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System reliability in the Nordic power market: A scenario analysis for 2030

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Renewable Energy

Preface

This thesis concludes my master's degree in Renewable Energy at the Norwegian University of Life Sciences. None of the text used in the dissertation is taken directly from previously published or collaborative articles.

The model used for the scenario analysis is developed by Hans Ravn in collaboration with Jon Gustav Kirkerud and the Flexelterm Project. The interpretations of the results, processing of data, production of duration curves and time series and plots showing variations in the time series are my original work.

I would like to thank Erik Trømborg and Jon Gustav Kirkerud for steady guidance and stress management, patience advising in developing of the time series, and for running the model calculations through some unforeseen bumps in the road. I would also like to thank Torjus Bolkesjø and Hans Ravn for propositions and recommendations in writing the thesis.

To the students in the class of 2014 – Thank you for a great academic community and fun times with cheese and wine.

A special thanks goes to my family for solid support, Ben Sellars for language proofing, and my very own Henrik Hæhre Ingebrigtsen for extravagant lunches and joyful atmosphere in our "office".

Oslo, June 3 2016

Frida Wam Grønborg

Abstract

This study assesses the effect a higher penetration of variable renewable energy (VRE) and a shutdown of Swedish Nuclear power will have on the reliability in the Nordic power market in 2030. A probabilistic model was used to predict the loss of load probability (LOLP) and expected unserved energy (EUE). The model includes time series for demand and capacity utilization of wind-, photovoltaic-, run of river hydro power and nuclear power production. Two scenarios were analysed; (1) base scenario with a predicted capacity mix with high shares of VRE and some decrease in nuclear power production compared to today's capacities, and (2) complete shutdown of Sweden's nuclear power production. Both scenarios where run with the assumption of a)import and b)no import from countries surrounding the Nordic power market.

The most important findings are:

- The scenario analysis shows that the Nordic power market is able to handle exposed situations in 2030 if Sweden keeps some of its nuclear production, todays planned expansion of interconnections with surrounding countries is realized and an assuming extensive development in wind power production.
- A shutdown of Sweden's power production will give a decrease in the reliability compared to a situation with nuclear power and be just short of a satisfactory level of adequacy with a LOLP requirement of 1‰.
- The Nordic power market in 2030 cannot keep a satisfactory level of reliability without import from surrounding countries.

The current reliability in the Nordic power market is strong, but increased shares of VRE combined with reduced nuclear power production and/or increased consumption will require increased flexibility to maintain a satisfactory level of reliability in 2030. Measures to increase the flexibility, like demand response and increased transmission capacity, as well as the effect of demanding cold/dry years on total hydro storage capacity should be analyzed in further studies.

SAMMENDRAG

Denne studien undersøker effekten av en høyere andel variable fornybar energi og komplett utfasing av Sveriges kjernekraft vil ha på forsyningssikkerheten i Norden i 2030. En modell ble brukt til å beregne tap av last (LOLP) og tilhørende mengde ikke-levert energi. Modellen bruker tidsserier for forbruk og kapasitetsutnyttelse av vind-, sol-, uregulerbar vannkraft- og kjernekraftproduksjon. To scenarioer for kapasitetsmiks var analysert; 1) basisscenario med en høy andel variable fornybar kraftproduksjon og reduksjon i kjernekraftproduksjon, og 2) komplett utfasing av Sveriges kjernekraft, med antagelse om a)import fra omkringliggende land og b)ingen import.

De viktigste funnene er:

- Scenario analysen viser at forsyningssikkerheten i Norden i 2030 er god om Sverige beholder noe av sin kjernekraft og dagens planlagte utenlandskabler er realisert.
- En total utfasing av Sveriges kjernekraft vil senke forsyningssikkerheten sammenlignet med et scenario med kjernekraft, og gi lavere LOLP-verdier enn et vanlig krav på 1‰.
- Det nordiske energimarkedet kan ikke opprettholde et tilfredsstillende nivå på forsyningssikkerheten uten import fra omkringliggende land.

Dagens forsyningssikkerhet er god, men økte andeler variabel fornybar kraftproduksjon kombinert med utfasing av kjernekraft og/eller økt forbruk vil kreve økt fleksibilitet for å opprettholde dette i 2030. Tiltak for for øke fleksibiliteten, som forburkerfleksibilitet og økt overføringskapasitet bør analyserer i videre studier.

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List Of Abbreviations

CHP	Combined heat and power
COPT	Capacity Outage Probability Table
EUE	Expected Unserved Energy
FOR	Forced Outage rate
GAMS	General Algebraic Modelling System
LDC	Load Duration Curve
LOLE	Expected Unserved Energy
LOLP	Loss of Load Probability
NERC	North American Electric Reliability Corporation
NTC	Net Transfer Capacity
OECD	The Organization for Economic Co-operation and Development
PV	Photovoltaic
RLDC	Residual load duration curve
ROR	Run of River
SWDOWN	Downward Short Wave Flux
TSO	Transmission System Operator
VOLL	Value of Lost Load
VRE	Variable Renewable Energy
WRF	Weather Research and Forecast

1 INTRODUCTION

The power market has certain features that makes it unique. It deals with instant generation and consumption, the produce is hard to store, and consumption varies throughout the day and year. A reliable system is dependent on matching supply and demand continuously, subsequently: To satisfy all load requirements at all times. Climate change demands sustainability that in turn expands the objective of a reliable power system. The ultimate goal should be to make a power system that is not just sturdy, but also creates the least amount of discharge at acceptable costs.

NERC (2012)(National Electric Reliability Council) defines reliability as: "the degree to which the performance of the elements of the electrical system results in power being delivered to consumers within accepted standards and in the amount desired". NERC (2012) also subdivide the term reliability into the categories "security" and "adequacy". Security is the ability the system has to cope with sudden disturbances, and the adequacy is the ability of the system to meet the load at all times. Thus, he security term concerns short term operations, while adequacy deals with reliability on a long term basis considering the fluctuations in demand and supply.

The transition from fossil to renewable energy sources will influence the reliability of the power system. This thesis will investigate how the following changes will affect the reliability in the Nordic electricity market in 2030:

- Higher shares of variable renewable energy (VRE)
- Changes in nuclear production

The first point involves a higher penetration of VRE in the power system. VRE have characteristic properties that makes them harder to integrate than conventional power generating technologies. They are uncertain due to limited predictability, and variable due to natural variation in wind, sun and inflow. Studies have shown that these aspects of VRE increase the need for short-term balance and flexibility in the system (Holttinen et al. 2011), (DeMeo et al. 2007), (Ueckerdt et al. 2015). They are also location specific and the energy cannot be transported like solid fuels, making them non dispatchable, or unable to adjust their power output at request from power grid operators or of plant owners. A number of studies have investigated the effect a high share of renewable sources such as wind and photovoltaic (PV) production has on the reliability of a power system (Brouwer et al. 2014; Holttinen 2004; Milligan et al. 2016). Holttinen (2004) concludes that when wind power produces 10% of yearly gross demand, the operating reserves in the Nordic countries should be increased by about 2% of wind power capacity to ensure balance. Brouwer et al. (2014) show that a penetration rate of 20% of annual power generation the impact on present day power systems in OECD countries is substantial, and increases the combined reserve size by 8,6% of installed wind capacity. The results are also indicative for solar PV penetration. Brouwer et al. (2014) and Holttinen (2004) give descriptions on how to model VRE sources in power systems and showed that a comprehensive power system model needs to describe demand and production patterns in addition to transmission with a time step of maximum one hour. Milligan et al. (2016) describes different studies that investigates the effect multiple year data sets, in contrast to single year assessment, and transmission interconnections affect the results of reliability studies.

The second point concerns the future development in the nuclear production in Finland and Sweden. Sweden started their commercial production of nuclear power already in the 1970s. In the 1990s the government started a phase-out, but this proved difficult with a national goal of a carbon neutral power production in 2050. In 2015 all plans for further nuclear plants was stopped, and the further development are highly uncertain (Swedish Institute 2016). Unlike Sweden, that has a policy to reduce nuclear production, Finland wants to expand. If all planned capacity is implemented Finland's nuclear production may be 60% of their total electricity production in 2025 (IEA 2013). Although Sweden and Finland have different policies, the production is internationally controversial. The release of nuclear waste from production is an environmental concern, and a risk of reactor accidents causes fear in the surrounding population. On the other side, nuclear power is dispatchable, meaning they are able to adjust their power output at request from power grid operators or of plant owners, which increase the flexibility of a power system.

The studies mention above will be used as guidelines to give a valid assessment of the following objective:

How will 1) increased share of VRE and 2) reduced production of nuclear power affects the system reliability in the Nordic Power system in 2030?

A model analysis is carried out to investigate the effect two different supply scenarios will have on the generation adequacy in the Nordic market in 2030. One basis scenario with a higher share of VRE than today, and one scenario where Sweden's nuclear power is completely shut down. Both scenarios are run with and without the assumption of import in peak load hours from countries surrounding the Nordic market. The physical characteristics of an electric power system enables it to be described in mathematical terms, due to the interconnection throughout the system, making it possible to model. A model developed by Ravn (2016) is used to calculate loss of load probability (LOLP), and expected unserved energy (EUE), to evaluate the system adequacy. "Loss of load" refers to the instances when available capacity is inadequate to supply the load. The model is an addon to Barmorel, an open source model used to analyze electricity and CHP in international perspectives. The methodology involves using historical data for hourly demand and production as input to the model to analyze the generation adequacy in different prospective scenarios. Historical data is also used to look at variation patterns through different years and to generate load duration curves (LDC) and residual load duration curves (RLDC) for 2030.

Chapter 2 give an outline for the current state and development of the Nordic Energy market. Chapter 3 provides an overview of relevant concepts and definitions for generation adequacy. Chapter 4 will discuss the structure of the model and collection of data. Chapter 5 assesses the data and presents the results. The last chapter discuss the results and concludes the analysis.

2 The Nordic Power Market

2.1 Structure of the Nordic market

The Nordic energy market is generally an energy-only market, but transmission system operator's (TSO) use additional instruments, such as reserved capacity, to ensure system adequacy. An energy-only market is a market where generation owners get their revenue through sale of electricity to the market. The price is determined in equilibrium between supply and demand, and the price is usually a reflection of the marginal operating cost of the cheapest energy generation (Botterud & Doorman 2008). The intraday, and day-ahead market in the Nordic countries are organized in the power exchange Nord Pool.

The market is divided into price regions decided by the local TSO. As of 2015 Norway is divided into five, Sweden four, Finland one and Denmark two price regions (Figure 1).

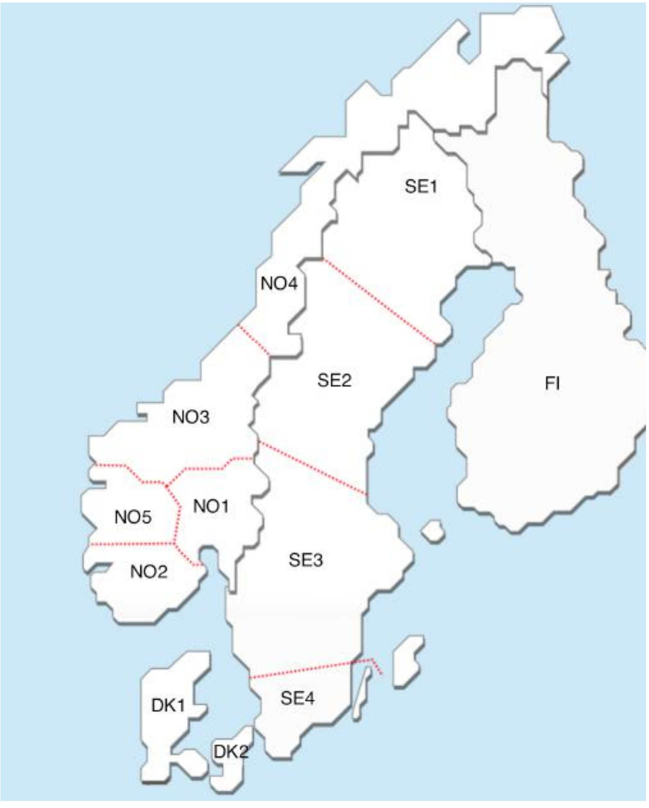


Figure 1: Nordic bidding areas

Norway was the first country to deregulate its market, initiated by the energy act in 1990, and have formed the basis for a deregulated Nordic market (Nord Pool 2016b). Today it is a common Nordic market with substantial exchange of power between countries.

2.2 Norway

Historically Norway has had low electricity prices (SSB 2015), due large volumes of low cost hydro power. This has led to large amount of electricity-intensive industry, and the highest electricity use per capita in the world (IEA 2015). Norway also uses a lot of electricity for space heating, leading to a peak demand highly dependent on temperature.

Norway produces, in a normal year, about 135 TWh electricity; divided between 96% hydro power, 2% thermal and 1% wind power (OED 2015). The large hydro reserves ensure a high percentage of renewables in the energy mix and are also the reason Norway often is referred to as the "green battery" of Europe. Variation in reginal and seasonal inflow and consumption give a need for power exchange. EU hopes that Norway's hydro power can be a possible energy storage capacity in the transition to renewable energy (European Commission 2011). The high share of hydro power is not always an advantage, and Norway is vulnerable for variations in inflow. The inflow to the Norwegian power plants can vary with 75 TWh for very dry or very wet years (Holmqvist 2014). Nevertheless, Norway usually produces more electricity than their own consumtion, and exports the rest (Figure 2). Nord Pool started as a marketplace to trade excess power within Norway, but it has developed to be Europe's biggest power market.

Norway has a number of policies to increase the production from VRE sources, but the most important for the VRE production is the Electricity certificate system. Sweden and Norway have a common system that took effect in 2012. The goal is to increase the production from renewable sources with 28,4TWh by 2020 (NVE 2015).

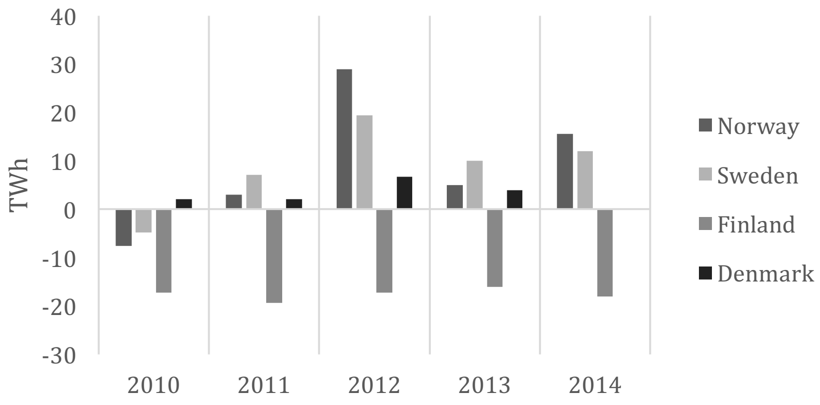


Figure 2: Net export/import of electricity in the Nordic countries from 2010-2014 (CIA 2015; Swedenenergy 2015). Export is showed as positive values.

2.3 Sweden

Sweden has a high energy consumption compared to other countries in the world, but has a low emission rate per capita due to their type of energy production. Sweden's production comes mainly from nuclear and hydro power (approximately 50 and 40% respectively) as seen in Figure 3, but increasing shares also comes from wind and renewable waste and biomass.

Most of Sweden's power production is in the northern part, but the main share of consumption is in the southern part. This is, in addition to an ambition for greater power exchange, the reason Sweden was divided into four power price areas (Figure 1) in 2011 (Swedish Institute 2016).

Nuclear power is tax-discriminated in Sweden, while wind and biomass are subsidized (World Nuclear Assosiation 2016). Renewable production is subsidized through the combined certificate system in Sweden and Norway.

Sweden has had net export of electricity the last few years (Figure 2), much due to an increase in wind power plants, and a decrease of electricity consumption from industry. The main part of Sweden's export goes to Finland (Swedenenergy 2015).

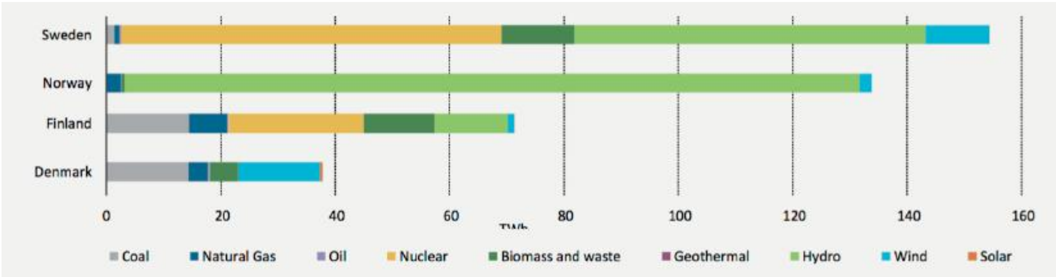


Figure 3: Electricity generation in the Nordic countries in 2013 (Nordon & IEA 2016)

2.4 Finland

Electricity consumption per capita in Finland is the highest in the European Union due to high intensity industry and cold temperatures.

30% of Finland's electricity production comes from Nuclear reactors (World Nuclear Assosiation 2015). Combined heat and power production (CHP), import and hydro power is the second, third and fourth largest contributor to their total electricity balance (Figure 3). The potential for increased large scale hydro production is small, but small-scale production can be expanded. Finland is the most forested country in Europe, and bioenergy is also an important part of the electricity production. In 2014 bioenergy was 17% of the total gross electricity generation (EC 2016).

Europe's Energy and Climate policy obliges Finland to increase the use of renewable energy by at least 38% of total consumption. One strategy to reach the goal is to maximize the use of bioenergy in the forest industry (The Finnish Government 2013).

Finland pioneered carbon tax in 1990 in an effort to mitigate climate change, and have been one of the leading industrial countries to use renewable energy. To ensure competitiveness of renewable energy sources the Finnish government have implemented subsidies for electricity, tax relief, energy taxation and investment in long term technology research and development (Karhunen et al. 2014).

Traditionally Finland has imported large amounts of electricity from Russia, but low prices in the Nordic market have resulted in a reversal of the energy relationship. In 2015, for the first time, Finland exported electricity to Russia. In return, Finland imports electricity from the Nordic regions (Figure 2).

2.5 Denmark

Denmark has a lower electricity consumption per capita than the EU average due to high electricity prices. The general taxes have given Denmark the highest household price in Europe (Eurostat 2015). Nevertheless, the consumption forecast shows an increase in the electricity consumption, due to increased use of electricity in the transportation sector, and increased use of electricity for heating. The electricity consumption is expected to increase by 11% from 2015 to 2024 (Energinet 2015).

Denmark's production has been relatively secure since the first oil crisis in 1975. Denmark was 95% dependent on oil, but since the conversion has had a more differentiated energy production consisting of coal, oil, natural gas and renewables (The Danish Government 2011). Denmark was the first country to install wind turbines, and currently have the highest level of wind power integration in the world. In 2014 Denmark produced a total of 32 TWh where 41% was on-, and offshore wind power. The goal for 2020 is 50% (EC 2016).

Denmark usually has a net import of electricity, with typically greater levels of import in wet years, when the reservoir levels in Sweden and Norway are high (eg. In 2012) (Figure 2).

In 2010 Denmark implemented net metering, a project that lets consumers and public institutions with solar panels send surplus production into the grid. This has increased the incentives to install solar panels. Danish energy sector players estimate that the solar power capacity will increase to 3400 MW by 2030 (Ministry of Foreign Affairs 2012).

Denmark's long term energy goal is to be completely independent from fossil fuels by 2050, while maintaining a stable supply and a greenhouse gas neutral energy sector (The Danish Government 2011). The focus for the transition is cost-effectiveness, meaning minimal subsidies to large scale technologies, and more research and development to make technologies competitive in the future.

2.6 Grid connections

To have a reliable and secure supply the market needs a grid that can transfer sufficient amount of electricity.

Statnett is Norways system operator and operates roughly 11,000km of high voltage transmission lines. Sweden's system operator is Svenska Kräftnet and controls a national grid with 15,000km of transmission lines. In Denmark the system operator is Energinet, and in Finland Fingrid is responsible for the grid. Denmark's and Finland's grid consists of 6800 and 14400 km transmission lines respectively (Figure 4).

Uncertainty surrounding development in the power system, and an expected increase in the need of transfer capacity has led to a historically high investment in the Nordic grid. The domestic connections between regions and countries are constantly reinforced and developed, and a number of new interconnections with countries outside the Nordic market are planned, including:

- NORDLINK: New cable between Tonstad/Ertsmyra in Norway and Wilster in Germany (underseas) – Commercial operation in 2020. Planned capacity is 1400 MW(Statnett 2013a).
- Skagerrak 4: Interconnection between Norway and Denmark. The submarine cable was in operation from December 2014 and has a capacity of 700MW. This expansion increased the transmission between Denmark and Norway to 1700WW (Statnett 2012).
- NSN interconnector: New cable between Suldal in Norway and Newcastle, England. The connection should be operational in 2020 and will increase transmission capacity by 1400MW (Statnett 2013b).

Statnett, anticipates that the power trading capacity between the Nordic countries and Europe will double over the next decade (Statnett 2015).

Figure 4: The power grid 2015 (Svenska Kraftnät 2016)

3 Concepts and definitions

3.1 Reliability indices

Historically, the adequacy has been assessed using capacity balances, where the total demand is compared to the sum of MW in generation plants, giving a capacity margin(DEA 2015). This methodology does not capture the variability of VRE. A probabilistic approach will capture more variables and give a more authentic representation of the generation adequacy.
Probabilistic methods for determining reliability indices can be divided into two techniques: Analytical and simulation (Boroujeni et al. 2012). The analytical uses analytical models and determines the indices from mathematical solutions. Simulation techniques, as used in this study, simulates the actual process and thus captures the random behavior of the input. A subdivision of power system reliability as viewed by this thesis can be seen in Figure 5.

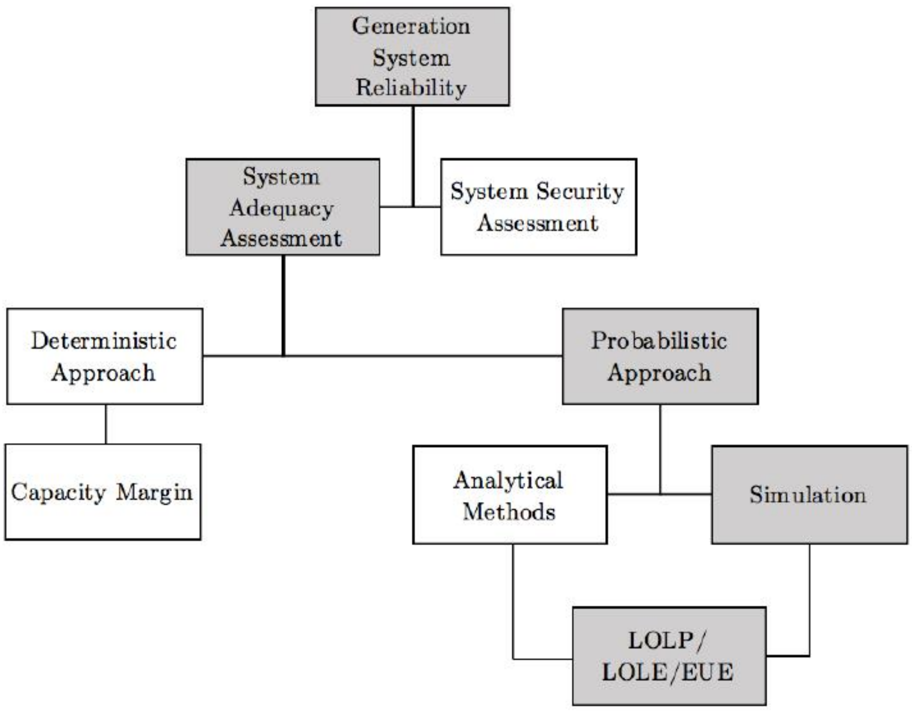


Figure 5: Subdivision of generation system reliability.

A number of indices can be used to assess reliability. The next paragraphs will include some of the most common measures for generation adequacy, and some relevant definitions used in reliability assessments.

3.2 De-rated Capacity Margin

The capacity margin is the difference in peak demand and available supply. This gives a static measurement of the generation adequacy, but does not consider variability in the adequacy due to climate variations over the time period. De-rated means that the supply takes into account the availability of the plant. The de-rated capacity margin is usually expressed as a percentage (DECC 2013).

3.3 Loss of Load Probability and Loss of Load Expectations

LOLP is a well-known probabilistic measure of how much time the load of a power system is expected to be greater than available capacity. It was first introduced by Calabrese (1947) and considers the quantity and mix of generation in relation to the anticipated load and the probability of forced outage. Variation in generation adequacy that might occur due to climate variations can be taken into account. The mathematical calculation of LOLP shown in eq. (1) (Milligan et al. 2016). As LOLP is a probability measure the value is a number between 0 and 1. Statnett and ENTSO-E uses a system requirement of LOLP not exceeding 1 ‰ (Engvall & Løvås 2010).

$$\mathrm{LOLP} = \mathrm{P}[\mathrm{C_i} < \mathrm{L_i}] \quad (1)$$

P: Probability
L: Expected load during day i
C_i: Available capacity during day i

A parallel term to LOLP is loss of load expectation (LOLE) which is the statistically amount of hours/days in which demand is not met in a year (DECC 2013). A common target value for LOLE is 1 day/10 years. The relationship between LOLP and LOLE is shown in the eq. (2) below (Milligan et al. 2016).

$$\mathrm{LOLE} = \sum_{i=1}^{N} P[C_i < L_i] = \sum_{i=1}^{N} LOLP \qquad (2)$$

N: Number of days in year

3.4 Expected Unserved Energy

Expected unserved energy (EUE) is a probabilistic measure that states the amount of outstanding demand not met by generation in a given time frame. Unlike LOLP, EUE expresses the amount of unmet demand. EUE is expressed as MWh over a set time period (DECC 2013). The calculation of EUE at time t, and EUE over the total period of time can be seen in eq. (3) and (4) .

$$\mathrm{EUE}_i = \sum\nolimits_i LOLP \cdot (L_i - C_i) \qquad (3)$$

$$EUE_{TOT} = \sum_{i=1}^{N} EUE_i \qquad (4)$$

D_t: Load demand at time t

3.5 Value of Lost Load

Value of loss load (VOLL) is the estimated amount a customer would pay to avoid disruption in supply (DECC 2013). This requires that a value is assigned to unserved energy.

3.6 Forced outage rate

Forced outage rate (FOR) is a measure of unit unavailability. A forced outage can occur when equipment fails, by operational errors, disruption in the supply chain for plant fuel etc. FOR is calculated (as shown in eq. (5) over a longer period of time, typically a year (Boroujeni et al. 2012).

$$FOR = \mathrm{f} = \frac{Forced\ outage\ hours}{In\ service\ hours + Forced\ outage\ hours} \quad (5)$$

The metrics presented here makes it possible to evaluate the generation adequacy in a market or country, and one or more criteria can make the basis for a reliability standard. At present, the generation adequacy does not have an international standard, and assessment of the reliability is conducted differently from country to country.

4 Method and materials

4.1 Model

The model in this study uses Balmorel as a data base, but with some augmentation. Figure 6 shows a sketch of the model.

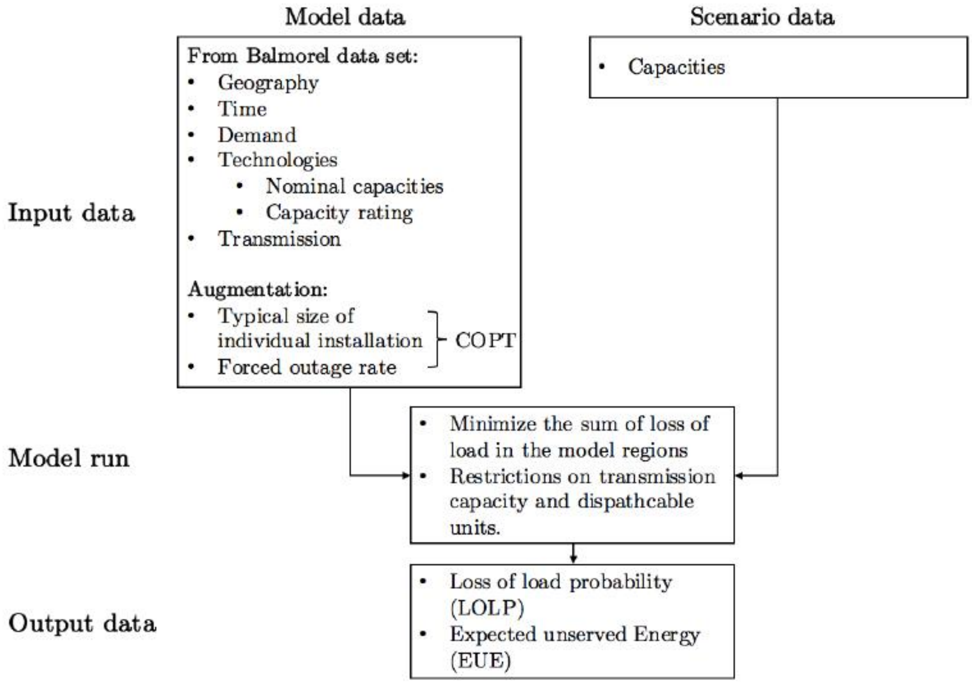


Figure 6: Sketch of the model

The Balmorel model is a linear partial equilibrium model simulating generation, transmission and consumption in competitive markets in the Baltic sea region. It was developed by a cooperation between organizations in Baltic countries to enlighten international aspects and develop future policies in a market with increased trading in electricity. The model is open source, and is available for download with full documentation (Ravn 2001). The model has been used in a number of studies (Goransson & Johnsson 2011; Juul & Meibom 2012; Munster et al. 2012).

The model applied in this study was developed by Ravn (2016) and is based on the method of convolution of derivation of the distribution of available dispatchable generation capacity. It calculates the probability distribution of available capacity, and the probability of the available capacity being a certain size. This can be used to give an estimate of LOLP to assess the generation adequacy. The concept of the calculations consists of four main steps, including:

1. Calculation of residual demand probability distribution
2. Calculation of the dispatchable generation capacity probability
3. Calculation of the probability that the transmission capacity on a particular line has a certain size.
4. Calculation of LOLP, EUE and VOLL if a value is assigned to unserved energy.

Simultaneous occurrences of the first three steps are taken into account. The last step will give a calculation of the probability of serving demand. The calculation is performed for every hour.

4.1.1 Geographical resolution

The Geographical solution consists of countries subdivided into regions and covers several countries with the same electricity market. The market consists of the Nordic countries (Norway, Sweden, Finland and Denmark) in addition to third region countries. Third region countries are countries that border the Nordic countries (Germany, Netherlands, UK, Estonia, Lithuania, Poland and Russia). The Nordic countries are subdivided into Nord Pool price regions. Transmission lines allow for exchange of power between regions, but is restricted due to limited capacity. Transfer capacity between third region countries is unlimited. Each region is given a time series to predict variability in demand, production and transmission. The time series is subdivided into hours and weeks and indexed as region and hours for demand and production, and hours and pairing of regions for transmission.

4.1.2 Mathematical framework

The model is a linear programming model where the goal is optimization of a linear programming function. A linear programming model consists of an objective function and constraints. The objective function (6) seeks to minimize the sum of loss of load in the model regions by counting the number of times the capacity is insufficient. This is represented by the positive variable VQEEQ_SOS(Y,IR,S,T,O) which turns to zero when there is sufficient capacity available to cover a (Y,IR,S,T,O). The sum of these occurrences gives the left hand side free variable VOBJ_SOS. LOLP is derived from this number. The objective function is subjected to the constraints in equation (7), which expresses that dispatchable production and import needs to be larger or equal to the residual demand minus export. To ensure feasibility of equation (7) the positive variable, VQEEQ_SOS(Y,IR,S,T,O) is added. The optimization period for the model is the year 2030, subdivided into time periods with hourly resolution.

$$VOBJ\_SOS = \sum_{Y,IR,S,T,O} 1 \cdot VQEEQ\_SOS(Y,IR,S,T,O) \tag{6}$$

$$\begin{aligned} GKAVAILCOMBMW&(Y,IR,S,T,O) + IREMKAP(Y,IR,S,T) \\ &+ \sum_{IRE} VX\_SOS\_T(Y,IRE,IR,S,T,O) \\ &\geq RESDEM(Y,IR,S,T) \\ &+ \sum_{IRI} VX\_SOS\_T(Y,IR,IRI,S,T,O) \end{aligned} \tag{7}$$

VOBJ_SOS: The number of times with loss of load

VQEEQ_SOS: Positive variable that represents the loss of load.

GKAVILCOMBMW: Available dispatchable capacity

IREMKAP: Capacity not included in convolution due to rounding, but is included in the total available dispatchable capacity.

VX_SOS_T: Transmission (Positive variable)

RESDEM: Residual demand

Y: Subset that represents year.

S, T: Subset of time segments in years. Subsequently week and hour.

IR: The regions simulated.

IRI/IRE: Represents pairs of regions, where the I and E represents importing- and exporting regions.

O: A set of simultaneous occurrences of residual demand, available dispatchable generation capacity and transmission capacity.

4.1.3 Principle of convolution

To predict the probability of a capacity being unavailable a capacity outage probability table (COPT) is created for dispatchable generation. The recursive expression used to build the table is showed in eq. (8), where one two state (Up or down) unit k, is added at a time. The variables P and f are considered random variables.

$$P(C_{k+1}^{a} \equiv x) = P(C_{k}^{a} \equiv x)f_{k+1} + P(C_{k}^{a} \equiv x - K_{k+1})(1 - f_{k+1}) \quad (8)$$

P: Probability

x: Total available capacity

C_{k+1}^{a}: Available capacity after insertion of unit k

K_{k+1}: Capacity of unit k+1

f_{k+1}: FOR for unit k+1

The initial value for $P(C_{0}^{a} \equiv x)$=1. The left hand side of the equation replaces $P(C_{k}^{a} \equiv x)$ when next unit is added. An example can be seen in Figure 7 where the basic elements are a number of units with a given size (MW) and FOR.

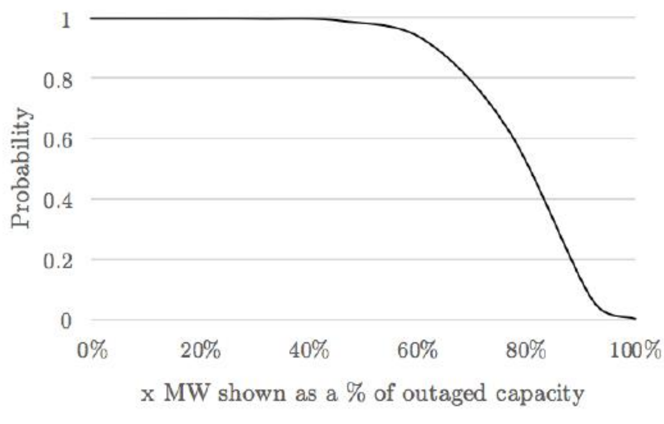


Figure 7: Example of convolution. The graph shows the probability that generation outage capacity will exceed x MW in a system with six 200 MW units with a FOR=0.01 and total capacity 1234 of MW.

Residual electricity demand (demand minus non-dispatchable fluctuating electricity generation) is also to be considered probabilistic. The joint probability of demand and fluctuating energy generation is found using time series and used to calculate the probability of residual demand being at least x MW.

A number of studies have pointed out that an interconnected system is an important aspect of reliability studies (Calabrese 1947; Milligan et al. 2016). Demand and supply in different areas is only partially correlated in different areas and can benefit each other. To include this in the model transmission is considered to be a probabilistic variable based on time series. The transmission capacities are given as time series with capacity rating where the capacity rating represents deviation from maximum net transfer capacity.

4.2 Load duration curve

A load duration curve (LDC) is generated to show the relationship between capacity utilization and load. A load curve shows load in chronological order, but a LDC sort the values in descending order. The load is typically collected from hourly demand for one year or longer, divided by maximum capacity to get normalized values. Schematics are shown in Figure 8.

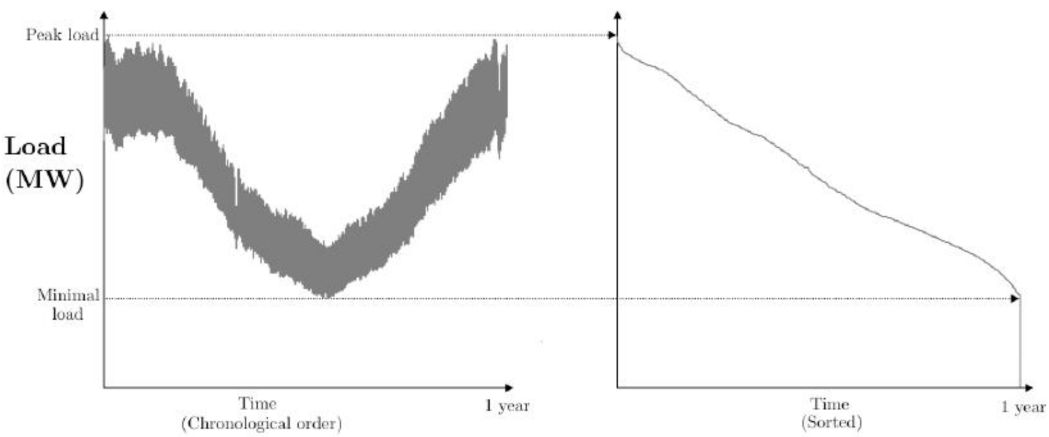


Figure 8: Schematics of load curve (adapted by Ueckerdt et al. (2015). The load curve (left) is sorted from largest to smallest value to derive the LDC (right). The figure shows the average load in region NO1 from 2000-2001.

4.3 Residual load duration curve (RLDC)

The residual load (RL) captures the relation of the different VRE supply profiles and demand by calculation the difference in load and production of VRE. It is based on time series of load and VRE supply.

The residual load is calculated for every time step (hour, day, week, month) and the residual load duration curves (RLDC) is derived by sorting the load curve from largest to smallest value as shown in in equation (9) to (11), and Figure 8.

RLDC is commonly used as illustrative examples, but also as input to models and as quantity tools to analyze systems (MacCormack et al. 2010; Ueckerdt et al. 2015).

The duration curve does not give a detailed description of the residual load in a time perspective. The sorting of the data from lowest to highest values implies loss of information of the exact point in time. Values that are similar and collide in the duration curve, are not always the same values that collide in the time series. However, low values will be sorted together, and in that way capture the total variability of the total time period (Ueckerdt et al. 2015), and give an indicator for the flexibility demand needed to ensure a reliable system. Negative values will indicate an overproduction of electricity from VRE sources, while positive values give the need for backup power production.

$$RLDC_c(t) = Sort\ (Load\ (t) - Generation_{VRE}(t)) \qquad (9)$$

$$Generation_{VRE}(t) = W_{On}(t) - W_{Off}(t) - PV(t) - ROR(t) \qquad (10)$$

$$\begin{aligned} W_{On}(t) &= \alpha_t^{Won} * C^{Won} \\ &\vdots \\ ROR(t) &= \alpha_t^{ROR} * C^{ROR} \end{aligned} \qquad (11)$$

RLDC(t): Residual load duration curve

$W_{On}(t)$: Production from Onshore Wind power.

$W_{Off}(t)$: Production from Offshore Wind power.

ROR(t): Production from run of river hydro power.

PV(t): Production from PV power.

α_t^{Woff}, α_t^{Won}, α_t^{PV}, α_t^{Ror} : Normalized production level for offshore wind-, onshore wind-, PV- and ROR hydro power production.

$C^{Won}, C^{Woff}, C^{PV}, C^{ROR}$: Capacity for offshore wind-, onshore wind-, PV- and ROR hydro power production.

4.4 Data

This chapter will address sources used to collect data, generation of complete data sets and processing to make the selection representative. The section 4.4.1-4.4.6 will discuss the data in the Balmorel model. Section 4.4.7-4.4.8 is augmentation data needed but not represented in Balmorel. LDCs and RLDCs was made using data in section 4.4.1-4.4.4.

All data is filed in present Elspot bidding areas, and is mainly collected from publicly available sources to ensure a basic principle of transparency consistent with Balmorel's open source ideal.

The data sets for production are synched with data sets for load and sorted chronologically following academic literature, that cautions against other methods (Holttinen et al. 2009; Holttinen et al. 2011; Keane et al. 2011). Weather is the driver behind wind-, photovoltaic- and hydro energy, and to some extend demand and a chronological pairing ensures to capture its influence.

4.4.1 Consumption

The data sets for consumption are collected with hourly precision. After generation of a complete dataset, it is divided by installed capacity to make numerical values that can be used for modelling purposes. The finished set consists of 113 976 recordings for each bidding area.

Norway

Data from 1.1.2000-31.12.2012 is collected from Nord Pool (2016a). Norway was divided into five Elspot/Elbas areas (NO1-5) in 2010 (Nord Pool 2015). Data from 2000-2010 is extrapolated by trend lines into areas (see Figure 9), assuming a linear relationship. For equations used, see Appendix A.

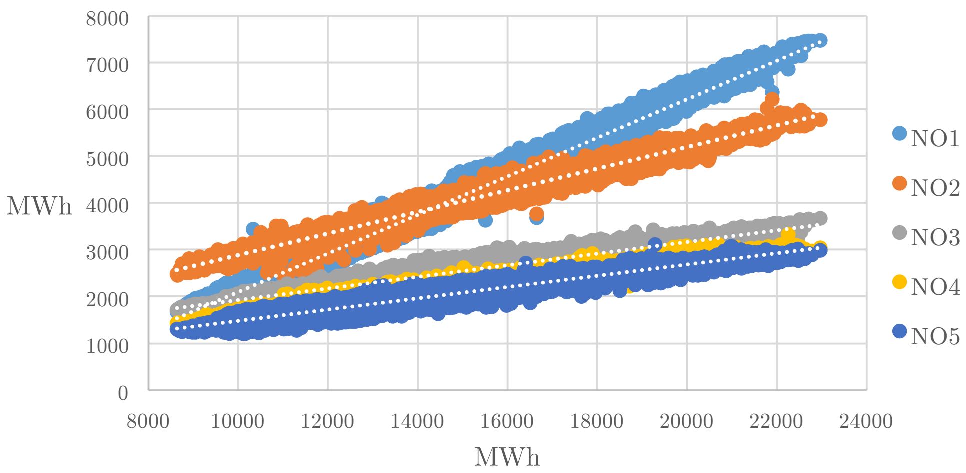


Figure 9: Extrapolated trend lines (2000-2015), Norway. The-axis shows the total consumption by MWh, and the y-axis shows the corresponding consumption in each area.

Sweden

Data from 2000-2012 is collected from Nord Pool (2016a). Sweden was divided into four bidding areas (SE1-4) in November 2011 (Nord Pool 2015). Preceding data has been extrapolated by trend lines into the four present areas (see Figure 10), assuming a linear relationship. For equations used, see Appendix A.

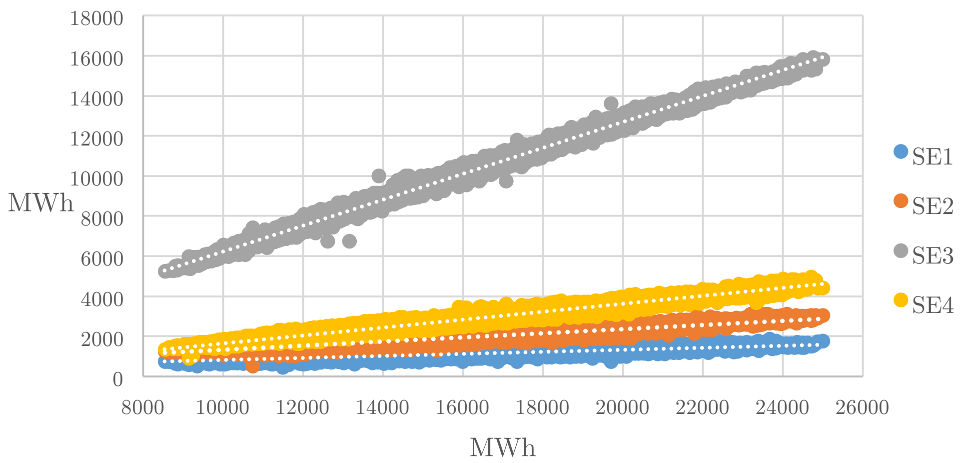


Figure 10: Extrapolated trend lines (2000-2011) in Sweden. The-axis shows the total consumption by MWh, and the y-axis shows the corresponding consumption in each area.

Denmark and Finland

Denmark and Finland are represented with two (DK1-2) and one (FIN) market area respectively. There have been no changes in the bidding areas since 2000, so consumption data from 2000-2012 is collected directly from Nord Pool's historical data base (Nord Pool 2016a).

Adjustment Factors

The consumption data used in the model is multiplied with an adjustment factor to level out irregularities not related to temperature and weather differences. Since the data sets are used as variability in the model it is desirable to level out drivers that contains differences related to economic activity, changes in energy effectivity or other drivers for demand not related to weather. Not removing these irregularities will impact the LOLP values and the validation of the data. To level out the data is consistent with Milligan et al. (2016). The adjustment factors used can be seen in Figure 11, and includes estimates of economic activity.

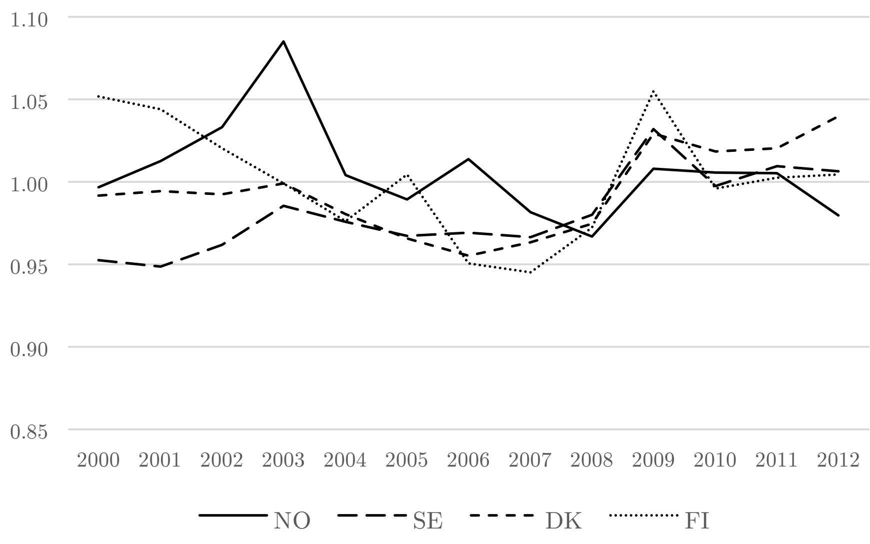


Figure 11: Adjustment factors used each year from 2000-2012 in the Nordic countries.

Growth rate

The growth rate in electricity and heat consumption is assumed to be corresponding to the growth rates in the EU Commission roadmap to 2050 (European Commission 2011). The assumed annual consumption can be seen in Table 1.

Table 1: Yearly consumption of district heat and electricity for the year 2030. Electricity consumption is given as net consumption (gross consumption - network losses - energy used for pumped hydro) while consumption for district heat is given as gross consumption. Values in TWh.

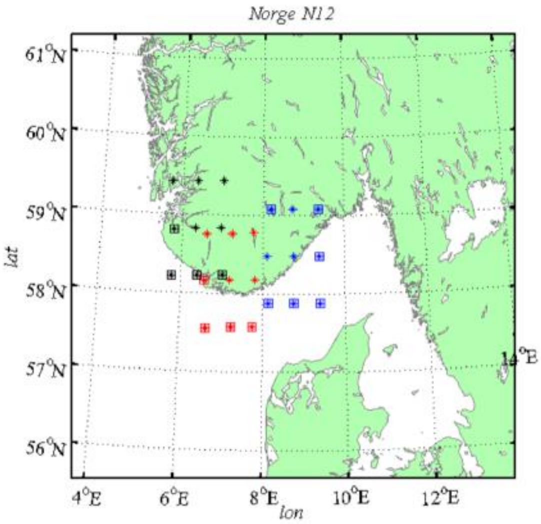
	Consumption of district heat	Consumption of electricity
Norway	8	117
Sweden	50	138
Denmark	34	31
Finland	36	83
Germany	-	549
Netherlands	-	120
UK	-	339

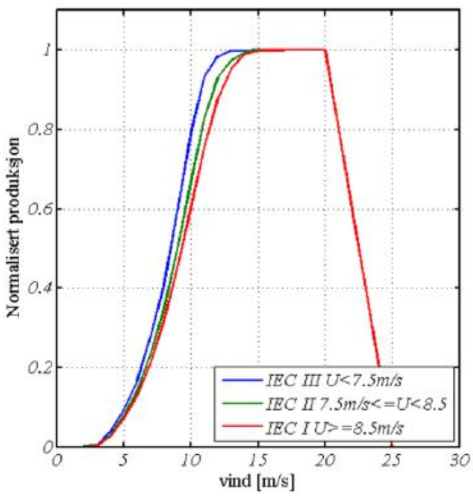
4.4.2 Wind Power Production

Data from 2000-2012 for wind power production is collected from a report calculating power production in Nordic Countries and Northern Europe. The calculations are executed using a mesoscale numeric weather forecasting model called the Weather Research and Forecast (WRF) model (AAkervik 2012). Further descriptions of calculations are based on this report. The generated time series shows hourly capacity utilization by considering wind speed and theoretical potential.

The calculations domain is executed on both offshore and onshore wind with a horizontal resolution of 6x6, and 18x18 square meters. In areas not covered by the 6x6 resolution 18x18 square meters is used. In each cell the changes in physical parameters (Wind, temperature etc.) are calculated.

To calculate wind power production time series, data sets are collected for certain nodes (Figure 13) . Where each node is modeled into 9 model points within a distance of plus and minus 0,6. This is illustrated in Figure 12a. The middle wind speed is collected at a height of 80 meters.





(a) (b)

Figure 12: (a) Overview of area N12 in Norway. The squared points are removed in the model due to high or low wind speed, or they have a location offshore (AAkervik 2012). (b) Power curves for different mean wind speeds (AAkervik 2012).

The time series for production are found by weighing the wind speed with a normalized power curve between 0 and 1 (to make it independent of actual installed power). Different power curves are used for various mean wind speeds (Figure 12b). The calculations assume a loss of 10% due to turbulence, downtime etc. in addition to wake loss in parks where turbines are positioned close together.

The production nodes seen in Figure 13 have been weighted and averaged to fit the Nordic bidding areas to make the data comparable with other data sets. The distribution of the nodes in the Nordic bidding areas can be seen in appendix B.

The finished data sets consist of 113 976 recordings for each bidding area for offshore and onshore wind power production.

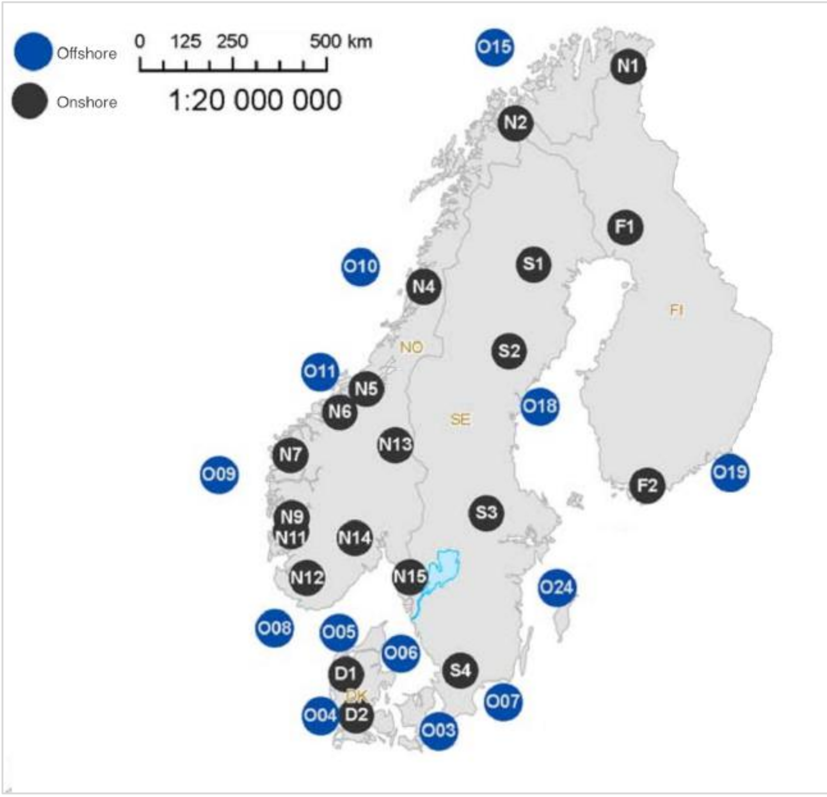


Figure 13: Wind power production nodes for the Nordic countries (AAkervik 2012).

4.4.3 Photovoltaic Power Production

Data for photovoltaic production was found using the same report as wind power production. AAkervik (2012) uses downward short wave flux at ground (SWDOWN) to calculate time series for production. The model takes into account both direct and diffuse short-waved insolation and is modeled into 9 model points within a distance of plus and minus 0,6 degrees. Insolation is averaged over the node points to even out local effects.

To calculate total insolation on a panel AAkervik (2012) has divided the solar radiation between direct and diffuse insolation. The model does not take into account albedo effects. Total insolation to the panel are given by:

$$G_p = B_p + D_p \tag{12}$$

The direct insolation on the panel are given by:

$$B_p = \frac{G - D}{cos\theta_z} \max(0, cos\beta) \quad (13)$$

and the diffuse insolation on the panel are given by:

$$D_p = D^{(1+cos\alpha)}/2 \quad (14)$$

G: Insolation from model

D: Diffuse part of insolation

K: Clarity index

F_D: Diffusivity index (Calculated by the clarity index)

The area and effectivity of the solar panel in addition to an assumed loss from wiring etc. are taken into account and the normalized production, P is calculated to be:

$$P = C_A C_{eff} C_l G_p \quad (15)$$

AAkervik (2012) has calculated production in 12 selected nodes (Figure 14) in Europe. The time series does not include production nodes in Norway, Sweden and Finland. It proved difficult to obtain good data sets on PV production representative for these countries. PV production is still not a large part of total power production, but it is increasing. This study is trying to give an overview of possible development in the Nordic countries in the future and a disregard of any future PV production in the areas will most likely not be realistic. Assuming similar production and development in Denmark as in Southern Sweden and Norway, data sets were generated. The finished set consists of 113 976 recordings for each bidding area.

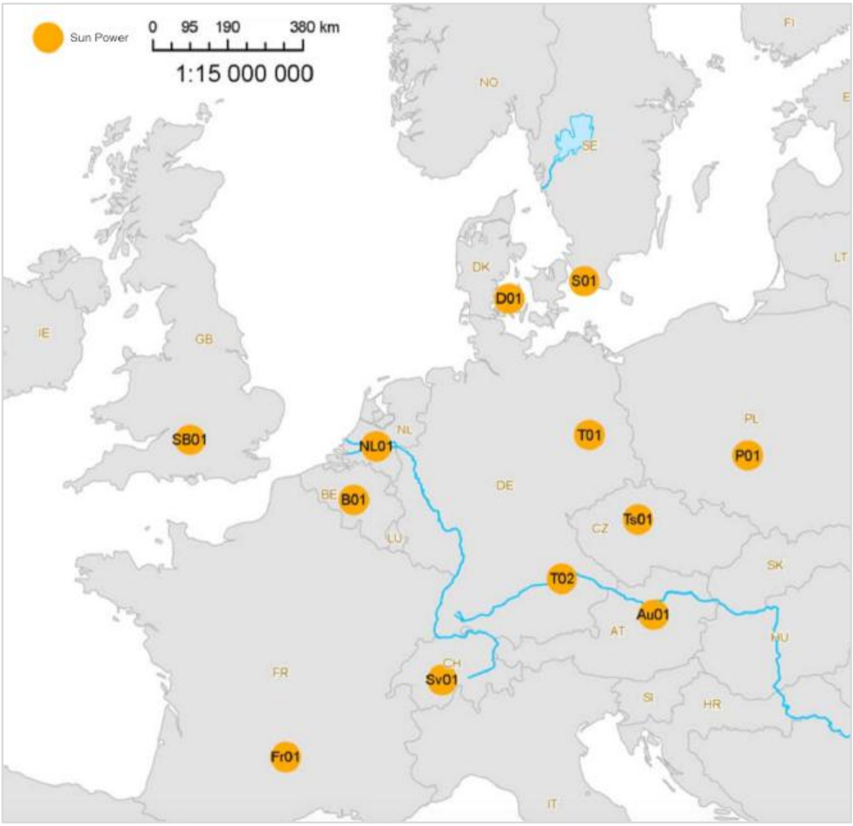


Figure 14: Photovoltaic power production nodes (AAkervik 2012).

4.4.4 Run of River Production

Production series for hydro without storage in Norway is based on data for weekly inflow energy from run of river (ROR) production in 2000-2012 and is collected from Statnett. Aggregated data series for inflow in Sweden is based on inflow for areas in Norway. Distribution of metering points in each zone can be seen in appendix D.

Inflow series for Finland from 2010-2014 are collected from Finnish Energy (2015). The data include hydro storage and ROR production. To single out ROR production the time series was divided with 1,8 (Assuming about 50% of the inflow goes to reservoir). The normalized values were obtained by dividing the production with max capacity value for ROR production in Finland in 2012 (1596 MW). The maximum limit for capacity utilization was set to 1. Denmark does not have any unregulated hydro power installed and the production was set to zero.

The finished data set consists of 113 976 recordings for each bidding area in Norway and Sweden and 43 823 recordings in Finland.

4.4.5 Nuclear Power Production

Historical data for nuclear production are collected from the open statistical sources Svenska Kraftnät (2015) and Finnish Energy (2015) for Sweden and Finland respectively. The time series are collected with an hourly resolution. Norway and Denmark have no nuclear production today, and does not have any existing policies to produce nuclear power in the future.

Hourly production data for nuclear production is complete from 1.1.2009-12.24.2012 for Sweden and consists of 122 712 recordings. The dataset for Finland is less extensive and consists of 43 814 recordings from 1.1.2010-12.24.2012.

4.4.6 Transmission

Data from transfer capacity for every hour is collected from Nord Pool (2016a) from 2013-2015. The data includes a set of reason codes for reduced transfer capacity (appendix E). Reduction caused by planned outages or maintenance is removed to ensure a time series that predicts variations in outages that can be multiplied for future years. The data is used as historical variations, and does not consider correlations with demand. The finished data set consists of 26 280 recording for each paired transmission interconnection. New interconnectors not present in the data set from 2013-2015 is assumed to have a 7.5 % probability of outage.

The maximum net transfer capacities between Nordic regions are set to capacities from ENTSOE (2016) (Appendix F). It is assumed that all new planned interconnections are carried out to strengthen the grid. A list of the new grid connectors is listed in Table 2.

Table 2: New interconnectors.

Project	Capacity	Year	From - to region
Southwest link	1200	2020	Eastern Norway - south mid Sweden
NordLink	1400	2019	Southern Norway - Germany
NSN interconnector	1400	2021	Southwestern Norway - UK
Kassø-Flensburg-Dollern	1500	2020–2025	Western Denmark - Germany
Krigers Flak	400	2019	Eastern Denmark - Germany
Cobra Cable	700	2020	Western Denmark - Netherlands
DE - NE Strengthening	2000	2017–2018	Germany - Netherlands
Vinking link	1400	2022	Western Denmark - UK
NorNED 2	700	2025	Southern Norway - Netherlands

4.4.7 Typical size of individual installation

The size of each individual installation in the regions is based on empirical data and some assumptions of the development in the future market. The size of each installation can be seen in appendix G.

4.4.8 Forced outage rates on supply mechanisms

The basis for FOR values used in this study is based on a report of Kiviluma and Kokkonen (2012), who have studied the need for capacity reserves in 2013-2017 in Finland.

Table 3: Forced outage rate (FOR) on supply mechanisms (Kiviluma & Kokkonen 2012)

Technology	FOR
Nuclear	0.021
Bioenergy	0.022
Oil/Gas	0.032
Coal	0.042
Hydro	0.020

4.5 Scenarios analyzed

To analyze the generation adequacy in the future it is necessary to make certain assumption of how the electricity market will progress and how it will impact the Nordic market in 2030. In this study the following predicted scenarios are analyzed (see Table 4 for details):

1. Baseline scenario: Assumes closure of some of Denmark's and Finland's coal production, in addition to a current planned shutdown of four nuclear power plants in Sweden. It is assumed that a few small planned CHP plants in Sweden and new planned nuclear power plants in Finland will be implemented. The scenario estimates an extensive development in new wind power.
2. Reduction in nuclear power production: Similar assumptions as in baseline scenario, but all of Sweden's nuclear power is shut down.

Both scenarios are run twice with the assumption of: a) Import form third region countries in peak hours equivalent to effect capacity reduced by possible outages, and b) no import from third regions during peak hours, i.e. the Nordic system is self-sufficient.

The model uses exogenously determined values based on earlier studies for the installed net capacities for different production technologies (Table 4). The values for each bidding area can be seen in appendix H.

Table 4: Installed net capacity per fuel used in the 2030 scenarios (GW). Numbers based on numbers from European Commission (2013)

		Nuc-lear	Nat-ural Gas	Hard Coal	Lign-ite	Oil-fired	CHP (and bioma ss)	Wind	Solar	Hydro	**Sum**
Scenario 1	Norway	-	-	-	-	-	-	4.1	-	36.1	**40.2**
	Sweden	6.7	-	-	-	1.2	5.2	9.4	-	16.9	**39.4**
	Denmark	-	-	-	-	0.6	4.2	6.7	1.4	-	**12.9**
	Finland	4.5	0.0	-	-	1.1	7.3	3.9	-	3.4	**20.2**
	Germany	-	20.0	18.0	14.6	1.0	31.2	67.1	68.0	11.0	**230.9**
	Netherlands	0.6	8.4	5.0	-	0.7	14.1	12.7	1.5	0.0	**43**
	UK	8.4	35.0	6.1	-	1.7	11.4	51.3	23.3	4.5	**141.7**
Scenario 2	Norway	-	-	-	-	-	-	4.1	-	36.1	**40.2**
	Sweden	-	-	-	-	1.2	5.2	9.4	-	16.9	**32.7**
	Denmark	-	-	-	-	0.6	4.2	6.7	1.4	-	**12.9**
	Finland	4.5	0.0	-	-	1.1	7.3	3.9	-	3.4	**20.2**
	Germany	-	20.0	18.0	14.6	1.0	31.2	67.1	68.0	11.0	**230.9**
	Netherlands	0.6	8.4	5.0	-	0.7	14.1	12.7	1.5	0.0	**43**
	UK	8.4	35.0	6.1	-	1.7	11.4	51.3	23.3	4.5	**141.7**

5 Results

5.1 Variability

The electricity consumption is highest in cold months (Nov-Feb) for all the Nordic countries (Figure 15 a-d). Norway and Sweden have similar seasonal profiles (Figure 15 a-b), with an even reduction through to the warmest months (Jul-Aug). Finland also have a reduction similar to Sweden and Norway, but with slightly higher consumption rate through the warmer months and a with a brief steep drop during mid-summer celebrations in late June (Figure 15c). Denmark uses less electricity for heating and has a smaller variation throughout the year with a standard deviation of 0.08, compared to Norway that has the highest variation with a standard deviation of 0.15 (Table 5). Denmark's reduction through the warmest months is comparable to the other regions (Figure 15d).

The seasonal wind power capacity utilization profiles are close to the consumption: High capacity utilization when consumption is high and temperatures are low (Figure 15a-d), causing a correlation between temperature and demand. However, the maximum wind capacity utilization is not coinciding with peak demand. The maximum wind capacity utilization occurs in hour 247-254 (11th of January) for all countries, while maximum demand varies from 0.92-94, depending on country, in the same hours (Figure 15). A closer look at wind capacity utilization in high demand periods (Figure 16), shows that sorting temperature with decreasing wind utilization gives a decreasing trend line for temperature. The figure shows some deviation from this trend line, but wind utilization 30% and lower have temperatures under or equal to -4 °C. The lowest point on the utilization curve is 7% with a temperature of -7.1 °C.

When comparing normalized consumption and utilization of production on a monthly- (Table 7), daily- (Table 5) and hourly basis (Table 5), the utilization is decreasing from hourly to monthly resolution for the maximum and increases for the minimum, but the average values fluctuates. Sweden has the lowest and Denmark the highest utilization of wind capacity throughout the year, but also the highest standard deviation

(Table 5-Table 7). On an average Norway has the lowest utilization of PV, but the highest inflow.

PV capacity utilization is invert from consumption and wind in Denmark. The production is highest in warm months (May-Aug) with low consumption and equal to zero in the coldest months (Figure 15d). The production data for Norway, Sweden and Finland are based on data sets for Denmark's production, and show similar results.

Inflow has a high variability through the year (Figure 15a-d and Table 5 to Table 7). It peaks in May-June when the consumption is relatively low for Norway, Sweden and Finland. Denmark has no hydro-capacity and is not included. The data sets show no correlation between wind- and hydro production (Figure 15).

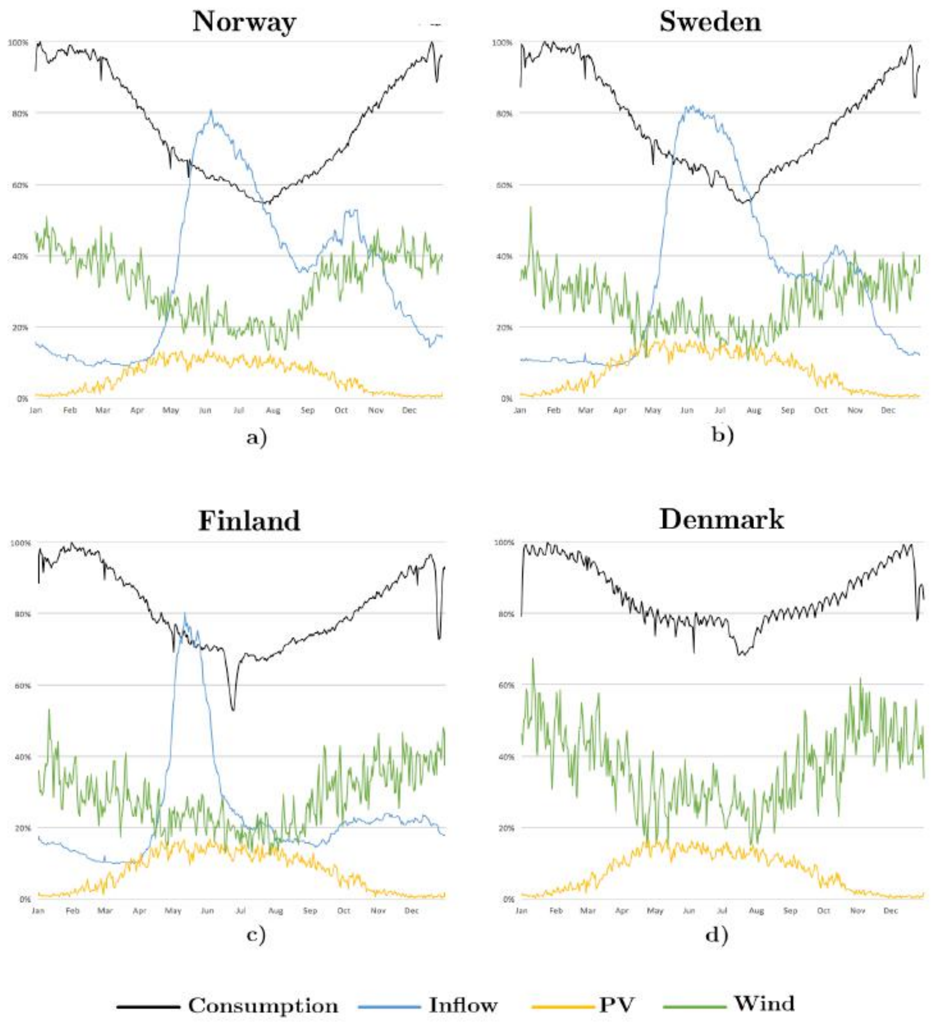


Figure 15 (a-d): Daily averaged normalized curves for consumption and capacity utilization of PV, wind and inflow throughout the year in the Nordic

countries. The curves are normalized relatively to the hourly peak load/maximum capacity for the VRE production and are based on data from 1.1.2000-31.12.2012.

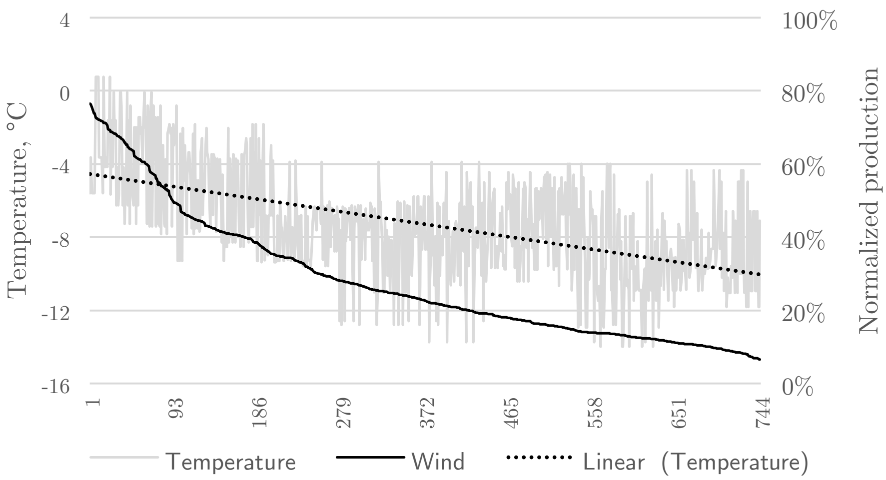


Figure 16: Duration curve for capacity utilization of wind in January 2010, the year and month with highest peak demand in Norway (Figure 18). The production is normalized relatively to the maximum with hourly resolution. Data points for temperature are sorted together with the load duration curve to ensure a matching timeline. Temperatures are collected for each Elspot area (NO1-5) from The Norwegian Meteorological Institute (2016) and averaged to mean temperatures over the whole area. The dotted line shows the trend line for temperature.

Table 5: Key figures for hourly normalized consumption relative to the hourly peak load and capacity utilization of wind, PV and inflow for an average year, based on data from 2000-2012.

		Norway	Sweden	Finland	Denmark
Wind	Max	0.56	0.58	0.56	0.70
	Min	0.10	0.07	0.08	0.08
	Average	0.32	0.27	0.28	0.37
	Standard Deviation	0.09	0.08	0.09	0.11
PV	Max	0.45	0.55	0.56	0.55
	Min	0.00	0.00	0.00	0.00
	Average	0.06	0.08	0.08	0.08
	Standard Deviation	0.10	0.12	0.12	0.12
Inflow	Max	0.75	0.67	0.59	-
	Min	0.08	0.06	0.07	-
	Average	0.32	0.27	0.17	-
	Standard Deviation	0.20	0.19	0.12	-
Consumption	Max	1.00	1.00	1.00	1.00
	Min	0.44	0.41	0.41	0.41
	Average	0.71	0.70	0.77	0.68
	Standard Deviation	0.15	0.14	0.11	0.13

Table 6: Key figures for daily normalized consumption relative to the hourly peak load and capacity utilization of wind, PV and inflow for an average year, based on data from 2000-2012.

		Norway	Sweden	Finland	Denmark
Wind	Max	0.51	0.54	0.53	0.67
	Min	0.13	0.11	0.12	0.14
	Average	0.32	0.27	0.28	0.37
	Standard deviation	0.09	0.07	0.08	0.11
PV	Max	0.13	0.17	0.17	0.17
	Min	0.00	0.00	0.00	0.00
	Average	0.06	0.08	0.08	0.08
	Standard deviation	0.04	0.05	0.05	0.05
Inflow	Max	0.75	0.67	0.59	-
	Min	0.08	0.06	0.07	-
	Average	0.32	0.27	0.17	-
	Standard deviation	0.20	0.19	0.12	-
Consumption	Max	0.81	0.85	0.84	0.87
	Min	0.44	0.46	0.45	0.59
	Average	0.62	0.66	0.69	0.74
	Standard deviation	0.12	0.12	0.09	0.07

Table 7: Key figures for monthly normalized consumption relative to the hourly peak load and capacity utilization of wind, PV and inflow for an average year, based on data from 2000-2012.

		Norway	Sweden	Finland	Denmark
Wind	Max	0.42	0.35	0.48	0.50
	Min	0.22	0.19	0.21	0.27
	Average	0.33	0.28	0.35	0.39
	Standard deviation	0.08	0.06	0.09	0.08
PV	Max	0.11	0.14	0.14	0.14
	Min	0.01	0.01	0.01	0.01
	Average	0.06	0.08	0.08	0.08
	Standard deviation	0.04	0.05	0.05	0.05
Inflow	Max	0.68	0.64	0.51	-
	Min	0.09	0.07	0.07	-
	Average	0.32	0.27	0.17	-
	Standard deviation	0.20	0.19	0.12	-
Consumption	Max	0.78	0.83	0.82	0.84
	Min	0.45	0.49	0.55	0.63
	Average	0.62	0.66	0.69	0.74
	Standard deviation	0.12	0.12	0.09	0.07

The data shows low consumption of electricity at night and high consumption in the middle of the day starting at approximately 6 AM for all countries, with a peak at around 6 PM. Denmark has less difference in consumption between seasons than the other countries, while all countries have a higher consumption in the winter than the summer (Figure 17).

The wind power production shows a relatively flat curve throughout the day both in winter and in summer, but with a lower production in the summer, and in the middle of the day for both seasons. The PV production is higher in the summer, and has a pronounced peak in the middle of the day (Figure 17).

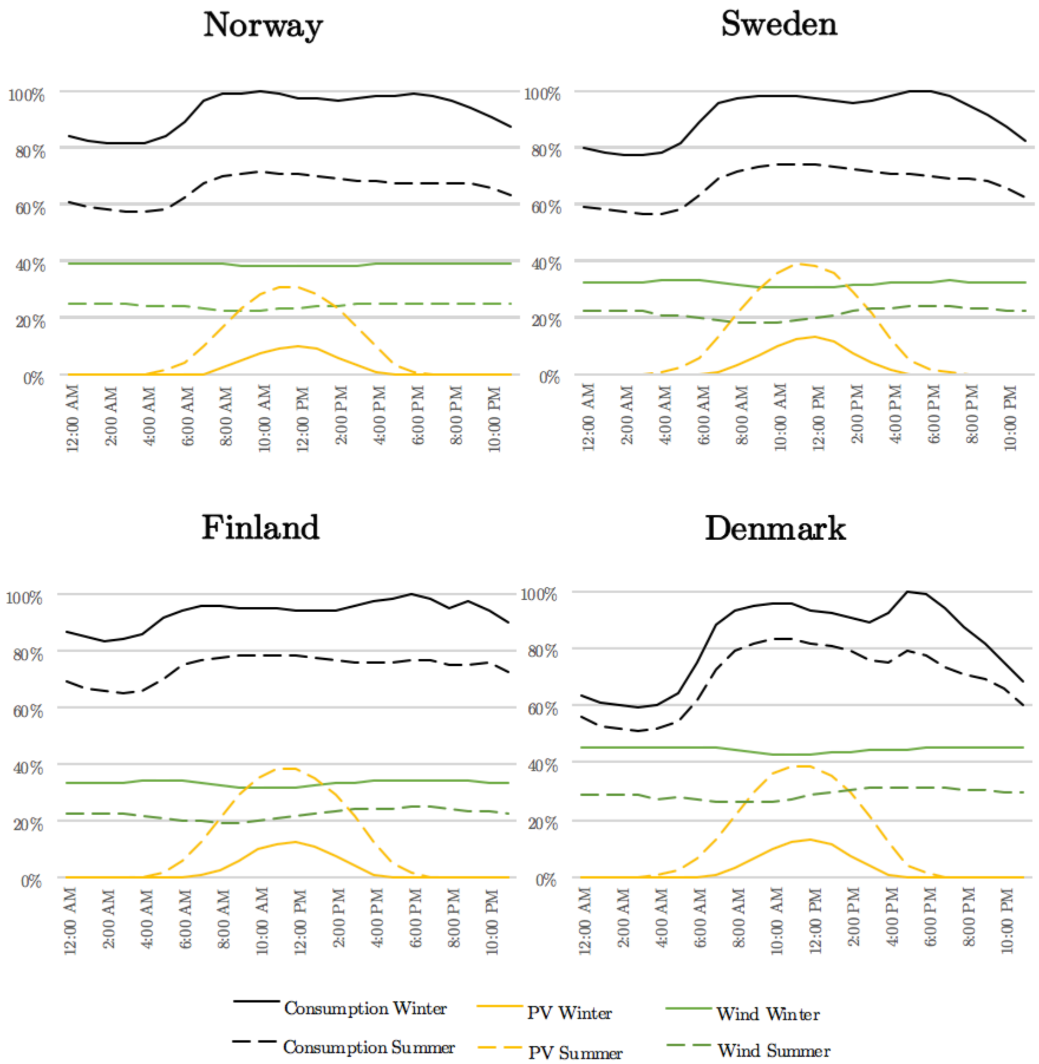


Figure 17: Curves for consumption and capacity utilization of PV, wind and inflow throughout the day in the Nordic countries. The curves are normalized relatively to the hourly peak load/maximum capacity for the VRE production and are based on data from 1.1.2000-31.12.2012

5.1.1 Annual peak demand

The peak load is found by considering the hour with highest electricity demand in the load profile. Overall peak load is found in 2010 for Norway, 2013 Sweden and 2011 for Finland, Denmark and the total combined demand. (Table 8 and Figure 18). Norway and Finland has had an increase of peak demand from 2000-2015 of 11 and 8 % respectively, while Sweden and Denmark have had a decrease of 2% and 5%. The total increase of peak demand in the Nordic countries is 4 % (Figure 18)

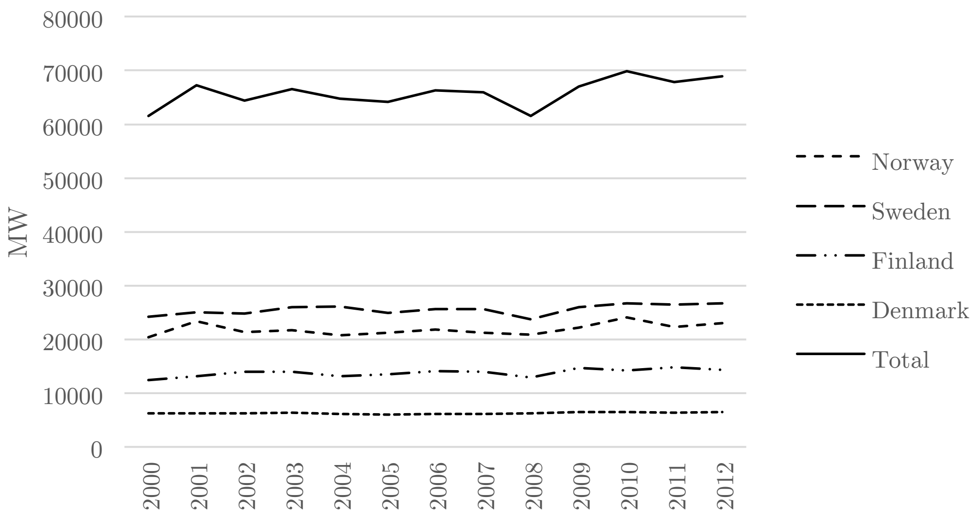


Figure 18: Peak demand in the Nordic countries from 2000-2012 derived from peak hour.

Table 8: Key figures for peak demand (MW) from 2000-2015.

	Norway	Sweden	Finland	Denmark	Total
Max	24116	27172	14838	6470	69851
Min	20344	23741	12441	5928	61510
Average	22002	25527	13798	6251	65989
Standard Deviation	1039	1014	639	155	2401

5.2 Residual load

LDCs and RLDCs for Norway, Sweden and Finland has more of a linear decrease rate than Denmark that has a curve that shifts inwards (Figure 19 and Figure 20). Denmark is the only country with an RLDC that crosses the abscissae. Norway has a RLDC curve that ends on 5 % of the load, while Sweden and Finland ends on 27 and 38 % of the load respectively (Figure 19).

Using an hourly resolution, Sweden and Finland has a close correlation between the load and the residual load. In contrast, Denmark and Norway has diverging curves (Figure 19). This trend can be seen with a daily resolution as well (Figure 20)

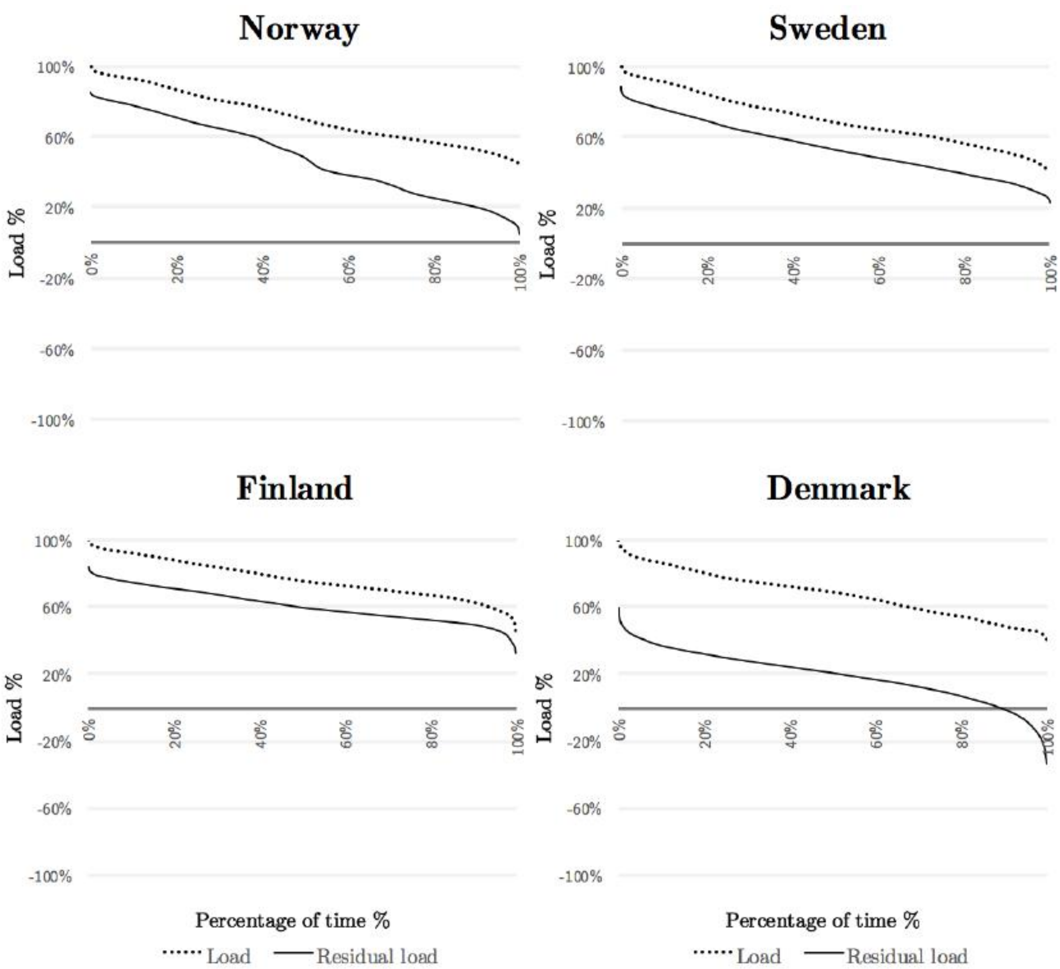


Figure 19: Duration curves for the residual load in Nordic countries in 2030 with hourly resolution. The load and residual load is normalized relatively to the maximum load. The year consists of 8760 hours.

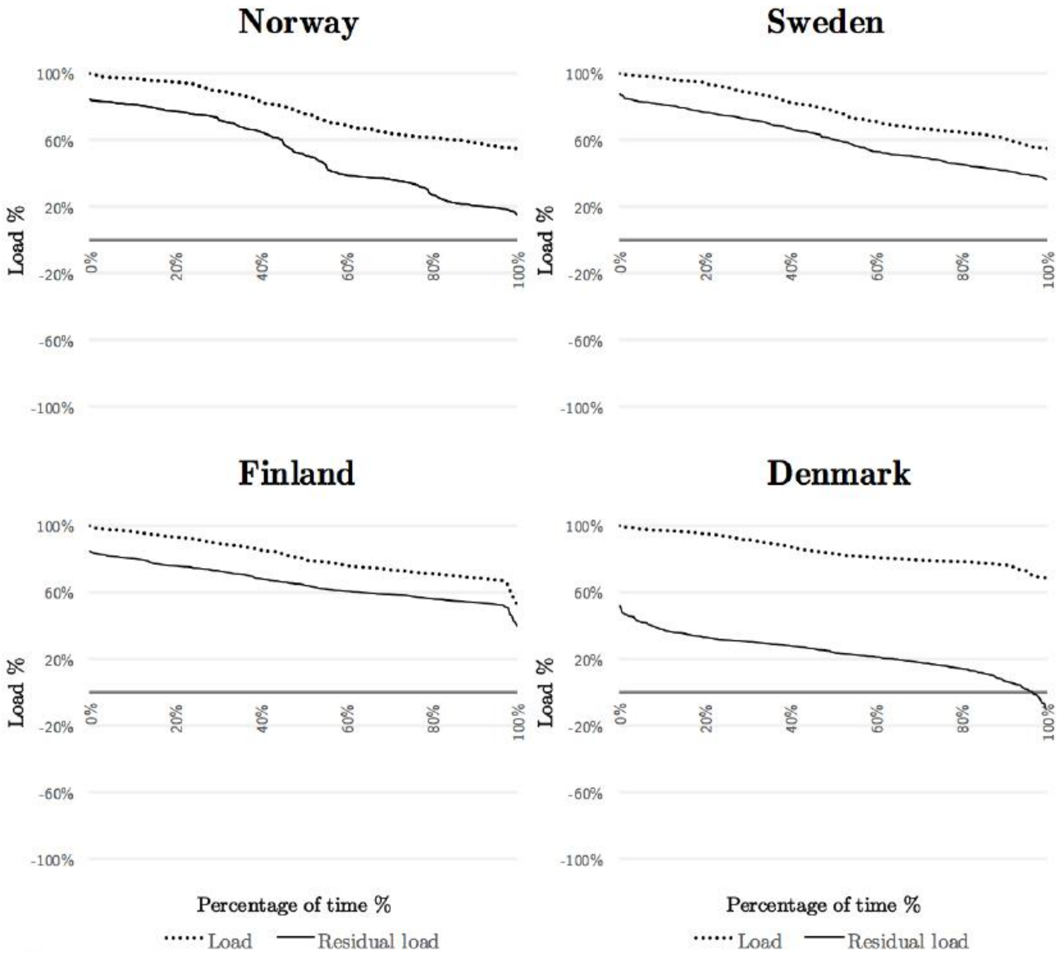


Figure 20: Duration curves for the residual load in Nordic countries with daily resolution from 1.1.2000-31.12.2012. The load and residual load is normalized relatively to the maximum load. Each year consists of 365 days.

Denmark is the only country that will have an over-production of VRE (when RLDC <0) This happens 11% of the time with an hourly resolution (Figure 19), and 3% of the time with a daily resolution (Figure 20). The hour with the largest amount of over-production gives an unused amount of energy of 1811 MWh at the most exposed hour. With a daily resolution the most exposed day has an over-production of 10313 MWh. With a monthly resolution there is no over-production (Table 9).

Table 9: Key figures for residual load from 1.1.2000-31.1.2012 (MWh)

Resolution		Norway	Sweden	Finland	Denmark
Hourly	Max	16074	19905	10433	3090
	Min	723	5307	3949	-1811
	Average	9080	12205	7591	975
	Standard Deviation	4077	3365	1225	773
Daily	Max	353444	422923	235203	51948
	Min	59833	173079	109198	-10313
	Average	217926	292921	182187	23411
	Standard Deviation	94765	71960	27975	11829
Monthly	Max	10272262	11812866	6793814	993313
	Min	2402798	5959239	4247135	422042
	Average	6628584	8909689	5541534	712094
	Standard Deviation	2897300	2147758	798388	170979

5.3 Scenario results

The system loss of load probability is smallest in scenario 1a, with a value of 0.002 % where Sweden keeps some of its nuclear power production and allows for import from third region countries. This percentage means that for the year 2030, the load will exceed the available capacity 0.002% of the time. The highest LOLP, of 0.987%, is found in scenario 2b with no import from third region countries and total shut-down of nuclear power in Sweden. The value of expected unserved energy is derived from the LOLP value and thus follows the same pattern. The lowest EUE is found in scenario 1a, and the highest is found in scenario 2b (Table 10).

Removing the nuclear power in Sweden in scenario 2a-b results in a larger value of both LOLP and EUE compared to scenario 1a-b, i.e. a decrease in reliability. With import the difference in LOLP value is 0.102 percentage points between scenario 1 and 2, and an increase in unserved energy of 1.6 TWh. No import gives a greater effect with a difference of 0.755 percentage points for the LOLP value and an increase in EUE of 23,6 TWh (Table 10).

Allowing import from third region countries gives lower values of both LOLP and EUE than no import. The most dramatic effect can be seen in scenario 2 where a self-sufficient Nordic market (2b) will result in an increase in LOLP of 0.883 percentage points, and an increase in EUE of

26.6 TWh compared to a situation with import from third region countries (2a) (Table 10).

Table 10: LOLP and EUE values resulting from running the model.

Scenario	Nuclear power in Sweden	Import from third regions in peak hours	LOLP (%)	EUE/year (TWh)
1a	Yes	Yes	0.002	0.17
1b	Yes	No	0.232	4.54
2a	No	Yes	0.104	1.63
2b	No	No	0.987	28.20

5.4 Sensitivity of COPT table

The data sets for typical size of individual installation and forced outage rate affect the probability of an outage $\geq$ x MW, and subsequently the LOLP value. Figure 21 shows an example of how the probability changes for different FOR values and unit size. A doubling or halving of unit size gives slightly different curves for the probability. A doubling or halving of the FOR values gives a much bigger impact on the curves.

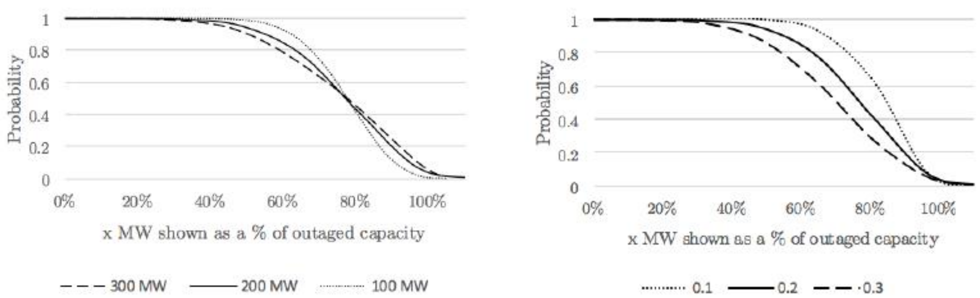


Figure 21: Example of changes in the probability that a generation outage capacity will exceed x MW with different unit size and FOR values. The left graph shows an example with FOR values of 0.2 and a total capacity of 1234 MW, with 4 (300 MW), 6 (200 MW), and 12 (100 MW) units to cover the capacity. The right shows the same example but with 6 units (200 MW) and FOR values from 0.1-0.3.

6 Discussion

6.1 Variability and duration curves for residual load

The results for variability showed that, in an annual perspective, demand is highest in cold months, and lowest in warm months. The use of electric heating is very common in the Nordic countries, and the demand naturally follows the temperatures. A typical day in both winter and summer shows a low consumption of electricity at night and high consumption in the middle of the day. This is due to the use of appliances and electric heating in the day time. Denmark has a closer relation between consumption in the winter and the summer due to a milder climate than the other Nordic countries.

Wind power production correlates with demand in an annual perspective. The correlation can be seen in Figure 15, that shows curves for production and demand, and where wind production follows the curve of the demand. The correlation can also be seen in Figure 19, that shows RLDC, where countries with high percentage of installed wind capacity have a closer correlation between RLDC and LDC. Sweden and Finland has the highest percentage of installed wind capacity compared to total VRE capacity (Table 4), and also the closest correlation between RLDC and LDC. The results in Figure 15 and Figure 16 also show low production in very cold temperatures. This is consistent with literature investigating wind power production in cold climates, where very high wind speed and icing reduces the production (Seifert & Richert 1997; Tammelin et al. 1998). This can also be seen on the capacity utilization of wind; with a monthly resolution, the average capacity utilization is higher in Denmark than in Norway, which has a colder climate (Table 7). Throughout the day the wind power production is inversely correlated with demand, and has a lower production in the middle of the day when the demand is high.

PV production is inversely correlated with production in a typical year. Figure 15 show highest production in warm months. This is explained by a higher insolation in summer months. The variability of PV production can also be seen in in Figure 19 where Denmark, which has the highest installed PV capacity in the 2030 scenarios, have a lower correlation between RLDC and LDC. The PV production shows a higher utilization in the middle of the day due to a higher insolation when the sun is high (Figure 17).

Denmark has the highest percentage of installed VRE compared to peak load (Table 4), and has an over-production of VRE in 11% of the hours. The overall correlation between load and residual load is still limited, and Demark also has the largest distance between the two curves. This gives the impression that VRE technologies does not decrease the capacity requirement of the system, due to its variability. This is consistent with literature investigating the effect large amounts of VRE has on the power system (Schill 2014; Ueckerdt et al. 2015).

Peak demand varies throughout the years as shown in Figure 18. It is not uncommon that the total energy consumption through the years stay more or less the same, but the peak load varies. Milligan et al. (2016) states that this is one of the reasons why single year studies of variation is less certain than studies that includes several years of data.

6.2 Loss of load probability and expected unserved energy

The results show that a total shut down of Sweden's nuclear power production will have a negative effect on both the LOLP and EUE values, i.e. decrease the reliability of the system, and that allowing import from third region countries will give a better reliability than without import.

By removing Sweden's nuclear power, the system will increase its share of renewable power production. Some reliability studies have shown that an increase in wind power generation without removing other production will increase the reliability of the system (MacCormack et al. 2010; Olsina et al. 2007). Both MacCormack et al. (2010) and Olsina et al. (2007) showed that when adding wind power production, in addition to holding the dispatchable power constant, the LOLP value will decrease. In scenario 2 in this study the share of VRE production increases by removing dispatchable units, and this gives a different result: reliability decreases with higher penetration of VRE. This is consistent with earlier cited literature that state that an increase in VRE penetration decrease the reliability of the system (Brouwer et al. 2014; Holttinen 2004; Phoon 2006). Phoon (2006) also states that a capacity increase with VRE gives high LOLE values (subsequently high LOLP values), but a higher capacity value on VRE improves the reliability. Some studies have shown that the the capacity value for wind can increase with high penetration over large areas, due to diversity (Holttinen et al. 2011). This study investigates the effects on system reliability, not the changes in each region. To see if the effect found by Phoon (2006) is consistent it is necessary with further studies that compares reliability in areas with high and low capacity utilization as seen in Table 5-Table 7.

The results show that third region interconnections will increase the reliability. It is widely known that interconnections between regions will have an impact on the reliability, as earlier mentioned in section 4.1.3. The demand varies in different regions, even though it is somewhat correlated, and interconnections allows for transmission capacity that can give lower LOLP values. Studies of the reliability have shown that interconnections between different regions will increase the reliability in both regions (Calabrese 1947; Ibanez & Milligan 2012). These findings are consistent with the results presented here.

Europe does not have a common standard to assess reliability and generation adequacy. However, the EU is working on guidelines for identification of adequacy problems (EEAG 2015). To assess the values in the results, Statnett's and ENTSO-E's requirement for LOLP values less than 1 ‰ is used (Engvall & Løvås 2010).

The results in Table 10 show that only scenario 1a will fulfill the requirement, meaning that the baseline scenario with import from third region countries gives an adequate reliability in 2030. Scenario 2a is only 0.004 percentage points over the requirement. Removing all of Sweden's nuclear power without replacing it with other alternatives will decrease the reliability and give an inadequate reliability compared to Statnett's and ENTSO-E's requirements. Both 1b and 2b shows excessive LOLP values, meaning values far above the requirements. This means that in a case of no import from third region countries the Nordic market will have a lower reliability than the requirement in 2030, independent of nuclear shutdown in Sweden.

6.3 Implications of results

The results show that an increase of VRE in the system decreases the reliability. The decrease is due to the characteristic properties of VRE already mentioned in the introduction: They are uncertain due to limited predictability, variable due to natural variation in wind, sun and inflow, and they are non-dispatchable, decreasing the flexibility of the system. The decrease in reliability when increasing the share of VRE in the system and the large effect interconnections with third region countries have on the results show the importance of including the effect of the variability in VRE sources and correct representation of interconnections in reliability studies.

The fact that the results show that scenario 1a is still under the required LOLP limit is good news for the development of future power systems with low emissions. It shows that systems with high shares of renewable energy can have a satisfactory level of reliability, and if Sweden's nuclear power is still in use, the reliability in the Nordic market in 2030 will be adequate. If Sweden's nuclear power is shut down scenario 2a shows that it will be necessary to replace the lost capacity with other sources or possibly increase the transmission capacities to have a reliable power system in the Nordic market. For situations when third region import is impossible the results in 1b and 2b shows that the Nordic market will have trouble to match supply and demand on a satisfactory level. Scenarios 1b, 2a and 2b all give theoretical situations where the reliability is low and demand is bigger than supply. In reality this may not be the case: increase in power price, demand response, import and reserve capacities can be used to balance shortage. Historically the Nordic market has been able to handle power shortages even though low inflow, problems with deliveries and coinciding effects on several occasions have caused a strained power balance. In 2009-2010 Sweden's nuclear power production was 2/3 of normal production, due to maintenance and and technical difficulties. This resulted in extensive use of Norway's hydro energy reserves to compensate for the reduction in nuclear power from Sweden. In addition, difficulties with import from the Netherlands, low temperatures and low inflow occurred. Combined, this resulted in a strained power balance, but it was not necessary to ration power and it did not cause a loss of load. This has not been the case for other power demanding seasons either, due to an increase in power prices and resulting reduction in consumption (mainly in industry), and use of reserves and import (Svenska Kraftnät 2010). The different scenarios still give the indication that the Nordic power market will need to implement measures to maintain a satisfactory level of reliability in 2030 should Sweden's nuclear power be phased out or if the planned interconnections with third region countries is not realized.

6.4 Method and validity

Several of the assumptions in the model may be a source of uncertainty regarding the validity of the results.

Firstly, the model assumes independence between hours for any one unit and that the FOR value of power plants are mutually independent. In reality a unit may be out for several of the following hours when it fails, and several plants may have the same energy carrier. LOLP does not differentiate between one large shortfall or several small ones, and thus it will not influence long term values of LOLP. The fact that LOLP does not give this indication for duration and severity of shortage may however be a problem for the LOLP being a satisfactory reliability measure as mentioned in several studies assessing reliability measurements (Kueck & Kirby 2004; Phoon 2006).

Secondly, the amount of hydro energy (MWh) available in a yearly perspective is not taken into account. Years with a high demand of energy can in a worst case scenario have used big volumes of hydro storage and have limited available capacity. Hydro with storage is handled in the model as any other two state unit, with a FOR of the capacity as shown in 4.1.3. To handle the total amount of hydro energy is outside the scope of the model, and may have an effect on the results in a yearly perspective.

The assumptions made in the input data sets may also be a source of uncertainty.

Figure 21 shows an example of how the probability changes for different FOR values and unit size. The area under the curve for probability of generation outage changes with different FOR values, i.e. affects the LOLP calculations. Changes in unit size gives only marginal changes in the area under the probability curve and thus affects the LOLP calculations less. This is consistent with other studies who have done calculations on how FOR values and unit size affect the expected values of LOLP including Azad and Misra (1996) and Boroujeni et al. (2012). Azad and Misra (1996) found that that a smaller unit size will have a large impact on CPU time, but give similar results for LOLP. Boroujeni et al. (2012) results showed that the FOR values have a direct impact on LOLP and will give different values. Ergo, the FOR values are more crucial than unit size when creating a COPT table representative for the system. Certain assumptions have to be made to regarding the size of the units and the FOR values and this may be a source of uncertainty for the validity of the results.

Both the assumptions made on connections between regions and between the Nordic market and third region countries will have an effect on the result, and different assumptions will give some variations in the results as stated in Milligan et al. (2016). This study tries to account for each outage by including transmission as a probabilistic variable. The data sets used to predict the probabilistic nature of available transmission capacity consists of recordings from 2013-2015. This is not the same sample years as the data sets used to predict probability in residual electricity demand (Consumption and VRE production consists of recordings from 2000-2012). As the data is used as historical observations, and have no correlation with the load curve it may be questionable to assume that the capacity rating for an hour gives a true representation of the transmission capacity. Nevertheless, the fluctuations give a representation of how the capacity rating on connections fluctuates through seasons, and can be used as a crude approximation.

A large dataset gives a good representation of the variability and captures fluctuations for wet and dry, cold and hot years, and thus gives a good representation of variability throughout a year. Milligan et al. (2016) raises the question of the number of years a data set needs to give a valid long term result for capacity value of wind. The study cites several studies that explore the significant number of years, but gives no final figure. It does state, however, that two studies have shown that 8-9 years can give a robust measurement of the wind variability but that even with 17 years of data the variability of wind is surrounded by considerable uncertainty. This study uses thirteen years of data from 2000-2012, and based on the statements in Milligan et al. (2016) this may be a source of uncertainty. Uncertainty regarding variations also increases as the future scenario moves further away from the sample years. It is difficult to predict exactly how a typical year in 2030 will look like, but this study's amount of data sets gives indication of how the production and load will vary.

In addition to the validity issues mentioned above there is, traditionally, some problems with LOLP as a reliability measure. Traditional calculations of LOLP does not include transmission between regions (Kueck & Kirby 2004). This study takes transmission into account. This gives regions with loss of load extra "emergency supplies" that can be retrieved from regions without loss of load at the time. LOLP in each region is therefore lower than it would have been without taking transmission into account. The transmission interconnections are significant for the results as mentioned earlier in section 4.1.3, and consistent with literature assessing reliability methods (Milligan et al. 2016).

Different calculations methods may also give different values of LOLP and make it difficult to make comparisons. Since there are several different ways to calculate LOLP, different methods may give different values (Kueck & Kirby 2004). Analytical methods usually use an expected value of the load and assumes that the peak load for a day lasts all day, which results in 365 computations. Other methods, as this study, models every hour's load, which gives 8760 calculations. The first method loses information about variations throughout the day, and gives a cruder approximation of the true value of LOLP. The model approach used in this study captures the variations throughout the day, but also the variations in residual supply and thus gives a more true approximation than analytical methods.

6.5 Further Work

Some model improvements, in addition to an expansion of the calculated indices and scenario could be assessed in order to improve the evaluation of the reliability in the Nordic Power Market in 2030:

- Include the total hydro power production from a yearly perspective in the model (Not only the run of river production as a time series): The large amount of hydro power in the Nordic market makes it one of the most important generation technologies in the system. Thus, a correct representation of all the available hydro power capacity is one of the most important aspects to include in future scenario analyses.
- Include a temperature data set in the model: Temperature forecast could give a more correct representation of the load if included in the model data. It could also make it possible to correlate the variability of transmission with the load, and account for a slight reduce/increase in NTC with warm temperatures and windy hours respectively, giving a more correct representation of transmission capacity.
- Include failures in distribution system in the model: It is not just power generation that affects the reliability of a system, distribution systems may also fail. Including a probability for failures in the distribution system gives a more complete assessment of the reliability. This can also be done as a separate study, due to the fact that distribution systems are essential independent of system level failure.
- Calculate VOLL: If a value is assigned to unserved energy, it is possible to calculate VOLL from the EUE. VOLL can be useful for the planning of a system as it can predict the minimal system cost for a satisfactory reliability level.
- Possible scenarios for further study: Different demand scenarios, including changes in electricity demand due to an increase in district district heating.

6.6 Conclusions

This study assesses how changes in the capacity mix will affect the Nordic power system in 2030. The assessment is done using a probabilistic model approach to calculate the loss of load probability (LOLP) and the expected unserved energy (EUE). Historical data is used to predict variations in demand and production in the model and to illustrate the variability in VRE by residual load duration curves and load duration curves. The capacity unavailability, the residual demand curve and outages on transmission lines were considered to be probabilistic in the model. Two supply scenarios were analysed; (1) base scenario with a predicted capacity mix with high shares of VRE and some decrease in nuclear power production compared to today's capacities, and (2) complete shutdown of Sweden's nuclear power replaced with VRE production. Both scenarios were run with the assumption of a) import and b) no import from countries surrounding the Nordic power market.

The results from the historical data sets show that demand generally follows the temperatures in an annual perspective, but throughout the day the consumption is highest when human activity is high. Wind generally correlates with demand through the year, but with a decrease in correlation for extreme temperatures, and with an inverse correlation throughout the day. PV is inversely correlated with demand through the year, but correlated with demand throughout the day. Giving low production of PV in the winter, but highest production in the middle of the day when the demand is high. Denmark is the only country with an over-production of VRE in 2030, and the peak demand varies through the years in the data set.

The scenario analyses show that the Nordic power market should be able to handle exposed situations in 2030, if Sweden

keeps some of its nuclear production, todays planned expansion of interconnections with surrounding countries is realized and an assumed extensive development in wind power production. A shutdown of Sweden's power production will give a decrease in the reliability compared to a situation with nuclear power, and be just short of a satisfactory level of adequacy, with a LOLP requirement of 1‰. The results also show that the Nordic power market in 2030 cannot keep a satisfactory level of reliability without interconnections and import from surrounding countries.

To do a simulation of future market predictions it is necessary to make certain assumptions on how the market will evolve from the present. These assumed values for supply and demand are in no way certain predicaments and will always be various degrees of guesswork. For example, the development in the electricity demand is an increase from present values, but the progression in the district heat market may give a different development, driven by technology, costs and/or politics. Based on the assumptions in this study the scenario analyses give an indication that the Nordic power market will need to take measures to maintain a satisfactory level of reliability in 2030 should Sweden's nuclear power be phased out or if the planned interconnections with third region countries are not realized.

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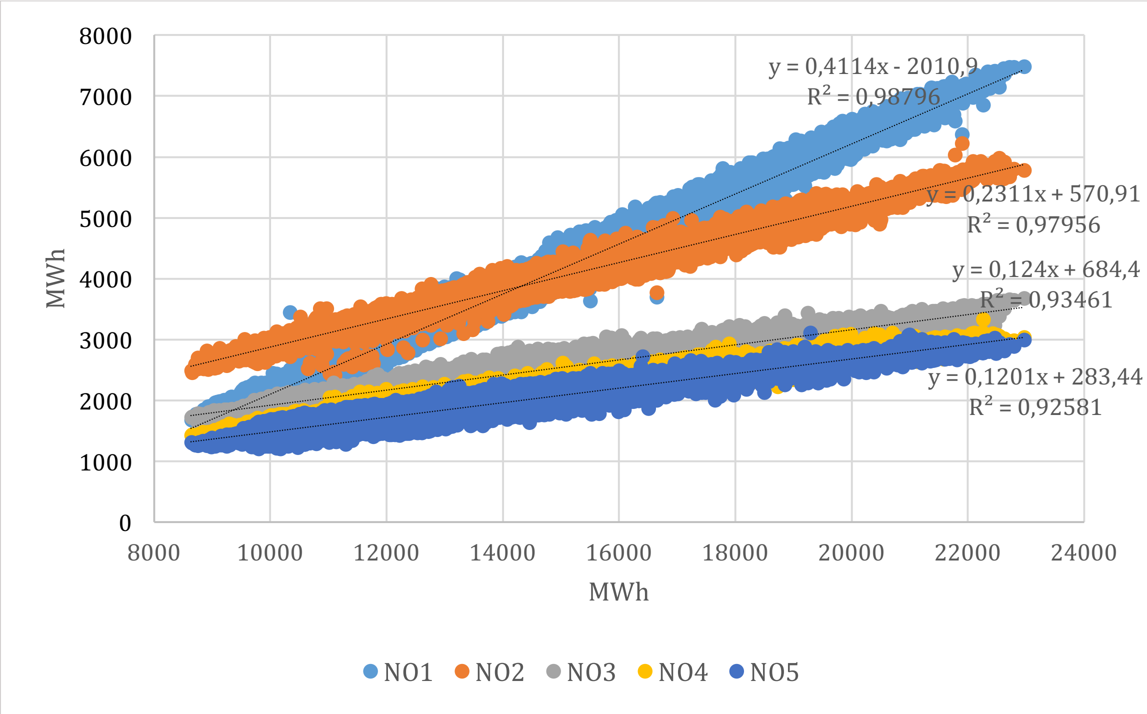
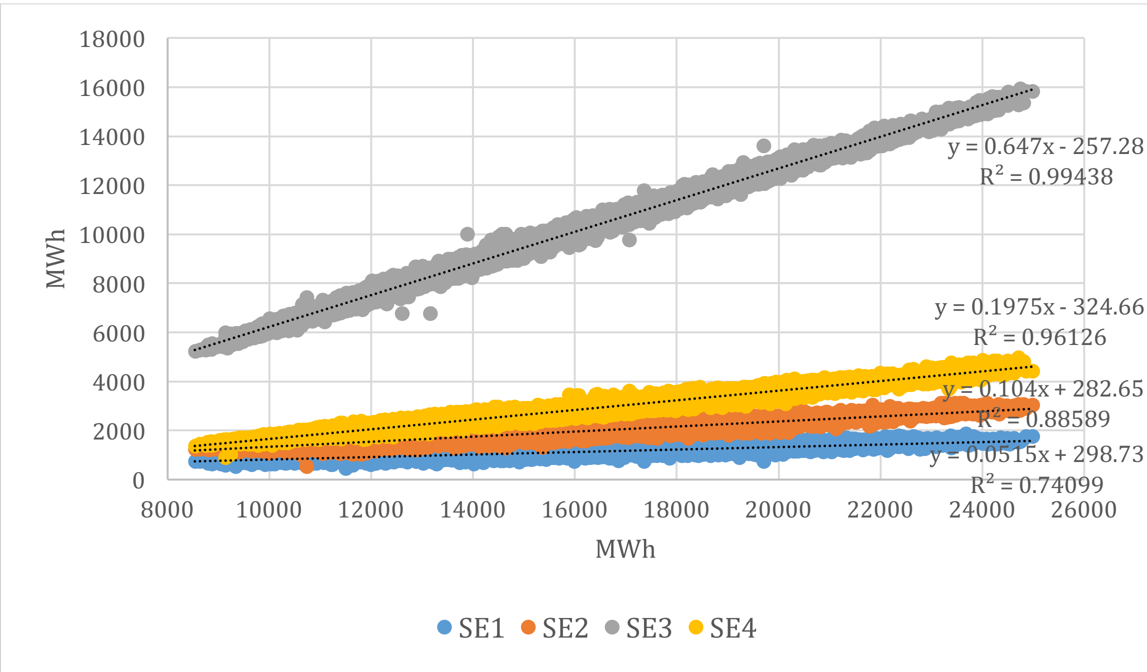
Appendix A

- Calculated trend lines for consumption with equations





Appendix B

- Distribution of wind calculation nodes in market areas

MARKET AREAS	CALCULATION NODES
ONSHORE	
NO1	N14, N15
NO2	N12
NO3	N6, N5, N13, N7
NO4	N1, N2, N4
NO5	N9, N11
SE1	S1
SE2	S2
SE3	S3
SE4	S4
DK1	D1
DK2	D2
FI	F1, F2
OFFSHORE	
NO2	O08
NO3	O11
NO4	O10, O115
NO5	O09
SE2	O18
SE3	O24
SE4	O07
DK1	O05, O06, O04
DK2	O03
FI	O19

Appendix C

- Distribution of photovoltaic calculation nodes in market areas

MARKET AREAS	CALCULATION NODES
NO1	D01
NO2	D01
NO3	D01
NO4	-
NO5	D01
SE1	D01
SE2	D01
SE3	D01
SE4	S01
DK1	D01
DK2	S01
FI	D01

Appendix D

- Distribution of metering areas for inflow in market areas

Norway

Market Areas	Metering Areas
NO1	Region East, Hallingdal
NO2	Telemark, South Norway, Region West-South
NO3	Trondelag, M0re, Indre Sogn, Region North-West
NO4	Finnmark, Troms, Svartisen, Helgeland
NO5	BKK, SKL

Sweden

Market Areas	Metering Areas
SE1	Troms, Svartisen, Helgeland
SE2	Trondelag
SE3	Region East
SE4	Region East

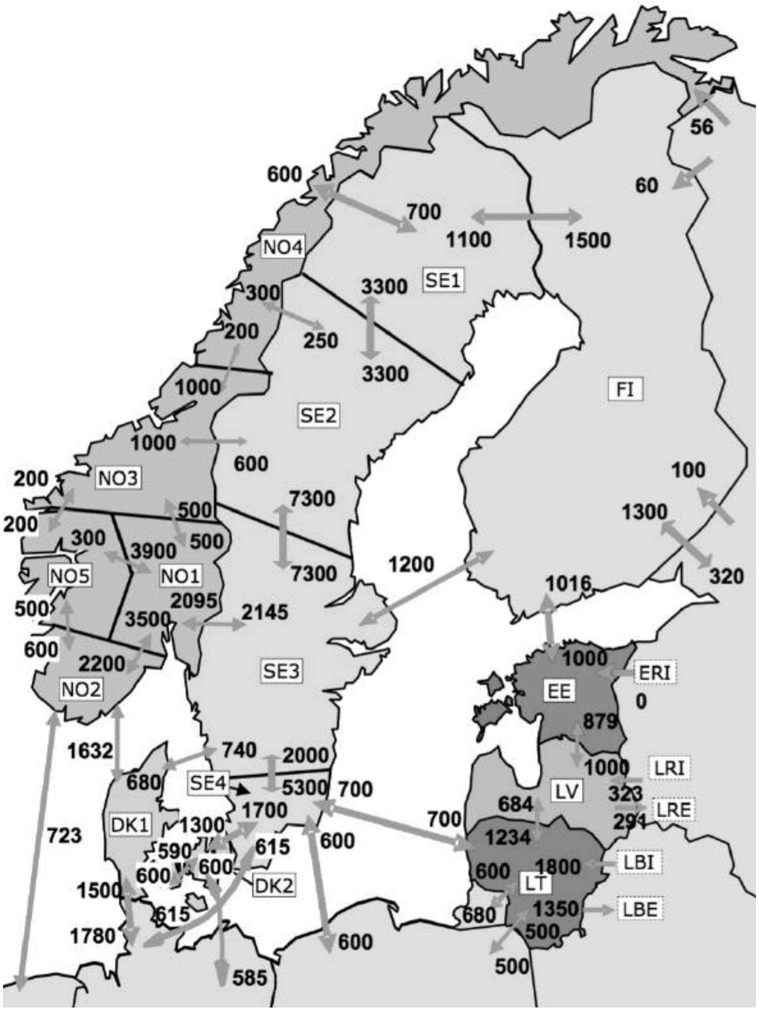
Appendix E

- Reason codes for reduced transfer capacity

Reason codes:					
10	Normal capacity (100 MW tole-rance)	17	Normal grid configuration	24	Prognosticated power flow
11	Planned outage on cross-border connection	18	Increased reliability margin	25	Thermal limitation
12	Network failure on cross-border connection	19	Unavailable system protection	60	CBO allocation of capacity in Elspot
13	Thermal limitation on cross-border connection	20	Reduced amount of operational reserves	90	Not Available
14	Planned outage	21	Constrained regional power balance	99	Other reason
15	Network failure	22	Step by step restriction		
16	Stability	23	Ramping in Elspot		

Appendix F

- Max net transfer capacity collected from ENTSOE (2016).



Net transfer capacity (NTC) values are given in MW (ENTSOE 2016).

Appendix G

- Unit size and FOR values

	Unit size	FOR
GCND_COAL1	400	0.042
GCND_COAL2	400	0.042
GCND_COAL3	400	0.042
GCND_COAL4	400	0.042
GCND_FUELOIL1	100	0.032
GCND_FUELOIL2	100	0.032
GCND_FUELOIL3	100	0.032
GCND_LIGNITE1	400	0.042
GCND_LIGNITE2	400	0.042
GCND_LIGNITE3	400	0.042
GCND_LIGNITE4	400	0.042
GCND_NATGAS1	200	0.032
GCND_NATGAS2	200	0.032
GCND_NATGAS3	100	0.032
GCND_NATGAS4	100	0.032
*GCND_NATGASGT1	200	0.032
*GCND_NATGASGT2	200	0.032
GCND_NUCLEAR	800	0.022
GCND_WOOD1	200	0.022
GCND_WOOD2	200	0.022
GCND_WOOD3	200	0.022
GCND_WOOD4	200	0.022
GCND_COFIRING	200	0.022
GCND_PEAT	200	0.022
GCND_WOODCHIPS	100	0.022
GHYRR_WATER	50	0.02
GHYRS_WATER1	200	0.02
GHYRS_WATER2	200	0.02
GHYRS_WATER3	200	0.02
GHYRS_WATER4	200	0.02
GHYRS_WATER5	200	0.02
GHYRS_WATER6	100	0.02
GHYRS_WATER7	100	0.02
GHYRS_WATER8	100	0.02
GHYRS_WATER9	100	0.02
GHYRS_WATER10	100	0.02
GPUMP_PHS	100	0.02
GSOLE_SUN	1	0.01
GWND_WIND	50	0.01
GWND_WINDOFFSHORE	200	0.01
Back-up-power	500	0
GEXT_PEAT_KELJONLAHTI	200	0.022
GEXT_PEAT_TOPPILA	100	0.022
GEXT_PEAT_SEVO	100	0.022
GBPR_COAL_HANASAARI	200	0.042

District heat technologies	Unit size	FOR
GEXT_MUNIWASTE	50	0.022
GEXT_COAL_LINK	50	0.042
GEXT_COAL_KYMIJARVI	150	0.042
GEXT_COAL_VASKILUOTO	200	0.042
GEXT_COAL_ENSTED	300	0.042
GEXT_COAL_ESBJERG	400	0.042
GEXT_COAL_ASNES2	400	0.042
GEXT_COAL_ASNES5	400	0.042
GEXT_COAL_NORDJYLLAND	400	0.042
GEXT_COAL_STUDSTRUP	400	0.042
GEXT_COAL_FYN	400	0.042
GEXT_COAL_AMAGER	250	0.042
GEXT_COAL_AVEDORE	250	0.042
GEXT_COAL	250	0.042
GEXT_NATGAS_ORESUND	400	0.032
GEXT_NATGAS_NOKIA	70	0.032
GEXT_NATGAS_MERTANIEMI	100	0.032
GEXT_NATGAS_TAMPERE	300	0.032
GEXT_NATGAS_VOUSAARI	400	0.032
GEXT_NATGAS_AVEDORE	150	0.032
GEXT_NATGAS_SKERBEK	400	0.032
GEXT_NATGAS	200	0.032
GEXT_BIOGAS	200	0.032
GBPR_STRAW_AVEDORE	50	0.022
GEXT_STRAW_STUDSTRUP	50	0.022
GEXT_STRAW	100	0.022
GEXT_WOODWASTE_HORNEBOR	40	0.022
GEXT_WOODWASTE	100	0.022
GEXT_WOODPELLETS_AVEDORE	300	0.022
GEXT_WOODPELLETS	100	0.022
GEXT_BIOOIL_VARTAN	200	0.032
GEXT_FUELOIL	100	0.032
GEXT_PEAT	100	0.022
GEXT_BIOOIL	200	0.032
GBPR_COAL_SALMISAARI	150	0.042
GBPR_COAL_SUOMENOJA	100	0.042
GBPR_COAL_NAANTALI	250	0.042
GHOB_BIOGAS	50	0.032
GHOB_RECYCLEDWOOD	50	0.022
GHOB_WOODWASTE	50	0.022
GHOB_WOODCHIPS	50	0.022
GHOB_DRYWOODCHIPS	50	0.022
GHOB_STRAW	50	0.022
GHOB_WOODPELLETS	50	0.022
GHOB_PEAT	50	0.022
GHOB_COAL_EXETS	50	0.042
GHOB_COAL	50	0.042
GHOB_LNG	50	0.032
GHOB_LPG	50	0.032
GHOB_NATGAS_EXETS	50	0.032
GHOB_NATGAS	50	0.032

District heat technologies	Unit size	FOR
GBPR_COAL_MARTINLAAKSO	150	0.042
GBPR_COAL_VARTAN	100	0.042
GBPR_COAL_SE3	50	0.042
GBPR_COAL	100	0.042
GBPR_MUNIWASTE_LINK	50	0.022
GBPR_MUNIWASTE_HOGDALEN	50	0.022
GBPR_MUNIWASTE_SE2EL	50	0.022
GBPR_MUNIWASTE_SE2OTHER	50	0.022
GBPR_MUNIWASTE_SE3EL	50	0.022
GBPR_MUNIWASTE_24	20	0.022
GBPR_MUNIWASTE_19	20	0.022
GEXT_AGDER	10	0.022
GBPR_MUNIWASTE_MORE	5	0.022
GBPR_MUNIWASTE1	5	0.022
GBPR_MUNIWASTE2	5	0.022
GBPR_MUNIWASTE3	5	0.022
GBPR_MUNIWASTE	20	0.022
GBPR_MUNIWASTE_65	20	0.022
GBPR_RECYCLEDWOOD_SE3EL	20	0.022
GBPR_RECYCLEDWOOD_SE3OTHER	20	0.022
GBPR_RECYCLEDWOOD_SE4EL	20	0.022
GBPR_RECYCLEDWOOD	20	0.022
GBPR_WOODWASTE_GOT	50	0.022
GBPR_WOODWASTE_25	20	0.022
GBPR_WOODWASTE_36	20	0.022
GBPR_WOODWASTE_ABY	50	0.022
GBPR_WOODWASTE_BRISTA	50	0.022
GBPR_WOODWASTE_FINEL	50	0.022
GBPR_WOODWASTE_FINOTHER	50	0.022
GBPR_WOODWASTE	20	0.022
GBPR_WOODCHIPS_HERNING	90	0.022
GBPR_WOODCHIPS_FINOTHER	30	0.022
GBPR_WOODCHIPS_08	20	0.022
GBPR_WOODCHIPS_25	20	0.022
GBPR_WOODCHIPS_37	20	0.022
GBPR_WOODCHIPS	20	0.022
GBPR_WOODPELLETS_HASSELBY	50	0.022
GBPR_WOODPELLETS_AMAGER	50	0.022
GBPR_WOODPELLETS	20	0.022
GBPR_PEAT_38	50	0.022
GBPR_PEAT	50	0.022
GBPR_BIOGAS	50	0.032
GBPR_STRAW	20	0.022
GBPR_NATGAS_EXETS	15	0.032
GBPR_NATGAS_RYA	250	0.032
GBPR_NATGAS_SE4EL	20	0.032
GBPR_NATGAS_GOT	50	0.032
GBPR_NATGAS_MAL	130	0.032
GBPR_NATGAS_40	30	0.032
GBPR_NATGAS_50	30	0.032

District heat technologies	Unit size	FOR
GBPR_NATGAS	30	0.032
GBPR_NATGAS_100	30	0.032
GBPR_NATGAS_VOUSAARI	150	0.032
GBPR_NATGAS_FINEL	20	0.032
GBPR_NATGAS_SUOMENOJA2	200	0.032
GBPR_NATGAS_GASAREA	20	0.032
GBPR_NATGAS_SUOMENOJA	50	0.032
GBPR_NATGAS_MARTINLAAKSOGT	50	0.032
GBPR_FUELOIL_EXETS	15	0.032
GBPR_FUELOIL_LINK	50	0.032
GBPR_FUELOIL	50	0.032
GBPR_HEAVYFUELOIL	50	0.032
GHOB_MUNIWASTE	50	0.022
GHOB_OTHERGAS	50	0.032
GHOB_BIOOIL	50	0.032
GHOB_FUELOIL_EXETS	50	0.032
GHOB_FUELOIL	50	0.032
GHOB_HEAVYFUELOI	50	0.032
GHOB_WASTEHEAT	50	0.022
GETOH_HEATPUMP	50	0.01
GETOH_HEATPUMP33	50	0.01
GETOH_HEATPUMP1	50	0.01
GETOH_HEATPUMP2	50	0.01
GETOH_HEATPUMP3	50	0.01
GETOH_HEATPUMP4	50	0.01
GETOH_ELECTRICBOILER	50	0.01
BACK-UP-HEAT	200	0

Industry CHP	Unit size	FOR
GBPR_IND_BIO	50	0.022
GBPR_IND_FOSSILE	50	0.032
GBPR_WOOD_IND	50	0.022
GBPR_PEAT_IND	50	0.022
GBPR_NATGAS_IND	50	0.032
GBPR_COAL_IND	50	0.042
GBPR_FUELOIL_IND	50	0.032
GBPR_COAL1	50	0.042
GBPR_COAL2	50	0.042
GBPR_COAL3	50	0.042
GBPR_FUELOIL1	50	0.032
GBPR_FUELOIL2	50	0.032
GBPR_FUELOIL3	50	0.032
GBPR_LIGNITE1	50	0.042
GBPR_LIGNITE2	50	0.042
GBPR_LIGNITE3	50	0.042
GBPR_NATGAS1	50	0.032
GBPR_NATGAS2	50	0.032
GBPR_NATGAS3	50	0.032
GBPR_WOOD1	50	0.022
GBPR_WOOD2	50	0.022
GBPR_WOOD3	50	0.022

Appendix H

- Installed capacities for VRE production in bidding areas

Table 11: Installed capacities used to create residual load duration curves (RLDC).

	Wind Offshore	Wind Onshore	PV	ROR
NO1	0	0	0	2399
NO2	0	426	0	3214
NO3	0	2771	0	2012
NO4	0	638	0	1686
NO5	0	298	0	976
SE1	0	1160	0	1266
SE2	0	4003	0	1917
SE3	0	2195	0	602
SE4	0	2059	0	173
FI	0	3910	0	1857
DK1	1972	3039	1030	0
DK2	1052	621	410	0

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