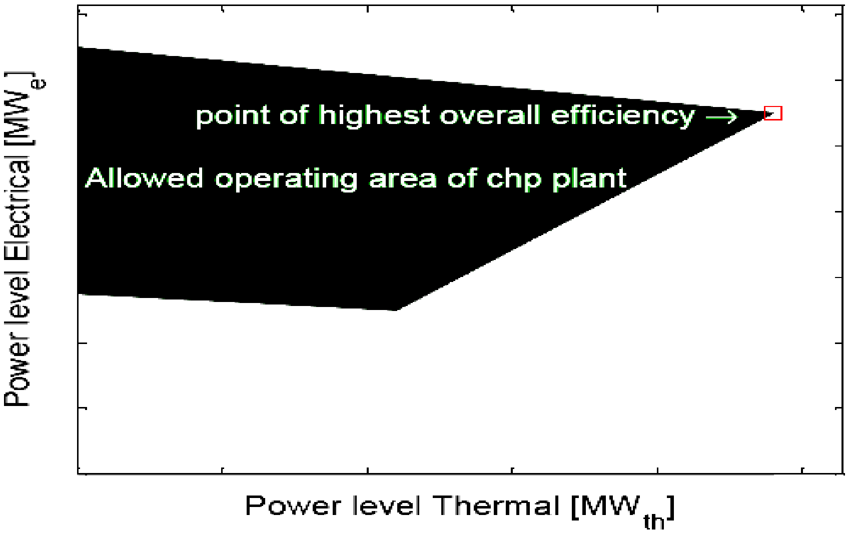


Figure 5: Operation area of Combined Heat and Power (CHP) units

Moreover, in order to apply a realistic view in the scheduling mostly of thermal generation, PowrSym3 comprises sophisticated outage models. Generator outages refer to all the possible events that can lead to total or partial unavailability of generating units. Outages can be distinguished in planned outages (scheduled maintenance) and unplanned outages (unexpected generator trips).

Planned outages are usually scheduled with the objective of minimising opportunity losses and the loss-of-load probability (LOLP), a widely used reliability measure in generation capacity planning. For this research, maintenance is scheduled such that LOLP is levelized throughout the year, with most maintenance scheduled at periods of relatively low load [9].

For the modelling of unplanned or forced outages, PowrSym3 includes six different models, but for this study the random Monte Carlo method will be used, since it's the most accurate method available and has reasonable calculation times. The random Monte Carlo method calculates the expected unit operation hours by averaging a number of outage scenarios created by a random number generator [9].

Hydro Power

For hydro power, the modelling concept obeys the basic operating principle of hydro-electric plants which is based on the conversion of potential energy of a water mass from a given height to electricity in the zero reference level, where the generators are located with a specific efficiency. The absence of thermodynamic processes, fuels and emissions make hydro power models relatively straightforward concept [9]. The three different types of hydro units within the database are:

- Reservoir hydro: It consists of a hydro power unit connected to a hydro reservoir. The important attributes are minimum and maximum hydro generation levels in MW, and the reservoir inflow, which is modelled as hydro energy available (GWh/week) for dispatch. However, the resolution on this attribute refers to long-range hydro scheduling, which is an issue, susceptible to high uncertainty, depending on seasonal precipitation forecasts, anticipated demand and market prices, which will be described in chapter 4.
- Run-of-River hydro: Run-of-river hydro comprises hydro power units with a generating capacity depending on the availability of the primary energy source, water. In case water is available, the unit must produce power or the water must be spilled, resulting in lost opportunity.
- Pumped-hydro: Pumped hydro is capable of storing energy by converting electricity into potential energy. Pumped hydro is modelled as a reservoir hydro unit with a pumping facility between the reservoirs. Its dispatch logic is dependent on the value-of-energy method [21]. The value of energy method depends on equation 1 and places a monetary value relative to pumping on the stored energy taking under consideration power price variations, operational aspects of thermal generation plant and storage reservoir size. V_p is the pumping value of energy, V_g is the generating value of energy, n is the net turn-around conversion efficiency, C_{var} are the variable operation and maintenance cost of the energy storage device,

P_p is pumping power, P_g is generating power, $C_{m,sys,t}$ is system marginal cost at time t, R is the reservoir level, Rmin is the minimum reservoir level and Rmax is the maximum. Thus, pumped hydro will generate only if the marginal cost is higher than the generating value of energy, store only if marginal cost is lower than the pumping value of energy, and be idle otherwise. Pumped-hydro is optimized last, with a target to minimise total system costs.

$$V_g = (V_p / n) + C_{var} \qquad (1)$$

$$P_p > 0 \text{ IF } V_P > C_{m,sys,t} \text{ AND } R \leq Rmax$$

$$P_g > 0 \text{ IF } V_G < C_{m,sys,t} \text{ AND } R \geq Rmin$$

International Exchange

As it was mentioned in the previous section about wind power, the market's gate closure time will be set for this study in 1 hour ahead. Thus, international exchanges are optimized up until the moment of operation, taking under consideration the best available wind forecast and scheduled as part of UC-ED such that all feasible transactions are made.

Wind Power

Wind power in PowrSym3 for this study, is realized as an available resource with zero marginal cost that can be fully integrated, unless technical constraints require its curtailment. The case that this thesis focuses on is the UC-ED of wind with perfect prediction. Perfect prediction refers to a flexible market design with 1 hour ahead, market clearance and even if it's not realistic, at the moment, the results can help to illustrate the technical limits (influencing parameters: transmission capacity, minimum load, spinning reserves and non-spinning reserves limitations) of maximum wind integration.

2.3 Simulation Model & Optimization Structure

The execution of PowrSym3 includes three time horizons and has a holistic approach; the annual horizon, which corresponds to reliability calculations and maintenance scheduling, the weekly horizon, which is used for the inclusion of outages and the scheduling of hydro and energy storage units. The weekly horizon can be also used for production cost optimization. Finally the basic operation time step can be chosen by the user, examples are 1 hour, 30 minutes or 15 minutes. The three time horizons are optimized holistically resulting in abundant and detailed information about the operation of generating units.

The simulations start with the model reading a control file that comprises data for heat areas and loads, system load for all nodes, wind power data and specific user defined attributes about the power system (*Figure* 6). The reliability model then, calculates the annual LOLP in hours per year applying the cumulant method [22]. This method analytically approximates expected generation levels and hourly load distributions using cumulants of the load and all possible operating states of each different generating unit type. This allows an accurate and fast production cost evaluations for larger numbers of simulations. After calculation of LOLP, load carrying ability, capacity surplus/deficit and desired reserves are calculated relative to a specified reliability index. This index may then be used for an annual optimisation of maintenance schedules. All the steps taken during the annual calculations are depicted in *Figure 6*.

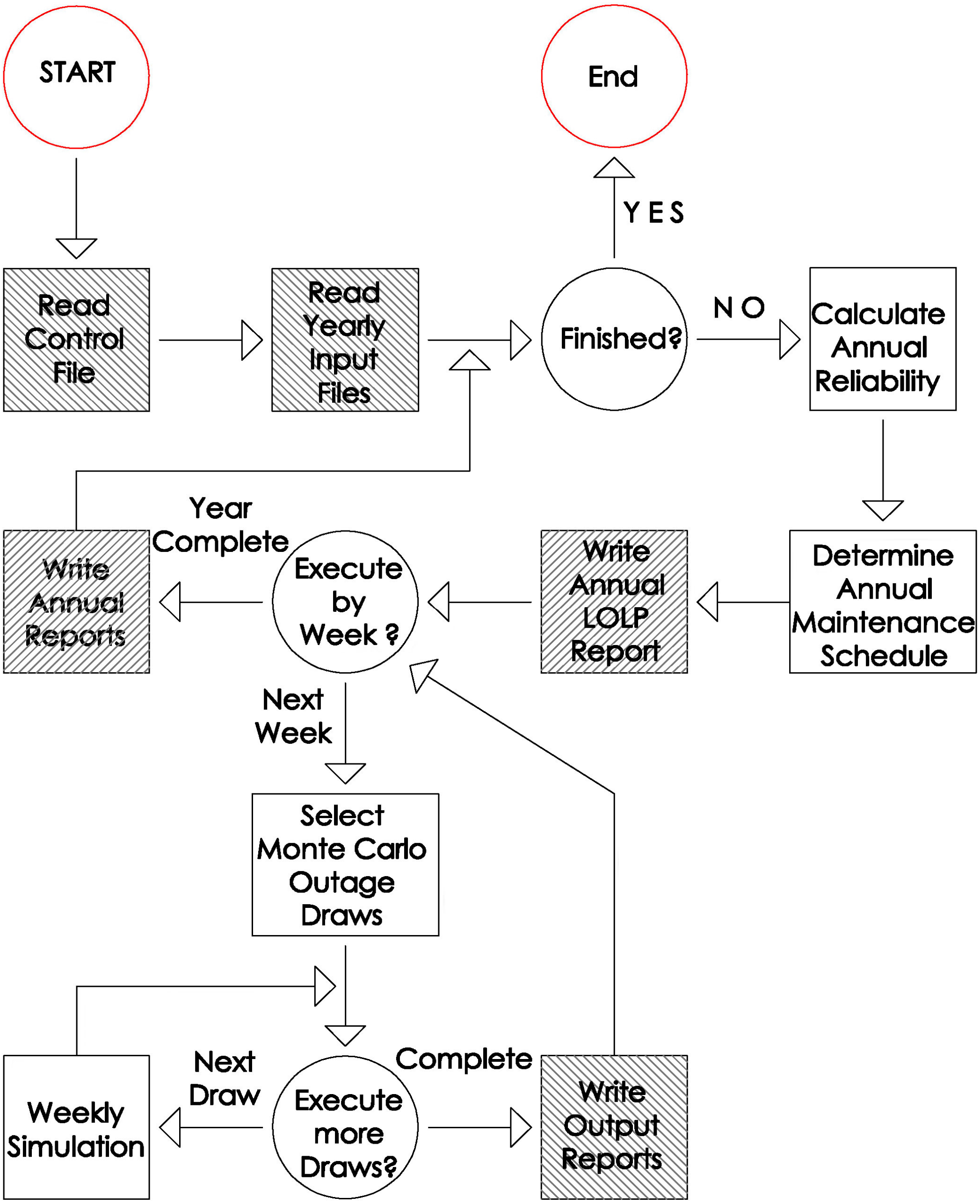


Figure 6: Annual execution flow diagram in PowrSym3

2.4 Model Specification

The existing model comprised a physical representation of the power system of W-UCTE, in 2014 (the year chosen for simulations) namely, the Netherlands (NL), Belgium (BE), Germany (DE), France (FR) and Great Britain (GB). The Dutch generating fleet is characterized by a large proportion of gas-fired plants, whereas Germany and Great Britain have a relatively large number of coal-fired units, while in Belgium and France the emphasis is on nuclear plants [23]. In this research, each country is assumed to be a central area with inland generation, load and interconnections with the neighboring areas based on [24] and information by the Dutch TSO. In Figure 7, a graphical representation of the W-UCTE system is depicted. The NODE area is a no-load and no-generation area, which is used to incorporate the transmission capacity limits for the Netherlands with Belgium and Germany, foreseen by TenneT (Dutch TSO) for the year 2014. Moreover, the interconnections between the Netherlands and Great Britain (BritNed), and France and Great Britain are high voltage direct current (HVDC) cables, whereas the rest are regular alternating current (AC) interconnectors.

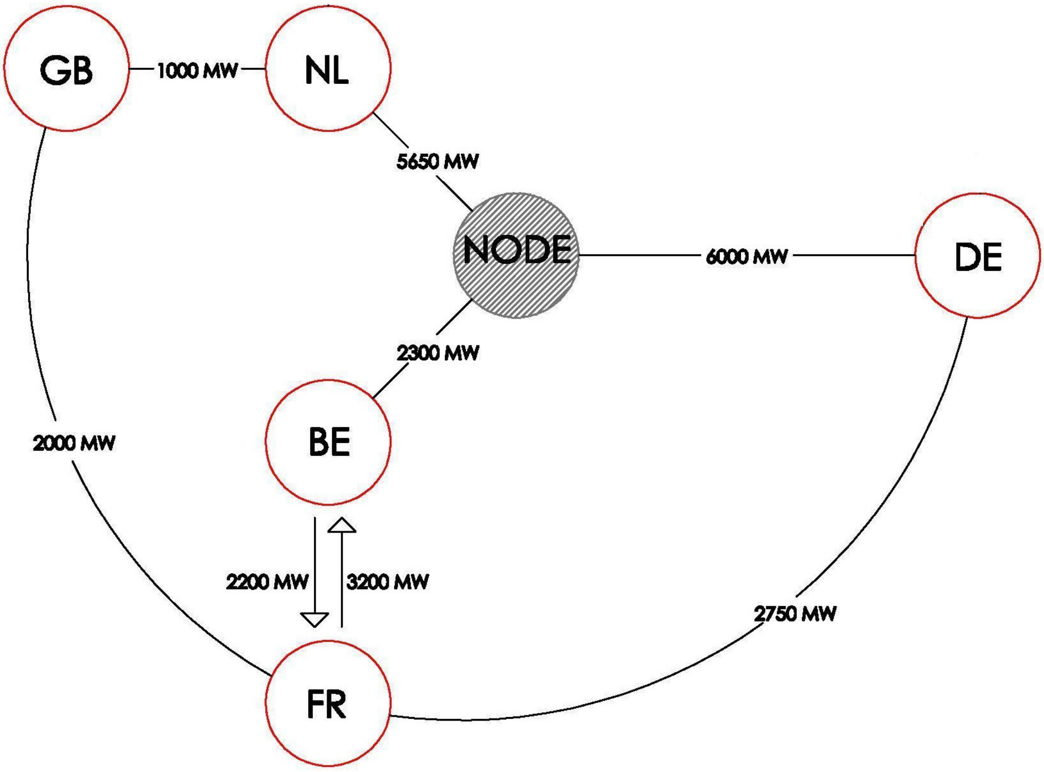


Figure 7: Areas and interconnections included in the existing database

Area Load

For the purpose of this research, relevant load data for each area have been obtained by W-UCTE, for the year 2007, making sure that correlations between momentary loads in each country are taken into account [9]. The data were processed accordingly for the year 2014, taking under consideration [25], [26]. Consequently, the consumption growth rates for Netherlands, Belgium, Germany, France and Great Britain were assumed: 1.15, 1.08, 1.03, 1.08, and 1.10.

Area Generation

For the generation units of each node, the TenneT generation unit database was used [24], along with the adequacy forecasts of W-UCTE [25], to include the already installed capacities of each country per technology, plus the future developments. By using the already validated models for the generation units in the Netherlands, and the aforementioned information, aggregate unit models with identical characteristics for each generation type were formed for every country. In Figure 8, the contribution of each generation type is depicted, without considering the installed wind power.

Regarding wind power, the only countries that comprise actual wind data are Germany and the Netherlands. For more details about the development of wind data for these two countries, information can be found in [9], [49]. However it must be noted that, wind power in Germany is modeled such that it is integrated with a higher priority than Dutch wind power in order to guarantee that wind power in the Netherlands is not integrated into the system at the expense of German wind power. The installed capacity of wind power in Germany is considered to be 32 GW and in the Netherlands ranging from 0 – 12 GW with various combinations of onshore and offshore installed capacities according to [9], namely, 2 GW onshore, 4 GW (of which 3 GW onshore and 1 GW offshore), 6 GW (4 GW onshore, 2 GW offshore), 8 GW (4 GW offshore), 10 GW (6 GW offshore) and 12 GW (8 GW offshore), the latter producing 41 TWh in this wind year or 33% of annual consumption in 2014 [9]. Consequently, the concentrated overview of the existing power system within the PowrSym3 database is summarized in Table 2.

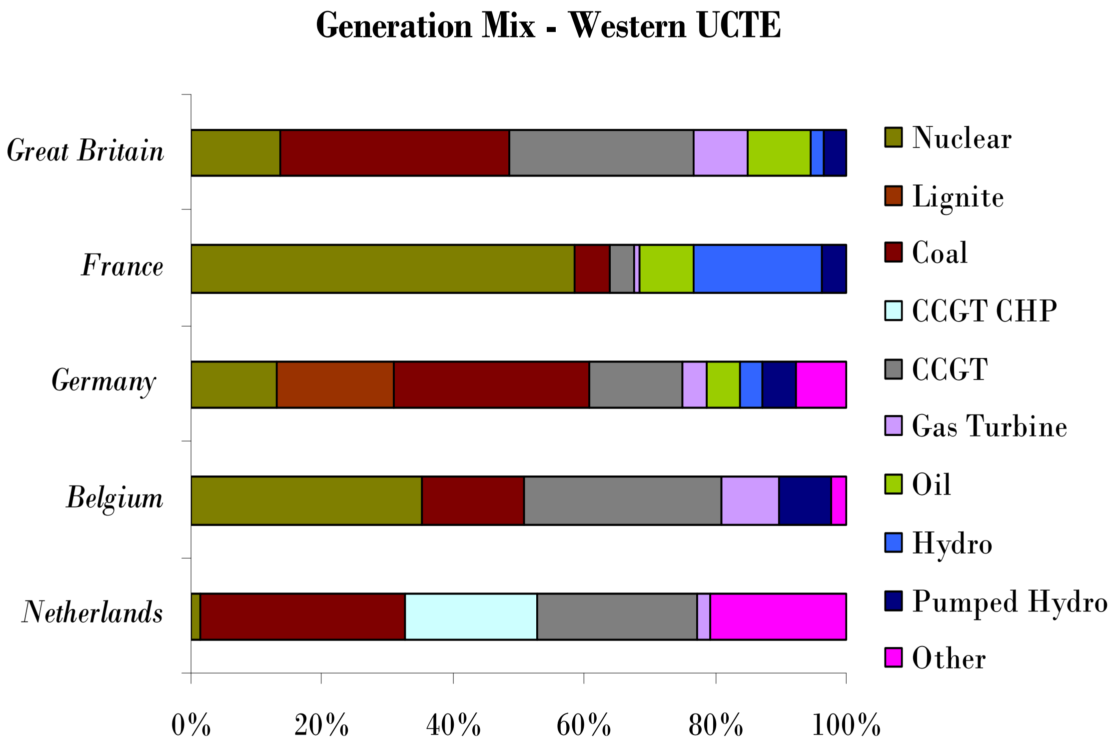


Figure 8: Generation mix percentages for W-UCTE countries assumed for 2014 (no wind power is considered) [24], [25], [26]

Technology	**Netherlands** GW	**Belgium** GW	**Germany** GW	**France** GW	**Great Britain** GW
Nuclear	0.4	5.9	14.1	64.9	11.9
Lignite	-	-	18.9	-	-
Coal	9.5	2.6	32.0	6.0	30.4
CCGT CHP	6.2	-	-	-	-
CCGT	7.5	5.0	15.1	4.0	24.4
Gas Turbine	0.6	1.5	4.0	1.1	7.0
Oil	-	-	5.3	9.2	8.4
Hydro	-	-	3.7	21.5	1.8
Pumped-hydro	-	1.3	5.5	4.2	3.0
Other	6.3	0.4	8.2	-	-
Total	30.6	16.7	106.8	110.9	86.9
Wind Power	0.0 – 12.0	-	32.0	-	-
Maximum Load	21	15.2	80.5	87.1	65.5
Total Demand (Twh/y)	126	97.0	518.0	550.0	367.0

Table 2: Installed capacities of generation technologies in 2014 for each area in W-UCTE

3. Nordel: the Nordic power system

3.1 Introduction

The cooperation between the Nordic TSOs was founded by the establishment of Nordel in 1963 [27]. Today Nordel, after the electricity market's liberalization, has evolved to an organization, which includes the Transmission System Operators (TSOs) of Norway, Sweden, Finland, Iceland and Denmark. Since Iceland is a separate part of the Nordel system, without physical interconnections with it, it will not be considered in the analysis. The main tasks of Nordel to ensure system responsibility across the national borders are summarized in the following principles:

a. To ensure the operational security of the power system and to maintain the power balance between supply demand.

b. To ensure the long term adequacy of the transmission system and to enhance the efficient functioning of the electricity market.

The Nordic power system comprises the synchronized systems of Norway (NO), Sweden (SV), Finland (FI), and the Eastern part of Denmark (DKE). Jutland (West Denmark, DKW) is synchronized with the W-UCTE system. Connections between the Nordic system and W-UCTE are established through a number of HVDC cables, which connect Sweden and Norway to West-Denmark and Sweden and East Denmark to Germany. Recently, a new HVDC line was taken into operation between Norway and the Netherlands (NorNed) [28].

From a market perspective, the Nordic countries have established the world's first international power exchange, Nord Pool, in 1996 when the Norwegian power exchange, was extended to include Sweden. Consequently, it included Finland, Western and later Eastern Denmark (2000) [27]. Its products are spot trading, financial trading and adjustment trading after spot trading has been cleared (after-sales market).

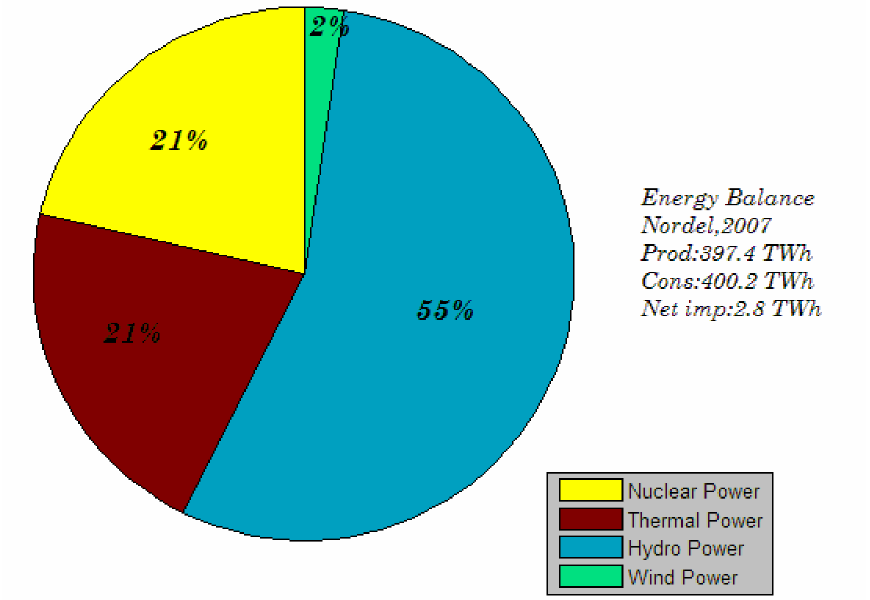


Figure 9: Distribution of generation in Nordel by energy source, 2007 [28]

Moreover, in order to depict the generation-mix of Nordel, Figure 9 was formed with data available from [28]. From this figure subsequently, it becomes evident that the Nordic system is dominated by hydro-electrical production, followed by nuclear and thermal, with the wind power acquiring at the moment a small percentage in the total generation.

However, this pattern is not the same for every country within the Nordic power system. When the focus is applied on each area separately, a great diversity can be observed (see Figure 10). More specifically, Norway's power comes essentially by hydro power stations. Sweden, in turn, can be divided in a hydro power dominated region situated along the Norwegian border, and a nuclear power dominated area in the South. Finnish generation mix is somewhat similar to Sweden, but with thermal power dominating. Finally, Denmark where large-scale wind integration is becoming a reality (20% of annual consumption is covered by wind), thermal generation is also the prevailing generation type, distributed among CHP units and condensing coal or biomass power plants.

Responsible for keeping the power and energy balance of the Nordic power system are the Nordel's TSOs. These are, Statnett for Norway, Affärsverket Svenska Kraftnät for Sweden, Fingrid Oyi for Finland, and Energinet.dk for Denmark. With a view to present the future developments, every year, Nordel publishes forecast reports for the 5-year ahead, horizon. According to accurate estimates [29], the installed capacity is expected to increase by the year 2012 to 8%, with investments mostly in nuclear and wind power, followed by thermal power and less in hydro. The average increase in total consumption is estimated to reach 4% compared to 2007, with the most located in Finland and Denmark with 5.5% and 7% respectively. Nonetheless, the Nordic electricity system is considered able to meet the estimated consumption and the corresponding typical power demand pattern in average conditions even without external imports [29]. The main challenges for the operation of the Nordic power and energy balance are the availability of hydro energy, which is dependent on annual precipitation, and bottlenecks in transmission within the Nordic system. Interconnections with more thermal-based power systems such as W-UCTE are important for securing sufficient energy and low prices during dry years, while these interconnections can be use for exports during wet years.

Under this framework, the installation and operation of the NorNed link between Netherlands and Norway, aims to contribute to the security of energy supply of the Nordic region, but also to minimize the total system's operating costs by inserting mainly cheap hydro energy in the fossil-fuel dominated W-UCTE system. More details about the NorNed cable can be found in Appendix A. The main uncertainties at the moment, regarding the operation of the NorNed link may be summarized in the following parameters: economical lifetime of the cable, availability of water resources in Norway, the level of future installed wind capacity in the Netherlands and market design.

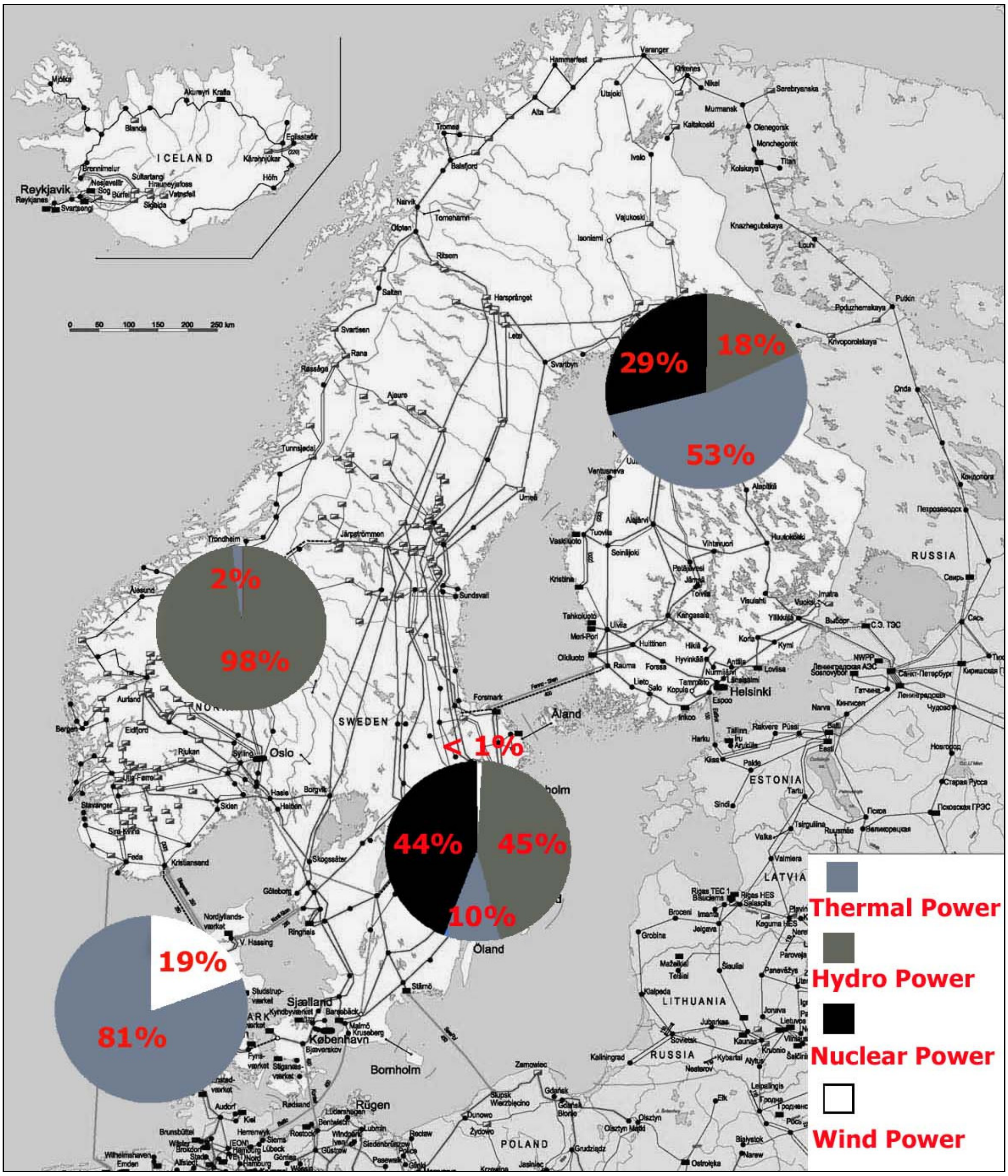


Figure 10: Distribution of energy source per country (2007)

For the economical lifetime of NorNed, as it appears from the documentation provided by the constructor (ABB), no experience has been obtained elsewhere in the world with so long (580 km) submarine cables older than 27 years [30]. The availability of the Nordic hydro energy along with the growth of the Dutch wind power can be critical factors upon deciding the amount of traded energy volumes. Moreover, the price difference between the two spot markets (Amsterdam Power Exchange and Nord Pool) will be also of importance for deciding the power flow direction of the cable. The obvious price difference between APX and Nord Pool depicted in *Figure 11*, for the 2007 year period, is expected to favour the Dutch total marginal cost by decreasing its value in times of excessive demand, while the Norwegian side may be favoured by the supply of invaluable energy in low inflow periods. It is important to notice that the price difference between the two markets is the product of the system's thermal operation.

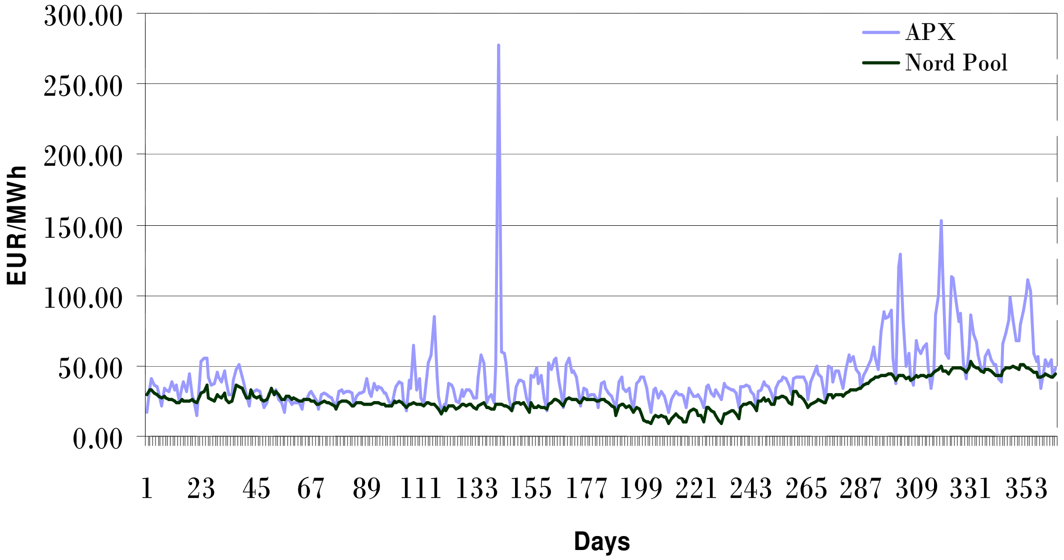


Figure 11: Average daily prices in APX and Nord Pool for 2007 [33], [34]

When the operational uncertainties are considered, the need for a physical model that would represent various operational scenarios becomes essential. In this way, a TSO like TenneT can monitor the response of the model upon various parameterization modes and decide upon future developments. This thesis focuses upon the extension of an existing model (W-UCTE), to include the Nordic countries in the unit commitment and economic dispatch (UC-ED) optimization that will be executed in PowrSym3.

Furthermore, the modelling approach will be discussed, initially by determining the technical factors taken under consideration in this research and consequently the monitoring variables will be indicated. Finally, the model development and the model's specification attributes will be presented.

3.2 Wind Power in Nordel

Large wind power penetration in the Nordic part of Europe is becoming a fact. For Denmark, this figure reaches almost 20% of its energy production and it's expected to increase even more. Sweden and Norway have also considerable amounts of wind power, but are still far from discussing large-scale wind integration within their power systems. However, the recent development from the Norwegian authorities, which is under consideration [39], namely to introduce mandatory electricity certificates, enhances significantly the country's environmental profile. Under this scheme, novel renewable power producers such as wind or small-scale hydro plants will be paid an additional subsidy on the price of the electricity itself. Under these circumstances, renewable energy and specifically wind power may have a quite promising future.

Forecasts about the future of wind power are found in a related study issued by the Nordel organization [40]. In this study, predictions about the future capacity of installed wind power are made based on technological developments, market's incentives and wind speed forecasts. The predictions are shown in *Table 1*, and graphically in *Figure 12*. Taking under consideration the existing data, the expected growth of wind power signifies a dimension that should be included in the modeling approach. Nevertheless, due to the absence of correlated to Dutch and German wind data for 2007 in Nordel, Nordel's wind power duration curve its not possible to be reproduced and used. Therefore, the effect of wind power will be measured statically in the present report, and taken rather arbitrarily. However, since the focus is on the large-scale wind integration within the Netherlands mainly, from a global system's perspective the obstacle of Nordel's wind power can be superseded with a static approach (section 3.4), without affecting the final results, significantly.

Year	**Norway** [MW]	**Sweden** [MW]	**Finland** [MW]	**Denmark West** [MW]	**Denmark East** [MW]
2005	280	500	82	2293	748
End of 2008	815	1250	200	2510	761

Table 3: Predictions on installed wind power capacity per country [40]

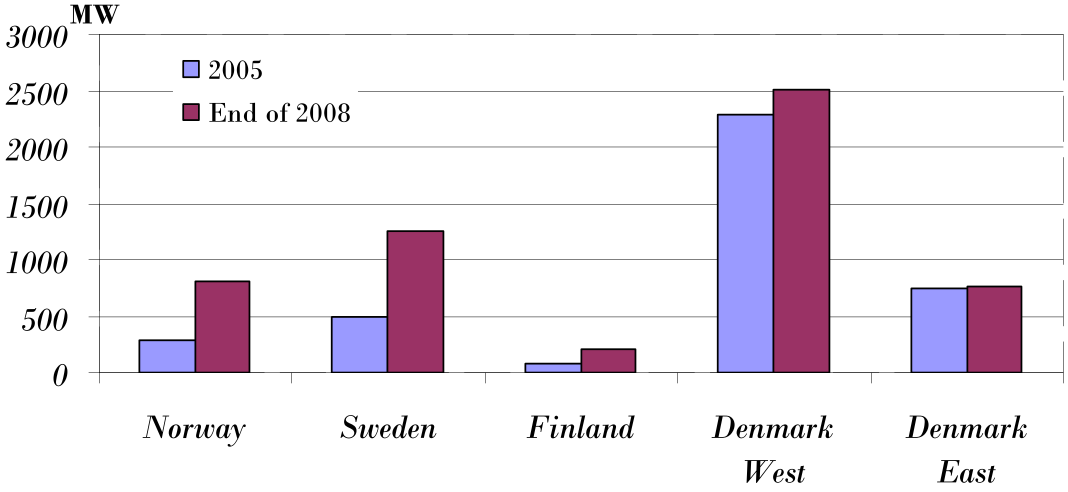


Figure 12: Installed wind power capacity in 2005 and prediction for 2008[40]

3.3 Simulation Parameters

The objective of a simulation is to present a yearly optimization unit commitment and economic dispatch (UC-ED) schedule, for a given scenario. Nevertheless, even if the resolution of the optimization is hourly, the printed output reports are concentrated weekly results and finally after 52 weekly steps, yearly results. More explanations about the weekly and hourly optimizations will be given in chapter 4. In order to assess the output of the simulation, some variables must be defined, which permit the monitoring and evaluation of each simulation. The variations of these variables in different scenarios will be also of importance to quantify, validate and confirm the modelling approach.

Technical Dimension

In section 1.2, power balancing and minimum load situations were highlighted from a global power system's perspective, as key limitations for the large-scale wind integration in the Dutch power system. The model therefore will include these limitations by monitoring a set of technical parameters:

- ENS: Energy-Not-Served is produced when spinning reserves (conventional generation and hydro type) cannot readjust to provide up-regulation (ramp up). In that case, the simulation output will have ENS indicated in the results.
- Spinning reserve violations: When wind power is decreasing and load is simultaneously increasing, spinning reserve requirements may be exceeded and this is indicated in the results.
- Wasted wind energy: In case wind, plus conventional generation exceed demand, wind energy in the Netherlands will be curtailed, resulting in waste of available wind energy.
- International exchanges: Large-scale wind integration in the Netherlands will undoubtedly influence the import and export strategy of the country. Therefore traded energy volumes, will be also monitored.
- Energy and emission savings: The operation of NorNed in the interconnected power systems of Nordel and W-UCTE, can signify important savings in terms of generated energy (GWh) and produced emission levels (Ktones CO_2)

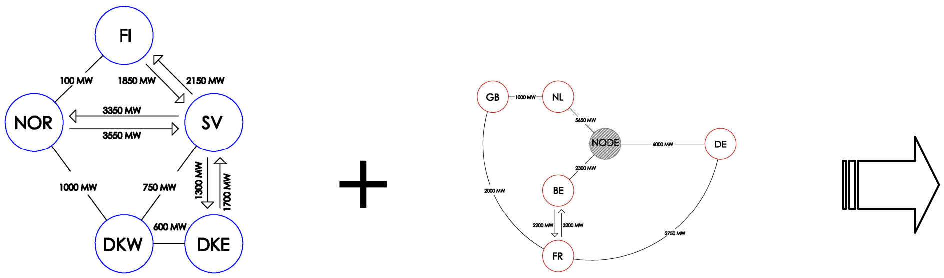
Economic Dimension

The economic impacts of wind energy on power system operation are mostly related to its low marginal cost. For example, in Germany which has quite a high wind penetration, it has been reported that wind energy integration reduces spot market prices [41]. Also, in markets where the emission of CO_2 comes at a certain price, the environmental benefits of wind power have a direct financial benefit, which corresponds with the levels of emissions that the thermal generation released during energy production of both load covering and regulation. The simulation variables for monitoring economic and environmental impacts of large-scale wind integration will be presented here:

- Total Operating Costs (M€/year) will be monitored for both the Netherlands and the overall power system (W-UCTE and Nordel). For highlighting the NorNed's contribution to the large-scale wind integration, costs will be also quantified under also this consideration.
- Utilization factors, in terms of capacity factors for conventional generation units.
- Emissions level (Mtones/year), in terms of CO_2, SO_2 and NO_x, which result from the power system's operation. Also here the focus will be the Netherlands, but also the overall impression.

3.4 Model Development

Developing a model in PowrSym3 requires the careful definition of the parameters that the program must take under consideration. In order to fulfil the main research objective, the first step is to develop representative models for the generation and load of each country of Nordel, namely Norway (NO), Sweden (SV), Finland (FI), Denmark-West (DKW) and Denmark-East (DKE), see *Figure 13*. The approach was based on the same logic followed in the formation of the W-UCTE system in order to generate a new compatible model, which on the one hand would represent effectively the Nordel region divided in 5 nodes and on the other hand would meet the requirements that the existing model posed. For calculating the parameters of the newly inserted nodes, extensive data analysis has been conducted. The analysis was based on several official publications and reports on the future generation mix of power systems in Europe [24], [25], [26], [28], [29], [39], [40], in order to decide the values for the system in 2014, of installed capacities per technology or the system load for instance. The reference year for the load data is 2007; however the simulations are conducted for the year 2014, which demonstrates the need to extrapolate the data accordingly, for the future horizon of 7 years ahead. Furthermore, the modelling approach for each dimension of the new power system will be presented.



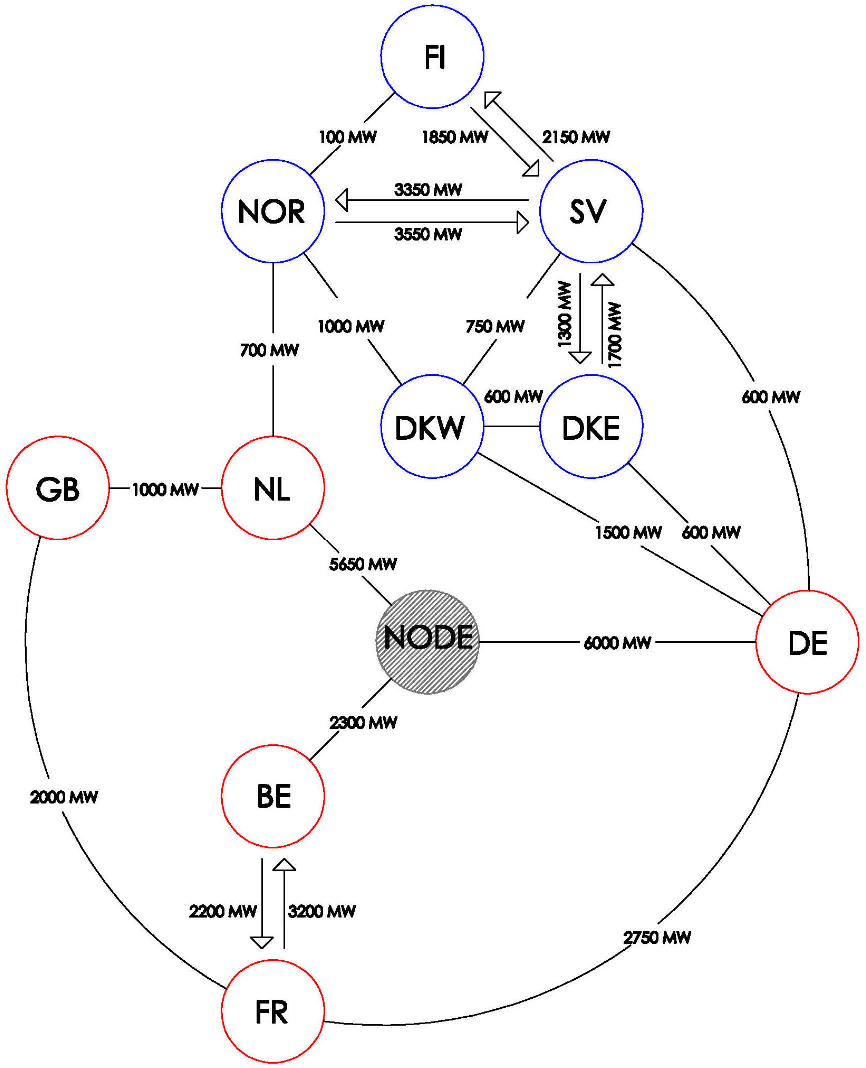


Figure 13: Extended with Nordel simulation model for year 2014

Development of Data for System Load and Wind Power

For the calculation of the load of each Nordic country, original data were used [42], obtained by Nord Pool. These were hourly load values for the year 2007, which were downloaded manually for each week, since total yearly load values with hour resolution were granted only after special permission. The 8760 load values for each country were converted furthermore, with the appropriate processing at the form that PowrSym3 requires. Moreover, in order to take under consideration also wind's penetration in the countries of Nordel in 2014, new load files were formed with the wind power effectively regarded as negative load, assisted by [40].

More specifically, in *Table 4*, the estimated wind power yield is presented for the end of 2008, along with the wind utilization, which is a factor similar to the capacity factor of conventional generation and results as a fraction of the actual generated energy divided by the energy that would be produced if wind power was in maximum output all over the year. A correct representation of wind power in these systems would involve an approach as presented in [9]. This involves the use of simultaneous wind speed measurements (time-series) throughout Europe, interpolation of the wind speeds to foreseen wind power locations and to the correct hub-height, and estimation of the hourly wind park output at these locations. In this way, correlations in time and space between the different wind parks are correctly taken into account. For this research, however, no wind speed or wind power time-series were available, except for the Netherlands and Germany. Therefore, a first-order estimate has been used to at least include wind power in some way.

Year	**Norway**	**Sweden**	**Finland**	**Denmark West**	**Denmark East**
Installed Capacity End of 2008 [MW]	815	1250	200	2510	761
Energy Yield End of 2008 [GWh]	2386	3365	520	6345	1934
Wind utilization factors	33%	31%	30%	29%	29%

Table 4: Installed wind power capacities and annual estimated yield for year 2008[40]

By combing data from [40], [28], [29], and reducing them to hourly values the static wind power available for every hour in each country is: 250 MW for Norway (840 MW of estimated installed wind power in 2014), 750 MW for Sweden (2100 MW of estimated installed wind power in 2014), 80 MW for Finland (220 MW of estimated installed wind power in 2014), 900 MW for Denmark West (2600 MW of estimated installed wind power in 2014) and 450 MW for Denmark East (1240 MW of estimated installed wind power in 2014). Consequently, the new load-less-wind files are formed, which is the product of the hourly subtraction of load in 2007 and wind power available for each hour in 2014.

Specifically for Finland, the formation of its load file contains an additional dimension. Since Finland apart from Nordel, is interconnected with Russia and Estonia, this parameter should also be included in the model. However, to develop representative models for these two countries is out of the scope of this research and therefore this dimension will be tackled at the moment also with a static approach. According to [28], the interconnections of Nordel, through Finland with Russia and Estonia, yielded for 2007 12 TWh of energy mainly produced by nuclear plants. This is a significant amount of energy that cannot be omitted since it is crucial for the power balance of Finland. Therefore this amount is reduced as the wind power to hourly resolution, resulting in 1300 MW/h. Subsequently, the final load file of Finland will be the product of hourly load in 2007 minus the contribution of wind and eastern interconnections, which results finally in 1500 MW/h.

Area Generation

For modelling the generation units in Nordel, decision had to be taken first, upon the generation mix and the installed capacities of each technology, foreseen for 2014. Based on the TenneT database of generation units [24] about the current installed capacities and on reliable estimates by Nordel [29], the final decisions are shown in *Table **5***. As it is evident, from *Figure 14* the

Nordel power-mix in 2014 will be still dominated by hydro power, followed by thermal power in terms of coal condensing power plants, CHP (Combined-Heat and Power) stations and Combined-Cycle Gas Turbines (CCGT). Investments in nuclear power are not excluded in Sweden and Finland and the nuclear power is the third generation option of Nordel. The growth however, compared to 2007 is noticeable in wind power. From 2% in 2007, wind power is expected to reach 6% of total generation in 2014, which is in symphony with the predicted sustainable future.

After installed capacities have been decided, the next step was to build the various models that describe the operation of each generation type. The modelling had the following approach: define parameters for each generation type and consequently form generation stations, which are clusters of units. Thus, models for coal, CCGT CHP, CCGT, nuclear, biomass and hydro generating stations were made, with the total number of installed units in each one, equalling the decided total installed capacity for each generation type. The characteristics of each unit in each station are fraction of the total in terms of unit power levels or heat rate levels etc.

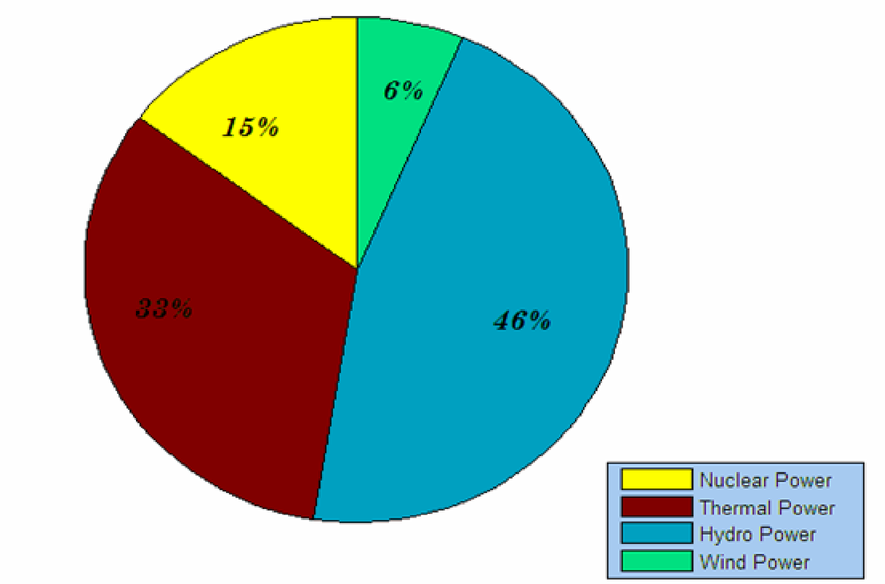


Figure 14: Estimated distribution of generation in Nordel by energy source, for 2014

Technology	**Norway** GW	**Sweden** GW	**Finland** GW	**Denmark-W** GW	**Denmark-E** GW
Nuclear	-	12.5	4.0	-	-
Coal	-	-	2.5	1.9	1.9
CCGT CHP	-	1.2	8.1	14.1	4.3
CCGT	1.0	1.3	1.0	1.0	0.3
Hydro	30	18.5	3.4	-	-
Other	-	2.7	1.9	-	-
Total	31.0	36.2	21.0	17.0	6.5
Wind Power	0.8	2.1	0.22	2.6	1.4
Maximum Load	21.6	26.5	14.8	3.7	2.6
Total Demand (Twh/y)	124.3	144.5	88.9	21.2	14.4

Table 5: Installed capacities of generation technologies assumed for 2014 in each area of Nordel

Conventional Generation

The principles for defining the most important parameters of conventional generation in Nordel were the same used in the existing database [9] and described in Section 2.1, before the addition of Nordel. Especially for their commit and dispatch logic it must be noted that also here the generation units have either a must-run, or an economic operation status. This means that must-run generating units will be committed at all times, producing energy between minimum and maximum power levels, and will be only de-committed if planned maintenance demands or if unexpected outages occur. On the contrary, economically committed and dispatched units will operate solely with a view to minimise total system costs. For the calculation of plant's efficiencies again the TenneT database was used [24] and the logic used in the development of W-UCTE model. The ramp rates for all units are considered 30 - 80 % of installed capacity per hour depending on technology. Unlike in France, nuclear plants in Sweden and in Finland are modelled without ramp rate, resulting in technical full-load operational status. Minimum up and down times in this study will be associated with start-up costs, and commitment, de-commitment costs which are however difficult to quantify, but are linked with how flexible is the power system under study is.

The fuel and emissions costs were also the same; for coal, oil, natural gas and uranium in cents/mil BTU (British Thermal Units) and in cents/ton for CO_2. The values are for coal, oil, natural gas and uranium, 2 €/mil BTU, 5 €/mil BTU, 5 €/mil BTU and 1 €/mil BTU respectively and for CO_2, 20 €/ton. For coal, oil and gas, the prices were validated, by converting them first into tones of oil equivalent, by [43]. In order to quantify start-up costs for the generation units, data were needed from utilities all over Nordel. However, since this was impossible, the TenneT database was used again, but the figures were not validated.

Specifically, for the modelling of the CHP units, the situation was somewhat different. Since in the existing database, there were only models and units for the Dutch heat areas, new heat areas were formed for the countries of Nordel and consequently, based on the validated plants of the Netherlands, novel CHP units were constructed for Sweden, Finland and Denmark (East and West). Moreover, for every heat area an equivalent CHP unit and a heat boiler were assigned to it. The commitment status of CHP was either set to must-run when referring to industrial heat or to economic operation for residential areas (offering the flexibility to de-commit when the load is low). Their operational efficiency for both power/heat can reach values of 87%. The most important technical parameters for Nordel are depicted in Table 6.

MR: Must – Run operation EC: Economic operation

Technology	***Nuclear***	***Coal***	***CCGT***	***CCGT CHP***
Commitment	MR	MR	EC	MR/EC
Dispatch	MR/EC	EC	EC	EC
Min up time [h]	168	16	4	4
Min down time [h]	168	16	6	6
Ramp Rate [% P/h]	-	30	80	80
Max Efficiency [%]	-	39	51	87
Unavailability [%]	20	15	14	14

Table 6: Conventional generation model for Nordel, 2014

Hydro Power

For modelling hydro power in Nordel, the situation is somewhat different than in the existing database of W-UCTE. Even if all types of hydro power, namely, reservoir, run-of-river and pumped hydro, have the same attributes as in the W-UCTE developed (hydro units clustered in stations assigned to one reservoir, with no fuel cost, minimum and maximum power levels, etc), in the Nordel model hydro power should be modelled, especially for reservoir hydro in a more detailed fashion, taking under consideration price differences between adjacent power markets, system load and water inflows. After all, as it is noted in a previous relevant study, a detailed approach for hydro power is needed when a model of the Scandinavian countries is to be developed [44]. However, a thorough analysis of how hydro is modelled will be given in chapter 4.

Interconnections

The number of interconnections between the countries of W-UCTE was extended from 8 to 19, to include all the links between the areas of Nordel and the interconnections with W-UCTE. Aiming to capture the future developments, the transmission capacities estimated for the power systems of Nordel and W-UCTE in 2014 were incorporated. For this study, [39], [25], [29] were used to assess and model the links. The interconnectors are regarded as power lines with specific transmission capacity in MW that start from an area X for example and finish in an area Y.

4. Annual Long Range Hydro - Scheduling

Hydro scheduling from a power system's planning perspective refers to the scheduling of hydro-power units within the system and comprises three time horizons. The hourly horizon refers mostly to the hourly energy that hydro units must yield in real-time and is a product of a daily optimization. The weekly horizon, which can also be found in literature as short-term scheduling [45][46][47], refers to the operation schedule of hydro units for a period of a week or more, depending on load predictions, conventional generation maintenance schedules, predicted wind energy and international exchange expectations. Finally, the annual horizon refers to the optimum way that a reservoir can be scheduled for a longer period of time such that the water within the reservoir will be enough to cover both the energy needs of all previous time steps, but also some of the first future periods. For all horizons, it applies that the load and the (expected) market prices are used for the optimization of the scheduling of hydro power.

What can be distinguished as common characteristic in each horizon is that decisions upon hydro scheduling for a specific time-interval are affected by the decisions of the previous time-step, which in turn have strong impact on the decisions of the next time-interval. In other words, the scheduling of hydro power is state/time dependent. For system with cascading hydro units (i.e. hydro units in series that are connected by water flows and use the same water supply for power generation), power generation in one unit also influences the reservoir level of another. Furthermore, since precipitation, load and market pricing must be forecasted, large uncertainties must be included in the optimization process. Therefore, optimizing hydro scheduling under these dependency characteristics is a highly complex issue. If it's considered that in reality hydro-power systems may have complex topologies with many cascaded reservoirs/power plants in the same river system [45], one can realize the complexity of optimizing hydro operation.

4.1 Decisive factors for long – range hydro scheduling

The problem of allocating hydro power's water resources effectively can be tackled initially by decomposing the problem in the three time horizons, annually, weekly and hourly and by optimizing each horizon with different solution techniques. In [45], long-term hydro scheduling refers to 5-years period, mid-term to 1 year or week and short-term scheduling to the real time hourly intervals. For this research, the weekly and the hourly horizon will be the mid- and the short-term respectively time periods. In addition those two will be a part of the PowrSym3 built-in optimization procedures, whereas the long-term scheduling will refer to the annual horizon and will be optimized with a first order approach.

Optimum long-range hydro scheduling is an issue, which is susceptible to high uncertainty, depending on seasonal precipitation forecasts, load probability and market prices. These risk factors are so important, that if they are not properly assessed in scheduling decisions they may lead to extreme scenarios for instance, of the country not being able to cover its load, or not fulfilling international exchange agreements. Therefore, decisions in long-range hydro scheduling in this study can be seen also as a strategic approach of how a country can use its water resources effectively so as to cover the inland load and moreover either to minimize total system's operating costs, or to maximize profits from international exchange. In Figure 15 the variation of the Norwegian aggregated reservoir is depicted for the period 2005 – 2007. Furthermore, in order to approach the problem of long-range hydro scheduling in the present study, some assumptions need to be made.

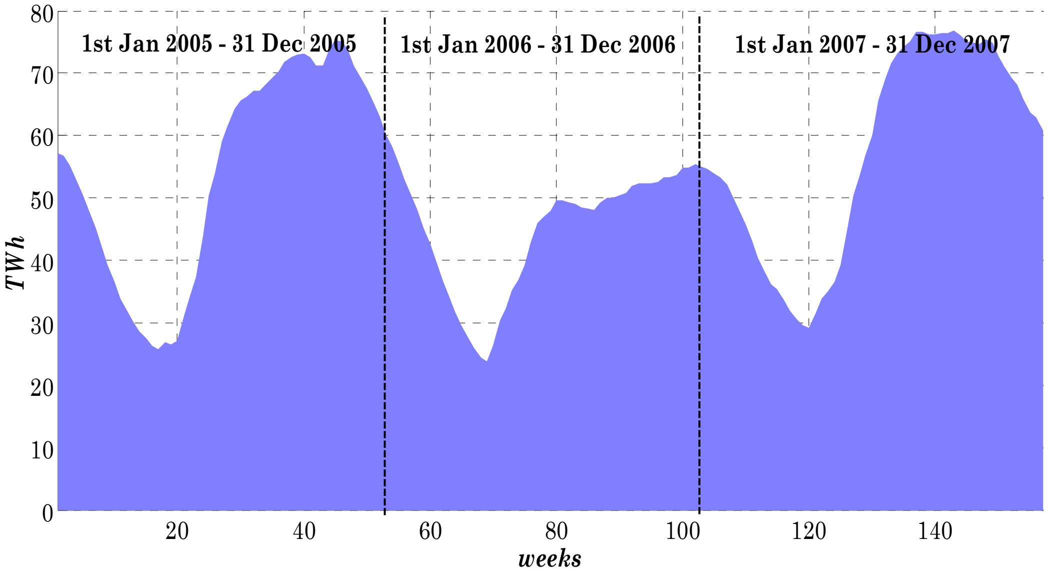


Figure 15: Reservoir state in GWh/week for Norway from 2005-2007 [28]

Assumptions

1. The first basic assumption is linked with how hydro power is fundamentally perceived in the modeling approach. In other words, the level of focus that must be applied on especially reservoir-hydro modeling may vary according to the needs of each study. For this research, it is assumed that hydro stations are emancipated from their physical constraints and therefore are clusters of units with no cascading effects. The only physical constraint that limits their yield is their total reservoir capacity in GWh, which can be defined as the equivalent maximum level that the water can reach in the reservoir without spillage. In addition, no vaporization losses are taken into account since this was out of the scope of the research and each hydro reservoir is considered solely as an aggregated but with limitations, cheap energy supply option. This aggregation is a gross approximation, but it seems sufficient for now to cover the needs of the modeling approach.

2. Another important assumption is that the hydro operator may use forecasts of seasonal precipitation based on several years' historical data that permit a relatively secure but still probabilistic view on future inflows. This means that the yearly seasonal pattern can be predicted with a definite but also acceptable forecast error, well enough. In other words, especially for Norway the inflow variability shows a specific seasonal pattern for the annual horizon and with low inflow periods expected every 10 years and extremely low inflows every 50 years [29]. In reality, for the decision of inflow

within the model, the TenneT database was used [24], which comprised probability values for weekly average inflows in GWh based on actual historical data.

3. An additional assumption is related with the price of electricity in the power markets. Since for this research, W-UCTE and Nordel are examined focused on the NorNed link between Norway and the Netherlands, the average daily price difference between APX and Nord Pool is also of importance when deciding the long-range hydro scheduling algorithm (page - 30 -, *Figure 11*). In that case, it is assumed that before the dispatch of hydro energy, the average weekly price difference can be predicted with high accuracy based again on historical data, conventional generation schedules, seasonal fixed import-export volumes and load predictions. As it is already mentioned, the prices of both markets correspond with the operation of the thermal system and therefore the historical values can be used to make reasonable scenarios for various price difference cases.

4.2 Optimization methods

The methods for long-range (1-year) hydro scheduling will be presented here and can be regarded as hydro allocation methods. Since Norway is the country with the most hydro power in Europe and is directly coupled to the Netherlands by means of NorNed, the analysis will refer mostly to the modeling of the Norwegian reservoir and will give suggestions about Sweden, Finland, France and Germany.

Before this research, the related studies [9], [44] were tackling the subject of hydro scheduling with a simplistic but also sufficient for their simulations approach; by taking into account initially the amount of total hydro energy produced for each country (France and Germany) for a given year and consequently dividing it equally into 52 weekly time-steps. Thus, the hydro-power stations would be producing each week, the total same amount of energy, optimized for each week differently (weekly optimum thermal-hydro coordination) but without considering weekly load variations (low- or high-load periods), price difference between adjacent power markets and inflow probabilities dependent on seasonal precipitation patterns. However, when the cases of especially Norway, or Sweden, which are based on hydro-power generation, are considered, the above-mentioned approach is not sufficient to highlight accurately the particularities of the studied power systems.

With a view to chose the amount of available weekly hydro energy for dispatch, the proposed hydro allocation methods will be a first order approximation, of the complex long-term hydro scheduling problem. However, the analysis will reveal that the certain improvements need to be made in the modeling approach in order to simulate hydro models in a more effective fashion. Likewise, the optimization methods, which for this thesis can be seen also as hydro-energy dispatch strategies, introduce a more realistic view of how the hydro generation can be dispatched properly, either to minimize total system costs or to maximize profits from exports. The common characteristic of all described optimization methods is the prioritization of covering the inland demand (e.g. Norway). In other words, the operator when referring to Norway, will dispatch for every week, hydro energy (GWh/week) ≥ total load (GWh/week), demonstrating in this way the first limitation in the modeling approach of a hydro reservoir. At this point, it must be noted that the optimization - allocation methods in this study are almost deterministic (based on high occurrence probability patterns) however for further research stochastic variables should be used instead, to depict precisely inflow probabilities, load prediction forecast errors and future power markets' prices. Moreover, even if

In order to include the effects of load, inflow and price difference (between APX and Nord Pool) in the scheduling of hydro energy, three indicators are formed, which are depicted in *Figure 16*, with equal weight factors.

Load factor

The initial aim of the optimization approach of Norwegian hydro was to cover the inland load at all times and consequently the first step was the formation of the load factor. The load factor is a fraction of the weekly expected demand with respect to the total expected annual load. In this way, the operator has a first indication of how much energy has to be dispatched for every week to supply the system load, given a predicted inflow with high occurrence probability due to the use of historical data and the state of the reservoir in the start of the year in question. The total load in 2007 for Norway was 124 TWh.

Inflow factor

The formation of the inflow factor, represents the influence that a seasonal precipitation pattern can have on the state of the reservoir and consequently on the hydro energy available for dispatch. Similar to the load factor, the inflow parameter is divided into 52 weekly time-intervals and normalized by a fraction of the expected inflow for a week divided by the total inflow expected for a year. In this case the TenneT database [24] was used to take into account the seasonal pattern of precipitation translated into weekly inflow in GWh based on probability time values. Nevertheless, even if the seasonal pattern can be well enough predicted, the long-term inflow prediction is subject to high uncertainty and it will be considered rather arbitrarily, inserting into the model and the simulation low, medium and high inflow years.

Price factor

Considering the predictability of the previous influencing factors, the price parameter is the most uncertain. Since prices are dependent on technical (generation-mix, power system's flexibility etc.) and socio-economical factors (consumption patterns, weather variations, energy intensity of a country's economy etc.), a safe prediction upon the daily and consequently average weekly future prices is not possible for the long-term horizon. However, in order to depict the importance of this parameter, it can be assumed that the price factor will be a fraction of the average weekly hydro energy to be dispatched according to price difference between APX and Nord Pool and the annual expected hydro generation (based on inflow and load predictions).

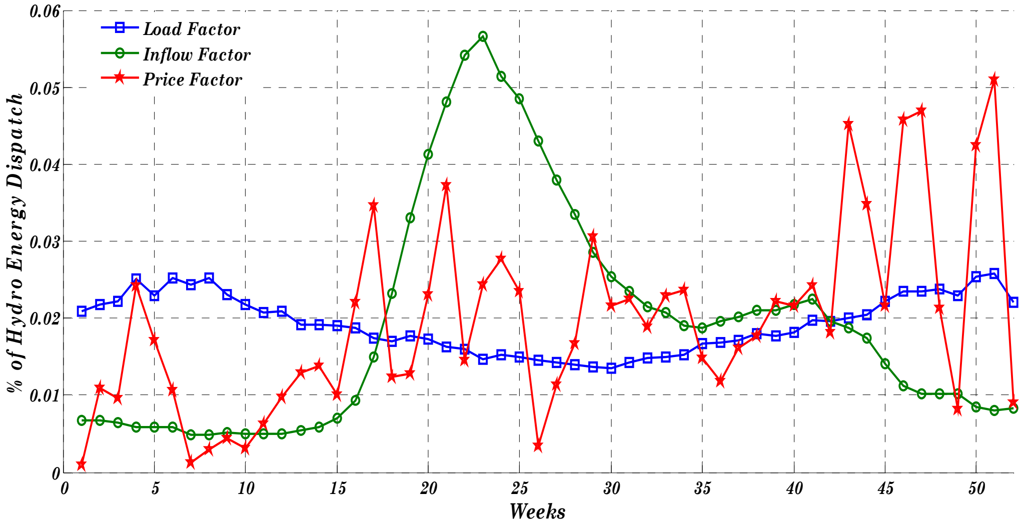


Figure 16: Influencing factors in long-range hydro scheduling of the Norwegian hydro-power (based on 2007 data)

Optimization Methods

Considering the effect of these factors in the optimization approach, the long-range hydro scheduling strategy gains a realistic foundation for the modeling of hydro power in Nordel, upon which various approaches can be investigated. Likewise, the decomposition of the problem in different influencing factors can be used to scale the factors in priority sequence. In other words, the operator of the Norwegian aggregated reservoir taking into account the expected energy yield, which is based on load and inflow predictions as well as on future price regarding imports/exports, can decide how to distribute hydro energy optimally in 52 time-steps (weeks) so as to meet the prioritized targets that were initially set. The limitations are the amount of inflow and the reservoir capacity, which were previously mentioned.

The hydro allocation methods that are proposed in this research are experiments of state/time dependence variations and signify the need for a preprocessing computational tool, which will take under consideration various historical data for the operation of the thermal system, reservoir structure (to include cascade effect), inflow patterns, load variations and stochastic wind profiles. Initially, it could produce specific marginal cost curves for the operation of the total predicted power system. The final product of this preprocessing computational tool though, should be the weekly hydro allocation, properly optimized.

Experiments

In the present study, the three factors are just representative of the decisive factors in hydro optimization logic. Consequently, the first priority of the operator that can be recognized is to dispatch enough hydro energy to cover the inland weekly demand. Under this constraint the significance of the load factor ranks highest than the other two. Consequently a first order strategy can result if only the Norwegian load is taken into account by multiplying the load factor with the total expected energy yield. If the effects of inflow and price difference are also considered in the optimization approach, it can be seen that the resultant 52 hydro energy/week decisions will change (see *Figure 17*). However, it is found that the minimum value of the load dependence (load factor) for a given predicted energy yield that is permitted so as the weekly hydro energy will be always more than the load, is 0.89 (89%). Consequently, by taking as minimum value for the load factor 0.89 and varying the weights of load, inflow and price factor, different strategies for the long-range hydro scheduling can be obtained. Furthermore, by estimating the total annual energy yield, which for Norway in 2007 was 137 TWh and the weekly inflow probabilities in GWh for an average inflow year (TenneT database), the optimization methods for three weights combinations result.

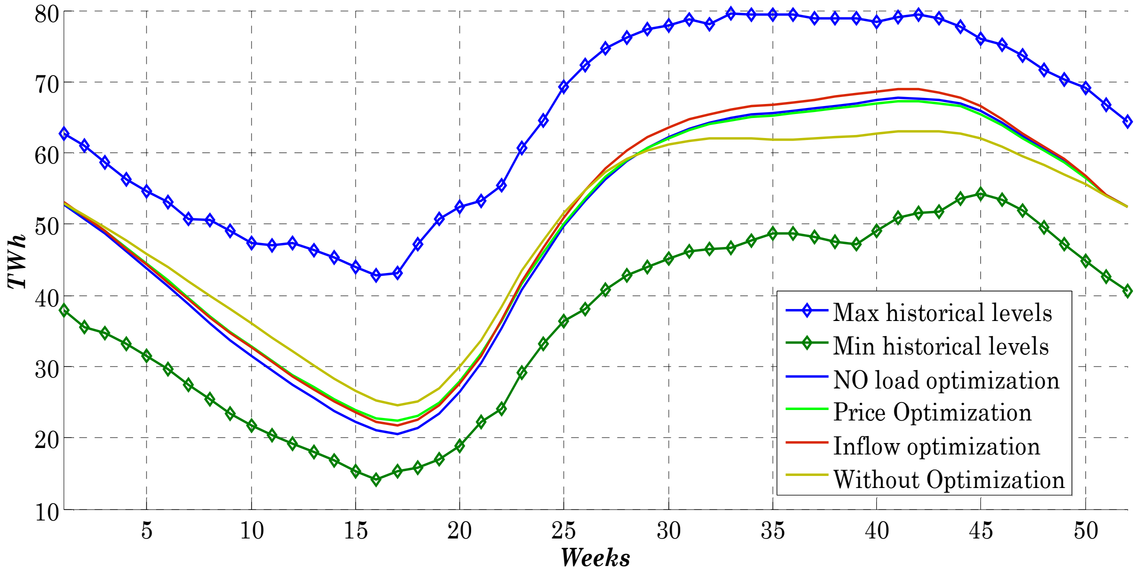


Figure 17: Utilization curves of the Norwegian reservoir for various optimization schemes in an average inflow year.

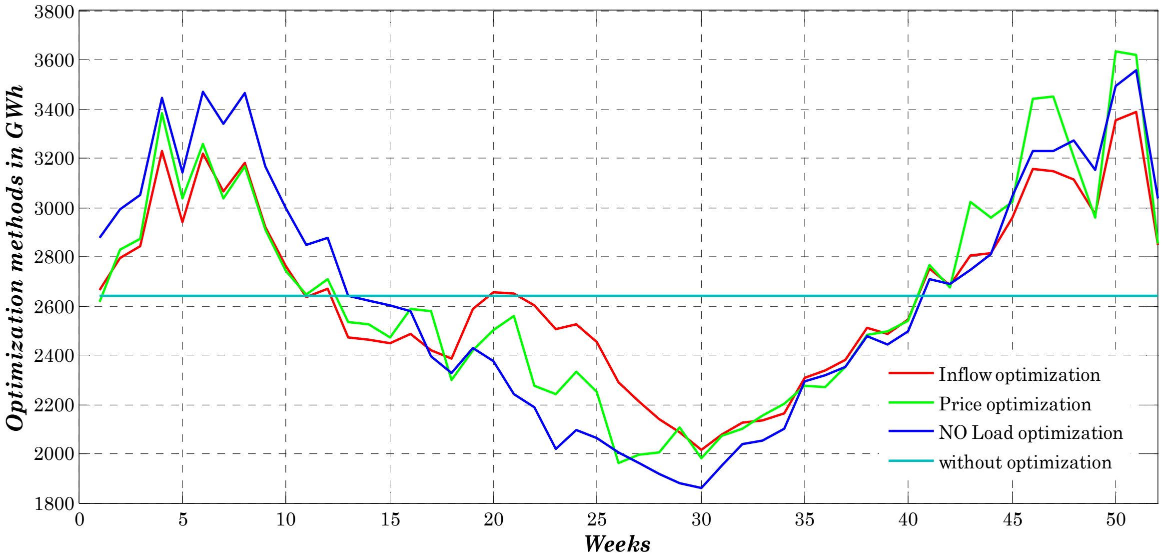


Figure 18: Optimization methods for long-range hydro scheduling

In *Figure 17* the reservoir state is depicted for the three proposed approaches. The figure is formed by adding the inflow (TenneT [24]) and subtracting the outflow, which is the hydro energy for dispatch in each time-step from the reservoir state in GWh in the previous time-step. Furthermore it can be seen that there is not much difference here between the various hydro allocation strategies and the case with constant outflow, and that all curves fall between the min and max historical averages for reservoir utilization.

The optimization methods depicted in *Figure 18* represent three different approaches that can be used for the scheduling of hydro in the long-term horizon. The first, (blue line), depicts an optimization scheme based solely on covering the total weekly load for a given year based on data by 2007, whereas inflow (red line) and price optimizations (green line), have the same load dependence (90% load factor) but different weights for the inflow and price factors, namely 8%, 2% and 2%, 8% for inflow and price, respectively. The case without reservoir optimization method is also depicted for comparison reasons. Their impact on power system's operation can be monitored by means of total operating costs, after simulations have been conducted.

Undoubtedly, there are numerous schedules that can be created according to the previous analysis. The different approaches may comprise the effects of neighboring countries load factors and various combinations between price or inflow factor. For instance, since Sweden is the main importer of Norwegian energy, the Swedish load factor can be also taken into account to formulate a new long-range hydro schedule. Likewise, the existence of the NorNed cable may be the reason for Norway to synchronize its reservoir utilization with the Dutch load, with a view to maximize profits from exports.

Conclusion

Optimization of hydro scheduling may be a problem subject to high uncertainty. Therefore, with a view to produce optimum unit commitment and economic dispatch (UC-ED) schedules for a large system such as the W-UCTE and Nordel, a deterministic approach might be imprecise for extracting results on absolute values of system's attributes. However it's not prohibitive for extracting conclusions upon trends and strategic issues, especially, when the problem is decomposed into three time horizons, with different optimization tools for each horizon. Consequently, the optimization of long-term scheduling will be performed by a deterministic approach based on fine predictions and the mid- and short-term scheduling for the totally system will be part of the probabilistic PowrSym3 optimization process (see *Figure 19*).

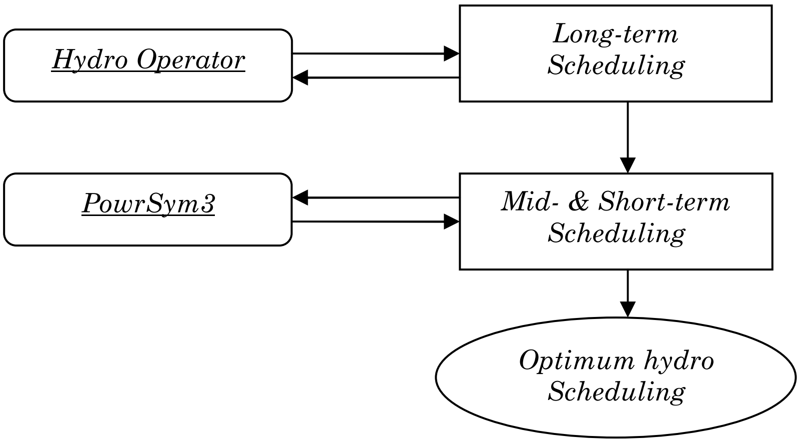


Figure 19: Hydro scheduling problem decomposition

4.3 PowrSym3 built-in weekly optimization

As it was mentioned in chapter 2, within PowrSym3, apart from the annual horizon, UC-ED is optimized also for the weekly and hourly horizon. The first step before weekly optimization starts is the determination of the weekly random outage draws. The outage model selects in a random manner which generators will be tripped for each time-step for a specified number of iterations (Monte Carlo draws); each iteration is then saved and consequently used, as input for a weekly simulation. For extracting optimum results, PowrSym3 has the ability to optimize the UC-ED schedules based on load predictions and wind's forecasts, first with heuristics and then with dynamic programming. However, for this study, only the heuristics were taken under consideration, since the additional computation time that dynamic programming optimization demands was overwhelming for such a large system (W-UCTE and Nordel).

More specifically for the weekly optimization, first hydro stations are scheduled using a price levelling algorithm, which refers to the time-related constraints such as generation cost, operational aspects of thermal units (maximum or minimum generation levels, ramp rates etc.) and hydro reservoir size. Consequently, the hydro schedule is optimized based on the system's marginal cost, while taking into account reservoir size limits, load prediction and wind power forecasts. The model then uses heat demand for different areas, system load, wind power and wind power forecasts for the scheduling of thermal generating units, which are also subject to technical constraints. Based on the operational cost estimates obtained thus far, energy storage is scheduled such that the total operating costs over the week are minimised [9].

For the hourly optimization which is a part of the weekly optimization, it is sufficient to mention that the heuristic optimization approach is based on the following principles:

- First the output of previous week optimization is considered.
- Then, all available units are set into maximum power levels, considering technical constraints.

- Consequently, decremental cost arrays are found for each hour.
- Finally, the model finds the most expensive unit(s) and de-commits them or ramps them down.

These approaches, for the weekly and hourly horizon along with the annual horizon are the three different optimization tasks that PowrSym3 performs and they are coupled to each other by means of marginal costs and outage predictions. However when the focus is applied on hydro-power, the problem is that the optimization of hydro power is performed only for the weekly and hourly horizon. These two correspond to the short-term scheduling of hydro, whereas for long-term hydro scheduling little attention is given.

The issue with long-range hydro scheduling within PowrSym3 can be observed only from a high perspective. More specifically, in the part where hydro power in PowrSym3 is presented in section 2.2, it is pointed out that the hydro power inflow is modelled as energy available for dispatch in GWh/week, bound by technical constraints (minimum and maximum power levels, ramp rate etc). This corresponds to a specific record in the database (see *Table 1*), named HYDRO ENERGY, which allocates a specific amount of energy to be delivered for the whole week. While, internally for the week, PowrSym3 optimizes the dispatch of this amount of energy under the operational constraints of each short-time step, the decision upon which HYDRO ENERGY to set is left arbitrarily to the user.

Moreover, all the recent related studies [9], [44], were considering HYDRO ENERGY at a fixed energy amount (GWh/week), which was the same for each week. However, since hydro power until now was part of the UC-ED schedule of countries with variety in generation-mix (f.i. France and Germany), this imperfection was not that noticeable. Therefore, the assumption for hydro energy was well enough accepted. Nonetheless, for the modelling of a country such as Norway with almost entire hydro power generation this assumption are not enough to capture the operational characteristics of the area and its reservoirs and consequently adopting it resulted in violations of technical constraints such as energy-not-served (ENS) or excessive dump hydro power in the initial trial simulations. Therefore, the new approach will be adopted so as to optimize hydro power for the long-term using the various optimization methods described in section 4.2

5. Simulation Set-Up & Data Evaluation

UC-ED simulations with PowrSym3 are the final step following the model development process, so as to assess the results, investigate the impacts of NorNed on the large-scale wind integration in the Netherlands and finally decide upon the suitability of the model. It is assumed that electricity markets function well and that transmission constraints are defined by the interconnection capacities between each area. The target is the extraction of an optimum UC-ED schedule such that the objective function of total system operating costs (including heat, power and emission costs) is minimized, while all the following constraints are met:

- Electricity and Heat demand in all areas.
- Ramping capabilities of generation units.
- Minimum up-time and minimum down-time of conventional generation.
- Minimum and maximum output of generation units.

In the following sections, a pre-assessment of the developed model will be presented and consequently the system integration scenarios will be analyzed.

5.1 Simulation model analysis

Before describing the simulation scenarios, a pre-assessment of the developed Nordel model is needed. The existing model of W-UCTE was initially designed to investigate on the one hand the impacts of large-scale wind integration in the Netherlands [9] and on the other hand to explore solutions so as the power system will integrate more wind power. However, the objective of this study is to develop a model, which can simulate the coupling between the power systems of Nordel and W-UCTE. Therefore, apart from the obvious extension of the model's database, also the dimensions of the total system should be differentiated so as PowrSym3, would cope with increased number of operational areas, transmission links, reservoirs, generation units and heat or electricity loads.

Among the improvements, the most important one was the handling of the Norwegian hydro units. In the first version of the W-UCTE data-model, the commitment of hydro units due to the absence of a purely hydro-dominated system did not pose any problems in the analysis. However, in this study, the old design was preventing the Norwegian hydro units to commit properly and resulted in unexpected high levels of energy-not-served (ENS). Therefore, the W-UCTE model was adjusted for Nordel with the goal of committing hydro units in Norway properly.

Undoubtedly, the development of a detailed model for almost 200 generation units in the Netherlands and in nine more transmission areas, along with their interconnections, suitable for power system studies is a long-range project, which may need years of validation and research. However, the suggested approach, aims to set the basis for the future formation of an accurate model of such a large extent. Therefore, before viewing the scenarios and consequently the simulation results, some dimensions must be analyzed in more detail.

Model's Limitations – Weaknesses

Considering the current Nordel model, there are some weaknesses that allow the analysis to be based only on relative results rather than on absolute values. These weaknesses originate to some extent from the absence of needed data, due to confidentiality reasons or due to their large volume and high scatter of needed information sources. At another extent the limited time that this project is due (9 months graduation project), allows only the development of an approximate rather than an accurate model. Moreover, the imperfections of the used data and the observed disagreements between the various sources, has also an impact on the final model. After all, the possession, of the accurate data and license to use for simulation purposes mostly lies in the hands of each country's TSO.

Likewise, the model comprises only representative and not specific models of all generation units in Nordel, which in turn yields approximate results. Furthermore, wind power in Nordel is conceived rather arbitrarily, solely as fixed negative load. Thus, the variability of wind is considered only in the load-less-wind files but without stochastic characteristics. Moreover, since W-UCTE and Nordel models are not isolated but interconnected in reality with the rest of Europe and Russia, some significant interconnections especially of Sweden with Poland and Russia, plus Estonia with Finland are not modelled. Especially for Finland, these interconnections supply the country with cheap and valuable for the security of supply nuclear energy, which for 2007 reached 12 TWh. In order to include this somehow in the analysis, the Finnish load is a product of load in 2007 less wind in 2014, less energy from Russia and Estonia.

Considering, the approximations in the modelling approach, but also the limitations in terms of time and data, the simulation model may be appreciated as sufficient to observe trends for the future horizon. The delivered model forms a good basis for further developments, aiming improvements to facilitate even more accurate results.

5.2 System Integration Scenarios

The simulations of unit commitment and economic dispatch (UC-ED) in this research are carried out for a future year 2014, with a resolution of 1 hour. At first an optimised unit maintenance schedule is calculated ahead of each simulation. Furthermore, unscheduled outages are defined using the Random Monte Carlo method for all generating units, pumped-hydro storage units and heat boilers, for every week. Unit commitment and dispatch are then centrally optimised (well functioning electricity markets) in order to achieve minimum operating cost at the system level, while all technical constraints are met.

Furthermore spinning reserves are provided by the non-despatched capacity of committed generating units. Therefore, all coal- and natural gas-fired generating units in the Netherlands sized 60MW and above are assigned with a spinning reserve contribution of 1% of nominal power. For the rest of the areas a minimum spinning reserve requirement is determined based on the largest unit installed in each area. For the Netherlands, a spinning reserve of 1600 MW (twice the largest unit) is formulated, for other areas except Norway the spinning reserve is estimated at 2000 MW. However, prior to the simulations, the system integration scenarios are formulated in order to represent the cases described in the previous chapters. The selected simulation scenarios are depicted in *Figure 20*, which equal 23 total simulations.

(PP: Perfect Prediction,MI: Medium Inflow,HI: High Inflow,LI: Low Inflow,GP: Gas Power)

WP	***Without NorNed***	***With NorNed***
00	MI – PP – NO load opt	MI – PP – NO load opt
02	MI – PP – NO load opt	MI – PP – NO load opt
04	MI – PP – NO load opt	MI – PP – NO load opt
06	MI – PP – NO load opt	MI – PP – NO load opt
08	MI – PP – NO load opt	MI – PP – NO load opt
10	MI – PP – NO load opt	MI – PP – NO load opt
12	MI – PP – NO load opt	MI – PP – NO load opt

10 GW WP, With NorNed
PP – MI – Without Opt
PP – HI – NO load opt
PP – LI – NO load opt
PP – MI – Inflow Opt
PP – MI – Price Opt
PP – NorNed2 – NO load opt
PP – BritNo – NO load opt
PP – BritNo&NorNed2 – NO load opt
PP – MI – GP – NO load opt

Figure 20: System Integration Scenarios

Base Simulation Variants

The base scenario will be used to quantify the technical, economical and environmental impacts of NorNed on the UC-ED and consequently the large-scale wind integration. The base simulation variants consider seven levels for wind power capacity installed in the Netherlands (0-12 GW) for two cases with and without NorNed. The wind prediction method used for the base simulations is the perfect prediction, which refers to a flexible market design with 1 hour ahead, clearance. Thus, the actual wind power levels are exactly known in all stages of UC-ED. For comparison reasons, an additional simulation will be conducted for 10 GW of installed wind and 0-MW forecast, which refers to a situation where wind power is not considered during the planning of UC-ED schedule, although, is taken into account in the operational stage. Furthermore, in the base scenario the optimization method that will be used for the Norwegian reservoir is the NO load strategy (see section 4.2), applied for an average medium inflow year based on data from 2007 so as the load will be correlated with the generation.

Additional Variants

Since this study focuses upon the relation of NorNed with the large-scale wind integration in the Netherlands, also the characteristics of the Norwegian system must be represented in the simulations. Therefore, more simulations will be conducted for the case of 10 GW of installed wind power in the Netherlands. More specifically, two simulations for various inflow situations: high and low inflow in Norway. In 2007 the inflow was around 137 TWh, therefore the product of low inflow will be taken as the 2007 inflow values minus 8 TWh (129 TWh). In the same logic high inflow year will be regarded the

2007 inflow values, plus 8 TWh (145 TWh). With a view to demonstrate the impacts of various reservoir management strategies in the system operation, two additional simulations for the Inflow and Price optimization (see section 4.3) will be executed. Moreover, in order to depict the Gas Power scenario [39] (3000 MW of CCGT by 2020), discussed by Statnett (the Norwegian TSO), an additional simulation will be performed for this case. From the aspect of future grid developments, three more simulations will be conducted for the case of NorNed2 (by doubling the interconnection capacity to 1400 MW), of BritNo (HVDC line of 1000 MW discussed by the British TSO) and finally for the case when both NorNed2 and BritNo are present.

Sensitivity Analysis

Since, apart from the results, also the model's performance is of concern, a number of simulations must be devoted to the investigation of model's sensitivity under extreme parameterization. Therefore, some more simulations will be executed to assist the sensitivity analysis that will be presented in section 6.2.

6. Simulation Results

The main objective of the simulations scheme applied in this thesis is double: On the one hand to investigate the impacts of various scenarios on the operation of a large part of the European power system, and on the other hand to identify the weak links in the model development process. A graphical representation of the way that the simulations were executed is depicted in *Figure 21*. The simulation results will be reported and graphically represented in order to assist the analysis. The results are various optimized UC-ED yearly schedules for all generation units in the W-UCTE and Nordel with the assumption that all feasible transactions among the different areas are made.

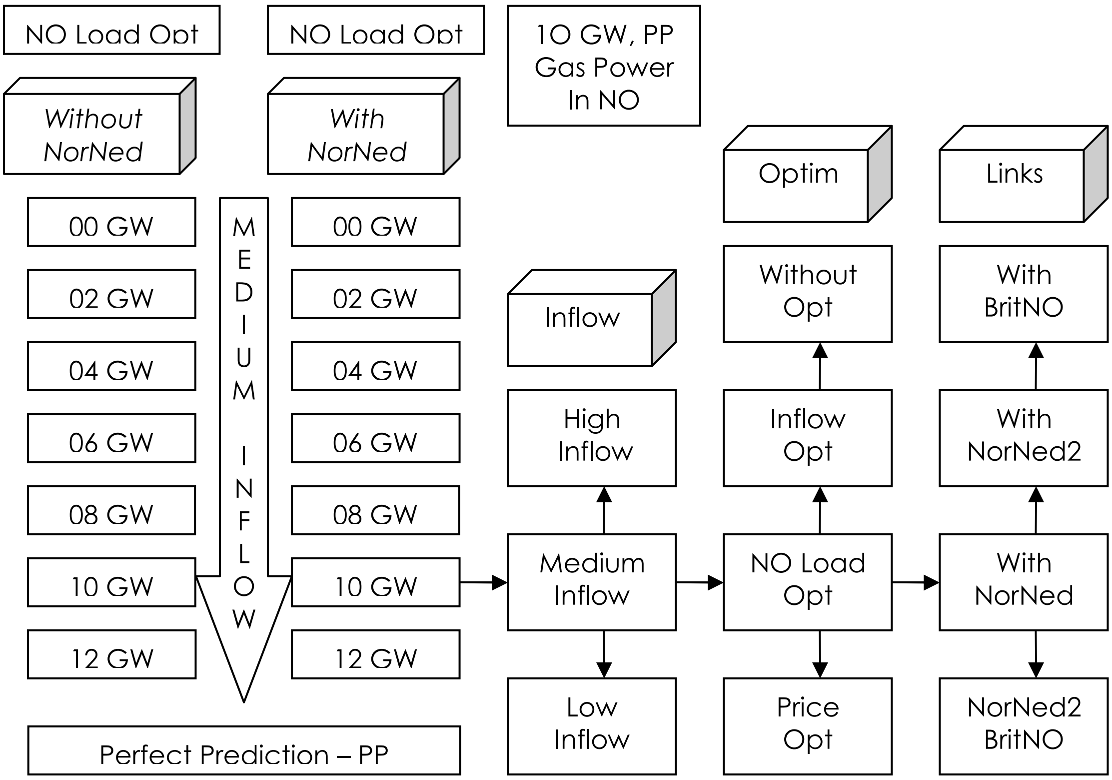


Figure 21: Flow-diagram of simulation scheme

6.1 Analysis of the results

Technical impacts

The simulation results for all variants, do not report neither energy-not-served (ENS), nor spinning reserve violations in any area within W-UCTE or Nordel. The only case with some ENS reported is when no optimization strategy for the Norwegian reservoir is applied, which in turn enhances the opinion that long-range hydro scheduling strategies should be adopted for this research. For the rest of the cases, it can be concluded that sufficient up-ward and down-ward regulation capacity is available at all times during the year in order to balance the aggregated load and wind power variations. This was rather expected, since the total installed capacity in the specific model design is large compared to the maximum load. An important characteristic of the developed model is that a large amount of wind (0-12GW) and hydro power

(Nordel) are present. Because both energy sources are integrated within the power system with almost zero marginal cost, the competition of these two resources is inevitable.

Wasted Wind Energy

Initially, since the software was not dimensioned appropriately for such a large system study, in order to simulate the model and produce no ENS, the degrees of freedom of the Norwegian reservoirs had to be decreased. Therefore the output of the hydro power units is never reduced to zero in this model. A consequence of this convention is that when the Netherlands is directly coupled to Norway by NorNed, there is more wasting of available energy sources, either wind or hydro due to the high respective hydro reservoir levels. This is a drawback of the simulation set-up and not a technical integration limit of wind power in the power system; however, this imperfection is accepted under the existing framework.

In *Figure 22* the wasted wind energy in the Netherlands is depicted for various wind power penetrations and flexible international exchanges, which are scheduled almost until the moment of operation (1 hour ahead, market gate closure time). Indeed, if this case is compared to *Figure 4*, where wasted wind energy is presented for the case with fixed imports, wind energy seems to be integrated with lower difficulty within the power system. The common characteristic between the two figures is that wasted wind energy starts to increase from the 04 GW of installed wind power and on, especially due to the higher capacity factor of the off-shore wind power, which starts to apply after this level.

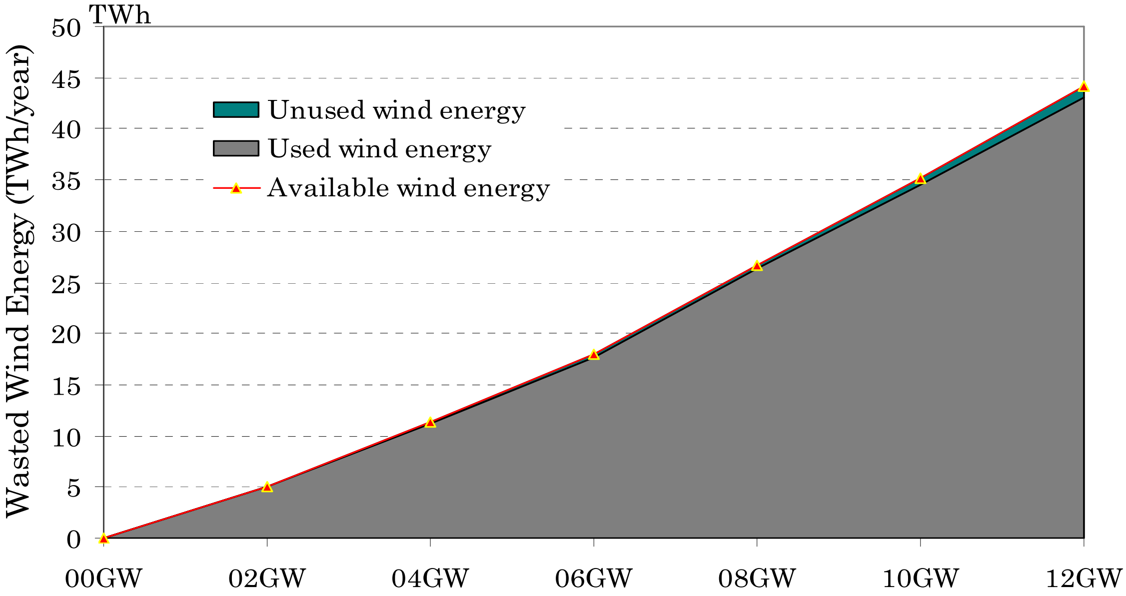


Figure 22: Wasted wind energy in the Netherlands for 0-12 GW of installed wind power and flexible international exchange

The fact that hydro energy is competing with wind energy can be seen from the increase in wasted wind energy for various inflow situations in Norway. In *Figure 23,* a representation of the wasted wind energy levels per week is given for the three inflow periods. Apart from some particular weeks, where hydro is not hindering wind integration, the general impression for the annual horizon is that the total wasted wind energy increases from 580 GWh, to 645 GWh and to 662 GWh for low, medium and high inflow respectively. Therefore in wet years, the Dutch exports of wind energy to Norway may be limited.

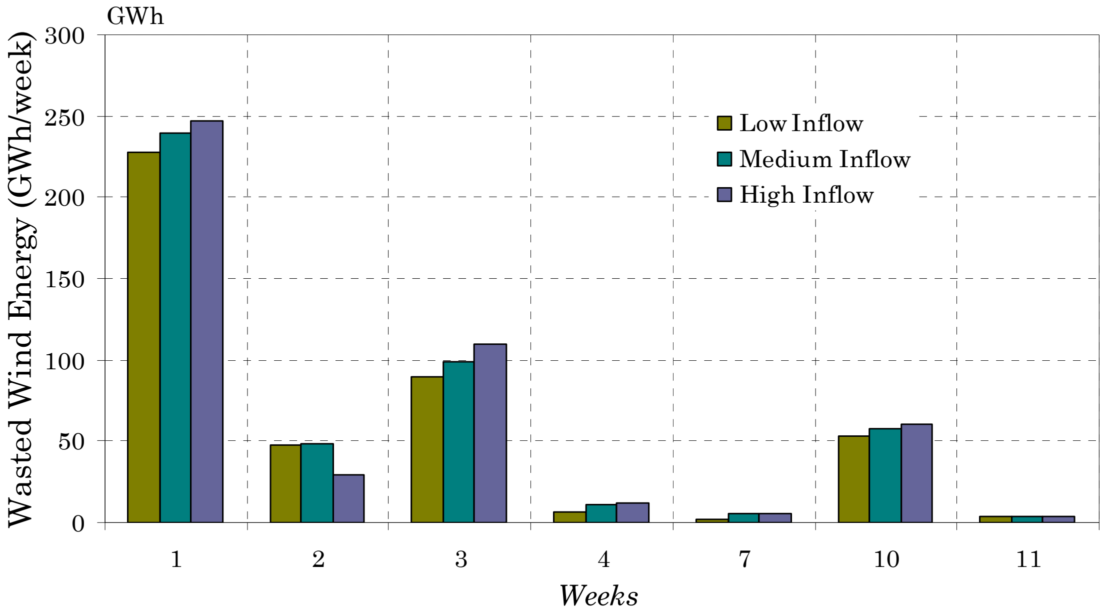


Figure 23: Wasted wind energy for different inflow levels and specific weeks, 10 GW of installed wind power in the Netherlands

In order to depict the wasted wind energy levels for various interconnection scenarios was formulated. As it is evident, when no interconnections are present, the levels of wasted wind energy mainly due to minimum-load problems in the Dutch isolated system are quite high, which is already proved in [7] and [9]. For the various interconnection scenarios, wasted wind energy levels are much lower.

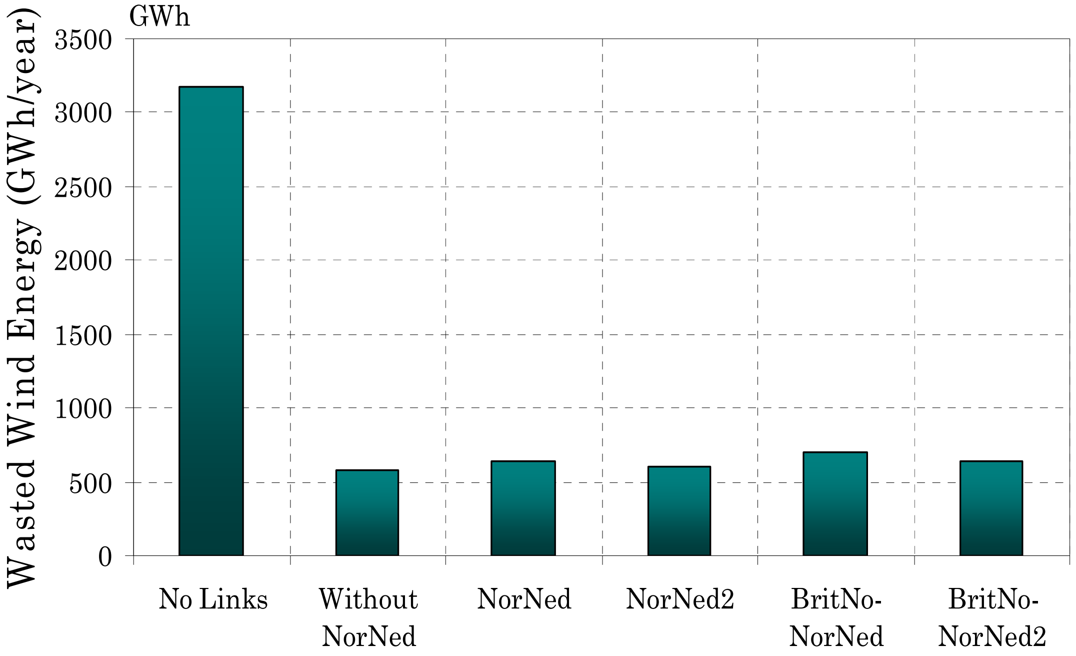


Figure 24: Annual Wasted wind energy for various interconnection scenarios, 10 GW wind power

What should be expected is that the wasted wind energy levels should be reduced, while interconnections among the areas are increased. However, this is not viewed accurately since the model is not yet perfect.

International Exchange

In this study, market gate closure time is considered to be at 1 hour ahead, which in turn means that almost no forecast error is present and international exchanges are scheduled optimally until the moment of operation. Therefore, the installed wind power (0-12GW) in the Netherlands has a direct impact on the exchanges between the countries, which have thermal power as base generation, namely in principal the countries of W-UCTE (*Figure 25*). Moreover, it is clear, that the large-scale integration of wind power in the Netherlands turns the country from net importer to net exporter. Especially, when France and Germany are considered, it can be observed that in periods of high wind in the Netherlands, German imports from France decrease.

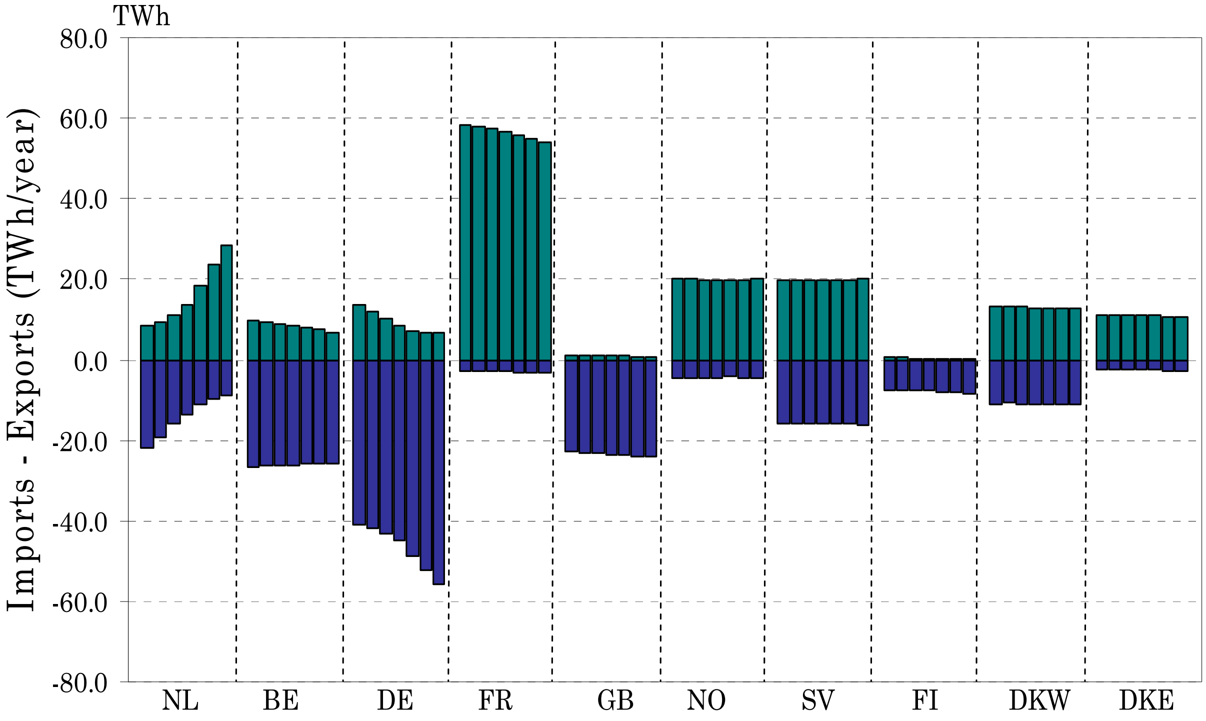


Figure 25: International exchange in W-UCTE and Nordel areas for 0-12 GW wind power installed in the Netherlands for all links including NorNed and medium inflow in Norway

On the contrary, for the countries of the hydro-dominated Nordel, the increase in wind power does not influence their traded energy volumes significantly. This is a physical consequence of the almost zero marginal cost that hydro energy has, and therefore since wind has also zero marginal cost, during the optimization of the UC-ED schedule, wind and hydro resources are acting competitively. This can be seen especially in Germany, where the presence of cheap energy in neighboring areas decreases the full-load hours of German coal-fired and to a lesser extent of CCGT units. The levels of competition are defined by the amount available for exchange, wind or hydro energy at each time-step and by the transmission capacities between Germany and the neighboring areas. In other words, since the Netherlands and Nordel have both large interconnections capacities with Germany, wind power and hydro power will also compete in the transmission level.

If international exchange is viewed from the water inflow perspective (see *Figure 26*), the traded energy volumes for the W-UCTE are slightly varied with the effect being more obvious in Germany, which decreases its conventional generation output even more so as to integrate more hydro energy from Nordel. As it was expected, Norway is increasing its exports and decreases its imports, with the increase in inflow. This in turn has an impact on the Dutch exports, which are lower at high inflow years, due to the competition by the Norwegian hydro. In addition, the presence of abundant water resources in Norway is reducing also the full – load hours of thermal generation in the rest of the countries of Nordel, and consequently raise their net imports.

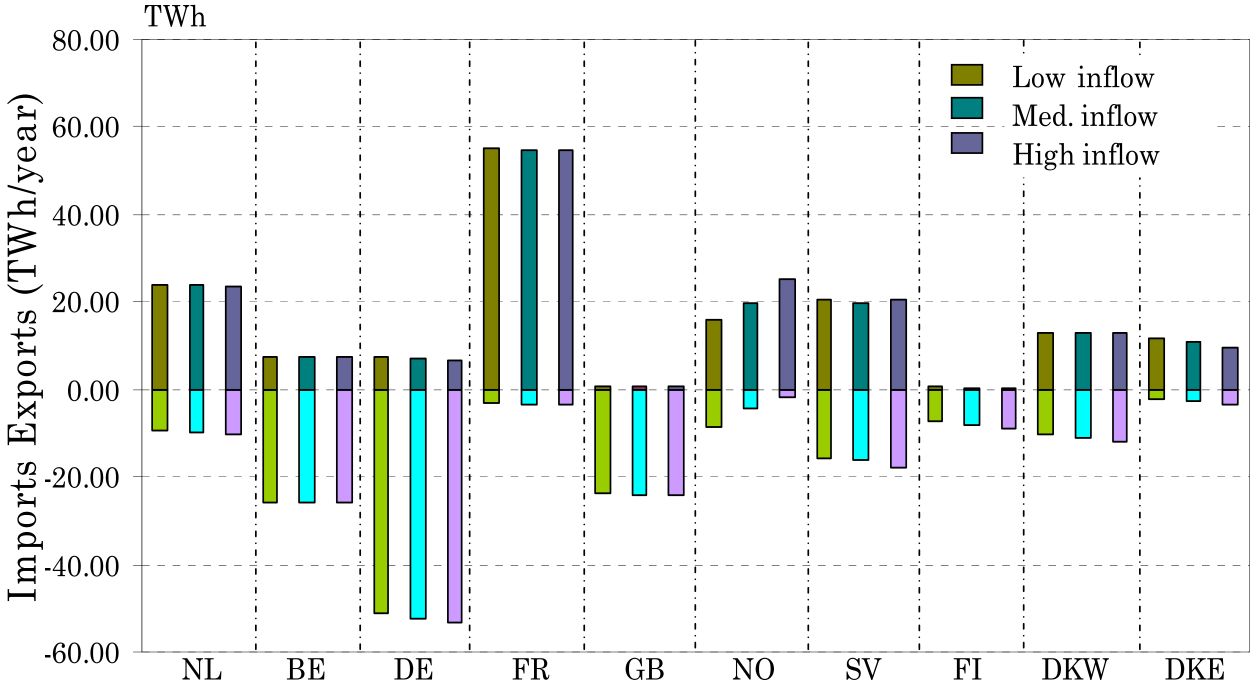


Figure 26: International exchange for 10 GW wind power and various inflow situations in Norway

Likewise, when the various optimization methods for the long-range hydro scheduling of the Norwegian reservoir are considered, the impact in international exchange volumes is less visible in the countries of W-UCTE and therefore they are not depicted in *Figure 27*. What can be observed is the large difference between the case without optimization and the rest of the methods, especially for Sweden and Norway. However, as it is explained in chapter 4, this is not a realistic approach for the long-range hydro scheduling, because it dispatches the same amount of hydro energy each week, regardless of inflow probabilities, markets' price differences and load covering limitations. Moreover, also judging by the resulting ENS, this method is not correct for the representation of a purely hydro-dominant area as Norway and it is used only for comparison reasons. The impact of the optimization methods can be better viewed in the next section about economics from the operational cost savings point of view. It must be though clear that the optimization methods are just indications and for more accurate results on hydro allocation a pre-processing optimizing tool is needed.

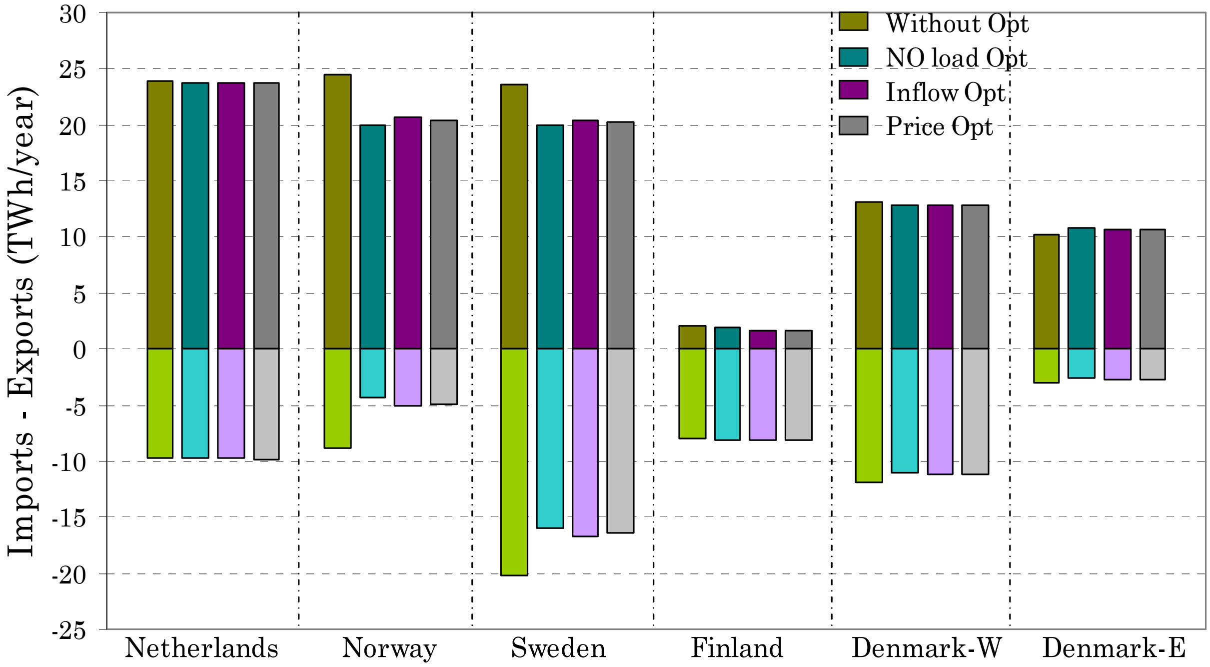


Figure 27: International exchange in Nordel for 10 GW installed wind power in the Netherlands and various optimization methods of the Norwegian reservoir

Apart from the traded energy volumes, the power flow direction of the NorNed link between the Netherlands and Norway is also of high importance for the respective TSOs (TenneT and Statnett). Since, NorNed is a HVDC cable, polarization reversals affect the lifetime of the cable and may pose limits for the exchange of energy volumes. Therefore, in *Figure 28*, the power flow direction is depicted as a percentage of time that the cable is polarized in one direction. As it is evident, the increase in the Dutch wind power will clearly influence the power flows of the cable, which nonetheless will continue to be mainly from Norway to the Netherlands, due to the observed marginal cost difference between the two systems. Moreover, with increasing wind power penetrations more polarity reversals are to be expected.

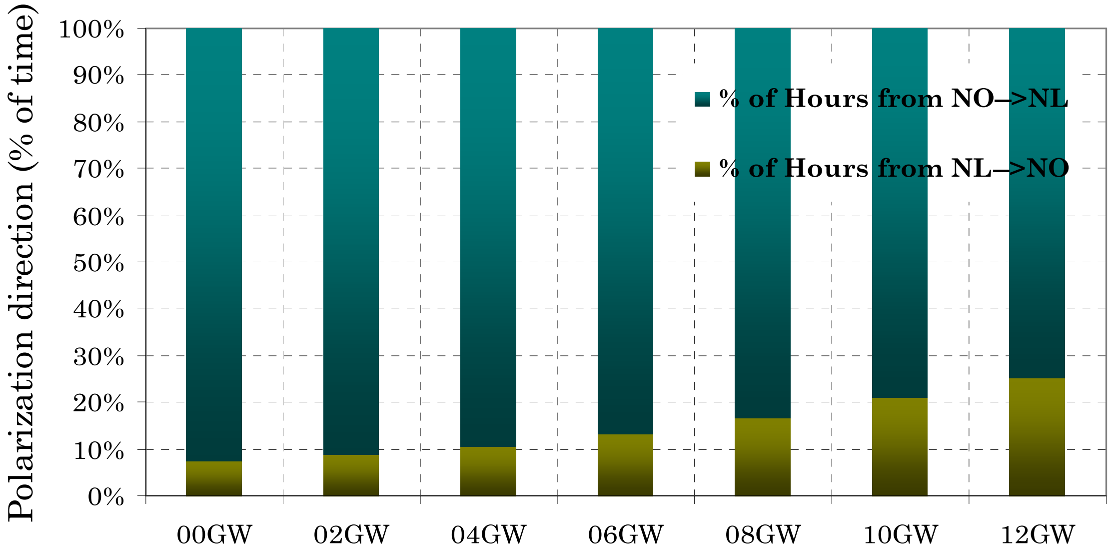


Figure 28: NorNed power-flow direction, 2014

Economic impacts

The economic impacts of NorNed in the large-scale wind integration in the Netherlands will be demonstrated in this section. Therefore, the case of no international exchange and the two cases with international exchanges when NorNed is present or not, will be compared. In this way, the significance of international exchanges for the integration of wind power will be evaluated and the additional implications that NorNed may has will be discussed.

As *Figure* 29 shows, the operating cost savings increase with the amount of wind power installed. The highest cost savings, when there is no international exchange, can be explained by the higher marginal cost of the Dutch isolated system, if compared to the marginal cost of the total system. Indeed, even if this would mean more wasted wind energy, the savings by wind power are much higher for isolated systems. However, this may be balanced by the additional amounts of wind energy which are integrated within the system when international exchanges are present, with higher overall socio-economic benefits. As it is evident, the operation of NorNed increases the savings for the total system.

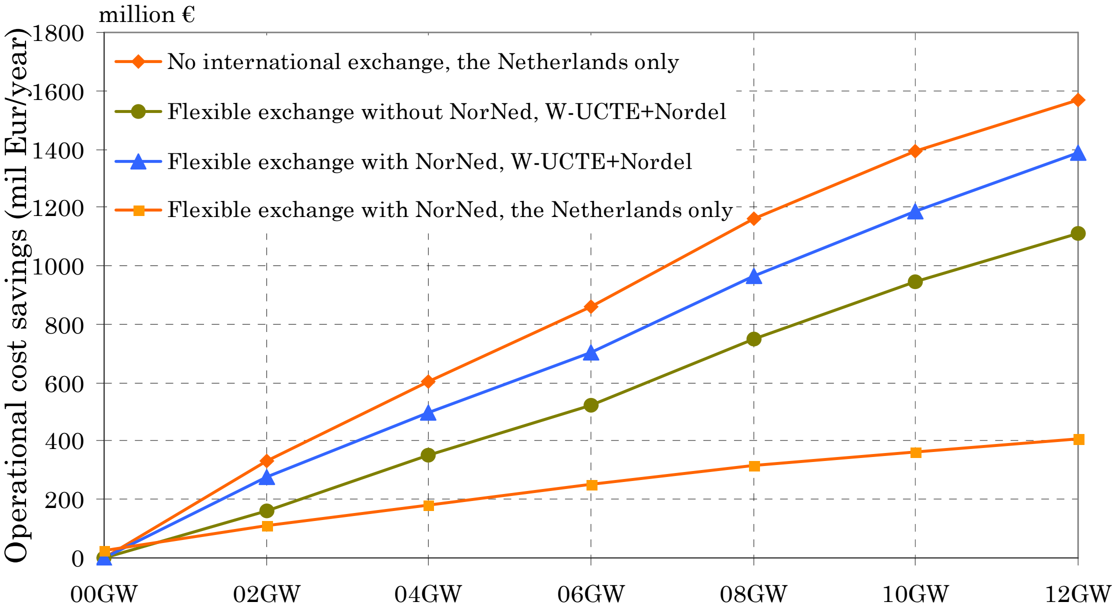


Figure 29: Annual operating cost savings of wind power and NorNed

Especially for the case of Netherlands where the wind power revolution is realized, the cost savings resulting from wind integration correspond with approximately 35% of the total system cost. This is turn means that the rest of the nine operation areas are realizing the 65% of the total operating cost savings under the impact that the high correlation between the German and Dutch wind power (0.73) has on the results. When compared to the cost savings without NorNed, the overall economic benefit is higher in presence of the cable. Indeed, this can be clearly viewed in *Figure* 30, where the economic benefits have been quantified. If the preprocessing tool for hydro allocation was present, the difference between the two cost saving curves would be even higher and the cost savings for the total system at high wind penetration levels should approach the total cost savings of the Dutch isolated system

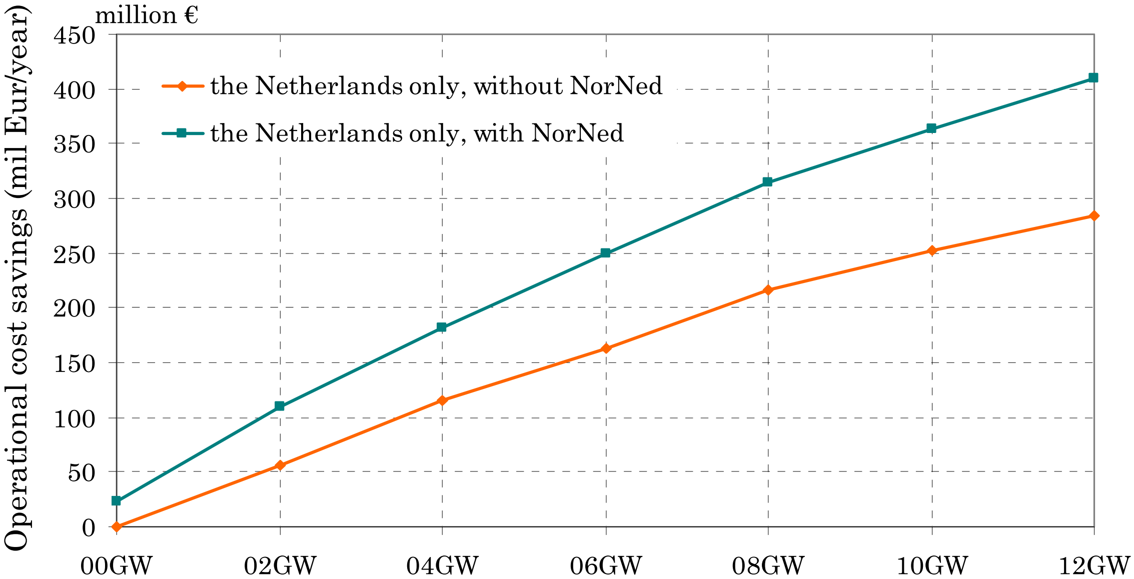


Figure 30: Combined annual operating cost savings of wind power and NorNed

When the case of 10 GW of installed wind power in the Netherlands is considered and the varying parameter is the inflow in the Norwegian reservoir, the operational cost savings compared to low inflow periods are clear (*Figure 31*) for the total system and especially for Germany, which is the largest importer of the Nordel's hydro energy. The impact of increasing inflow in Norway is influencing significantly also the fossil-fuel powered Denmark, particularly in Denmark-East. Indeed, the existence of water resources in the neighboring Norway decreases the generation output of CHP and coal units. The effect is less visible in France, due to the fact that the country has relatively high hydro energy levels and abundant must-run nuclear power.

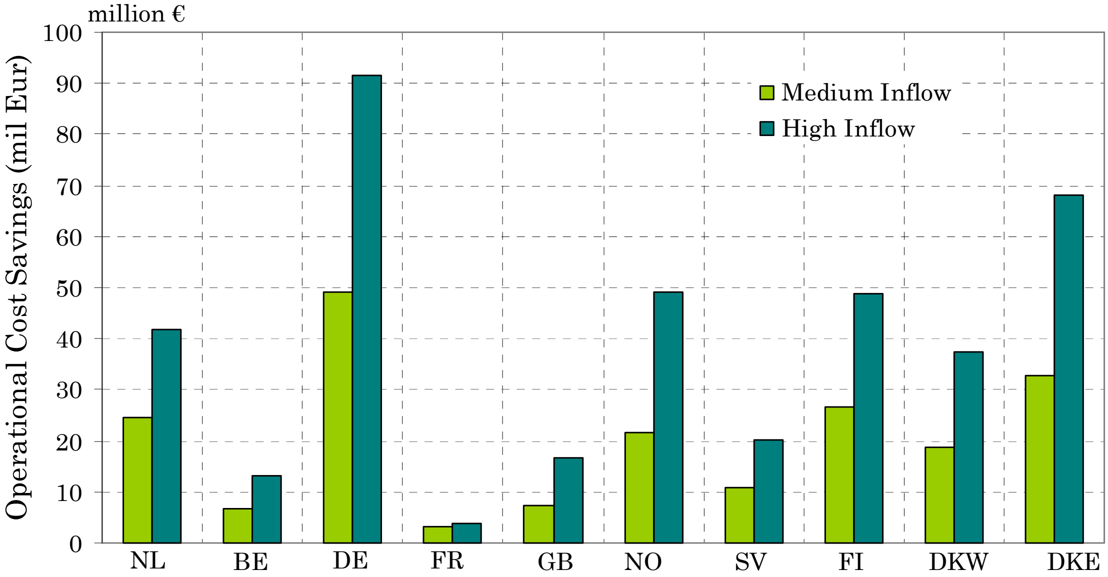


Figure 31: Operation cost savings of various inflows for 10 GW of installed wind power

With a view to investigate the impact that the various optimization strategies of the Norwegian reservoir have on the economic benefits that the

Netherlands and Norway can obtain by the operation of the NorNed link, *Figure 32* has been formulated. The operational cost savings here are produced by comparing the total operating costs of various methods with the case when no optimization is considered.

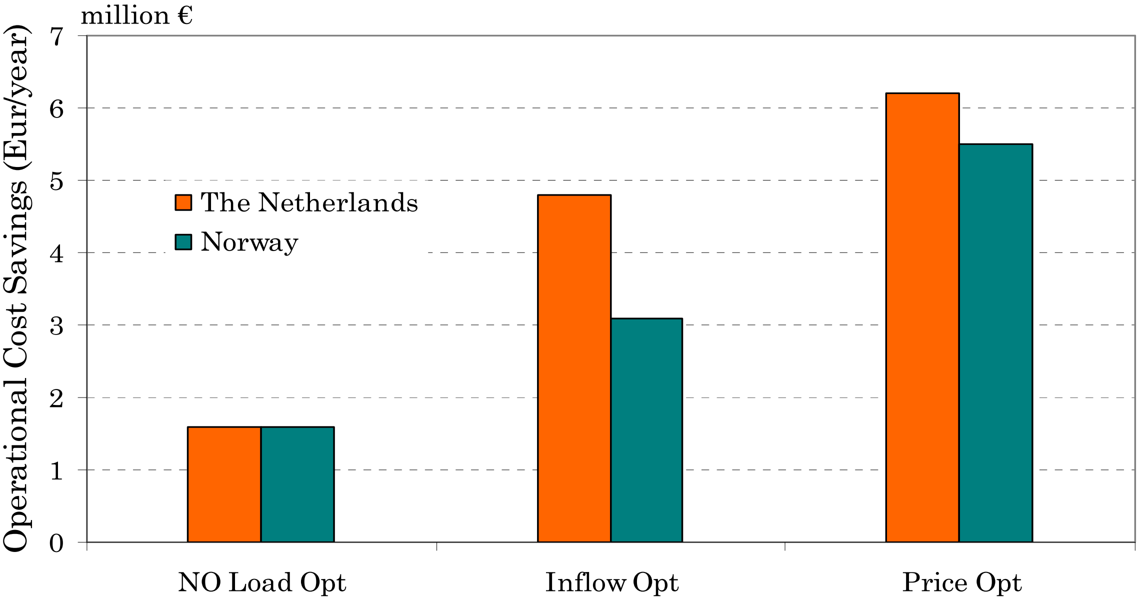


Figure 32: Operational cost savings for 10 GW of installed wind power in the Netherlands and various optimization strategies of the Norwegian hydro-reservoir

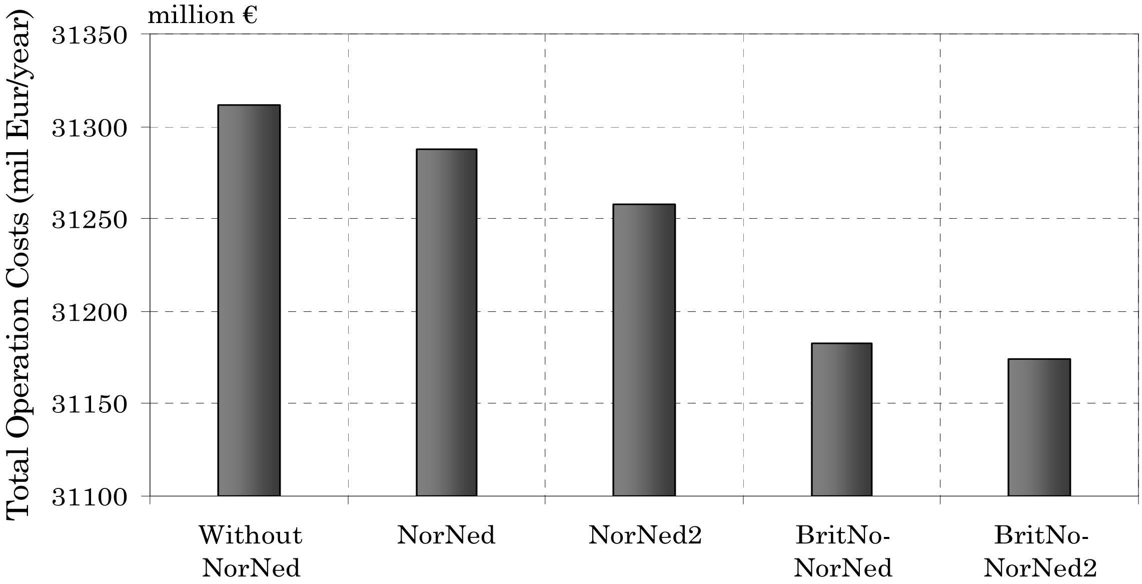


Figure 33: Operating costs of W-UCTE and Nordel system, for 10 GW of installed wind power in the Netherlands and various interconnection scenarios

Indeed, the savings increase when the decisive factors for the allocation of weekly hydro energy are varied. Therefore, if instead of solely covering the Norwegian load, also realistic probability values of inflow are taken into account, the economic benefits are higher. The profits can be even higher if apart from the load and the inflow, the price difference between the two markets is taken more into account. In other words, if the hydro operator allocates the weekly hydro energy dependent on the price factor, the operational cost savings increase more for both countries and especially for the Netherlands.

In the same logic, the operational costs of various interconnection scenarios for the total system of W-UCTE and Nordel are depicted in the next figure. NorNed2 represents a discussed option for the extension of NorNed1 capacity to the double. As it was expected, since the model has large amounts of cheap energy, the existence of additional interconnections reduces the total system operating costs considerably. However, since in this study the international exchange volumes are scheduled until the moment of operation, *Figure 33* shows a first sign of saturation when BritNo, and NorNed2 are installed. In other words the installation of additional links cannot offer proportionally more economic benefits, since the marginal cost differences between the various areas decrease with increasing transmission capacity.

Environmental impacts

The simulation results clearly demonstrate that wind power leads to saving of significant amounts of CO_2 emissions. It can be noted that emission savings also positively impact operating costs, since CO_2 emission savings are part of the total operating cost. However, as it is already mentioned in-adequacy of the software specific design and the high correlation with the German wind power, result in more discarded Dutch wind energy, which in turn decrease the emission savings at some extent. The results for emission savings for SO_2 and NO_x show similar trends as CO_2. In *Figure 34*, the emission savings of NorNed are higher for lower wind penetrations. In the range from 6 – 8 GW, the reduction is probably due to the high capacity factor of off-shore wind, but at high wind penetrations again the total emission savings increase. This happens because from 8 - 12 GW the amount of available wind energy is so high, that it can compete in the same terms with hydro power.

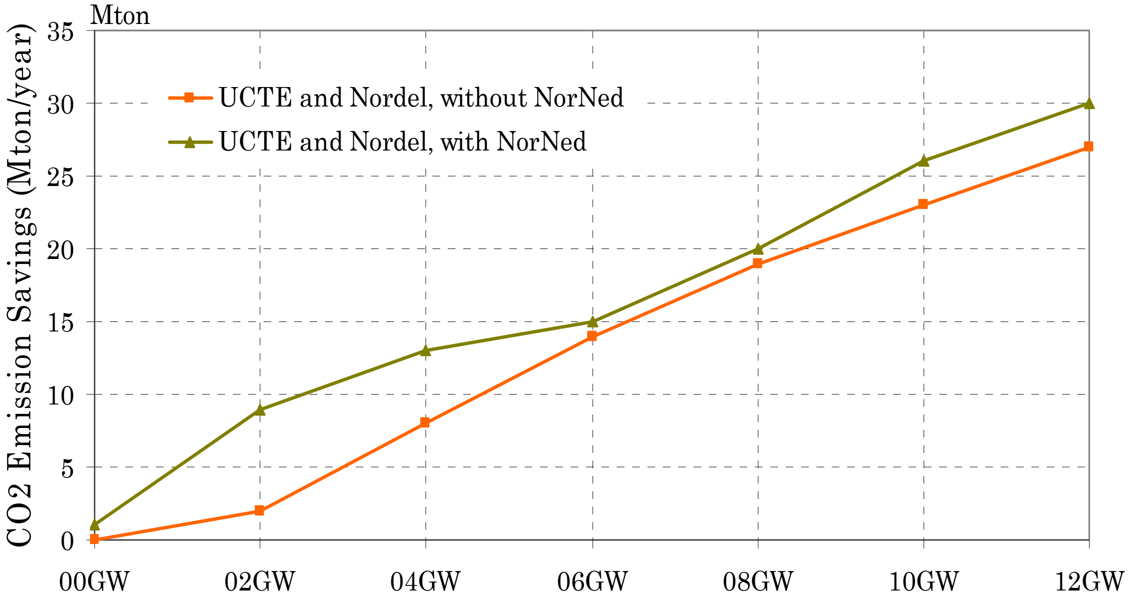


Figure 34: CO_2 emission savings of the overall system (W-UCTE and Nordel) for 0-12 GW of wind power in the Netherlands

Gas Power Scenario in Norway

The Gas Power scenario in Norway refers to the installation of additional 3000 MW of gas turbines until 2020, which could ensure that Norway will have a positive power/energy balance also in dry years. The simulation results for this case signify an increase in total emissions and operational costs. However, since Norway is depending its power generation mostly on hydro power, the addition of 3 GW of thermal generation, on the one hand increases significantly its exports and on the other hand offers the possibility to save water resources for critical periods. However, this scenario will not be analyzed furthermore, since it's outside of the focus of this research.

6.2 Sensitivity analysis and reflection

Sensitivity analysis

In order to investigate the robustness of the developed model and to explore the impacts of varying assumptions and scenarios, a simple sensitivity analysis will be carried out. The factor that is influencing significantly the simulation results is the existence of abundant cheap energy, either wind power in the Netherlands or hydro power in Nordel and especially Norway. Therefore, in the sensitivity simulations this amount will be differentiated, by adding additional water resources in France and consequently studying the results. In this way the elasticity of the model's overall operational cost may be investigated. Furthermore, the sensitivity analysis will explore the effect of fuel cost increase and finally conclusions can be drawn about the performance of the developed model

Sensitivity to high hydro

More specifically, for the simulations, France is producing approximately 65 TWh of hydro energy. This corresponds with almost 1250 GWh of produced hydro energy on average per week. If this is varied from 1250 to 2050 GWh per week, France will consequently produce almost 107 TWh, namely 42 additional TWh of cheap hydro energy, or in other words 35% more. The question that arises is at what extent this can impact the system's unit operational cost, the total operating costs savings and the total generated energy, under the technical constraints that the model poses. Therefore, the base case with low French hydro power will be compared to the case with high French hydro power. The target of this comparison is to illustrate how much difference a 35% increase of the French hydro can bring to the system marginal cost, while wind power is increasing (0-12GW).

As it was expected the increase of wind power in the Netherlands results in a reduction of the total system's operational cost for both cases of French hydro power. This can be seen clearly in *Figure 35*. The difference between the two lines shows at what extent the hydro power increase, affects the operational costs. Furthermore, it is important to notice that the geographic allocation of hydro energy in France somehow compensates also for the effect of wasted wind in the Netherlands, which results mainly from the absence of preprocessing hydro optimization tool (see *Figure 36*). In the same logic, it can be induced that hydro power from France competes at some extent with hydro power from Norway.

From this result, it can be concluded with higher certainty than before that the extension of the W-UCTE model with the hydro-dominated Nordel, needs a further improvement of the accuracy of the developed basic model, so as hydro power in Norway will not act competitively to the Dutch wind in the simulations and hydro resources in each area will be integrated in a correct hydro-thermal coordinated fashion for such an enlarged power system.

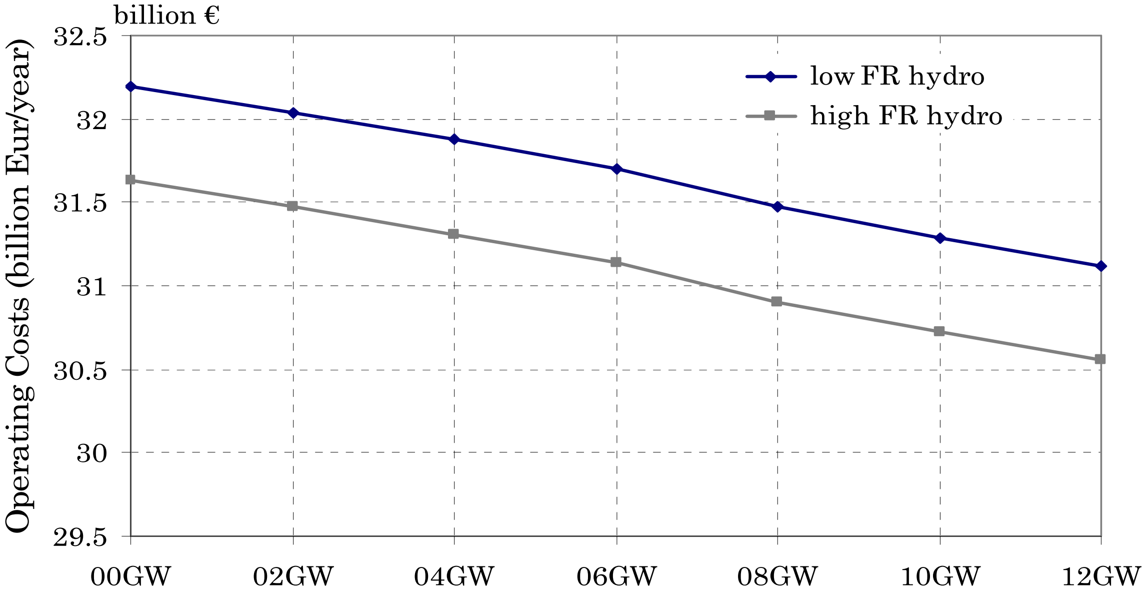


Figure 35: Total system's operational cost for 0-12 GW of installed wind power in the Netherlands and low-high hydro power in France

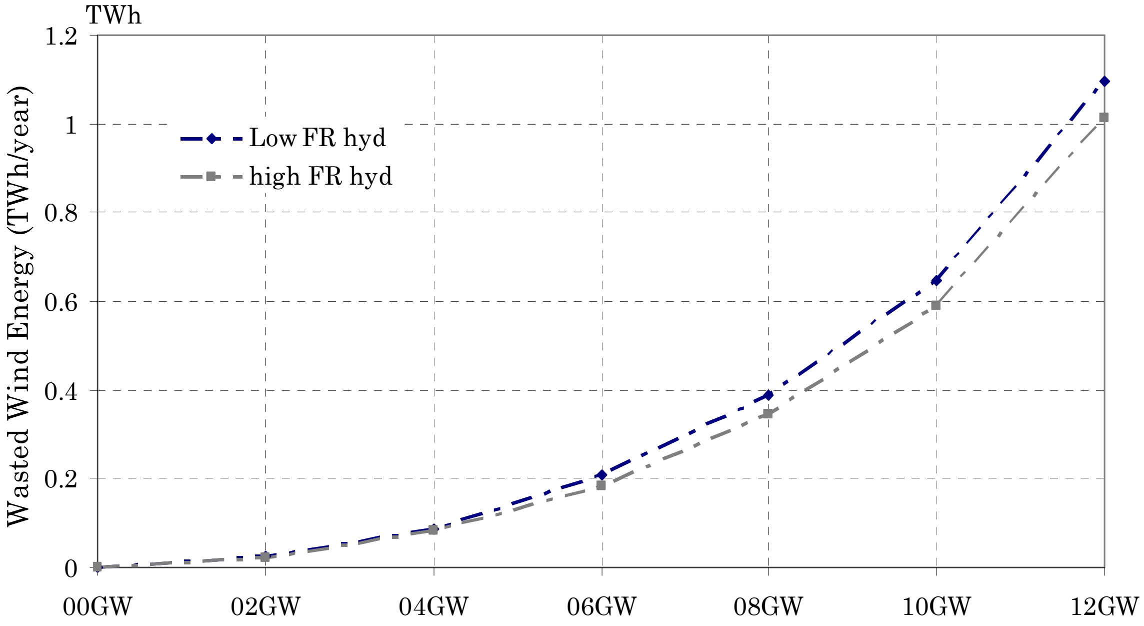


Figure 36: Wasted wind energy levels for 0-12GW of installed wind power in the Netherlands and low-high hydro power in France

Sensitivity to fuel/emission cost increase

The examination of the model's behaviour to price variations will continue with the case of increased fuel and emission costs. Thus, the case of 10 GW of installed wind power in the Netherlands is chosen and the fuel/emission costs are increased by 35%. This case will then be compared to the base of 10 GW and business as usual low fuel/emission costs scenario; consequently, the differences will be highlighted.

The results of the sensitivity analysis regarding the fuel/emission cost increase confirm the fact that the demand and supply of electricity are highly inelastic quantities. In other words, the amount of demanded or generated energy will not vary according to price variations. This means that the consumers will buy the same amount of electricity even when prices are higher, unless efficient use or energy storage comes into picture. From the system operational cost perspective, the 35% increase in fuel/emission cost has two important impacts. The first is that the average marginal cost (€/MWh) for the total system is increasing, from 11.7 €/MWh in the low price case to 15.2 €/MWh in the high price case, which corresponds with an almost 30% of increase. In economic terms, this means that the operational cost is indeed effectively inelastic. A second important observation is that the increase in fuel/emission prices by 35%, results in less wasted wind energy; 645 TWh to 620 TWh of wasted wind energy for the low and high price case respectively. As it was expected, the increase in the total system operating costs causes the modeled power system to integrate more wind energy.

Reflection

One general criticism of the modelling approach applied in this research, is that simulation models are usually highly complex, with many parameters, state-variables and non-linear relations. Under the best circumstances, such models have many degrees of freedom and, with judicious fiddling, can be made to produce virtually any desired results, often with both a plausible structure and plausible parameter values [48]. At one extent, the developed model can produce with a suitable input data variation whatever results the developer might wish. It must be pointed out however that, by definition, a model is a representation of the real world in programming terms, to be used for supporting difficult decisions. In developing simulation models, it must therefore be borne in mind that all models have limitations and use assumptions to simplify the analysis. The target of the simplifications is to facilitate complex procedures without inserting errors in the results. In the end, the responsibility of determining the applicability of a simulation model to the real world lies with the model developer. This reflection serves as a reminder of this.

With the proposed modelling approach, the North-Western European interconnected system was extended to include the Nordic countries, namely, Norway, Sweden, Finland, and Denmark (East and West systems). The simulations results have shown, that even with an optimum international exchange scheme, where imports and exports are decided until the moment of operation, the wind power in the Netherlands may have to compete with hydro power from Nordel. Furthermore, when France is configured with high hydro power, this effect of competition is extended and Germany, which is the largest importer in the model, has more possible options for importing cheap electricity, wind from Netherlands, hydro from Nordel and hydro from France.

When observing the model from a high-level perspective and considering the inputs, the simulation results can be explained well. However, the represented model is not yet sufficient to allow the operator to rely adequately on the simulation results for decision support. At first, the absence of Italy, which is a large importer of the French nuclear energy, is clear. This affects mostly Germany, which in this model is importing all the inexpensive energy from France, decreasing in this way the full-load hours of its coal and lignite units. Moreover, the absence of Russia and Estonia from the modelled areas leaves Finland with an energy deficit. Finally, from the aspect of wind power in Nordel, the modelling approach was too simple to include its effect realistically and therefore correlations of Dutch and Nordic wind power, which are likely to alter the general picture, are not taken into account.

In order to produce the most reasonable simulation results with respect to ENS, the degrees of freedom of the Norwegian and Swedish hydro power units in the model had to be decreased. However, with a view to present optimum UC-ED schedules under higher uncertainty in the future, the model design must be slightly altered to allow the hydro units to operate with higher degrees of freedom even for a larger system, which will include also Italy and some other countries with cheap base-load power, such as nuclear and hydro.

Furthermore, a new executable version of the model with larger dimensions is needed so as to deal satisfactorily with the large amount of input data (at least ten operational areas, at least fifteen different hydro reservoirs, increased number of interconnectors, system loads or heat areas and wind power in Nordel and Europe as separate wind parks at least at the country level). After that, the model then can be calibrated and validated further.

7. Conclusions & Recommendations

In the past decade, wind power has become a generation technology of significance in a number of countries. A further integration of more wind power into the power systems can be foreseen. Nevertheless, wind power has different characteristics than conventional generation technologies in the sense that its primary energy source, the wind, cannot be controlled. The wind power's variability and limited predictability have significant implications on power system operation. The presence of liberalized, international electricity markets adds another dimension to the complex challenge of integrating wind power into power systems. From a system planning perspective, wind power complicates both the commitment and economic dispatch (UC-ED) of generation units, but also the amount of reserves required for power balancing in real-time. Possible solution for the problems that large – scale wind power integration has, by means of electrical energy storage, electrical boilers and efficient CHP units have been examined in the past [9][44].

In this research, important steps have been taken towards an international power system model for wind power integration studies. The existing Western-W-UCTE European model was extended to include the Scandinavian power system. This research, focused on investigating the role that international exchange can play, in the integration of wind power. The regarded case is the Netherlands with increasing wind power penetrations (0-12GW), interconnected to both the W-UCTE and Nordel power systems. Thus, the significance of international exchange may be realized and the additional benefits of NorNed link can be furthermore explored. The research approach comprised several steps including a literature survey, the extension of an existing UC-ED simulation model, careful definition of the simulation parameters that characterize the total system, reporting and finally analysis of the simulation results.

7.1 Conclusions

Simulation Results

Wind power integration within the power system is partly facilitated by the presence of strong international links between countries. International links undoubtedly increase the security of energy supply and may have lower capital investments costs than the energy storage integration options for wind power (OPAC, UPAC) [9]. The optimum benefits from international exchanges are obtained when the market closure time is moved to 1 hour, ahead. In this way, the negative effect of wind power forecast errors on system operation costs can be minimized.

Moreover, the technical limits of the power system may be highlighted. Indeed, minimum-load situations during high wind – low load periods are expected to present the first technical integration limit for wind power. One more limit is posed by the high correlation of German and Dutch wind power. International exchange (availability of transmission capacity for exports) may therefore not be available at all times, which results in wasted wind energy in the Netherlands. The wind power variations additional to those of the load are integrated within the power system effectively, since sufficient ramping capacity is present at all times.

Especially for NorNed, the operation of the cable clearly favors the system in terms of cost/emission savings. With the chosen minimum output levels of the hydro reservoirs in Norway, there is more wasting of available energy sources, either wind or hydro. This can be also perceived as an implicit competition between wind power from the Netherlands and specifically hydro power from Norway. The reason for that is that both generation technologies are considered to have the same, zero marginal cost and therefore, they are competing in the transmission level and the availability period.

When considering the long-range hydro scheduling issue, the results show that the way that the Norwegian reservoir will be utilized affects the profitability of the total system. Specifically for the Netherlands and Norway, which are linked by NorNed, an optimum management of the Norwegian hydro power based on the price difference can lead to even higher cost/emission savings especially for the Netherlands. This difference is sustained by the limited transmission capacity between the two systems. However, if interconnections are extended with additional links (NorNed2, BritNO), the benefits that the countries obtain are not equally proportional to the increased capacity, but tend to saturate after a certain level of MW. Furthermore, when a low inflow year is compared to a medium and then to a high inflow year, the economical and environmental benefits are clearly higher for the total system, even if more wasted wind energy results in the Netherlands. Therefore, especially in very wet years, exporting wind energy from the Netherlands to Norway might be pointless since the Norwegian reservoir may be already full. However, since the hydro system of Norway is not represented in a detailed fashion in this study, this suggestion cannot be verified, unless sufficient information is available.

Modeling approach

The modeling approach is concluded to be useful and valid and furthermore contributes to the objective of this study. The resultant model is a reasonable first representation of the discussed power system and is capable of producing optimum UC-ED schedules with various inputs of inflow variation, reservoir optimization strategies, interconnection scenarios and wind power penetrations. Simulation results can be explained well and show the correct operation of the model, but illustrate the need to improve the model further. The advantages of an extended European model are likely to be large, especially for large-scale power system planning research and studies. Its value is appreciated by Dutch TSO TenneT, which will develop this model further in-house to be used for future international system studies.

For the hydro allocation / optimization methods suggested in this research it can be concluded that undoubtedly improve the results from the till recently applied method. However, the use of factors that influence the hydro allocation is just an indication and not the solution to the long-range hydro scheduling problem.

7.2 Recommendations for further research

For a closer representation and consequently a more accurate research, the wind power of the Nordic countries for the future horizon should be precisely calculated, using the method applied for the Netherlands and Germany [9]. In order to achieve a correct representation of wind power in Nordel, simultaneous wind speed measurements (time-series) throughout Nordel should be used. Consequently, the wind speeds should be interpolated to foreseen wind power locations and to the correct hub-height, to estimate the hourly wind park output at these locations. In this way, correlations in time and space between the different wind parks are correctly taken into account.

By combining the related research results, it is important to mention that if specific reliable unit data for any area within the model are present, the developed country's generation records in the database should be replaced by them. Thus, the accuracy of the modelling approach is increased. With a view to represent all the key players in the European power system, he model should be furthermore enlarged with Italy, Poland, Estonia, and parts of Russia. In this way the system planner can have a complete picture of the European power system and the results gain higher significance in decision support. In this case, an upgrade of the software's capabilities and a new calibration of the model will be needed for PowrSym3 to cope with such an increased number of input data.

Furthermore, the research showed that a correct representation of hydro power within PowrSym3 requires a long-range hydro scheduling approach, which in this study is based on various influence factors and has been applied only for the reservoirs of Norway. However, for a more realistic model, reservoir management logic should be extended also to the other modelled areas that have hydro power in their generation portfolio. In this way, the hydro power within the model will be controlled better and the effect of competition with wind power would be mitigated. Especially if hydro power is assigned a negligible operating cost, it will not commit in expense of wind power. Thus, the technical limits for wind power system integration will be viewed more precisely. Since the use of the hydro-scheduling influence factors is used only for indication, future models should include a pre-processing computational tool to produce the optimum weekly hydro allocations. This optimization can be based on dynamic programming and heuristic algorithms and should take into account historical data for the operation of the power system and stochastic values for the uncertain variables (wind, precipitation etc).

As it becomes evident a validation of the total system, even with the already developed countries will take time and effort. However, the existence of an accurate, validated model for large-scale power system studies can serve a TSO well enough in a large range of situations from decision support to strategy design. This would be even more accurate if the transmission bottlenecks within the operating areas were modelled as well. Moreover the model could be extended to include also other system limitations such as long-term load contracts, which take certain generation units out of short-term markets. In an ideal situation, the must-run status of certain generation units (base-load power) could be replaced by high start-up operating costs and the units' dispatch could be solely economical.

8. Bibliography

[1] *J.J.Grainger, W.D.Stevenson, Power System Analysis, McGraw – Hill International Editions, ISBN 0-07-113338-0;*

[2] *Advanced Electricity Storage Technologies Program: Review Paper Published by the Australian Greenhouse Office, Department of the Environment and Heritage, 2005;*

[3] *J.F.Manwell, J.G. McGowan, A.L. Rogers, Wind Energy Explained, J.Wiley & Sons, ISBN 0-47-84612-7;*

[4] *Wind Energy Association, Worldwide Data, Press Release available at* www.wwindea.org;

[5] *Wind Map 2007, European Wind Energy Association (EWEA), available at www.ewea.org;*

[6] *L.Colasimone, EWEA, Security of energy supply: off-shore wind can be the answer to Europe's energy crunch, 2004;*

[7] *TenneT, TSO of the Netherlands, Quality & Capacity Plan 2006-2012, Arnhem December 2005;*

[8] *J.G.Slootweg, Wind Power; Modelling and Impact on Power System Dynamics, PhD thesis, Delft University of Technology, The Netherlands, 2003;*

[9] *B.C.Ummels, Power System Operation with Large-Scale Wind Power in Liberalised Environments, PhD thesis, Delft University of Technology, The Netherlands, 2008;*

[10] *J.Grassin, Vehicle-to-Grid, Improving wind power integration, Master thesis, Technical University of Denmark, Lyngby 2007;*

[11] *H. Holttinen, B. Lemstr¨om, P. Meibom, H. Bindner, A. Orths, F. Van Hulle, C. Ensslin, A. Tiedemann, L. Hofmann, W. Winter, A. Tuohy, M. O'Malley, P. Smith, J. Pierik, J. O. Tande, A. Estanqueiro, J. Ricardo, E. Gomez, L. S¨oder, G. Strbac, A. Shakoor, J.C. Smith, B. Parsons, M. Milligan, and Y. H. Wan. Design and Operation of Power Systems with Large Amounts of Wind Power, State-of-the-Art Report. Technical report, Working Paper 82, VTT Finland, 2007. 119 pp;*

[12] *B.C.Ummels, E.Pelgrum, M.Gibescu, W.L.Kling, Comparison of Integration Solutions for Wind Power, Report in cooperation with TenneT & the Delft University of Technology;*

[13] *G.Dany, Power Reserves in Interconnected Systems with high wind power production,IEEE PowerTech Proceedings, 2001;*

[14] *B.Ernst, Analysis of wind power ancillary services characteristics with German 250-MW wind data, 1999, available at www.nrel.gov ;*

[15] *G.Papaefthymiou, Integration of Stochastic Generation in Power Systems, PhD thesis, Delft University of Technology, The Netherlands, 2007;*

[16] *H.Holttinen, Optimal electricity market for wind power, Energy Policy journal, 2005;*

[17] *H.Holttinen, J.Kiviluoma, Impacts of wind power on energy balance of a hydro dominated power system, VTT Technical Research Centre of Finland;*

[18] *M.v.Werven, F.Oostvorn, Barriers and drivers of new interconnections between EU and non EU electricity markets, ECN-C-06-006;*

[19] *S.Butler, The nature of UK electricity transmission and distribution networks in an intermittent renewable and embedded electricity generation future, Imperial College;*

[20] *Operation Simulation Associates, Inc. PowrSym3 User's Manual v361d2. Technical report, OSA;*

[21] *R. Babb, Pumped hydro dispatch by the value of energy method in a production cost model, Operation Simulation Associates, Ringgold, Georgia;*

[22] *J. P. Stremel, R. T. Jenkins, R. A. Babb, and W. D. Bayless. Production Costing Using the Cumulant Method of Representing the Equivalent Load Curve. IEEE Transactions on Power Apparatus and Systems, PAS–99(5):1947–1956, Sept./Oct. 1980;*

[23] *M.Vermeulen, M.Mulder, W.Reek, G.Thomeer, M.de Kleijn, Market Monitor: Development of the wholesale electricity market 2006, The Netherlands Competition Authority, The Hague, December 2007;*

[24] *TenneT Generating Unit Database, Technical Report, 2008;*

[25] *W-UCTE, System adequacy forecast for 2008-2020, Technical report, Union for the Coordination of Transmission of Electricity, 2008;*

[26] *TenneT, Quality and Capacity Plan 2008-2014, Technical report, TenneT TSO, developed in 2008;*

[27] *Nordel, Development and integration of regional electricity markets, Abstract from the annual report of 2005;*

[28] *Nordel, Annual Statistics Database, 2007, available at: www.nordel.org ;*

[29] *Nordel's Balance Group, Energy Balances 2011 – Power Balances 2011-2012, Nordel, May 2008;*

[30] *J.S.Koreman, B.Pajaarvi, T.Worzyc, T. Andersröd, the NorNed HVDC Cable link: A power transmission highway between Norway and the Netherlands, ABB, TenneT, Nexans;*

[31] *TenneT, NorNed dossier: Aanvraag NorNed project op basis van artikel 31.6 Elektriciteitswet, August 2004;*

[32] *DTE, Decision on the application by TenneT for permission to finance the NorNed cable, Dutch Office of Energy Regulation, December 2004;*

[33] *Statistics, Daily prices Nord Pool spot, 2007, available at: www.nordpoolspot.com ;*

[34] *Statistics, Daily prices APX spot, 2007, available at: www.apxgroup.com ;*

[35] *APX, Consequences of the NorNed cable for the APX Dutch market, MEMO to TenneT by May 2004;*

[36] *Tabors Caramanis & Associates, Cost and Risk analysis for a Norway-Netherlands HVDC interconnector, May 2004;*

[37] *APX, Simulation of market coupling across the NorNed cable, June 2004;*

[38] *Statnett, Model for balance settlement on the Norwegian side of NorNed cable, Customer information, 2007;*

[39] *Statnett, Grid development plan 2005 - 2020, available at: www.statnett.no ;*

[40] *Nordel, Wind power in Nordel – Systems impacts for year 2008 -, Nordel, January 2007;*

[41] *S.Bode, On the impact of renewable energy support schemes on power prices, Technical report, Hamburg Institute of International Economics, 2006;*

[42] *Nord Pool, Hourly load values for 2007, available at: www.nordpoolspot.com ;*

[43] *BP, Statistical Review of World Energy, 2008;*

[44] *R.Offeren, Integration of large scale wind power in the Dutch electricity system with interconnections to neighbouring power systems, Master thesis, Delft University of Technology, 2008;*

[45] *O.Fosso, M.Belsnes, Short-term hydro scheduling in a liberalized power system, Power System Technology 2004, PoweCon 2004 International Conference, Vol.2, Issue 21-24 Nov. 2004, Pages: 1321 – 1326;*

[46] *F.Viramontes, H.Hamilton, Optimal long-range hydro scheduling in the integrated power system, IEEE Transaction on Power Apparatus and Systems, Vol-PAS 97, Jan 1978;*

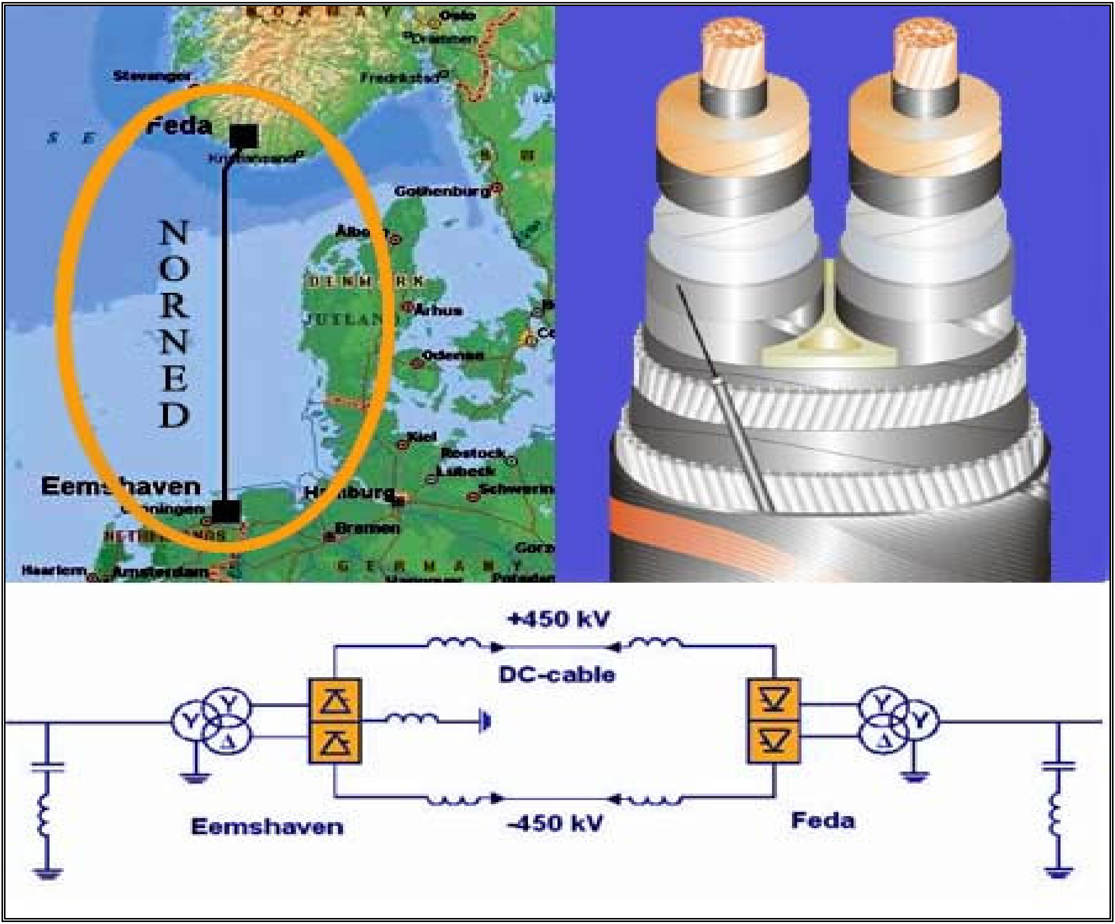
[47] *S.Wan, R.Larson, A. Cohen, Marginal cost method for deterministic hydro scheduling, IEEE Transaction on Power Apparatus and Systems, Vol-PAS 103, Jun 1984;*

[48] *G. Hornberger, R. Spear, "An approach to the preliminary analysis of environmental systems", Journal of Environmental management, 1981, 12, 7-18*

[49] *M.Gibescu, A.J.Brand, W.L.Kling, Estimation of variability and predictability of large-scale wind energy in The Netherlands Wind Energy, Wiley Interscience, Published Online: Sep 29 2008*

9. Appendix A: The NorNed cable

From the 6th of May of 2008, the world's longest submarine high-voltage cable is operational: The NorNed HVDC between Norway (Feda) and the Netherlands (Eemshaven).



NorNed Map, cable's characteristics and simplified one-line diagram

Technical Characteristics

The main circuit configuration, which is shown in (bottom part), consists of a 12-pulse converter ± 450 kV with the midpoint earthed and one first and then two cables with mass-impregnated paper insulation, of 580 km total length. The transmission voltage is effectively 900 kV, resulting in low currents and consequently low losses (4% at 600 MW [30]). The DC link is designated to operate continuously at 700 MW, when all converters cooling equipment is in operation. The two converter stations, one in Feda (NO) and one in Eemshaven (NL), are connected to 300 kV AIS (air-insulated switchgear) and 300 kV GIS (gas-insulated switchgear) substations, respectively. Furthermore, the DC side in Eemshaven is installed in a DC hall to avoid problems with flashover due to salt contamination from the sea. When the voltage is switched-on the system is able to reach ramping speed of approximately 20 MW/min [30], leading to a full power reversal at almost an hour. However, considering the market needs, higher ramping speeds might be demanded to follow closely the market's design. Therefore, it has been already taken under consideration in the design of the installation and the ramping speed can be adjusted accordingly, so as to obtain maximum flexibility in the operation of the link [30], leading to full power reversals even at half an hour.

Economics-Market Considerations

The facilitation of this link under the existing and the future regimes in the power systems, primarily aims to benefit both the individual countries (Norway and Netherlands), but also the entire networks of W-UCTE and Nordel. This first interconnection of Norway to the continental Europe, which is believed to have all the advantages mentioned in section 1.3, in terms of price difference between the connected systems, contribution to the security of supply and possibility for optimum UC-ED scheduling, was expected to operate with high anticipation from the involved parties.

The NorNed project is a joint venture of the two system's TSOs (Tennet in the Netherlands and Statnett in Norway). The costs associated with the total NorNed's completion reached 600 million €, but the benefits that both countries expect to extract from this initiative, overbalance this expense. More specifically, according to [31], TenneT refers to the following overall advantages of the cable:

- Considerable trading margin due to differences in spot prices between both countries.
- Contribution to security of supply in both countries.
- Promotion of the operation of market's forces and the liquidity of the Dutch electricity market;
- Lower and more stable prices for the Netherlands.
- Supply of cheaper and emergency power from Norway.
- Import of sustainable and emission-free electricity into the Netherlands, produced by hydro power stations.

10. Appendix B: PowrSym3 Details

*Powr*Sym3

The utility industry is continually evolving with planning decisions subjected to increasing scrutiny. Utilities require tools that have evolved with them for production cost analyses, both short and long term. One of these tools is *Powr*Sym3. It is a chronological, multi-area, Monte Carlo production cost simulation model capable of high levels of optimization.

In today's competitive environment, the need for greater detail in system planning analyses has become increasingly important. The computational requirements of *PowrSym3* are satisfied by new efficient algorithms coupled with faster computing hardware--making the use of this full chronological model for short, medium, and long-term planning analyses possible. With *PowrSym3* the ability to compare alternatives under real system operating conditions is available now.

PowrSym3 represents the cumulative algorithmic expertise of over thirtyt-five years of production cost modeling. *PowrSym3* is the latest in a series of models which began with PowrSym in 1969 and continued with new developments and spin-off versions which are in use throughout the industry.

PowrSym3 combines the best of previous PowrSym algorithms with a new unit commit and economic dispatch algorithm that simultaneously solves all hours in each weekly horizon. This novel algorithm retains the same chronological detail of previous versions while allowing optimal allocation of fixed energy constraints such as energy limited fuels and emission caps. While previous chronological models could consider a small number of fixed weekly energy constraints by using an iterative method, *PowrSym3* can directly solve multi-fuel, multi-station contracts. Each fuel may have hourly, daily, and weekly minimum and maximum requirements, all of which may vary with time. *PowrSym3* achieves this solution with a network model directly integrated into the unit commit and dispatch algorithm.

*Powr*Sym3 is a multi-area, chronological, Monte Carlo production costing simulation model capable of detailed, short-term studies with high levels of optimization. It can also perform long-term system planning studies representing chronological system operating conditions. Multi-year system operation is simulated over sequential weekly optimization horizons with a time step of one hour.

Accurate simulation of chronological operating conditions, unit commitment optimization, energy storage optimization, multiple fuel allocation, Monte Carlo outage method, and a multi-area transport model allow *Powr*Sym3 to be used for short term optimization and operational planning studies. The same algorithms, optionally with lower optimization levels, are used to include dynamic system operating effects in long term system planning studies. *Powr*Sym3 allows system planners to evaluate future system configurations from an operations viewpoint not possible with most planning models.

The computational requirements of a chronological Monte Carlo model are satisfied by new efficient algorithms, faster computing hardware, and the possibility of parallel processing over local area networks. It is no longer necessary for system planners to give up operational detail in long range studies.

In addition to the ability to represent forced outages by either of two derating methods, *Powr*Sym3 has three Monte Carlo outage options. The classic random draw option allows multiple draw numeric convergence on a weekly horizon. The "smart" Monte Carlo option chooses a small set of statistically balanced draws for faster convergence. The semi-guided method achieves converged annual results in a single pass and is used for long range planning studies.

*Powr*Sym3 **algorithm features include:**

- Preservation of the chronological sequence of events
- Accurate unit dispatch
- Realistic unit commitment with dynamic optimization
- Pumped hydro simulation with reservoir constraints
- Hourly marginal and average cost calculations
- Monte Carlo/derating options for forced outage simulation
- Emission influenced commit/dispatch
- Complex fuel contract model with fuel blending
- Multi-area power transport model
- Energy limited fuel optimization
- Integrated reliability model
- Maintenance schedule optimization
- Combined heat and power simulation

*Powr*Sym3 **report categories include:**

- System reliability
- Reserve margin
- Capacity factors
- Energy generation
- Fuel consumption
- Number of unit starts
- Startup costs
- Fuel costs
- Power plant emissions
- Purchased power
- Total costs
- Inter-area transfers and wheeling charges
- Marginal costs
- Cogeneration heat reports
- Operation and maintenance costs

*Powr*Sym3 **applications include:**

- Generation expansion studies

- Optimization of pumped hydro design parameters
- Time-of-day pricing studies
- Revenue requirement studies
- Benchmarking of less detailed models
- Evaluation of demand side management options
- Hydro power evaluations
- Real time power exchange evaluation
- Power exchange contracting strategies
- Maintenance scheduling options
- Plant retirement studies
- Integrated resource planning
- Near term operational studies
- Real time resource scheduling
- Hourly marginal cost evaluations
- Fuel burn, fuel budgeting, and fuel contract evaluation