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Report

A carbon neutral power system in the Nordic region in 2050

D3.1 in the NORSTRAT project

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Nordic Energy Research

Report

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ABSTRACT
The aim of this report is to show how a fully integrated Nordic power system can become carbon neutral and what is profitable in terms of expansion of transmission grids in such a future. A scenario methodology is used to analyse the power system in 2050 by the EMPS model and an investment algorithm for evaluation of profitability of expansion of transmission links. The drivers "Volume of new RES" and "Integration with the Continental European system" are used to establish four main scenarios: Carbon Neutral (CN), Purely RES (PR), European Battery (EB) and European Hub (EH). In CN and in EB ca 140 TWh/y of new RES production is integrated into the Nordic system, in PR and in EH as much as 240 TWh/y. In CN and in PR the transmission capacities between the Nordic region and Continental Europe are kept at 2020-level. In EB and in EH they are increased according to profitability criteria. All fossil production in the Nordic countries is assumed phased out. In PR all nuclear production is assumed to be decommissioned as well. The demand is increased to 444 TWh/year. Distribution of new renewable production is mainly based on existing projects in 2012. About 65 GW internal transmission capacity in the Nordic region and 9.2 GW capacity between the Nordic region and Continental Europe are used as starting point for the analyses. The profitable increases are internally in the Nordic region: CN: 6.5 GW, PR: 22.8 GW, EB: 12.3 GW, EH: 24.5 GW, between the Nordic and Continental Europe: EB: 12.6 GW, EH: 20.3 GW.

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APPENDICES

SUMMARY

The Nordic Energy Technology Perspective (NETP) was released in 2013 and showed how the Nordic energy system can be developed in a more sustainable direction. This report is related to the NETP, but has a particular focus on the Nordic power system and what is profitable in terms of expansion of transmission grids to become carbon neutral. Furthermore the report is focusing on what role the Nordic power system can play in a future European system with limited emission of green-house gases.

A scenario methodology is used to analyse the future system. The scenarios are analysed by the EMPS model and an investment algorithm for profitable expansion of transmission links. A 26 node EMPS model for the Nordic region is used. Outside the Nordic region each European country is represented by one node. Furthermore, Germany and Great Britain are modelled in great detail. 41 years with statistical data about inflow to the hydropower system, wind and solar resources etc are used. Each week is analysed with 39 periods resolution resulting in 90 000 periods (representing about 358 000 hours) with simulations. Huge variations in the hydro, wind and solar resources are included in the dataset.

Four scenarios are analysed and in addition two sensitivity cases are considered. The two main drivers "Volume of new RES" and "Integration with the Continental European system" are used to establish the four main scenarios: Carbon Neutral, Purely RES, European Battery and European Hub. In Carbon Neutral and in European Battery ca 140 TWh/y of new renewable production is integrated into the Nordic system, in Purely RES and in European Hub as much as 240 TWh/y. The Nordic power system is assumed to be totally integrated, and transmission capacities between nodes internally in the Nordic system are increased according to profitability criteria. In Carbon Neutral and in Purely RES the transmission capacities between the Nordic region and Continental Europe are kept at 2020-level, thus including the known plans for the internal Nordic grid and interconnectors to Continental Europe. In European Battery and in European Hub they are increased according to profitability criteria. All fossil production in the Nordic countries is assumed phased out. In Purely RES all nuclear production is assumed to be decommissioned as well.

The new renewable production is to a large degree based on already defined projects for onshore and offshore wind production. In 2012 there were registered projects with approximately 185 TWh/y of new wind production in the Nordic region. Many of these will probably not be realised. However, the projects are assumed to reflect a localisation of the best wind resources. In addition to the new production from wind, it is also assumed some increase in the Norwegian hydropower production, some new bio production and 10 TWh/y from PV in Sweden and Denmark.

The demand in the Nordic region is assumed to increase from approximately 385 TWh/y in 2012 to 444 TWh/y in 2050. It is assumed that the demand in each region/EMPS node will increase/decrease according to expected population increase/decrease. Consumption in power intensive industries is assumed to be equal to 2012. In one of the sensitivity analyses, the total demand is reduced with 25% compared to the other scenarios in 2050. Furthermore, the new renewable production is about 25 TWh/y in addition to the 2012 level. In the other sensitivity scenario, only Swedish nuclear production is assumed be phased out in a Purely RES scenario.

The Continental European power system is assumed to be developed according to the vision of the European Commission for 2050. The development of the power system in Great Britain, Germany, the Netherlands and Poland are based on the DG Energy scenarios. The development of the power system in other European countries is from the EU 7th framework program project SUSPLAN and included 65-70% renewables in the power production portfolio.

Based on assumptions for development of power demand and integration of new renewable production, profitability of investments in high voltage transmission links is analysed. The results give indications about

profitable level/scale in the scenarios. More technical studies are necessary before it can conclude about specific links. A weakness with the study is the use of fixed lengths for all transmission connections: 130 km for HVDC and 80 km for AC connections. The analyses do not include regional and distributions grids, and investments in those grids will come in addition. About 65 000 MW internal transmission capacity in the Nordic region and around 10 000 MW capacity between the Nordic region and Continental Europe are used as starting point for the analyses.

The resulting profitability of expansion of transmission grids in 2050 are:

	Starting point	Carbon Neutral	Purely RES	European Battery	European Hub	Carbon Neutral low demand	Purely RES no nuclear Sweden
Total internal Nordic region	64 945	6 450	22 750	12 300	24 450	2 250	20 850
Total Nordic - Continental Europe	9 200	0	0	12 550	20 300	0	0
Total Continental Europe	295 100	205 750	210 250	186 000	180 600	202 900	206 450
Total Europe [MW]	**369 245**	**212 200**	**233 000**	**210 850**	**225 350**	**205 150**	**227 300**

A "Carbon Neutral" power system

The analyses show that there are more than enough new renewable resources in the Nordic region to phase out all fossil production (70-100 TWh/y), to cover increases in demand of about 50-60 TWh/y and probably also to phase out nuclear production. NORSTRAT is mainly based on increases in production from wind and bioenergy resources. As already mentioned, in 2012 projects for 185 TWh/year new wind production in the Nordic region are registered. The projects are in different phases and many of the projects will never be realized. However, they illustrate that the resources are available and can be exploited. Other resources such as more solar, tidal, wave, salt gradient power etc. may represent additional opportunities.

The profitable investments in the scenario "Carbon Neutral" are modest in the Nordic region: 6450 MW (about 10 % of the total Nordic high voltage transmission grid in 2012). The results are of course based on the assumptions: the fossil production is to a large degree substituted with renewable production in the same region and consequently the need for grid extension is limited.

A Purely Renewable power system in the Nordic region

In the Purely RES scenario all nuclear production in Sweden and Finland is phased out and substituted with renewable production. 22 750 MW of increased transmission capacity is found profitable in Purely RES. When nuclear production is phased out in Sweden, it results in a large imbalance in the middle of Sweden (SVER-SNO3). Without any increases in the transmission capacities compared to the system in 2012, there is rationing (curtailment of demand) in several regions in the Nordic countries. In particular there is rationing of up to 6.2 TWh/y in Sweden and 3.6 TWh/y in Finland in the coldest and driest year. After increasing the transmission capacities, there is no practically rationing left in the power system. More in-depth analyses are necessary to finally conclude about the security-of-supply.

The Nordic system in an European perspective Table 0-1gives an overview of the interactions between the Nordic and the European power systems in the scenarios. As shown, the Nordic region is in a net export position towards Europe in all scenarios.

Table 0-1 Overview of the Nordic power system in interaction with the European system in the NORSTRAT scenarios

Scenario	Net export [TWh/y]	Production in neighbouring countries compared with Carbon Neutral [TWh/y] **)	Increased grid capacity between Nordic region and the rest of Europe *) [MW]
Carbon Neutral	31	-	0
Purely RES	3	+ 22 gas	0
European Battery	33	-11 gas, + 1 bio,	12 550
European Hub	111	-57 gas, -1 coal, -1 nuclear, -4 bio	20 300

*) Does not include internal upgrade in the Nordic region
**) Great Britain, Germany, the Netherlands, Belgium, Poland, Estonia, Latvia, Lithuania and Russia. There will also be changes in other countries, so net export is not equal to changes in production in neighbouring countries.

Nordic power substitute fossil based power in neighbouring countries, dependent on the production portfolio in the neighbouring countries. In European Hub a main share of the increased export compared to Carbon Neutral substitutes gas production in Germany, Poland, Great Britain and the Netherlands.The largest export is in the European Hub scenario (111 TWh/y). In European Hub the Nordic region has a nuclear production of approximately 106 TWh/y, but nuclear production in Germany is assumed to be phased out. It will be more energy efficient to keep nuclear power closer to the consumption centres in Europe, instead of transporting the power long distances since this involves a lot of network losses.

The impact of demographic changes

Based on data from the statistical offices in the four Nordic countries, it is assumed a growth in population from 2012 to 2050 of 4.2 million inhabitants. Furthermore, based on information from the same offices particularly the populations in and around the large cities like Oslo, Stockholm, Copenhagen etc. are expected to increase. In NORSTRAT it is assumed increase in power demand related to the population increase. For several of the Nordic regions including large cities, a growing energy deficit is assumed. In particular, for the region NORGEOST (including Oslo), there are hardly any plans for new renewable power production, but a considerable growth in demand due to population increase. The demographic changes are to large extent impacting the profitability of new transmission capacities. Focus on energy efficiency and e.g. bio based power production in the Oslo-region may reduce the need for expansion of the transmission grids.

The increases in transmission capacities

Some connections are found profitable to increase in several scenarios. These connections are mainly:

- TELEMARK / SVER-SNO3 is a new connection not existing today, but represents the western branch of the South West Link between Tveiten in Norway and Barkeryd in Sweden which was cancelled in 2013. This connection is found profitable in all scenarios with capacities in the range (500 – 3900 MW). Although the link is not used a large part of the time in several of the scenarios it is profitable for several reasons:

1. In a case of a nuclear phase out in the SVER-SNO3 the link can provide power to Southern Sweden in times with high demand and low wind and solar power production.
2. For the European Hub and European Battery scenarios, the link is invested in mostly because SVER-SNO4 increases its capacity towards Continental Europe. This causes large investments between SVER-SNO3 and SVER-SNO4 and raises the price in SVER-SNO3, making it profitable to increase capacity from TELEMARK and Northern Sweden (SVER-SNO3).
3. In all scenarios, the link is important for balancing out wind and solar power variations in Southern Sweden with hydro power production in Southern Norway.

- SVER-SNO2 / SVER-SNO3 is increased in all scenarios (except for Carbon Neutral Low Demand), with the maximum increase of up to 4150 MW in European Hub. The investment algorithm finds the increase in this connection profitable due to the large surplus in Northern Sweden and Northern Norway which much be exported to the deficit areas SVER-SNO3 and NORGEOST, besides being exported further to Continental Europe.
- MORE / NORGEOST has a capacity of 400 MW in 2015. The capacity is increased from 450 – 2450 MW, depending on the scenario. The profitability of this investment is caused by the same drivers as the link between SVER-SNO2 / SVER-SNO3; a large transmission of renewable power in the north to demand centres in the south.

1 Introduction

The aim of this report
This report is a part of the Nordic Energy Research project NORSTRAT.

The overall objective of the NORSTRAT project is to build knowledge and understanding among politicians, decision makers and actors in the power industry about possible carbon neutral futures for an integrated Nordic power system in a time perspective up to 2050. The knowledge and understanding is based on quantitative scenario analysis of impacts on the electricity, and to some degree the transport and the heating system combined with the necessary governance aspects to enable the transformation.

The NORSTRAT project consists of several workpackages (WP). In WP1 a common knowledge platform about the status and the possibilities for the Nordic power system in a long term perspective was developed. WP2 investigates the impact and potential of electrification of the transport and partly of the heating sector. WP3 analyses the needs for transmission grids and storage from de-carbonizing the electricity, the transport- and partly the heating sector. The governance analysis in WP4 examines pathways for electrification of the transport and the transmission grid developments. Finally all the findings will be combined into a Nordic Energy Road Map for 2050 in WP5.

This report is the first of two reports from WP3. The aim of the report is to provide an overall picture of the need for development of the transmission system in the Nordic region in a time perspective to 2050. The need for expansion of transmission channels is analysed for a carbon neutral power system, and there is a particular focus on which role the Nordic power system may have in a European context. Two possible roles are exporter of green electricity and/or exporter of balancing services. The next deliverable from WP3, D3.2, goes more deeply into some of the results from D3.1.

The Nordic and the European transmission system
The Nordic Transmission System Operators (TSOs) (Svenska Kräftnet, Fingrid, Energinet.dk and Statnett) are responsible for developing their national grids and connection to other countries.

Nordel was founded in 1963 and was a body for co-operation between the transmission system operators in Denmark, Finland, Iceland, Norway and Sweden, whose objective was to create preconditions for a further development of an effective and harmonised Nordic electricity market. On 01 July 2009 Nordel was wound up. All operational tasks were transferred to ENTSO-E [entsoe, 2012]. ENTSO-E (European Network of Transmission System Operators for Electricity) represents all electric TSOs in the EU and others connected to their networks, for all regions, and for all their technical and market issues.

ENTSO-E publishes every second year a non-binding, Ten-Year Network Development Plan (TYNDP). The TYNDP is designed to increase information and transparency regarding the investments in electricity transmission systems which are required on a pan-European basis and to support decision-making processes at regional and European level. ENTSO-E created the Working Group (WG) TYNDP to lead the development and publication of the TYNDP. The first Pilot TYNDP was published in June 2010 and the second in July 2012. Those TYNDPs were based on the most up-to-date and accurate information regarding planned or envisaged transmission investment projects of European importance prior to its release.

ENTSO-E has defined six regional groups. The regional groups are designed to address the challenges for grid development and the integration of new generation, especially renewable energy sources, at a regional level through a structure which reflects the region's particularities and needs.

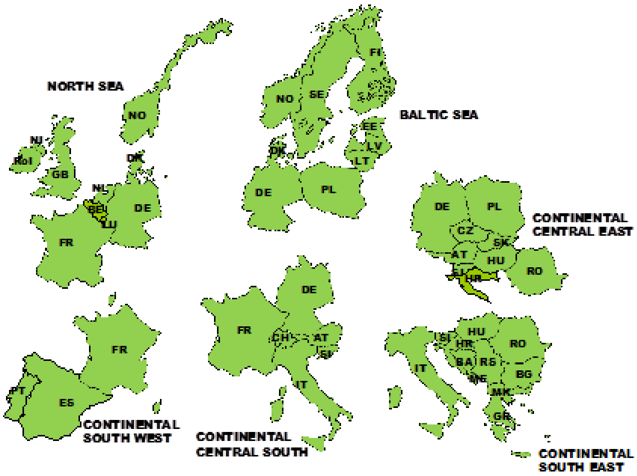

Figure 1-1 Regional groups for grid development planning in ENTSO-E [entsoe, 2012]

The next target for the TYNDP WG and the regional groups is the release of the next Ten-Year Network Development Plan in December 2014. The 2014 release will include six Regional Investment Plans, a System Outlook and Adequacy Forecast (SOAF) alongside the Europe-wide development plan which formed the core of the first TYNDP. As the level of detail and sophistication of the TYNDP increases, ENTSO-E hopes and expects that it will increasingly be seen as the key tool for aiding decision making regarding electricity transmission investments.

At a meeting in Copenhagen on the 25th of October 2010 the Nordic energy ministers agreed that investments that are socio economic profitable for the Nordic area shall be implemented. Thus, network transmission planning for the Nordic countries shall both have national as well as Nordic perspectives. The work described in this report can be considered as a contribution to the transmission planning at all three levels: national for each of the Nordic countries, Nordic and European.

The Nordic Energy Technology Perspective (NETP) was released in 2013 and showed how the Nordic energy system can be developed in a more sustainable direction. This report is related to the NETP, but has a particular focus on the Nordic power system and what is profitable in terms of expansion of transmission grids to become carbon neutral, and furthermore what role the Nordic power system can play in a future European power system based on a power production with limited emission of green-house gases.

The structure of this report

The methodology for the work is described in Chapter 2. The establishment of the input data for the analysis is described in Chapter 3. Chapter 4 describes the scenarios used in the analyses, and the results from the analyses are given in Chapter 5. The NORSTRAT results are compared with the results in the Nordic Energy Technology Perspectives in Chapter 6. In Chapter 7 there are discussions and conclusions of the work and also some description of what can be expected in the next deliverables from WP3 in the NORSTRAT project.

2 Methodology

A scenario methodology is used for analyses of a future carbon neutral power system and what kind of role the Nordic power system may have in a European context based on large volumes of renewables.

Models for optimizing system operation with large shares of hydropower are well suited for analysing future energy systems with large shares of renewable generation and storage capacity. This is the reason why the EMPS (EFI's Multi-area Power market Simulator) is used for assessment of the Nordic energy system with respect to minimization of operation cost, utilization of storage options and to forecast regional energy prices. The EMPS model is described in Appendix 1. The model can be combined with an investment algorithm and this is described in the same appendix.

The EMPS is an electricity market model that can handle systems with large shares of conventional and varying electricity generation as well as long- and short-term storage options such as hydropower. Each node (or region) is characterized by an endogenously determined internal supply and demand balance with distinct import and export transmission capacities to the neighbouring nodes.

The NORSTRAT analyses are performed with 26 node data model for the Nordic region and an additional representation of each European country see Figure 2-1. Furthermore, Germany and Great Britain are modelled in great detail. In addition Russia is represented by a node in the model (not shown in the figure). 41 years of statistical data are used in the analyses with data about inflow to the hydropower system, wind and solar resources. Each week is analysed with 39 periods resolution resulting of 90 000 periods (358 000 hours) with simulations. Included in the data set is a huge variation in the hydro, wind and solar resources. Only investments in transmission capacities are considered. Capacities for production are pre-defined for each scenario.

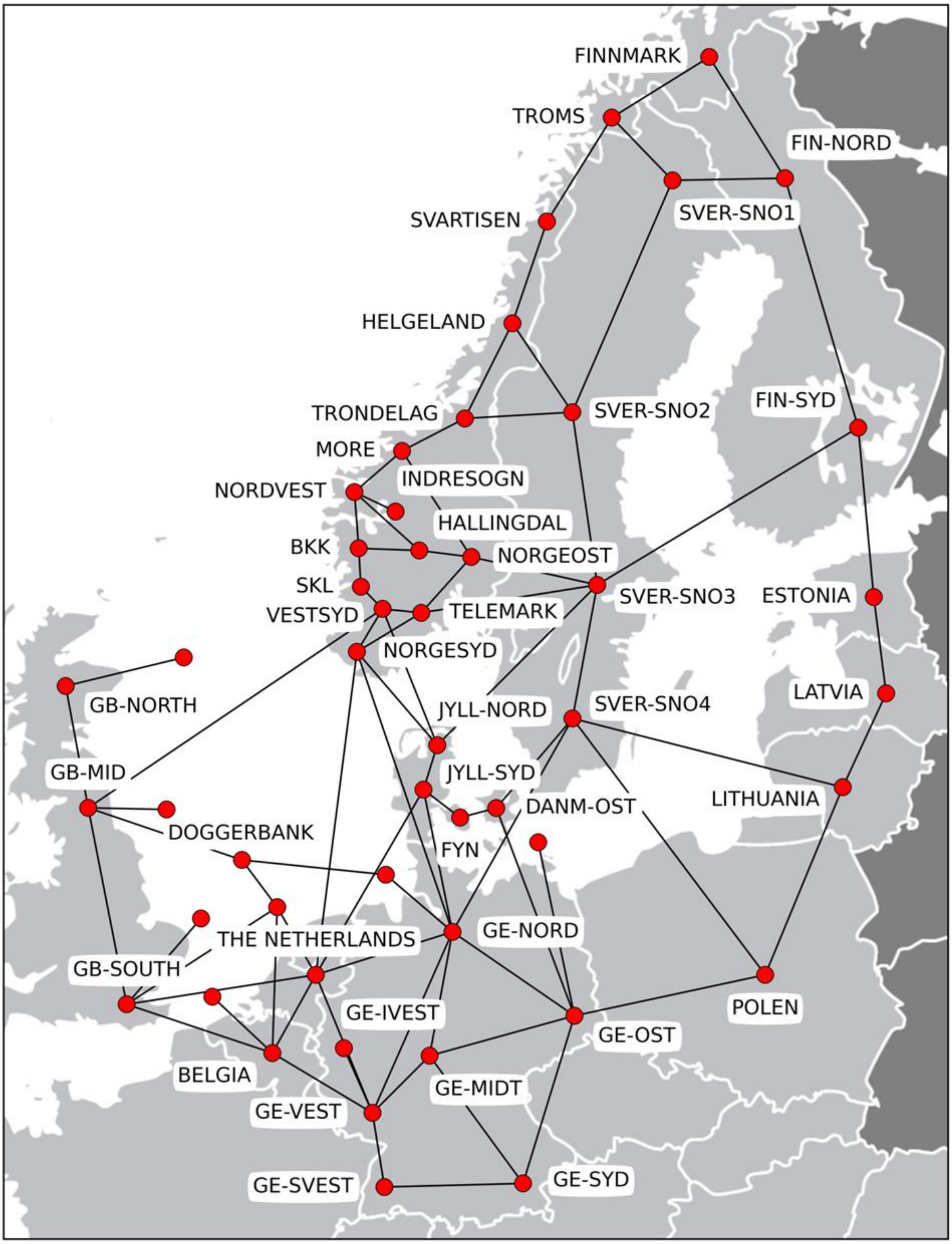

Figure 2-1 Regions (nodes) in Northern Europe included in the NORSTRAT project data set for the EMPS model

3 Input data

The methodology for establishing input data to the power system analyses is described in this chapter.
In the analyses of the development of the transmission system, at least two aspects are important to consider:

- The development of the demand, both in terms of volume and localization
- The production portfolio both in terms of capacity and localization. Since NORSTRAT is focusing on a carbon neutral future, possibilities for new renewable production will be of particular interest.

The time perspective is 2050, and in such a long perspective there will be large uncertainties related to the input data. In order to reduce the uncertainty as much as possible, the input data are to a large extent based on prognoses from the statistical offices in the Nordic countries and already identified projects for new renewable production.

Section 3.1 describes assumed development of demand. Section 3.2 to 3.5 describes the assumed potential for future wind, hydro, solar and bio production respectively. Section 3.6 gives and overview of the total assumption of renewable resources per country in the Nordic region, and 3.7 describes the assumed development in other countries. Section 3.8 describes assumptions related to transmission losses, and section 3.9 costs for increase of transmission capacities. Finally section 3.10 describes assumed fuel and CO_2 prices.

3.1 Development of demand

As already mentioned, in the NORSTRAT analyses both development of volume and localization of demand is important. It is assumed that the future changes in demand will be related to the future changes in population. The expected development in population per region to 2050 is described in Appendix 2. A possible change in demand is calculated based on the expected change in population per region multiplied with current consumption per inhabitant in the specific region. The estimated demand increase/decrease per country is shown in Table 3-1. The changes add up to 58 TWh/y increase in consumption for the four Nordic countries together. The largest increases are in Norway (26 TWh/y) and Sweden (21 TWh/y). Figure 3-1 shows assumed change in the demand based on the location of the expected increase/decrease in population multiplied with the current general consumption in the region.

Table 3-1 Estimated demand increase due to expected increase in population

	TWh/y
Denmark	3,5
Finland	7,5
Norway	26,0
Sweden	21,0
Total	58,0

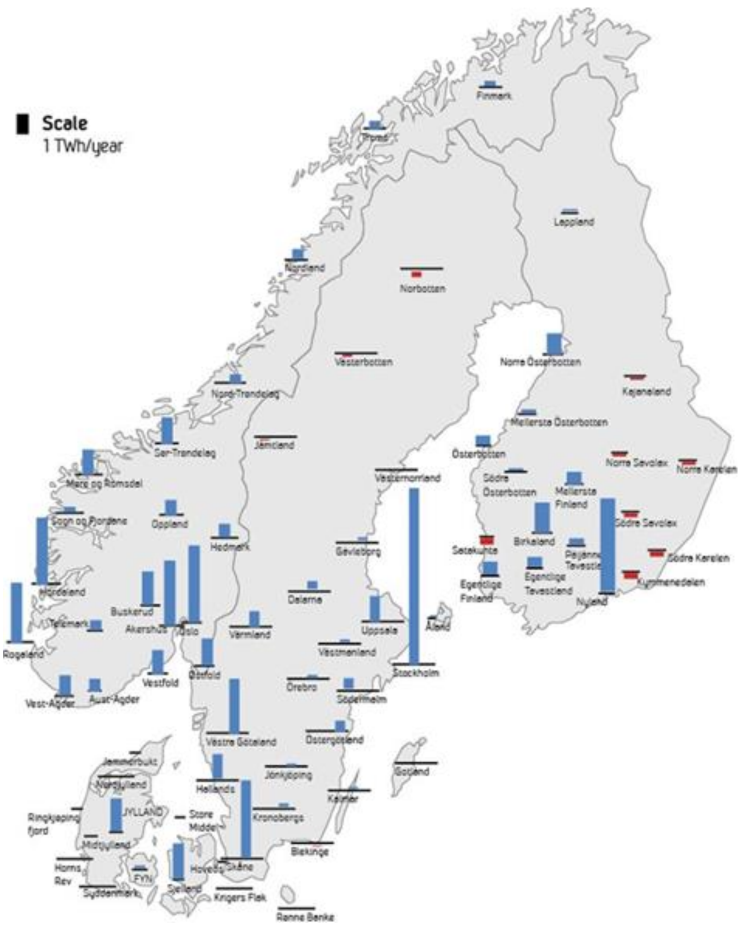

Figure 3-1 Location of changes in demand to 2050 based on expected population changes (Blue shows increase, Red shows decrease).

A data set from the Nordic TSOs for 2012 is used as starting point for scaling up (down) the consumption per region. Only general supply is scaled up. Consumption in e.g. power intensive industries is kept fixed from 2012 to 2050. The assumed demand for 2050 is shown in Table 3-2.

In the NORSTRAT analysis, demand is kept fixed in all four main scenarios at 444 TWh/y in total for the Nordic region. For one of the scenarios a sensitivity analysis of the demand is conducted, see Section 5.2.1. The demand assumed in NORSTRAT is at the same level as in the Nordic Energy Technology Perspectives [NETP, 2013], see Section 6.

Table 3-2 Assumed demand in the Nordic region in 2050 in NORSTRAT

TWh/y	Eurelectric [Eurelectric 2010]	NORSTRAT
	2010	2050
Denmark	34,2	39
Finland	85,8	96
Norway	130	152
Sweden	140,3	158
Total	390,3	444

3.2 Wind power production

In 2012 there were registered projects with approximately 185 TWh/y of new wind power production in the Nordic region. Many of these will probably not be realised in a short time perspective. However, the projects are assumed to reflect a localisation of the best wind resources.

3.2.1 Hourly wind energy time series from Reanalysis dataset

Wind speed time series are based on NCEP Reanalysis data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at [esrl, 2012].

The Reanalysis dataset covers 1948–today, with a temporal resolution of 6 hours and a spatial resolution of 2.5 degrees in both latitude and longitude. In order to get wind speeds at the selected points (see Figure 3-2) a two-dimensional interpolation of neighbouring Reanalysis points has been applied. In order to get hourly time series for wind speed, an interpolation of the 6-hourly values has been applied.

The geographical points selected for the generation of the wind energy time series and their connection to the EMPS area are shown in Figure 3-2. Blue circles indicate Reanalysis data points, which are separated by 2.5 degrees both in latitude and longitude. The coloured squares indicate the selected points representing the various EMPS areas.

Wind energy is computed from the wind speed using the same method as in the TradeWind project [TradeWind,2012]. Since the wind speed is the average and smoothed out wind speed for a wide area, and because the wind energy output represents many wind turbines, a regional power curve is used for the computation. This can be thought of as an average power curve for many wind turbines. The power curve used is shown in Figure 3-3.

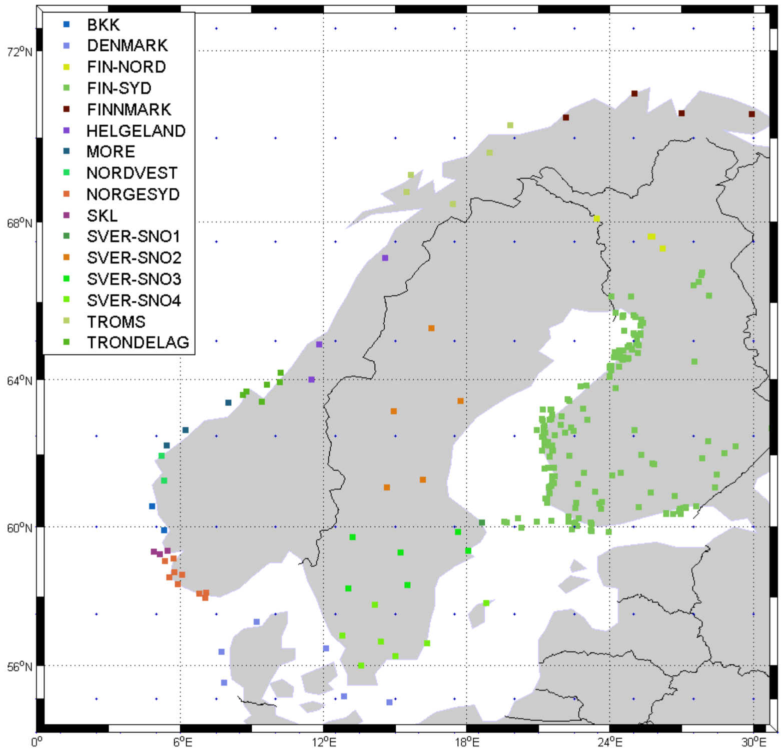

Figure 3-2 Wind connection points in EMPS model. Blue dots represent Reanalysis data points, and squares represent selected points for power time series

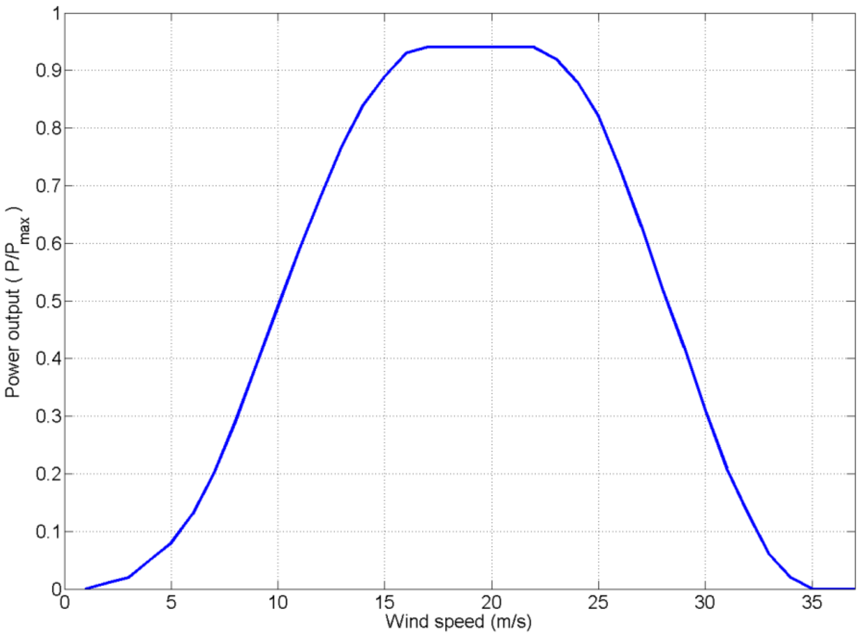

Figure 3-3 Regional power curve

In most cases there will be a significant discrepancy between the computed wind energy and the actual wind energy with this direct method. This is inevitable with such a coarse method.

3.2.2 Denmark

In [Energistyrelsen, 2011] it is identified possible locations for new offshore wind production in the period to 2025. New capacity of 4600 MW is assumed to give about 18 TWh/y of new production. Table 3-3 shows the detailed location of the potentials.

Table 3-3 Possible location of new offshore wind production in Denmark to 2025 [Energistyrelsen, 2011]

Location	MW
Krigers Flak A	600
Horns Rev A	600
Rønne Banke	400
Jammerbugt A	400
Ringkjøping Fjord A	400
Horns Rev B	400
Ringkjøping Fjord B	400
Krigers Flak B	200
Ringkjøping Fjord C	200
Jammerbugt B	400
Store Middelgrund	200
Total	4200

The potentials are identified based on factors like accessibility to the transmission network, shipping, nature, landscape, etc. All the possible offshore parks are located at least 12.5 km from shore, but in as shallow water as possible. Further investigation of, among others, seabed conditions is necessary before the offshore wind parks may be realised.

It is assumed that a new and improved structure will be established for the main parts of the power transmission network based on upgrading of part of the 132 kV and 150 kV to 400 kV. The new 400 kV structure can be used for integration of the new offshore wind parks. The exception is Rønne Banke where a new connection from Bornholm to Sweden will be necessary.

For some of the parks cooperation with other countries and their establishment of offshore wind parks may be useful like with Sweden for "Store Middelgrund" and with both Sweden and Germany for "Kriegers Flak".

3.2.3 Finland

Detailed information about possible new wind production in Finland is available on the web [FWPA,2012]. By the end of January 2012, 7800 MW of wind power projects were published of which about 3000 MW is offshore. Each possibility is detailed described by among other location, capacity, status, project owner, link to more detailed information etc. The projects are mainly located along the coast line.

The projects are in all types of phases from "feasibility studied" to "preparing for construction" and "under construction".

3.2.4 Norway

At the web page for the Norwegian Regulator there is detailed information about possible new wind production in Norway, both onshore as well as offshore [NVE, 2012]. The information is in terms of applications (projects) for establishing new wind turbines. The projects are in different phases and all of them will probably not be realized. However, similar as for Finland the projects reflect the location of the wind power resources. Thus, for NORSTRAT the analysis of new wind power production is based on the projects identified at the Regulators web page. Table 3-4 gives an overview of the onshore wind projects registered at the web page. Furthermore, at the same web page there is information about offshore wind projects of all together 40 TWh/y potential production.

Table 3-4 Sum of onshore wind power projects at the Norwegian Regulator in 2012 [NVE, 2012]

Phase	MW	TWh
Consession given	4575	13
Applied for consession	4006	11
Evaluation by regulator	4241	13

3.2.5 Sweden

In 2009 "Riksdagen" decided to plan for 30 TWh/y power production from wind resources in 2020. 10 TWh/y should be based on offshore wind resources [svenskenergi, 2012]. By the end of 2012 the wind production will be approximately 8 TWh/y.

Information about new onshore wind power production under construction or identified as a project are given by Svensk Vindenergi. Projects including more than 17 GW onshore wind production are identified (including the already installed capacity of about 3 GW).

The projects are sorted in the 4 areas the Swedish power system is currently divided in.

Table 3-5 Identified onshore wind power production projects Sweden 2012 [Svensk Vindenergi 2012]

[MW]	SVER-SNO1	SVER-SNO2	SVER-SNO3	SVER-SNO4	Total
I drift	188	460	1223	870	2740
Under construction	119	435	323	155	1032
All permissions given	367	2074	395	108	2944
Permisson evaluation	1812	3717	3364	1345	10237
Total	2486	6686	5304	2478	16953

Nearly 3 GW onshore wind power production are already installed. If the other identified projects of 14 GW are realized and 2500 hours per year of production is assumed, it will result in 35 TWh/y new production.

According to [4Coffshore, 2012] there are about 0.5 TWh/y installed offshore wind production in Sweden, there are given permission for more than 7 TWh/y and there are registered projects that may give another 23 TWh/y production.

3.3 Hydropower production

Increase of hydropower production is expected only for Norway. Potential for new production in Norway is identified by information available at [NVE, 2012]. The Regulator has to give concession for all new hydropower projects. NVE has made information available through their web page for all projects they have received either application for or message about. At the Regulators web page there is information about the following projects:

- Concession given: in total 2023 MW capacity and 12081 GWh/y
- Recommendation given: in total 454 MW and 1335 GWh/y
- Application received: in total 3866 MW and 9267 GWh/y

Each of the projects is described in detail. Most of the projects are small scale projects of less than 10MW. Many of the projects in the category "Concession given" have received permission many years ago. Thus, for the NORSTRAT analysis all projects with permission from before 2007 were excluded from further analysis. There are projects of 1373 MW and with a potential production of 4637 GWh/y which have received concession since the beginning of 2007.

Projects which have received permission after 2007 and projects which have received recommendation where included in the NORSTRAT scenarios with the lowest volume of new hydropower production. Further, for the scenarios with the highest volume of new hydropower production, the projects identified by application to the Regulator were also included.

All the projects are described by location, capacity and expected yearly production.

Reduction of hydropower production as a consequence of the Water Framework directive is not considered in the NORSTRAT analyses.

3.3.1 Increased capacity in the Norwegian hydropower system

In addition to the potential for increased hydropower production described in the previous section, possible increase in generation capacity in the Norwegian hydropower system (for balancing purposes) is based on a study [CEDREN 2011]. In this study only increases in generation capacity as well as pumping in existing plants is considered, thus there is no new energy (as in the previous section) or storage capacity added to the system. The study aimed at identifying possibility for new regulating power in the southern Norway, resulting in three different scenarios with different generation capacities. The more conservative, with a new generation capacity of 11200 MW shown in the table below, is used in the NORSTRAT study.

Table 3-6 Increased hydro generation capacity in the Norwegian system in NORSTRAT [CEDREN, 2011]

Type	Power unit	Increase (MW)	Upper res.	Lower res.
Pump	Tonstad	1 400	Nesjen	Sirdalsvatn
Pump	Holen	700	Urarvatn	Bossvatn
Pump	Kvilldal	1 400	Blåsjø	Suldalsvatn
Power	Jøsenfjorden	1 400	Blåsjø	Jøsenfjorden
Pump	Tinnsjø	1 000	Møsvatn	Tinnsjø
Power	Lysebotn	1 400	Lyngsvatn	Lysefjorden
Power	Mauranger	400	Juklavatn	Hardangerfj.
Power	Oksla	700	Ringedalsvatn	Hardangerfj.
Pump	Tysso	700	Langevatn	Ringedalsvatn
Power	Sy-Sima	700	Sysenvatn	Hardangerfj.
Power	Aurland	700	Viddalsvatn	Aurlandsfj.
Power	Tyin	700	Tyin	Årdalsvatnet
		11 200		

In addition new generation capacity in the northern part of Norway is based on NVE [NVE,2011]. The capacities are shown in the table below.

Table 3-7 Increased hydropower capacity in the northern Norway in NORSTRAT [NVE, 2011]

Power unit	Increase (MW)
Trollfjord	2 x 50.0
Fagervollan	2 x 243.0
Lassajavrre	6 x 200.0

3.4 Solar production

There were no registered projects for future solar power production as it was for wind and hydro power production. For Sweden a review indicates that the long term realistic potential of the roof top photovoltaic (PV) in Sweden is in the order of 5 TWh/y corresponding to a fifth of the long term technical potential on buildings [Energimyndigheten, 2007]. A rough estimate of a long term potential of 5TWh/y was also made for Denmark. The potentials in Norway and Finland were assumed to be limited and set to zero. The potential of solar power production in the Nordic countries will anyway be very low compared to the potentials of production from wind, hydro and bio energy.

To obtain time series for solar resources underlying data has been obtained from [Nasa, 2009]. The data series contain values from 1 January 1984 until 31 December 2005, i.e. data for 22 years. The data series are based on a combination of measurements and meteorological models, and the given quantities refer to averaged values over an area of 1 degree in east-west direction and 1 degree in north-south direction. A given area is referred to by the southwest corner. E.g. data for 35°N / 10°E gives the averaged value for the area 35-36°N / 10-11°E. Moreover, the data are daily averages, using midnight local time to separate one day from the other.

3.4.1 Computation of generated solar power based on insolation data

The first step in the transformation is to decompose the total radiation into direct (beam) radiation and indirect (diffuse) radiation. This is necessary because direct radiation on a solar panel depends on the angle between the beam and the panel surface, while the indirect radiation is isotropic (same in all directions).

The next step is to compute a daily profile for the radiation based on the daily averages. This is necessary because the raw data has a lower time resolution (24 hours) than the desired output (1 hour). Even to get daily average power production, it is necessary to go through this (or some equivalent) step, since the energy reaching the solar panel depends on the angle as mentioned above, and because this angle varies with time in a non-linear way.

Hourly values generated for this project give average values for the intervals 00:00 – 01:00, 01:00 – 02:00 etc. Time refers to GMT.

When the hourly values for direct and indirect radiation on a horizontal surface has been computed, the next step is to compute the radiation on tilted surfaces. The direction of the solar panel is given by its normal vector, which can be described by two angles (spherical decomposition), the angle from zenith (altitude angle), and the angle from south (azimuth angle). The position of the sun depends on time of year, time of day, as well as latitude and longitude of the observer.

The last step in the computation of power from radiation depends on the properties of the solar panel. Two parameters have been taken into account in the current case

- Conversion factor – this factor specifies how much of the solar radiation reaching the solar panel is converted to electric power. The value used here is 12%. (E.g. at 1000 W/m^2 solar radiation, the panel generates 120 W/m^2 of power)
- Electrical efficiency factor – this factor specifies how much of the generated power in the solar panel reaches the grid, i.e. is not lost in the conversion. The value used here is 78%.

These factors can vary from country to country and depend on the equipment installed. The values indicated above (12% solar conversion, 78% efficiency) are realistic for photovoltaic (PV) panels, but generation based on solar heating (use of mirrors to heat water which then drives a steam turbine) is not well described by this method.

3.4.2 Solar generation time series

Solar PV generation time series have been generated using the method outlined above for a chosen point in Denmark and for two points in southern Sweden. The generation of the solar time series are based on the following:

- The time series are based on normalised capacity (1 GW for each country)
- Fixed PV panels pointing south with a zenith angle of 60° has been assumed
- Leap year days (29 Feb) have been excluded
- Weekly values count week 1 from 1 January, and week 52 ends with 30 December.

3.5 Bioenergy production

Techno-economic potential for biomass resources is given in [Alkangas, 2007] and shown in Figure 3-4.

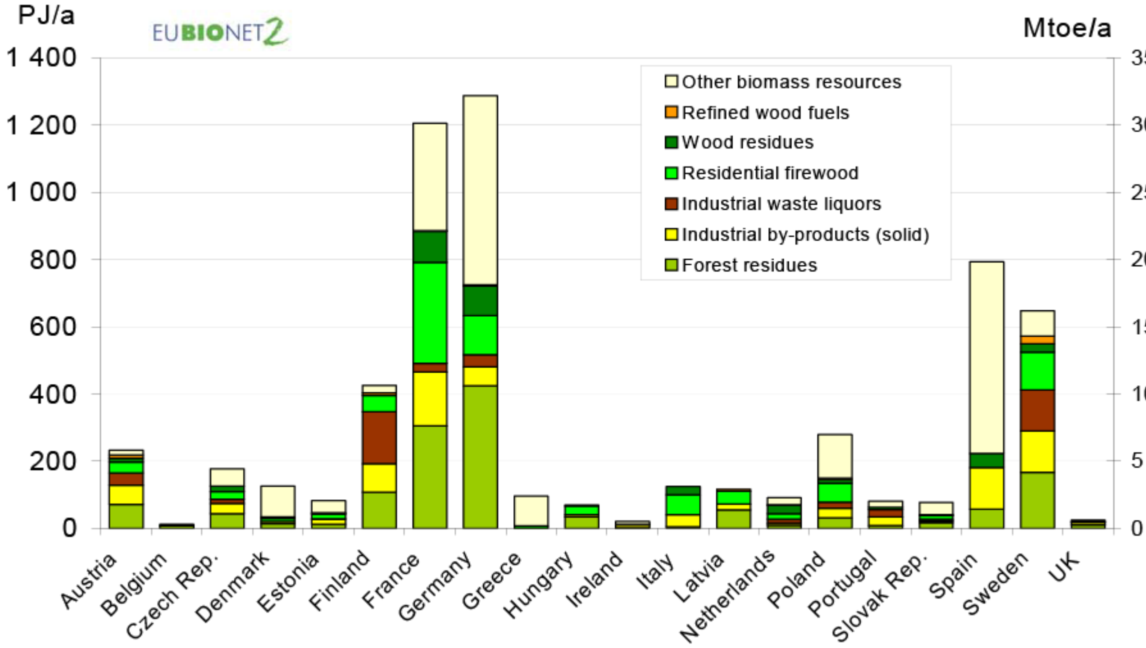

Figure 3-4 Techno-economical biomass resources in 20 European countries [Alkangas, 2007]

If all the resources where used for power generation it would approximately represent 45-50 TWh/y for Denmark, 110 TWh/y for Finland and 180 TWh/y for Sweden. NORSTRAT is based of using a minor share of the potentials shown in Figure 3-4.

3.6 Potential for new renewable production

There is a huge potential for new renewable based power production in the Nordic region. A survey of different sources shows registered projects with nearly 200 TWh/y of possible new production. Among other there are registered about 80 TWh/y of onshore wind projects and more 100 TWh/y with offshore wind projects. Table 3-8 shows the registered wind power projects in the Nordic region per country.

Table 3-8 Registered wind power projects in the Nordic region in 2012

	TWh/year	Onshore	Offshore
Denmark	Investigation	0	20
Finland	All phases	11	14
Norway	Concession given	12.6	0
	Applied for concession	11.2	0
	Investigation	12.6	39.6
Sweden	Concession given	4.2	7
	Investigation	30	23.6
	Total	**81.6**	**104.2**

In Table 3-9 and Table 3-10 there are two cases for new renewable energy in the Nordic region. Both tables describe large potentials for new renewable power production. Table 3-9 describes the lowest case with "only" 152 TWh/y new renewable production while Table 3-10 describes a future with 248 TWh/y new production. The main difference between the volumes is offshore wind production. The two tables are used as basis for the scenario description.

Table 3-9 Potential for new renewable based power production in the Nordic region, "Lowest case"

Country	Technology	Assumed volume of new production [TWh/y]	Reference to documentation	Comments
Denmark				
	Offshore wind	25	Ca 20 TWh/y registered as new projects at [4Coffshore, 2012]	Location given at [4Coffshore, 2012]
	PV	5		
Finland				
	Onshore wind	10	There are applications for 5GW increased capacity at [tuulivoimayhdistys, 2012]	Locations given at [tuulivoimayhdistys, 2012]
	Offshore wind	14	According to applications in [4Coffshore, 2012]	Locations given at [4Coffshore, 2012]
	Bio	20	Potential of 110 TWh/y, [Alkangas, 2007]	
Norway				
	Onshore wind	13	Concession already given by Regulator [NVE, 2012]	Location give per project at [NVE, 2012]
	Hydro	10	Registered projects at Regulator for more than 15 TWh/y [NVE, 2012]	Location give per project at [NVE, 2012]
Sweden				
	Onshore	20	14 000 MW (35 TWh/y) of registered projects in excel sheet from Svensk Vindenergi	Location per EMPS area given in excel sheet from Svensk Vindenergi
	Offshore	20	Registered project for 30 TWh/y in [4Coffshore, 2012]	Locations given at [4Coffshore, 2012]
	Bio	10	Potential of 180 TWh/y [Alkangas, 2007]	
	PV	5		
Total		**152**		

Table 3-10 Potential for new renewable based power production in the Nordic region, "Highest case"

Country	Technology	Assumed volume of new production [TWh/y]	Reference to documentation	Comments
Denmark				
	Offshore wind	40	Ca 20 TWh/y registered as new projects at [4Coffshore, 2012]	Location for 20 TWh/y given at [4Coffshore, 2012]
	PV	5		
	Bio	5	Potential of 45 TWh/y [Alkangas, 2007]	
Finland				
	Onshore wind	10	There are applications for 5GW increased capacity [tuulivoimayhdistys, 2012]	Locations given at [tuulivoimayhdistys, 2012]
	Offshore wind	30	Projects with 14 TWh/y registered in [4Coffshore, 2012]	Locations given at [4Coffshore, 2012]
	Bio	25	110 TWh/y, [Alkangas, 2007]	
Norway				
	Onshore wind	13	Concession already given by Regulator [NVE, 2012]	Location give per project at [NVE, 2012]
	Hydro	20	Registered projects at Regulator for more than 15 TWh/y	Location give per project at [NVE, 2012]
	Offshore wind	30	Projects for nearly 40 TWh/y registered at [NVE, 2012]	Location per project at [NVE, 2012]
Sweden				
	Onshore	30	14 000 MW (35 TWh/y) of registered projects in excel sheet from Svensk Vindenergi	Location per EMPS area given in excel sheet from Svensk Vindenergi
	Offshore	30	Registered projects for 30 TWh/y in [4Coffshore, 2012]	Locations given at [4Coffshore, 2012]
	Bio	10	Potential of 180 TWh/y [Alkangas, 2007]	
	PV	5		
Total		**253**		

For some of the new renewable production it was challenging to identify exact which EMPS node it "belonged" to. Thus, some of the production may in the NORSTRAT analysis have been located on a neighbouring node. E.g. all new production in Finland is located in FIN-SYD. Another distribution of the RES resources will of course impact the profitability of new transmission links.

3.7 Development in other European countries

The development of the power system in UK, the Netherlands, Germany and Poland is based on [DG Energy, 2009] and further projections to 2050. The Reference scenario in that report is based on the development of the EU energy system under current trends and policies. It includes current trends on population and economic development including the recent economic downturn and takes into account the highly volatile energy import price environment of recent years. Economic decisions are driven by market forces and technology progress in the framework of concrete national and EU policies and measures implemented until April 2009. Further it includes policies adopted between April 2009 and December 2009 and assumes that national targets under the Renewables directive 2009/28/EC and the GHG Effort sharing decision 2009/406/EC are achieved in 2020.

Development in other countries in Europe is from the SUSPLAN project in the EU 7th framework program [SUSPLAN, 2012]. The share of renewables in the production portfolio is around 65-70%, and nuclear is assumed to be phased out in Germany. Russia is assumed to have less focus on integration new renewable production, and has a considerable gas power production in 2050. The input capacities and the demand is the same for all scenarios. The resulting power production will be slightly different from scenario to scenario because of the interaction with the Nordic system.

3.8 Transmission losses

In [NOU 1998] the transmission losses in Norway are assumed to be 2%. The same percent is assumed for the whole Nordic region.

3.9 Costs for increase of transmission capacities

Development of costs for increase of transmission capacities is based on data from Green scenario in the SUSPLAN project. The methodology for establishing the cost development is described in [SUSPLAN, D3.1].

Table 3-11 Annualized AC and HVDC expansion costs for investments in 2050

HVDC[Euro/MW]	AC [Euro/MW]
22156	5424

Note that the specific expansion costs are given for HVDC cables with an average line length of 130 km and HVAC overhead lines with an average line length of 80 km, thus the distance between the nodes do not affect investment costs. Further work related to the development in cross border transmission capacities should aim to reflect real distances between countries and load centers.

3.10 Fuel and CO_2 prices

Fuel and CO2 prices are the same as in the Nordic NETP 2DS and shown in Table 3-12.
Table 3-12 Fuel and CO2 prices used in all NORSTRAT scenarios [Nordic ETP, 2013]

Hard coal	USD 2010/GJ	2,1
Natural gas	USD 2010/GJ	8
Crude oil	USD 2010/GJ	41,4
Liquid biofuels	USD 2010/GJ	22-29
CO2	USD/t	160

4 NORSTRAT Scenarios

A main objective of the NORSTRAT project is to build knowledge among decision makers and politicians about carbon neutral futures for the Nordic power system and also partly the transport and the heating system. The impact from the transport and the heating systems is included in further studies in NORSTRAT. The scenarios in this report are focused on carbon neutrality in the power system. Several other aspects are also included:

- Increased share of renewable production in the power system including possibilities for export of green electricity from the Nordic region.
- Degree of integration to the European power system. Two paths are investigated:
  i) Nordic Balance – the Nordic region as a carbon neutral region related to electricity and transport.
  ii) European Hub – the Nordic region as a major exporter of green electricity in Europe.
- The role of nuclear in a carbon neutral Nordic power system is considered.

Some outputs from the scenario analysis are:

- Profitable increases in transmission infrastructures within the Nordic region, between the Nordic region and neighbouring countries and between countries in Europe outside the Nordic region
- Development of electricity balances internally in the Nordic region and in other countries in Europe
- Development of electricity prices in the Nordic region and in neighbouring countries to the Nordic region

For the NORSTRAT project 4 main scenarios and two sensitivity analyses within these are defined. Two factors are chosen to span out 4 futures: degree of integration with the rest of the European system and volume of new renewable based production.

The Nordic power system is assumed to be totally integrated, and transmission capacities are increased according to profitability criteria. Degree of integration with the rest of the European system are analysed for to cases: i) capacities as in the present system ii) increased based on profitability criteria.

As shown in section 3.6 there are huge potentials for new renewable production in the Nordic region. If all fossil production is phased out, up to 100 TWh/y need to be substituted. Further, as shown in the same chapter, an expected increase in population may result in an increase in demand of about 50-60 TWh/y. Thus, a carbon neutral Nordic power balance for 2050 should be based on about 100-150 TWh/y new renewable production.

Further, as shown in Section 3.5, it is possible to develop as much as 200-250 TWh/y of new renewable production in the Nordic region mainly based on already existing projects. A lot of such new production has to be onshore or offshore wind, and there will probably be a need for more balancing sources. In the NORSTRAT scenarios, up to 20 GW of new capacity is made available in the Norwegian hydropower system. 200-250 TWh/y of new renewable capacity gives an opportunity to phase out the nuclear production in the Nordic region.

The 4 main NORSTRAT scenarios are shown in Figure 4-1. As shown in the figure, the degree of integration with the rest of Europe and the volume of new RES included in the Nordic power production is used to span out the 4 scenarios:

- **"Carbon Neutral"** has the same transmission connection to the rest of Europe as in 2015. In addition some of the existing plans for new capacity are implemented. The fossil production is phased out and substituted with 100- 150 TWh/y new RES based production.

- **"Purely RES"** has 200-250 TWh/y new RES based production and the same transmission capacities to the Nordic neighbouring countries as in 2015, including known plans. The nuclear and the fossil production in the Nordic region are phased out.
- **"European Hub"** is based on 200-250 TWh/y new RES in the Nordic region and up to 20 GW new capacity in the Norwegian hydropower system. The transmission capacities between the Nordic region and the rest of Europe are increased based on profitability assessments.
- **"European battery"** has 100-150 TWh/y of new RES based production in addition up to 20 GW new capacity in the Norwegian hydropower system. Transmission capacities between the Nordic region and its neighbouring countries are increased based on profitability assessments.

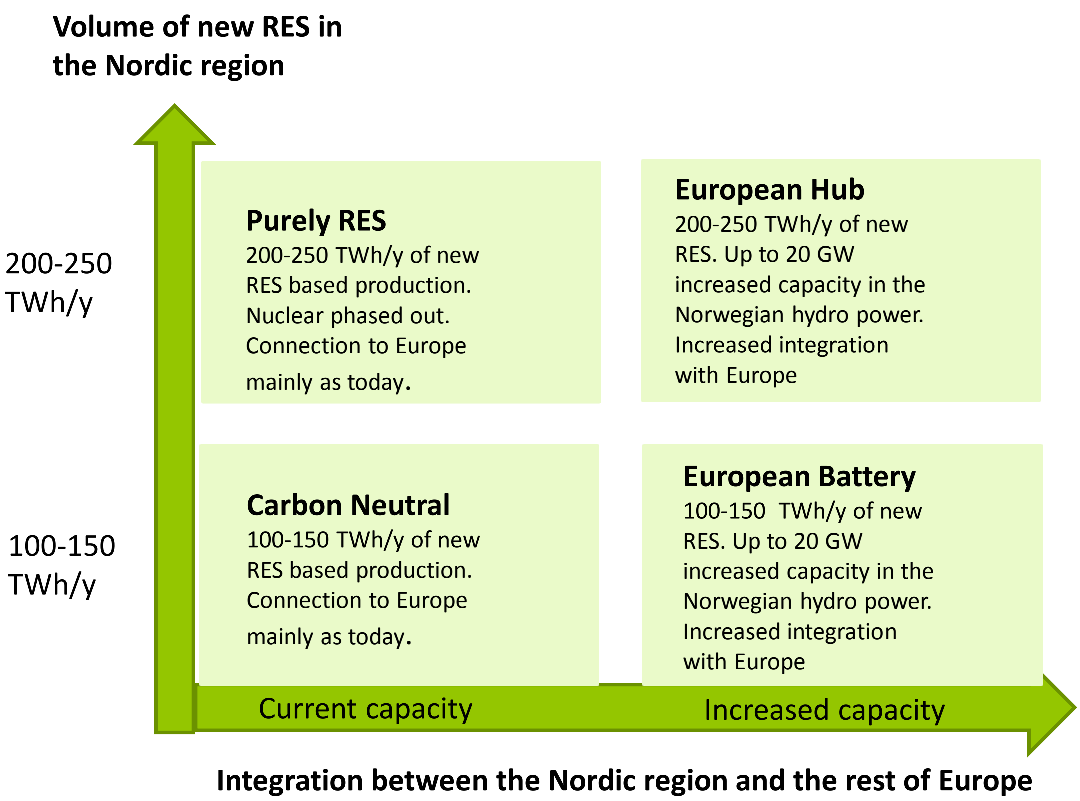

Figure 4-1 NORSTRAT main scenarios

For the 4 main scenarios, there will be two sensitivity analyses:
Carbon Neutral: Demand is reduced with 75 TWh/y compared to 2012. The same demographic changes to 2050 as in other NORSTRAT scenarios are assumed, thus a larger share of the demand will be in and around the large cities than in 2012. New renewable production is 25 TWh/y in addition to the 2012 production.

Purely RES: Only the Swedish nuclear production is phased out. The new renewable production is limited to about 200 TWh/y.

Regarding the 20 GW of new capacity in the Norwegian hydropower system, the capacity is included in terms of increased capacity in already existing plants and by adding pumping capacity according to the possibilities described in Section 3.3.1. However, in the simulations, pumping within the week is not made possible (the ReOpt algorithm is not used), so in these analyses the increased capacity only has a seasonal effect.

5 Analysis results

The results from the NORSTRAT analyses are presented in the following sections. Section 5.1 provides some help to understand the results. Results from each of the scenario analyses are presented in the sections 5.2- 5.5. Section 5.6 goes more in-depth into the results related to profitable expansion in the transmission system.

5.1 About the results

In the description of results there are graphical presentations of the production portfolios for Europe outside the Nordic region. The following countries are included in the presentations:
Albania, Austria, Belgium, Bosnia-Herzegovina, Bulgaria, Croatia, Czech, Estonia, France, Germany, Great Britain, Greece, Hungary, Italy, Latvia, Lithuania, Luxembourg, Macedonia, Moldova, the Netherlands, Poland, Portugal, Romania, Serbia, Slovakia, Slovenia, Spain and Switzerland,

There are separate wind parks (named OWP) for the following countries: Belgium, Great Britain, the Netherlands and Germany,

The start capacities for the grid analyses are shown in Table 5-1, which include the known plans of transmission increase within the Nordics and between the Nordic countries and Continental Europe in the following years. Two connections which are not established today are included, VESTSYD – JYLL-NORD and TELEMARK – SVER-SNO3, refer Figure 2-1.

The transmission grid between Russia and neighbouring countries are kept at the 2015 level in all scenarios.

For all the scenarios a map showing the flow in the transmission system after increases of transmission channels is shown. The arrows in the maps show the net direction of the power flow over the year. The size of the channels between two nodes shows the volume of the net power flow over the year. The net power flow is calculated for all periods in all 41 years with simulations. The result is divided by 41 to get the average net flow for a year. In theory such a net flow can be zero.

Several of the figures are showing results gathered together, e.g. one big figure with four smaller figures showing the duration curve for a specific channel for each of the four scenarios. The reader should be aware that the smaller figures gathered together may have different scaling. E.g. in Figure 5-27 showing the duration curve for the channel between SVER-SNO3 and SVER-SNO4, the maximum on the y-axis is different for all four scenarios. Also for figures showing prices in different regions, the scaling will in many cases be different for the small figures gathered together in one figure.

Table 5-1 Grid starting point for scenario analyses (MW)

A	B	A<-->B
FINNMARK	TROMS	500
FINNMARK	FIN-NORD	50
TROMS	SVARTISEN	1200
TROMS	SVER-SNO1	600
SVARTISEN	HELGELAND	1200
HELGELAND	TRONDELAG	1500
HELGELAND	SVER-SNO2	350
TRONDELAG	MORE	2000
TRONDELAG	SVER-SNO2	1000
MORE	NORDVEST	1500
MORE	NORGEOST	400
NORDVEST	INDRESOGN	925
NORDVEST	BKK	1000
NORDVEST	HALLINGDAL	800
BKK	HALLINGDAL	2000
BKK	SKL	1500
SKL	VESTSYD	2500
VESTSYD	NORGESYD	2200
VESTSYD	TELEMARK	2000
VESTSYD	JYLL-NORD	0
HALLINGDAL	NORGEOST	3300
TELEMARK	NORGESYD	2000
TELEMARK	NORGEOST	3300
NORGEOST	SVER-SNO3	2050
SVER-SNO1	SVER-SNO2	3300
SVER-SNO1	FIN-NORD	1500
SVER-SNO2	SVER-SNO3	7300
SVER-SNO3	SVER-SNO4	6700
SVER-SNO4	DANM-OST	1700
FIN-NORD	FIN-SYD	2000
JYLL-NORD	JYLL-SYD	2600
JYLL-SYD	FYN	1600
NORGESYD	JYLL-NORD	1700
TELEMARK	SVER-SNO3	0
SVER-SNO3	FIN-SYD	1350
SVER-SNO3	JYLL-NORD	720
DANM-OST	FYN	600
DANM-OST	TYSK-OST	600
SVER-SNO4	LITHUANIA	700
FIN-SYD	ESTONIA	1000
JYLL-SYD	TYSK-NORD	1500
NORGESYD	TYSK-NORD	1400
NORGESYD	NEDERLAND	700
VESTSYD	GB-MID	1400
NORGESYD	SORLAN-OWP	1000
SVER-SNO4	TYSK-NORD	600
SVER-SNO4	POLEN	600
JYLL-SYD	NEDERLAND	700
Total		75145

5.2 Scenario Carbon Neutral

In the Carbon Neutral scenario, power demand is increased in the Nordic region to 444 TWh/y as described in Section 3.1. All fossil production is phased out and approximately 140 TWh/y of new production from renewable resources is included in the system compared to 2012. The main share of the increase is based on wind production – nearly 100 TWh/y of new wind production is established. The transmission capacities internally in the Nordic region are increased according to profitability criteria, but capacities between the Nordic region and other countries are kept at 2012 level. The power production in the Nordic countries is shown in Figure 5-1 and the power balances are shown Figure 5-2. The Nordic region is in average exporting 31 TWh/y.

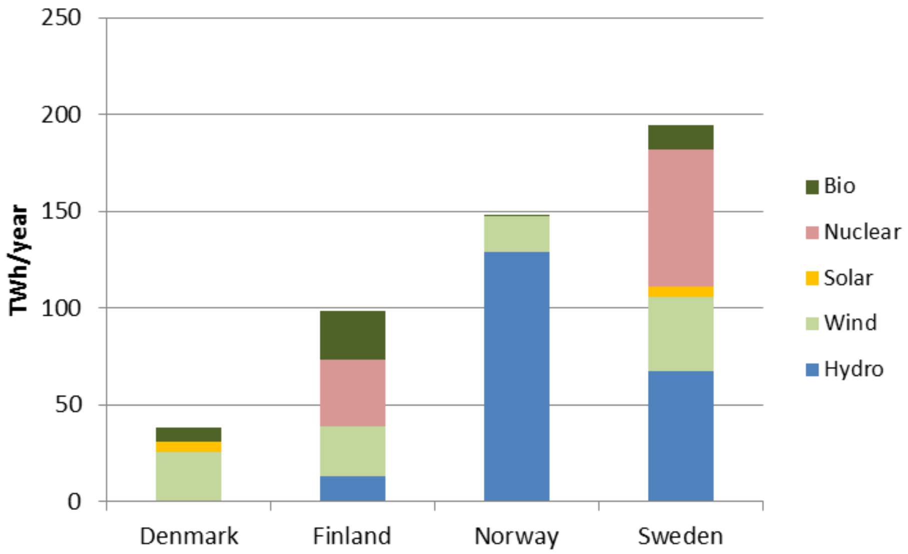

Figure 5-1 Power production in the four Nordic countries in 2050 in Carbon Neutral

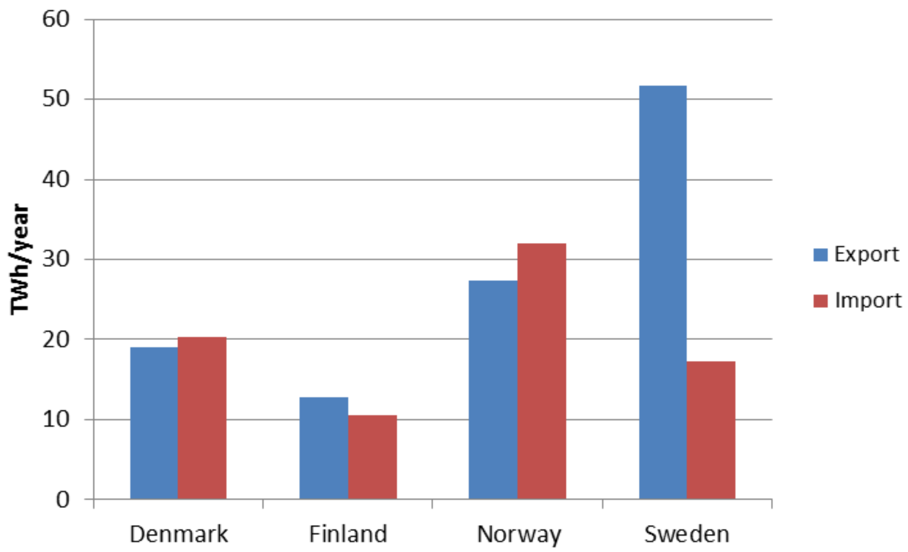

Figure 5-2 The power balances for the four Nordic countries in Carbon Neutral in 2050

The production portfolios in the Europe outside the Nordic region (for list of countries see Section 5.1) are shown in Figure 5-3, and the power balances for the neighbouring countries to the Nordic region are shown in Table 5-2.

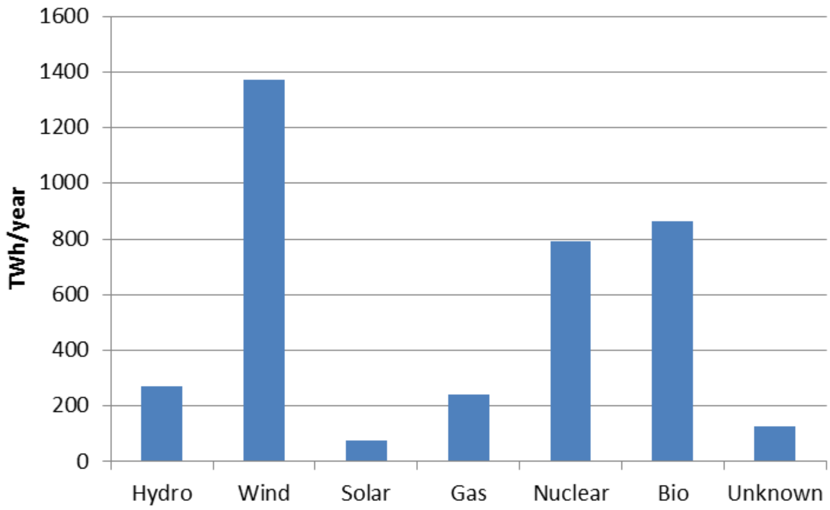

Figure 5-3 Production portfolio Europe outside the Nordic region in Carbon Neutral 2050

Table 5-2 Power balances in neighbouring countries in Carbon Neutral 2050

TWh/year	Export	Import	Demand	Hydro	Wind	Solar	Gas	Coal	Nuclear	Bio
Belgium	17	38	115	0	7	3	23	0	26	35
Belgium_OWP	12	0	0	0	12	0	0	0	0	0
Estonia	1	9	12	0	0	0	1	0	0	3
Great_Britain	97	147	416	5	67	4	83	0	53	161
Great_Britain_OWP	148	3	0	0	146	0	0	0	0	0
Latvia	7	9	12	0	0	0	4	0	0	6
Lithuania	24	34	16	0	0	0	2	0	0	4
The Netherlands	104	74	131	0	16	5	77	0	24	41
The Netherlands_OWP	66	13	0	0	53	0	0	0	0	0
Poland	32	97	174	1	37	0	3	0	0	71
Russia	0	10	882	89	0	0	595	0	188	0
Germany	121	367	639	0	113	62	42	1	0	186
Germany_OWP	109	10	0	0	99	0	0	0	0	0
TOTAL	739	811	2398	95	551	74	830	1	291	508

The power balances for each of the nodes in the Nordic region are shown in Table 5-3. The node with the largest energy imbalance is NORGEOST (including among other Oslo) with a deficit of approximately 36 TWh/y. NORGEOST has a large imbalance already in 2012, but the need for import to the region is increased with about 18 TWh/y in the period 2012 to 2050. Hardly any of the new renewable production is located in NORGEOST.

Another region with considerable changes compared to 2012 is region 3 in Sweden (including Stockholm). The demand is increased with 12 TWh/y, and it is added 8 TWh/y of new wind power production and 3 TWh/y of PV production. Furthermore, SVER-SNO3 is impacted by its adjacent regions SVER-SNO2 with an increased wind production of in average 10 TWh/y and SVER-SNO4 with new wind production of 15 TWh/y. SVER-SNO2 exports 33 TWh in average per year, while SVER-SNO4 has a deficit of 6 TWh/y. Power is flowing from the surplus regions in the north of Sweden to the deficit area in SVER-SNO4.

Also in the southern part of Finland there are large changes. The region goes from a deficit situation in 2012 of approximately 13 TWh/y to a surplus in 2050 of 6 TWh/y. The demand is increased with 7-8 TWh/y due to increased population in the Helsinki region. All fossil production is phased out, and new production from renewable resources is included based on 25 TWh/y of wind and 25 TWh/y of bio energy.

Table 5-3 Power balance for each of the nodes in the Nordic region in 2050 in Carbon Neutral

TWh/year	Export	Import	Demand	Spillage	Hydro	Wind	Solar	Nuclear	Bio
BKK	3	7	11	1	7	1	0	0	0
DANM-OST	4	13	16	0	0	2	2	0	1
FIN-NORD	7	11	12	1	7	0	0	0	0
FIN-SYD	14	8	83	0	6	25	0	34	25
FINNMARK	2	2	4	1	3	1	0	0	0
FYN	2	4	3	0	0	0	0	0	1
HALLINGDAL	14	1	1	2	14	0	0	0	0
HELGELAND	7	4	7	1	10	1	0	0	0
INDRESOGN	3	0	3	0	6	0	0	0	0
JYLL-NORD	14	8	4	0	0	10	1	0	0
JYLL-SYD	15	12	16	0	0	14	2	0	3
MORE	5	9	13	1	7	2	0	0	0
NORDVEST	6	3	3	0	5	0	0	0	0
NORGEOST	3	39	51	4	15	0	0	0	0
NORGESYD	20	17	18	2	18	3	0	0	0
SKL	3	8	10	0	5	0	0	0	0
SORLAN-OWP	3	0	0	0	0	3	0	0	0
SVARTISEN	4	1	0	0	3	0	0	0	0
SVER-SNO1	15	4	10	0	19	1	0	0	0
SVER-SNO2	45	11	16	2	37	11	0	0	2
SVER-SNO3	47	51	101	0	10	9	3	71	6
SVER-SNO4	23	29	30	0	2	17	3	0	3
TELEMARK	17	14	8	1	12	0	0	0	0
TROMS	4	1	7	1	8	2	0	0	0
TRONDELAG	8	7	11	1	6	5	0	0	0
VESTSYD	18	9	1	1	10	0	0	0	0
Total	305	274	443	19	210	108	10	105	41

Figure 5-4 shows the profitable increases in transmission capacities (to the left) and the net power flow over the year (to the right). As shown in Figure 5-4 except for a few channels, the increases are limited. The largest expansions of the transmission network are between SVERIGE-SNO3 and NORGEOST (950 MW) and between TELEMARK and SVER-SNO3 (1400 MW). The energy surplus in the northern Sweden is exported to the deficit region around Oslo and to Denmark as shown in Figure 5-4. More in depth information about the increases of transmission capacities and the exchange on several of the channels are given in Section 5.6.

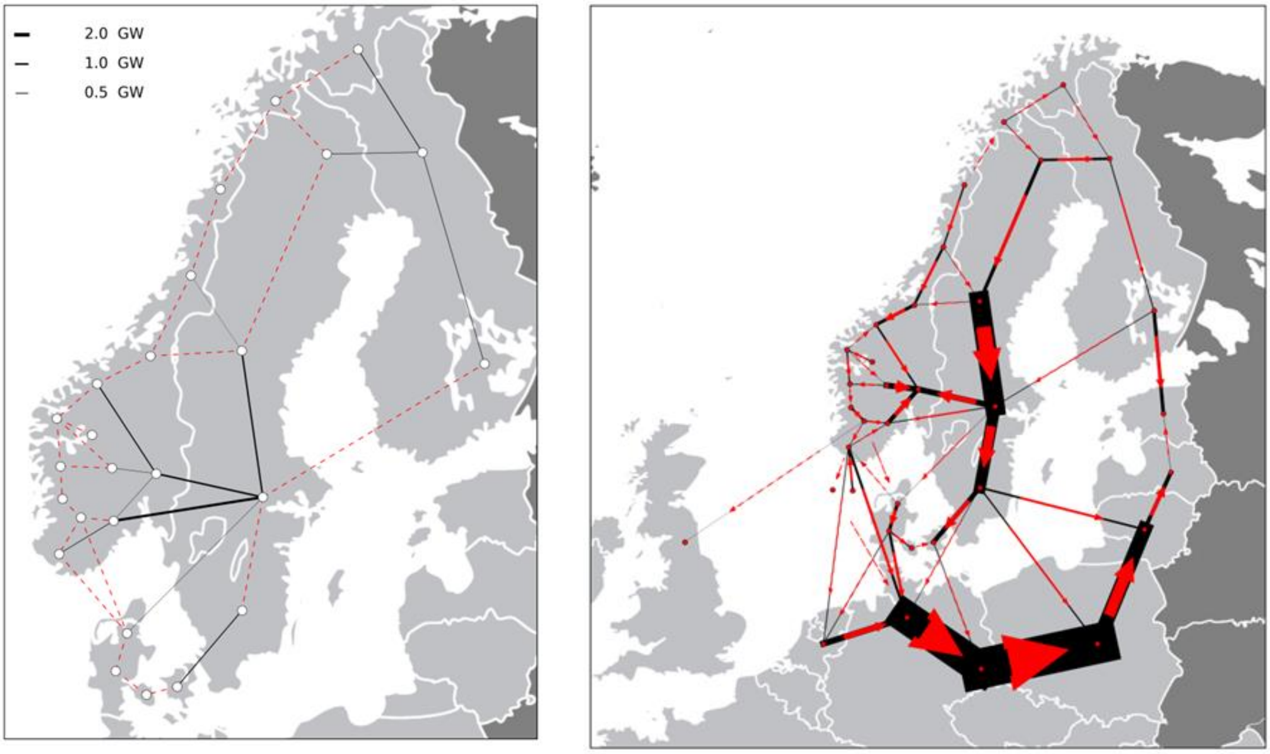

Figure 5-4 Profitable increases in transmission capacities in the Nordic region in Carbon Neutral (to the left) and map showing directions of power flow (to the right)

The Nordic region is, as already mentioned, exporting approximately 31 TWh/y. Sweden has a net export of 34.5 TWh/y and is exporting to Norway, Denmark, Poland and Germany. Norway is importing 4.6 TWh/y, Finland is exporting 2.6 TWh/y and Denmark is importing approximately 1.4 TWh/y.

Figure 5-5 shows the power prices in the regions including the Nordic capitals and also in some neighbouring countries to the Nordic region.

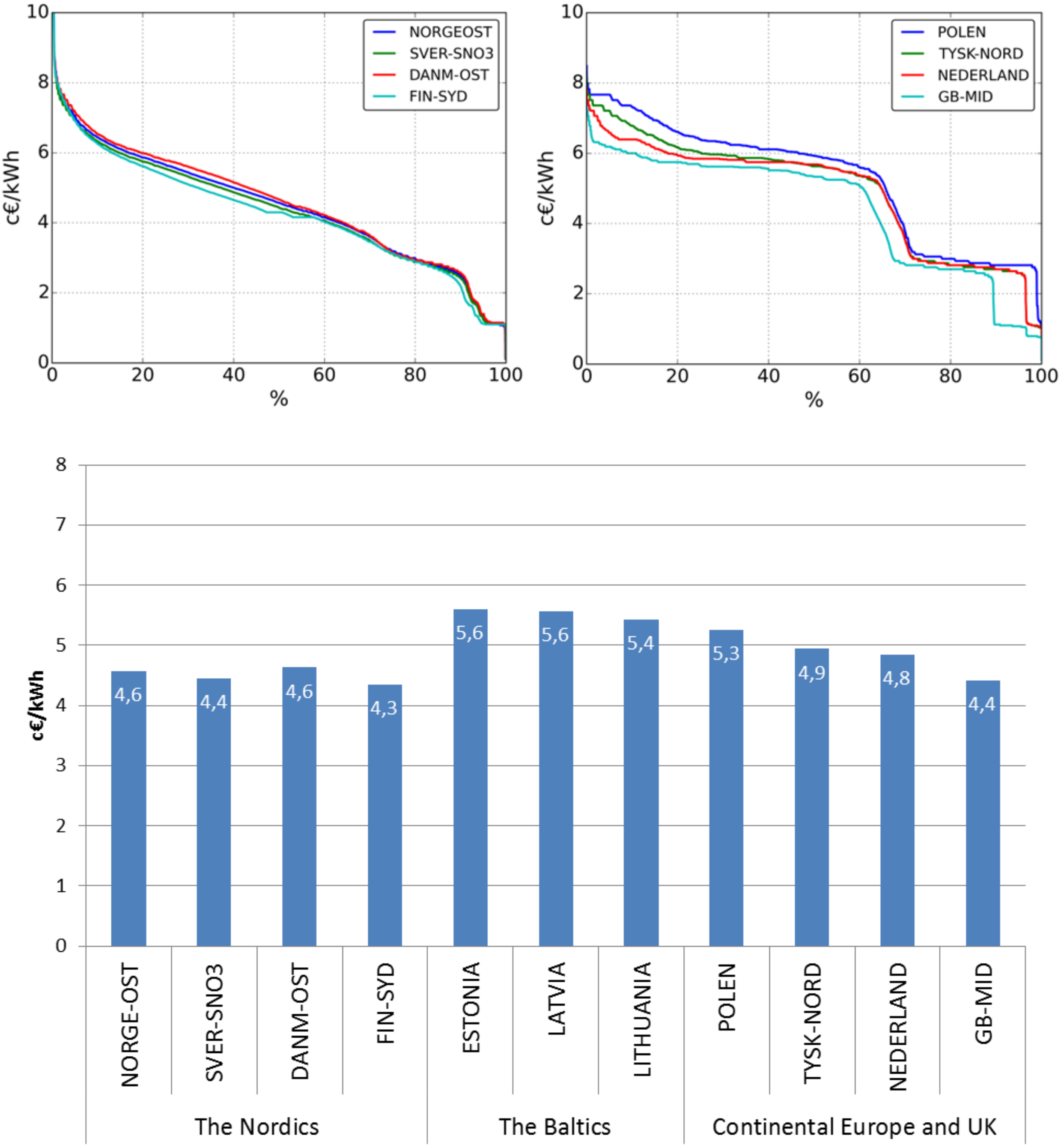

Figure 5-5 Power prices in the Nordic capitals and in neighbouring countries per simulation hour in Carbon Neutral [EuroCent/kWh]

5.2.1 Scenario Carbon Neutral – Low Demand version

In the Low Demand version of the Carbon Neutral scenario an alternative path for how a carbon neutral future can be obtained is analysed. The demand is reduced to 334 TWh/y or approximately 25% compared to the other scenarios in 2050. This represents ca 14% reduction in consumption compared to 2012. The scenario is based on the same demographic changes as the other scenarios. The same share of energy efficiency is assumed for all parts of the Nordic region, i.e. the percent of demand reduction is equal for all nodes in the Nordic system.

All fossil production is phased out and only a limited share of new renewable production is assumed to be built. The hydropower production is unchanged compared to Carbon Neutral. The wind production in the Nordic region is about 36 TWh/y in 2050 compared to 108 TWh/y in Carbon Neutral. The solar production is reduced from 10 TWh/y to 2 TWh/y. The bio production is 35 TWh/y per year compared to 41 TWh/y in the Carbon Neutral "main scenario". The wind, solar and bio capacities are reduced with approximately the same percent in all nodes in the Nordic region compared to the "main" Carbon Neutral scenario. In the analyses it is not allowed to invest in transmission capacities between the Nordic region and the Continental Europe.

The power production portfolio in the Nordic region is shown in Figure 5-6 and the power balance for each of the four countries is shown in Figure 5-7. The net export from the Nordic countries to the Continental Europe is about 58 TWh/year in the Carbon Neutral Low Demand scenario. Denmark is the only Nordic country which is in a net import position.

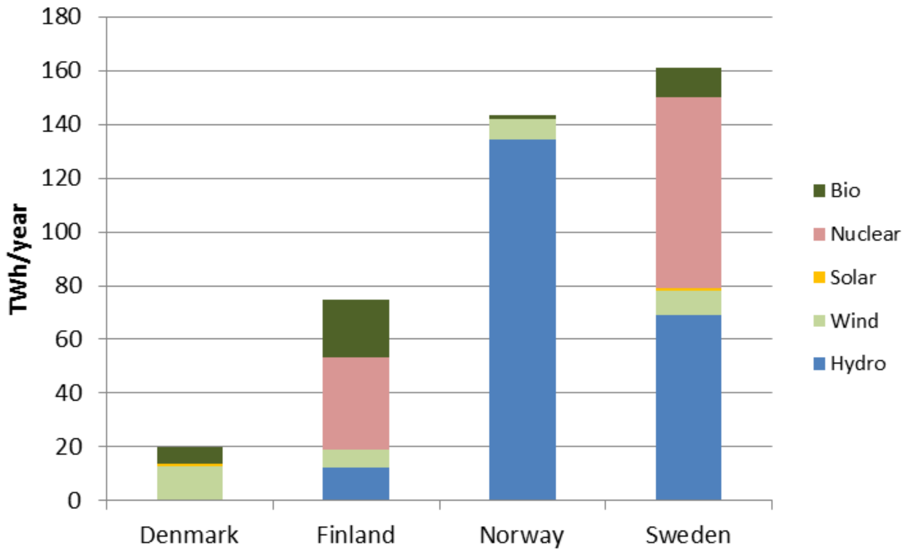

Figure 5-6 Power production in the four Nordic countries in Carbon Neutral – low demand version in 2050

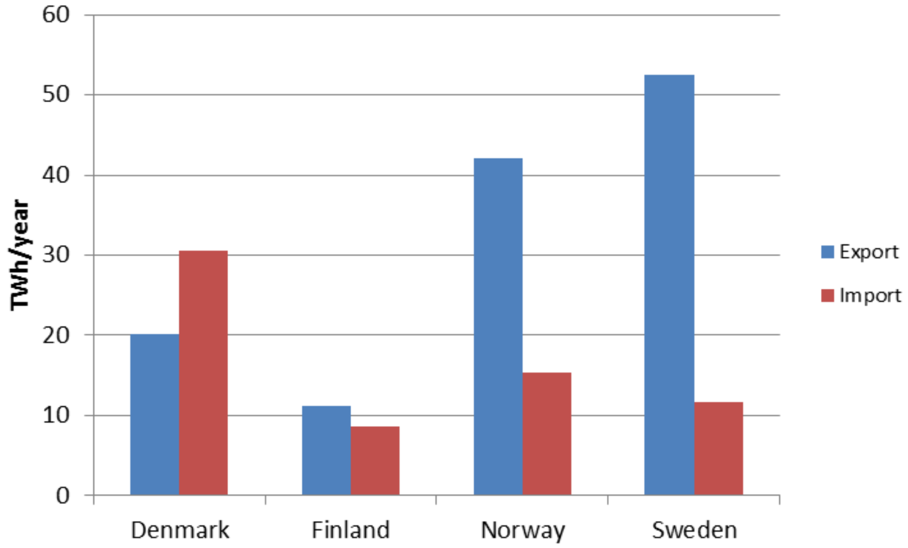

Figure 5-7 Power balances in the four Nordic countries in Carbon Neutral – low demand version in 2050

Table 5-4 shows the power balances per node in the Nordic region. The approximately same percent of reduction in consumption for all nodes results in more TWh/y reduction for the nodes with the highest consumption, i.e. NORGEOST (including Oslo), SVER-SNO3 (including Stockholm) and FIN-SYD (including Helsinki). The power balance in NORGEOST is improved with about 12 TWh/y compared to the Carbon Neutral "main scenario". The improvement also impacts the profitability of new transmission lines as shown in
Table 5-5. In Carbon Neutral, it was profitable to increase the capacity between SVER-SNO3 and TELEMARK with 1400 MW, but in Carbon Neutral Low demand only 500 MW is found profitable.

Denmark is in an imbalance situation with more limited deployment of new renewable production than in the "main scenario". It would probably have been more realistic to assume more renewable production in Denmark. It is not very likely that Denmark will phase out its fossil production without substituting it with a large volume of new renewable production.

All in all the increases in transmission capacities which are profitable in the Nordic region are only ca one third in the Low demand scenario compared to the Carbon Neutral "main scenario", see
Table 5-5. The increases in transmission capacities could have been reduced even more if more renewable production had been assumed in Denmark. Anyway, the demand is covered in all simulated situations. There are some limited periods where renewable production is surplus in the system. Carbon Neutral Low Demand indicates that it is possible from a system perspective to develop a Carbon Neutral power system in the Nordic region with focus on energy efficiency and limited deployment of new renewable power production and limited increases in transmission capacities.

Table 5-4 Power balances for each of the nodes in the Nordic region in 2050 in Carbon Neutral – Low Demand

TWh/year	Export	Import	Demand	Spillage	Hydro	Wind	Solar	Nuclear	Bio
BKK	5	6	9	1	8	0	0	0	0
DANM-OST	8	15	12	0	0	2	0	0	1
FIN-NORD	6	8	9	1	7	0	0	0	0
FIN-SYD	11	7	63	0	5	6	0	34	21
FINNMARK	2	2	3	1	3	0	0	0	0
FYN	2	4	2	0	0	0	0	0	0
HALLINGDAL	16	2	1	2	15	0	0	0	0
HELGELAND	9	3	5	1	11	0	0	0	0
INDRESOGN	3	0	3	1	6	0	0	0	0
JYLL-NORD	16	16	3	0	0	3	0	0	0
JYLL-SYD	16	18	12	0	0	7	0	0	2
MORE	6	8	10	1	7	1	0	0	0
NORDVEST	7	4	3	1	6	0	0	0	0
NORGEOST	7	31	39	4	15	0	0	0	0
NORGESYD	25	19	13	2	19	1	0	0	0
SKL	4	7	7	0	5	0	0	0	0
SORLAN-OWP	3	0	0	0	0	3	0	0	0
SVARTISEN	4	0	0	0	3	0	0	0	0
SVER-SNO1	16	3	7	0	20	0	0	0	0
SVER-SNO2	44	15	12	2	37	3	0	0	2
SVER-SNO3	59	47	76	0	10	2	1	71	6
SVER-SNO4	29	43	23	0	1	4	1	0	3
TELEMARK	15	10	7	1	12	0	0	0	0
TROMS	5	1	6	1	9	0	0	0	0
TRONDELAG	8	8	8	1	6	2	0	0	0
VESTSYD	18	9	1	1	10	0	0	0	0
Total	344	284	334	19	216	36	2	105	35

Table 5-5 Profitable increases in transmission capacities in the Nordic region in 2050 in Carbon Neutral versus Carbon Neutral Low Demand version

[MW]		CN	CN low demand
FINNMARK	TROMS	0	0
FINNMARK	FIN-NORD	450	400
HELGELAND	SVER-SNO2	100	0
MORE	NORGEOST	650	450
VESTSYD	JYLL-NORD	0	50
HALLINGDAL	NORGEOST	200	0
TELEMARK	NORGESYD	350	0
TELEMARK	NORGEOST	200	0
NORGEOST	SVER-SNO3	950	0
SVER-SNO1	FIN-NORD	300	0
SVER-SNO2	SVER-SNO3	850	0
SVER-SNO4	DANM-OST	550	600
FIN-NORD	FIN-SYD	300	0
TELEMARK	SVER-SNO3	1400	500
SVER-SNO3	JYLL-NORD	150	250
TOTAL		6450	2250

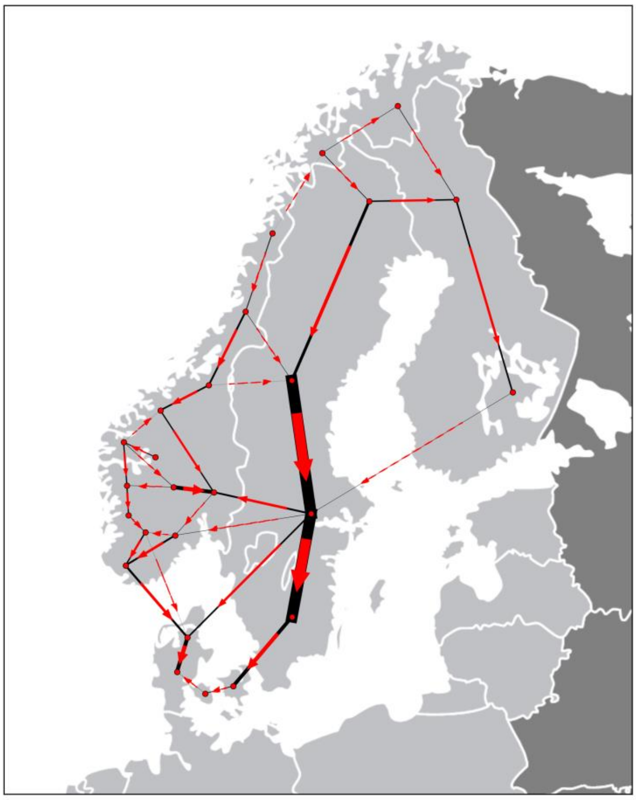

Figure 5-8 Net yearly power flow Carbon neutral Low demand 2050

5.3 Scenario Purely Renewable

In the Purely RES scenario in the Nordic region in 2050 power demand is increased to 444 TWh/y as described in Section 3.1. All fossil and nuclear production is phased out. As shown in Figure 5-9 large volumes of new renewable generation are included in the Nordic power system, in particular wind production in all four countries and bio production in Finland. The total wind production in the Nordic region is 179 TWh/year compared to 14 TWh/year in 2012. The hydro production in Norway is also increased with nearly 20 TWh/year in average compared to 2012. The transmission capacities internally in the Nordic region are increased according to profitability criteria, but capacities between the Nordic region and other countries are kept at the same level as in 2015 (including known plans). The power balances are shown in Figure 5-10. The Nordic region is nearly in balance with an average export of 3 TWh/y. Both Finland and Sweden will be in deficit situations due to the phase out of the nuclear production and an increase in demand compared to 2012. Norway will be in a surplus situation based on high wind power production (46 TWh/y) and increase in hydropower production.

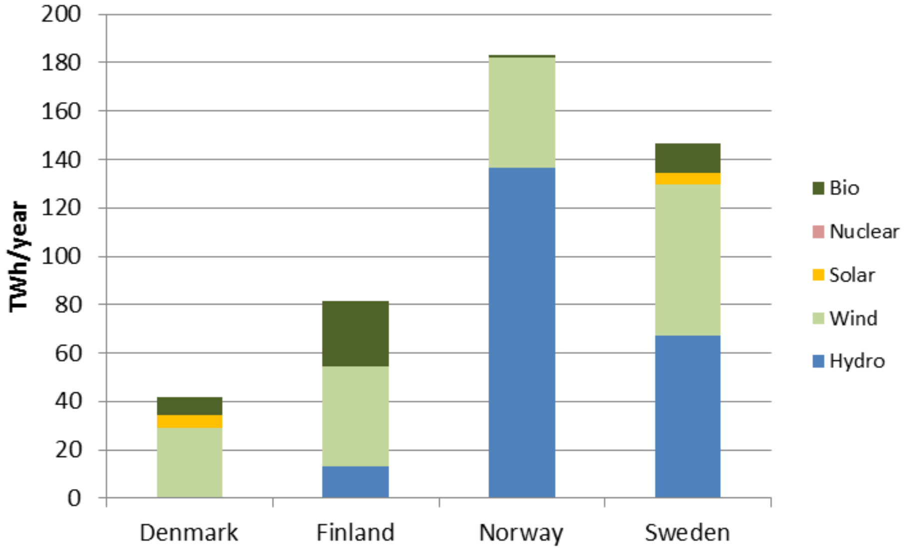

Figure 5-9 Power production in the four Nordic countries in 2050 Purely RES

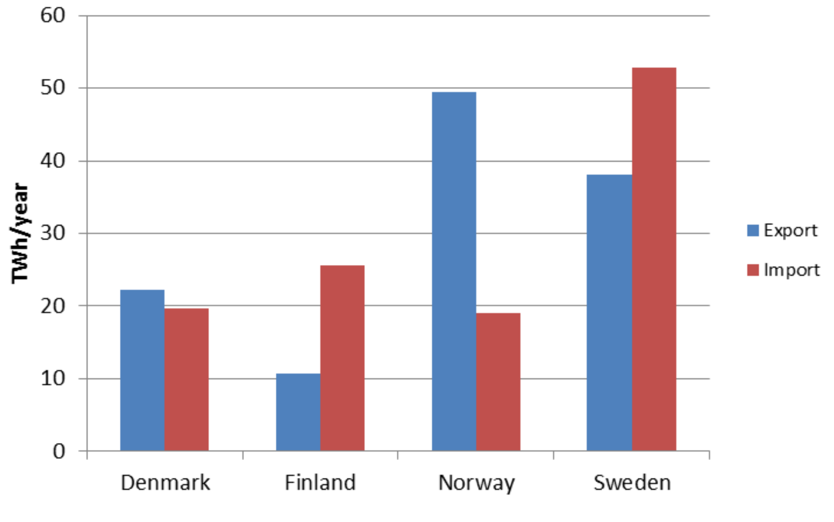

Figure 5-10 The power balances for the four Nordic countries in Purely RES in 2050

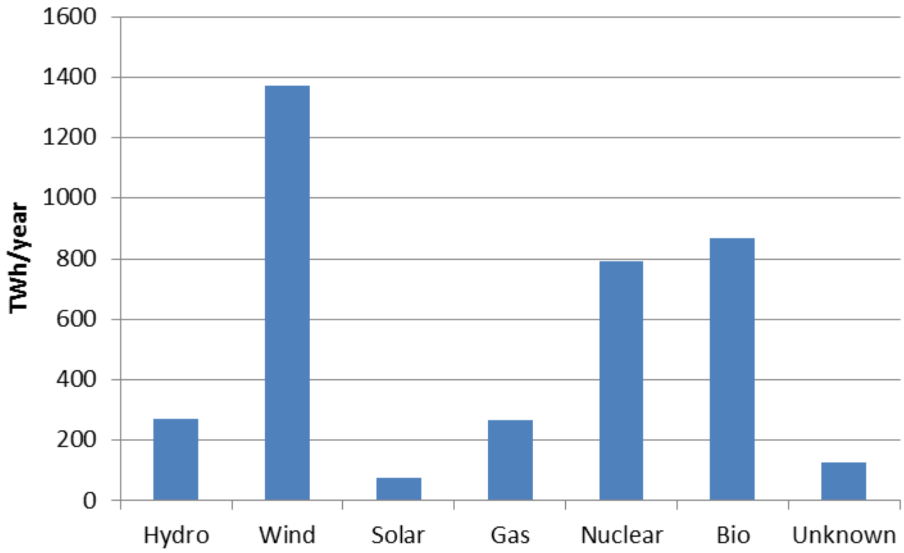

Figure 5-11 Production portfolio Europe outside the Nordic region in Purely RES 2050

Table 5-6 Power balances neighbouring countries Purely RES 2050

TWh/year	Export	Import	Demand	Hydro	Wind	Solar	Gas	Coal	Nuclear	Bio
Belgium	17	36	115	0	7	3	25	0	26	35
Belgium_OWP	12	0	0	0	12	0	0	0	0	0
Estonia	2	10	12	0	0	0	1	0	0	3
Great_Britain	101	143	416	5	67	4	91	0	53	161
Great_Britain_OWP	149	3	0	0	146	0	0	0	0	0
Latvia	9	11	12	0	0	0	4	0	0	6
Lithuania	27	37	16	0	0	0	2	0	0	4
The Netherlands	110	73	131	0	16	5	84	0	24	41
The Netherlands_OWP	67	14	0	0	53	0	0	0	0	0
Poland	36	100	174	1	37	0	3	0	0	72
Russia	0	9	882	89	0	0	596	0	188	0
Germany	128	371	639	0	113	62	45	1	0	186
Germany_OWP	109	10	0	0	99	0	0	0	0	0
TOTAL	767	817	2398	95	551	74	852	1	291	508

The power balances for each of the nodes in the Nordic region is shown in

Table 5-7. The node with the largest power imbalance is SVER-SNO3 with a deficit of approximately 72 TWh/y due to the close down of the nuclear production in the region. SVER-SNO4 has developed from a deficit area (6 TWh/y) in Carbon Neutral to a surplus area (8 TWh/y). SVER-SNO1 and SVER-SNO2 are exporting about 50 TWh/y. A main part is exported to SVER-SNO3.

Before transmission capacities are increased, there are periods with rationing in several of the Nordic regions: BKK, DANM-OST, FIN-SYD, FYN, INDRESOGN, NORDVEST, NORGEOST, SVER-SNO3 and SVER-SNO4. The highest volume of rationing is in SVER-SNO3. It is in average 1,5 TWh/y, and is in a maximum year 5.0 TWh. The highest rationing in the whole Sweden is 6.2 TWh and 3.6 TWh in Finland during a year. After the increase of transmission capacities the periods of rationing are almost completely removed.

Table 5-7 Power balances for each of the nodes in the Nordic region in 2050 in Purely RES

TWh/year	Export	Import	Demand	Spillage	Hydro	Wind	Solar	Nuclear	Bio
BKK	2	5	11	1	8	1	0	0	0
DANM-OST	2	10	16	0	0	2	2	0	2
FIN-NORD	15	20	12	1	7	0	0	0	0
FIN-SYD	11	22	83	0	6	41	0	0	26
FINNMARK	5	5	4	1	3	1	0	0	0
FYN	2	5	3	0	0	0	0	0	1
HALLINGDAL	15	2	1	2	14	0	0	0	0
HELGELAND	10	3	7	1	10	4	0	0	0
INDRESOGN	3	0	3	1	6	0	0	0	0
JYLL-NORD	19	10	4	0	0	12	1	0	0
JYLL-SYD	16	12	16	0	0	16	2	0	3
MORE	11	5	13	1	7	12	0	0	0
NORDVEST	7	4	3	1	6	0	0	0	0
NORGEOST	4	40	51	4	16	0	0	0	0
NORGESYD	27	13	18	2	19	13	0	0	0
SKL	2	7	10	0	5	0	0	0	0
SORLAN-OWP	3	0	0	0	0	3	0	0	0
SVARTISEN	4	1	0	0	3	0	0	0	0
SVER-SNO1	23	6	10	0	19	7	0	0	0
SVER-SNO2	50	17	16	2	36	11	0	0	2
SVER-SNO3	17	89	101	0	10	13	3	0	6
SVER-SNO4	22	14	30	0	2	31	3	0	3
TELEMARK	27	24	8	1	12	0	0	0	0
TROMS	10	1	7	1	9	7	0	0	0
TRONDELAG	5	4	11	1	7	5	0	0	0
VESTSYD	18	10	1	1	10	0	0	0	0
Total	331	327	443	21	217	179	10	0	43

NORGEOST (including among other Oslo) has as in Carbon Neutral a power imbalance of approximately 37 TWh/y. In Carbon Neutral NORGEOST is importing large volumes from SVER-SNO3, but in Purely RES SVER-SNO3 is also in an import situation. The power imbalance in NORGEOST is covered by increased renewable production in Norway, but in other regions than NORGEOST. The connection between NORGEOST and MORE is increased with 1800 MW compared to 650 MW in Carbon Neutral. Furthermore it is increased with 750 MW between TELEMARK and NORGEOST compared to 200 MW in Carbon Neutral. The connection between TELEMARK and NORGESYD is also increased with 2450 MW, and NORGEOST is importing from both MORE and NORGESYD.

The increases in capacities (to the left) and the net yearly power flow (to the right) are shown in Figure 5-12. As shown in Figure 5-12 one of the largest increases in capacities is from SVER-SNO2 to SVER-SNO3. The connection is increased with 2150 MW compared to 850 MW in Carbon Neutral. Furthermore, new renewable production in the northern part of Norway is exported to Sweden and Finland. The capacity between TROMS and SVER-SNO1 is increased with 550 MW compared to 0 MW in Carbon Neutral and between HELGELAND and SVER-SNO2 with 1050 compared to 100 MW in Carbon Neutral. The flow from HELGELAND to region 2 in Sweden is shown in Figure 5-32 (up to the left). Norway also exports to Sweden from TELEMARK, and the flow from TELEMARK to region 3 in Sweden in Figure 5-30 (up to the left).

FIN-SYD is also in a deficit situation after phase out of the nuclear production. Transmission capacities are increased between the north of Sweden and Finland with 1750 MW compared to 300 MW in Carbon Neutral. Furthermore capacities are increased with 1900 MW between FIN-NORD and FIN-SYD compared to 300 MW increase in Carbon Neutral. Some of the surplus in TROMS (9 TWh/y) and in SVER-SNO1 (17 TWh/y) is imported to Finland as shown in Figure 5-34.

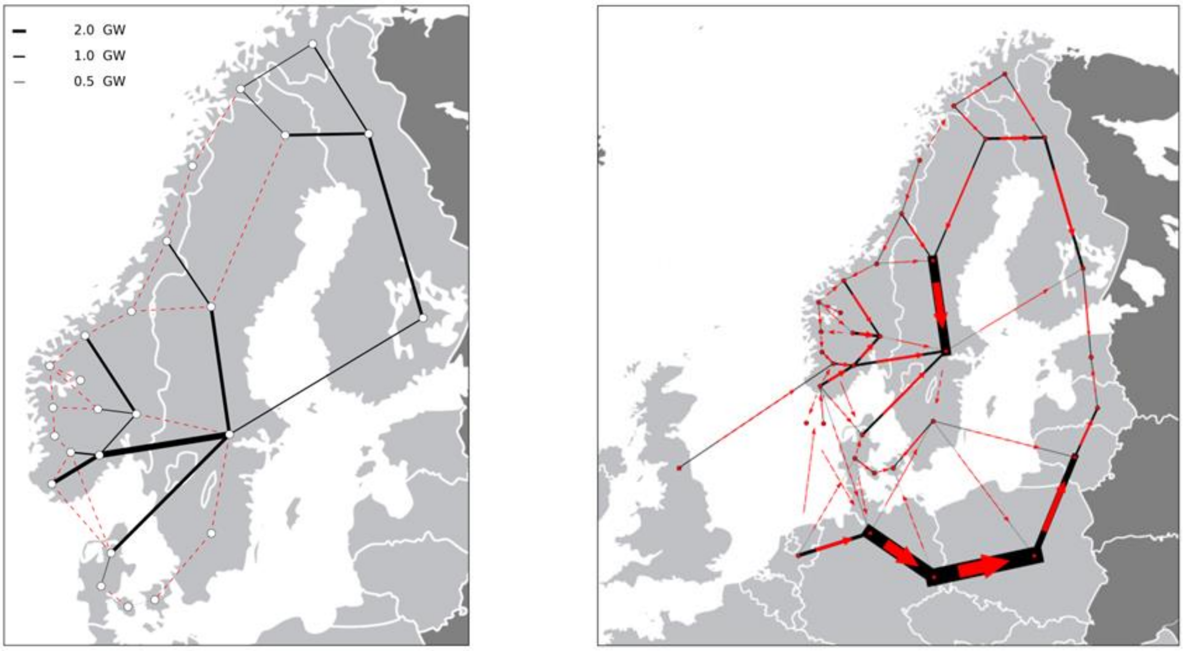

Figure 5-12 Profitable increases in transmission capacities in in the Nordic region in Purely RES (to the left) and the net yearly power flow (to the right)

Figure 5-13 shows the power prices in the regions including the Nordic capitals and neighbouring countries to the Nordic region. There are some periods with prices over 10 c€/kWh (less than 3% of the time) in the Nordic region which are not shown in the figure to make it more readable. The price goes up to rationing price (400 c€/kWh) in some few hours, causing a small amount of curtailed demand.

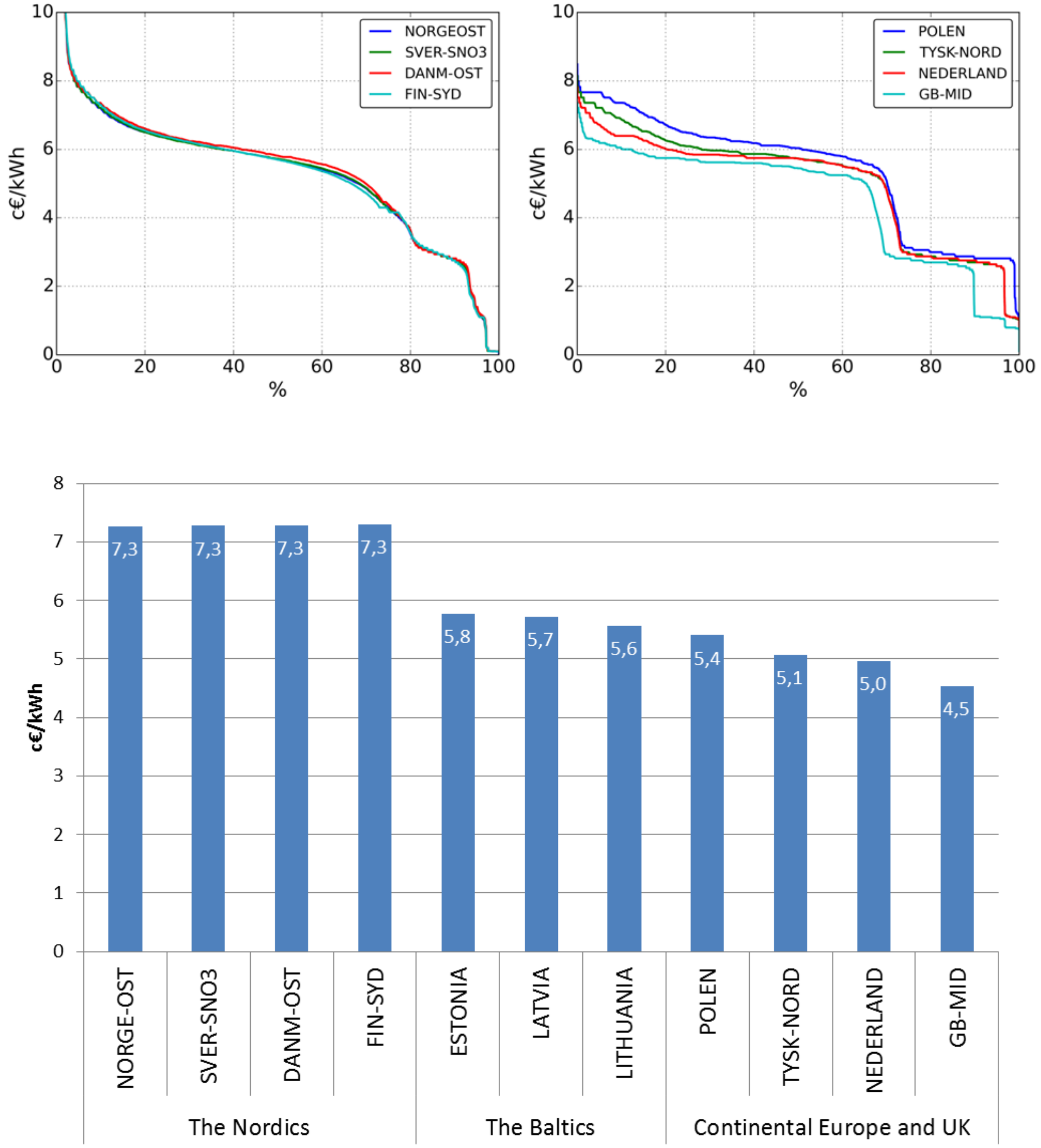

Figure 5-13 Power prices in the Nordic capitals and neighbouring countries per simulation hour in Purely RES [EuroCent/kWh]

5.3.1 Decommissioning only Swedish nuclear power production

A variation of the Purely RES scenario (and may be a more realistic) is to phase out only Swedish nuclear production. Nuclear production in Finland is kept unchanged. New renewable production is also to some degree reduced compared with the "main" Purely RES scenario. In Finland the yearly production from wind plants is reduced from 41 to 34 TWh/y, and the production from biomass is reduced from 26 TWh/y to 24 TWh/y.

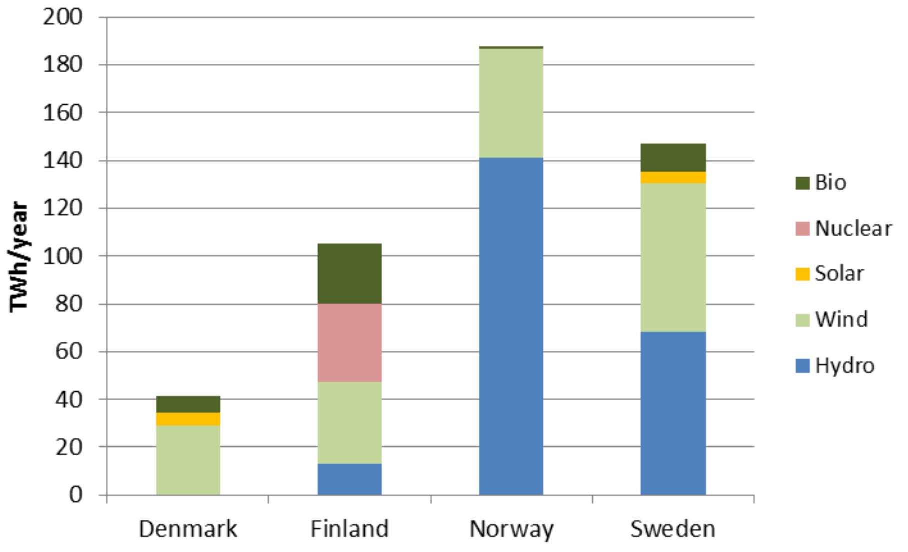

Figure 5-14 Power production in the four Nordic countries in Purely RES in 2050 when only Swedish nuclear production is phased out

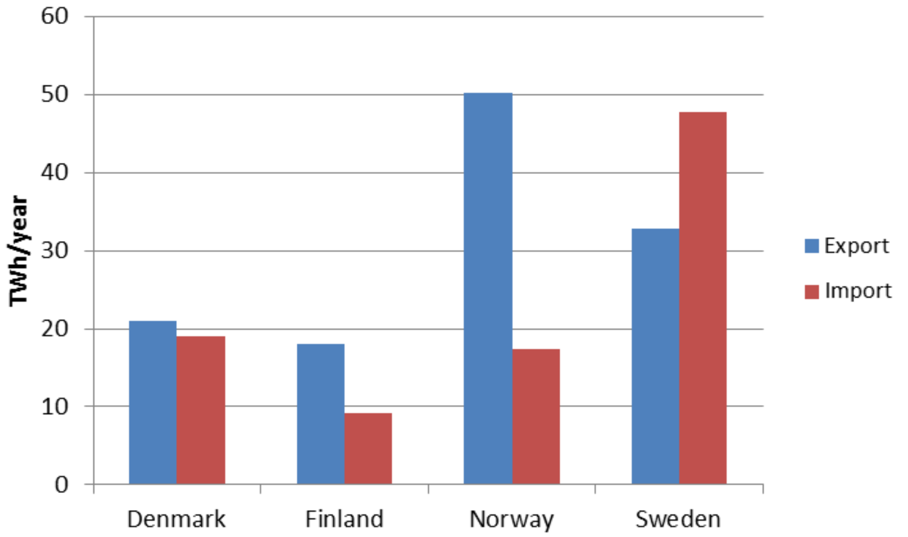

Figure 5-15 Power balances in the four Nordic countries in Purely RES in 2050 when only Swedish nuclear production is phased out

Table 5-8 Power balances for each of the nodes in the Nordic region in 2050 in Purely RES decommissioning only Swedish nuclear

TWh/year	Export	Import	Demand	Spillage	Hydro	Wind	Solar	Nuclear	Bio
BKK	3	6	12	1	9	1	0	0	0
DANM-OST	4	12	16	0	0	2	2	0	1
FIN-NORD	7	11	12	1	7	0	0	0	0
FIN-SYD	20	7	83	0	6	34	0	33	24
FINNMARK	3	2	4	1	3	1	0	0	0
FYN	2	4	3	0	0	0	0	0	1
HALLINGDAL	16	2	1	2	15	0	0	0	0
HELGELAND	12	4	7	1	11	4	0	0	0
INDRESOGN	3	0	3	1	6	0	0	0	0
JYLL-NORD	16	8	4	0	0	12	1	0	0
JYLL-SYD	16	12	16	0	0	16	2	0	2
MORE	13	6	13	1	8	12	0	0	0
NORDVEST	7	4	4	1	7	0	0	0	0
NORGEOST	4	41	52	4	16	0	0	0	0
NORGESYD	28	13	17	2	19	13	0	0	0
SKL	3	7	10	0	6	0	0	0	0
SORLAN-OWP	3	0	0	0	0	3	0	0	0
SVARTISEN	4	1	0	0	3	0	0	0	0
SVER-SNO1	26	9	10	0	20	7	0	0	0
SVER-SNO2	62	30	16	2	36	11	0	0	2
SVER-SNO3	21	93	101	0	10	13	3	0	6
SVER-SNO4	25	17	30	0	2	31	3	0	3
TELEMARK	23	20	9	1	12	0	0	0	0
TROMS	10	1	8	2	10	7	0	0	0
TRONDELAG	6	5	11	1	7	5	0	0	0
VESTSYD	18	9	1	1	10	0	0	0	0
Total	352	323	445	22	222	171	10	33	40

The main differences in profitable increases in transmission capacities between Purely RES and Purely RES phasing out only Swedish nuclear production is shown in Table 5-9 and the net yearly power flow for the latter case is shown in Figure 5-16. As shown in the table less capacity will be profitable between the north of Sweden and the north of Finland. Instead it will be more profitable to invest in capacity from north to south of Sweden (SVER-SNO2 – SVER- SNO3). As shown by comparing Figure 5-12 and Figure 5-16, more power is flowing from north to south of Sweden.

Table 5-9 Main differences in profitable increases in transmission capacities between Purely RES and Purely RES phasing out only Swedish nuclear production

[MW]		PR	PR no nuc Sweden
FINNMARK	TROMS	550	50
FINNMARK	FIN-NORD	1000	600
TROMS	SVER-SNO1	550	800
HELGELAND	SVER-SNO2	1050	1050
MORE	NORGEOST	1800	2100
BKK	SKL	0	200
VESTSYD	TELEMARK	1000	1000
HALLINGDAL-	NORGEOST	600	600
TELEMARK	NORGESYD	2450	2450
TELEMARK	NORGEOST	750	900
SVER-SNO1	SVER-SNO2	0	950
SVER-SNO1	FIN-NORD	1750	150
SVER-SNO2	SVER-SNO3	2150	3600
SVER-SNO4	DANM-OST	0	300
FIN-NORD	FIN-SYD	1900	1050
JYLL-NORD	JYLL-SYD	350	0
TELEMARK	SVER-SNO3	3900	3450
SVER-SNO3	FIN-SYD	800	800
SVER-SNO3	JYLL-NORD	2100	750
TOTAL		19550	18300

Figure 5-16 Net yearly power flow in the Nordic region in 2050 in Purely RES decommissioning only Swedish nuclear production

5.4 Scenario European Battery

In the European Battery scenario in 2050 power demand is increased to 444 TWh/y as described in Section 3.1. All fossil production is phased out and approximately 140 TWh/y of new production from renewable resources is included in the system compared to 2012. The main share of the increase is nearly 100 TWh/y of wind production. In European Battery transmission connections between the Nordic region and other countries are increased according to profitability criteria. The power production in the Nordic countries is shown in Figure 5-17 and the power balances are shown in Figure 5-18. The starting point for the analysis (demand, power production capacities etc.) is the same as for Carbon Neutral, but in European Battery it is possible to increase the transmission capacities to countries outside the Nordic region.

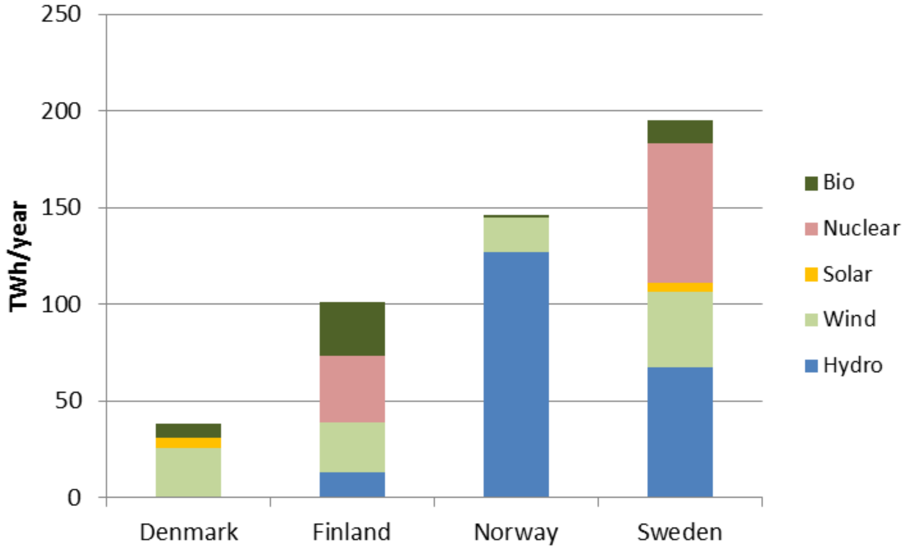

Figure 5-17 Power production in the four Nordic countries in 2050 in European Battery

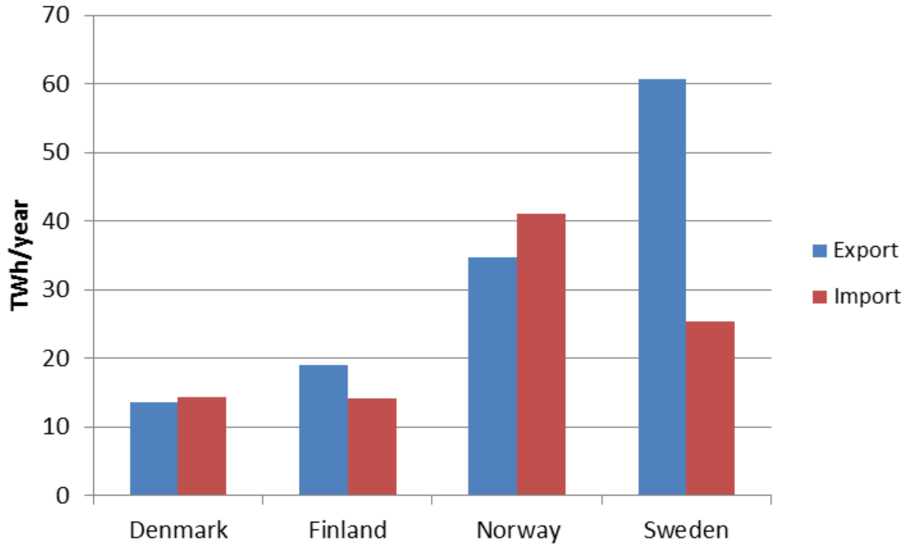

Figure 5-18 The power balances for the four Nordic countries in European Battery in 2050

The production portfolios in the other European countries (for list of countries see Section 5.1) are shown in Figure 5-19, and the power balances for the neighbouring countries to the Nordic region are shown in

Table **5-10**. Comparing the power balances for Europe for European Battery and Carbon Neutral shows that the gas production is reduced in European Battery with 10 TWh/y and substituted with import from the Nordic region. The gas production is reduced in several of the neighbouring countries to the Nordic region, among other Great Britain, the Netherlands and Germany.

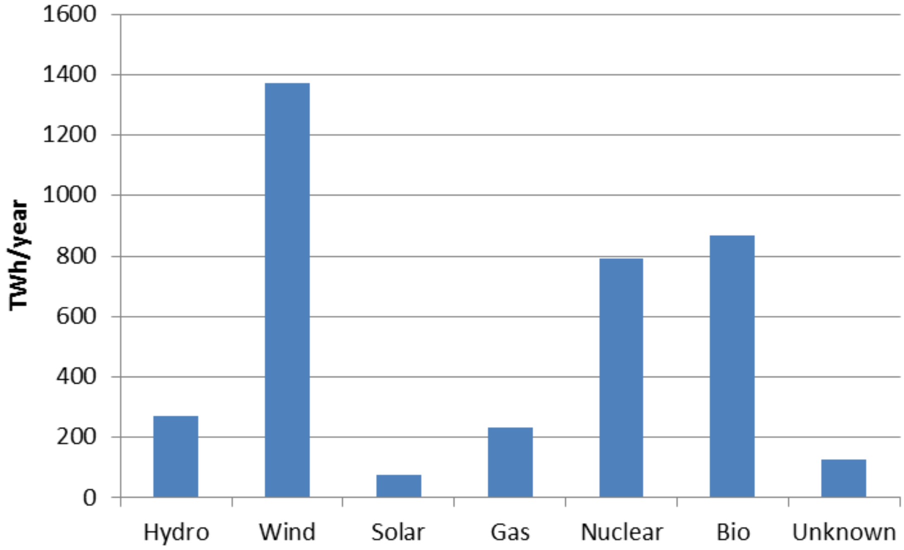

Figure 5-19 Production portfolio Europe outside the Nordic region in European Battery 2050

Table 5-10 Power balance neighbouring countries European Battery 2050

TWh/year	Export	Import	Demand	Hydro	Wind	Solar	Gas	Coal	Nuclear	Bio
Belgium	17	38	115	0	7	3	23	0	26	35
Belgium_OWP	12	0	0	0	12	0	0	0	0	0
Estonia	8	16	12	0	0	0	0	0	0	3
Great_Britain	99	154	416	5	67	4	77	0	53	162
Great_Britain_OWP	148	2	0	0	146	0	0	0	0	0
Latvia	8	10	12	0	0	0	4	0	0	6
Lithuania	18	29	16	0	0	0	2	0	0	4
The Netherlands	95	69	131	0	16	5	74	0	24	41
The Netherlands_OWP	64	10	0	0	53	0	0	0	0	0
Poland	20	84	174	1	37	0	2	0	0	72
Russia	0	10	882	89	0	0	595	0	188	0
Germany	96	343	639	0	113	62	41	1	0	186
Germany_OWP	107	8	0	0	99	0	0	0	0	0
TOTAL	693	774	2398	95	551	74	819	1	292	509

The Nordic region is in European Battery exporting 33 TWh/y in average, while in Carbon Neutral the region exports 31 TWh/y. With the increased capacities to other countries, power prices increase and it is profitable to utilise available production capacities like bio and nuclear power and increase some production in European Battery (see Table 5-11).

Table 5-11 Power balances for each of the nodes in the Nordic region in 2050 in European Battery

TWh/year	Export	Import	Demand	Spillage	Hydro	Wind	Solar	Nuclear	Bio
BKK	3	7	11	1	7	1	0	0	0
DANM-OST	2	10	16	0	0	2	2	0	5
FIN-NORD	8	12	12	1	7	0	0	0	0
FIN-SYD	20	11	83	0	6	25	0	35	27
FINNMARK	2	2	4	1	3	1	0	0	0
FYN	3	5	3	0	0	0	0	0	1
HALLINGDAL	14	1	1	2	14	0	0	0	0
HELGELAND	7	4	7	1	9	1	0	0	0
INDRESOGN	3	0	3	0	5	0	0	0	0
JYLL-NORD	12	5	4	0	0	10	1	0	0
JYLL-SYD	13	10	16	0	0	14	2	0	3
MORE	4	8	13	1	7	2	0	0	0
NORDVEST	6	4	3	1	5	0	0	0	0
NORGEOST	4	40	51	4	15	0	0	0	0
NORGESYD	17	14	18	2	18	3	0	0	0
SKL	5	10	10	0	5	0	0	0	0
SORLAN-OWP	4	1	0	0	0	3	0	0	0
SVARTISEN	4	0	0	0	3	0	0	0	0
SVER-SNO1	16	5	10	0	19	1	0	0	0
SVER-SNO2	46	13	16	2	37	11	0	0	2
SVER-SNO3	54	57	101	0	10	9	3	72	6
SVER-SNO4	40	47	30	0	2	17	3	0	3
TELEMARK	29	26	8	1	11	0	0	0	0
TROMS	4	2	7	1	8	2	0	0	0
TRONDELAG	6	6	11	1	6	5	0	0	0
VESTSYD	37	31	1	1	9	0	0	0	0
Total	362	330	443	20	208	108	10	107	47

The profitable increases in transmission capacities (to the left) and the net yearly power flow (to the right) are shown in Figure 5-20. As shown in Figure 5-20 some of the largest expansions of the transmission network are from the northern (SVER-SNO2) to the southern part of Sweden. Furthermore, there are large increases between TELEMARK and SVER-SNO3. Compared to Carbon Neutral there are also large increases in capacities to neighbouring countries like Denmark-Germany (950 MW), Sweden-Poland (2850 MW), Sweden – Lithuania (1100 MW), Finland – Estonia (1300 MW) and Norway – Great Britain (6200 MW).

Even though the demand and the production capacities are the same as in Carbon Neutral, the power flows are different. In European Battery Sweden exports more of its surplus to Poland and Lithuania and less to Norway compared to Carbon Neutral. The power imbalance in NORGEOST is partly covered by import from SVER-SNO3, but also from internal production in Norway. Norway is also importing from Great Britain to VESTSYD. Furthermore, less power flows from Sweden to Denmark than in Carbon Neutral, because Sweden in European Battery establishes direct connections to other countries.

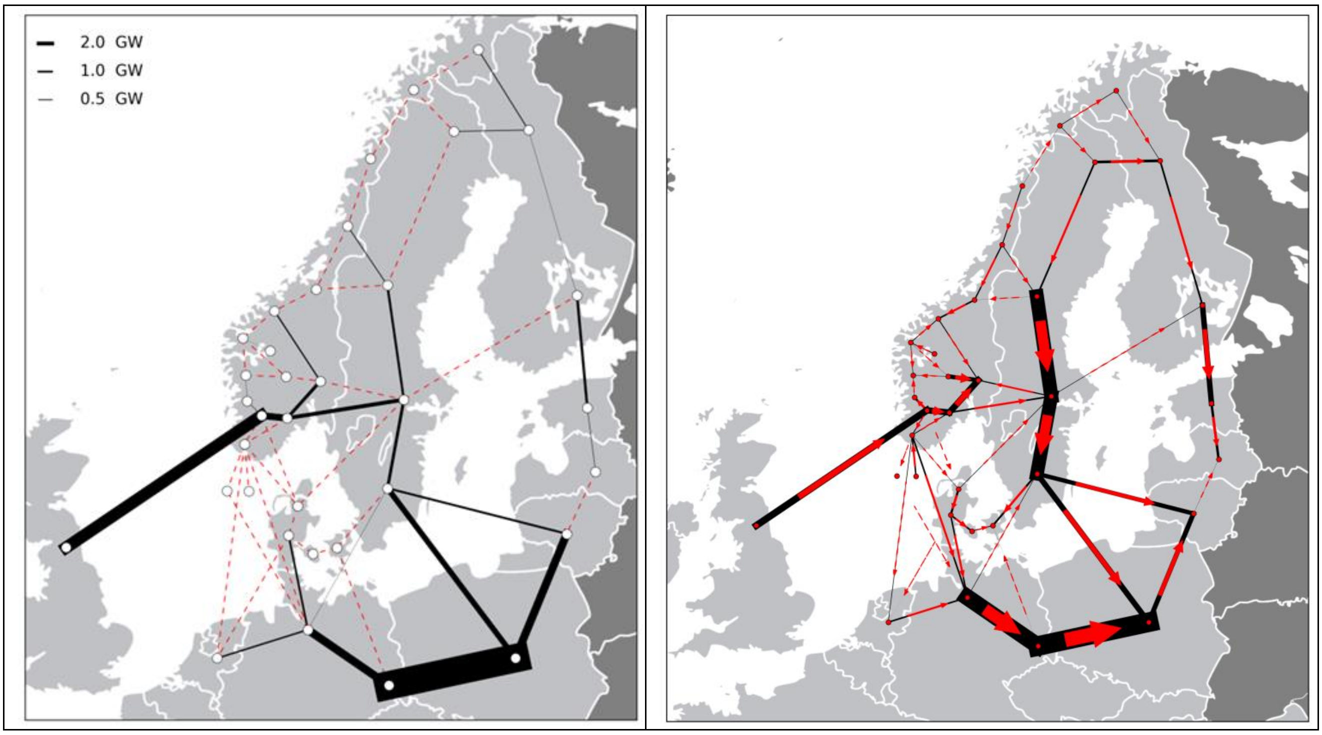

Figure 5-20 Profitable increases in transmission capacities in the Nordic region in European Battery (to the left) and net yearly power flow (to the right)

Sweden is exporting in average 35 TWh/y and the connections to Poland are shown in Figure 5-42 and to Lithuania in Figure 5-43 (down to the right in all figures). Sweden has a small import from Germany as shown in Figure 5-41.

Norway is importing 7 TWh/y in average in European Battery. Figure 5-44 (down to the right) shows the exchange between Norway and Great Britain, Figure 5-39 (down to the right) to Germany and the Figure 5-40 to the Netherlands. Norway is in total importing from Great Britain, but exporting to Germany and the Netherlands. Norway is probably working as a transit country for power from Great Britain to the Netherlands and Germany.

Figure 5-21 shows the power prices in the four regions including the Nordic capitals and in four neighbouring countries. There are only small differences between the Nordic regions and the Netherlands and Poland. Comparison between Figure 5-21 and Figure 5-13 illustrate that the prices in the Nordic region increase with increased integration to the rest of Europe. On the other hand, the very high prices shown in Carbon Neutral are avoided. The prices seem to be more stable in European Battery.

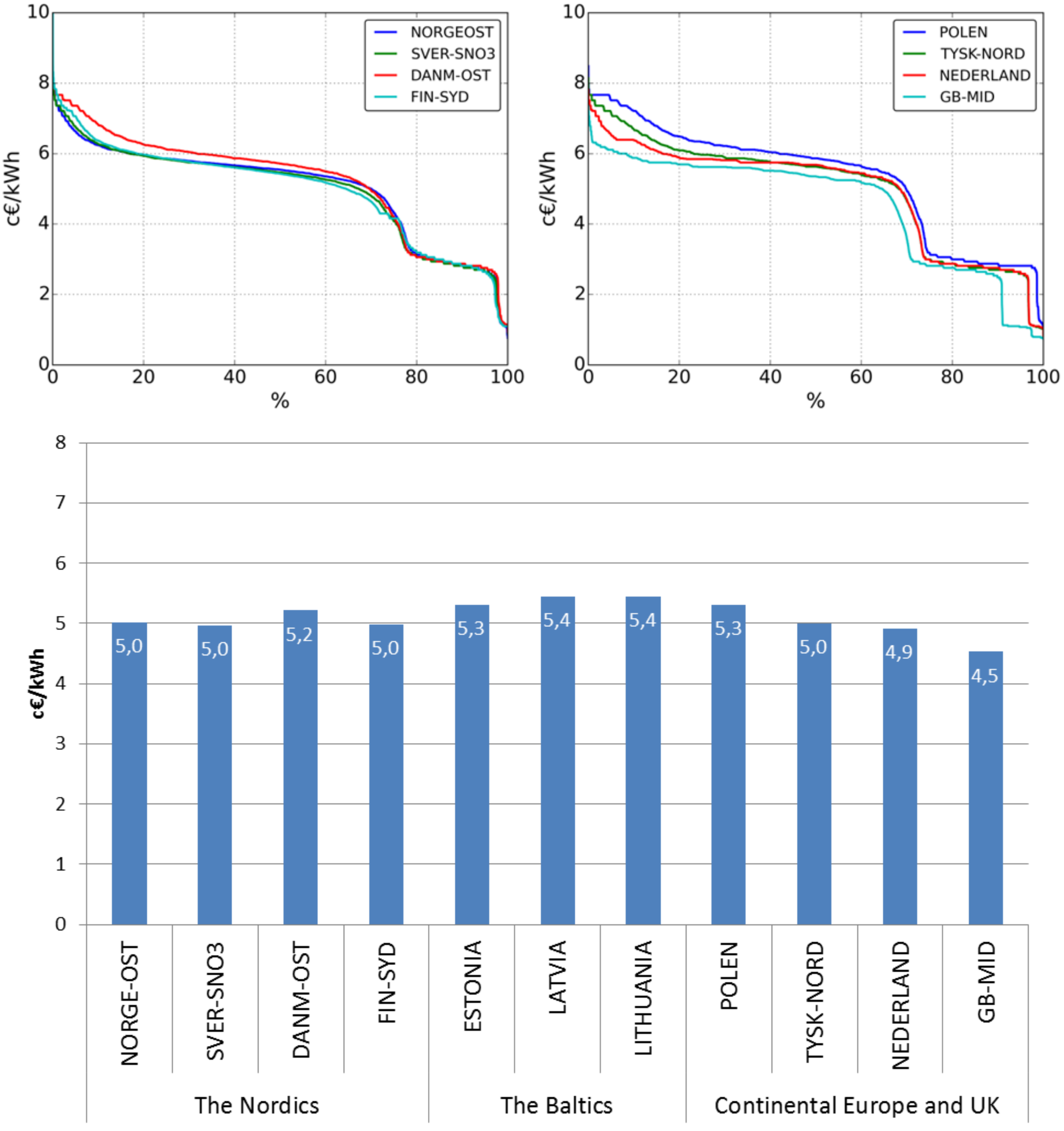

Figure 5-21 Power prices in the Nordic capitals and four neighbouring countries per simulation hour in European Battery [EuroCent/kWh]

As already mentioned the only difference between Carbon Neutral and European Battery is the possibility to increase the connections to countries outside the Nordic region. By comparing the results from the two scenarios we can conclude:

- The average power prices increase in the Nordic region with increased connections to neighbouring countries. The prices are not impacted in countries like the Netherlands and Poland.
- On the other hand, the prices seem to be more stable with increased connections. The very high prices in a few periods in Carbon Neutral are not visible in the scenario with increased connection to Europe.
- The gas production in neighbouring countries like Great Britain, Germany and the Netherlands are reduced with about 10 TWh/y. At the same time the bio production in Continental Europe is increased with about 10 TWh/y.
- The export and import from/to Denmark is reduced in European Battery compared to Carbon Neutral. In Carbon Neutral Denmark is to some degree used as transit land for energy transfer from Sweden to Germany. In Carbon Neutral Sweden has increased its own connection to Germany and less of the flow goes through Denmark.
- The investments in transmission capacities are nearly double (12 300 MW) internally in the Nordic countries in European Battery compared to Carbon Neutral, but limited increase in export from the Nordic region to Continental Europe (2 TWh/y). The investments in capacities are driven by the power price difference. Even though there is a reduction of gas production in neighbouring countries of 11 TWh/y, the reduction in emissions of GHG seem to be very low compared to the huge investments in transmission capacities.

5.5 Scenario European Hub

In the European Hub scenario in 2050 power demand is increased to 444 TWh/y as described in Section 3.1. All fossil production is phased out and approximately 220 TWh/y of new production from renewable resources is included in the system compared to 2012. The main share of the increase is approximately 165 TWh/y of new wind production. In European Hub, transmission connections between the Nordic region and other countries are increased according to profitability criteria. The power production in the Nordic countries is shown in Figure 5-22 and the power balances are shown in Figure 5-23. The Nordic region is exporting about 112 TWh/y in total, and all four countries are in an export position. The energy surplus in Denmark is only a few TWh/y.

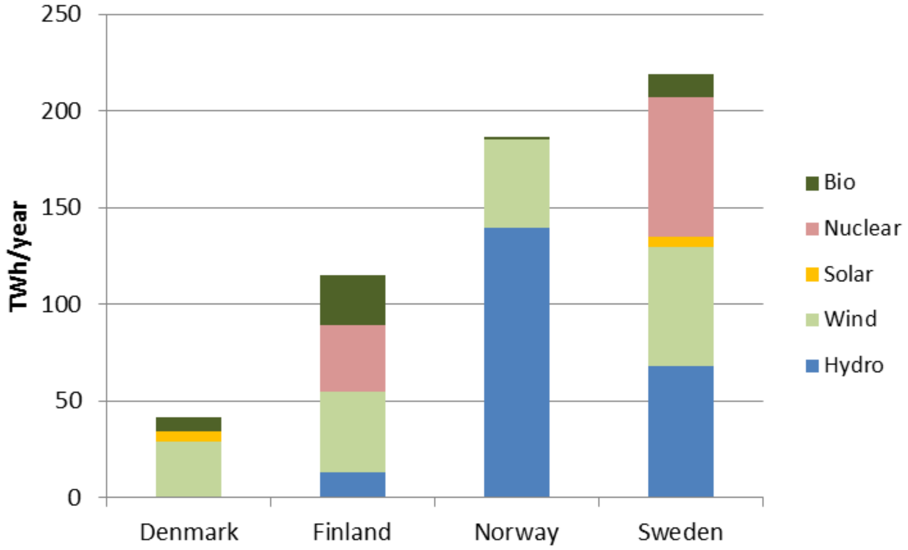

Figure 5-22 Power production in the four Nordic countries in 2050 in European Hub

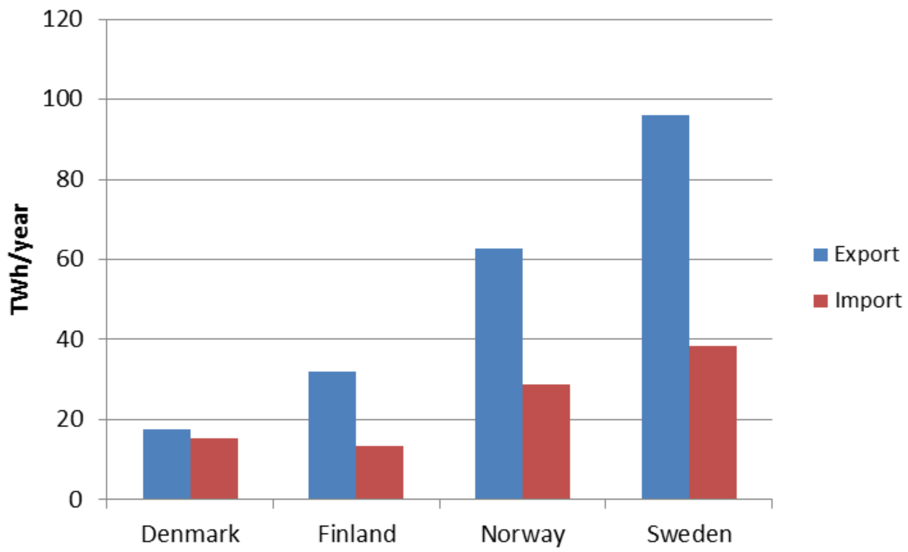

Figure 5-23 The power balances for the four Nordic countries in European Hub in 2050

The production portfolio in the other European countries (for list of countries see Section 5.1) is shown in Figure 5-24, and the power balances for the neighbouring countries to the Nordic region are shown in Table 5-12. By comparing Table 5-2 and Table 5-12, we find that 55 TWh/y of gas production in Great Britain Germany and the Netherlands is substituted with production in the Nordic countries.

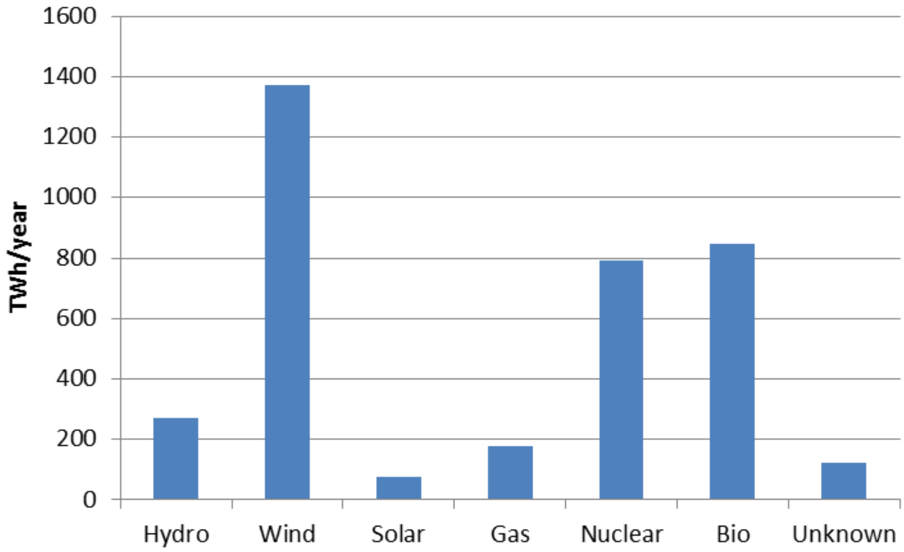

Figure 5-24 Production portfolio in Europe outside the Nordic region in European Hub 2050

Table 5-12 Power balances neighbouring countries European Hub 2050

TWh/year	Export	Import	Demand	Hydro	Wind	Solar	Gas	Coal	Nuclear	Bio
Belgium	15	41	115	0	7	3	19	0	26	35
Belgium_OWP	12	0	0	0	12	0	0	0	0	0
Estonia	18	27	12	0	0	0	0	0	0	3
Great_Britain	88	163	416	5	67	4	58	0	52	161
Great_Britain_OWP	148	2	0	0	146	0	0	0	0	0
Latvia	16	19	12	0	0	0	3	0	0	5
Lithuania	22	33	16	0	0	0	1	0	0	4
The Netherlands	84	74	131	0	16	5	57	0	24	41
The Netherlands_OWP	65	12	0	0	53	0	0	0	0	0
Poland	14	83	174	1	37	0	1	0	0	68
Russia	0	10	882	89	0	0	595	0	188	0
Germany	77	333	639	0	113	62	32	0	0	186
Germany_OWP	106	6	0	0	99	0	0	0	0	0
TOTAL	665	804	2398	95	551	74	767	0	291	504

The power balances for each of the nodes in the Nordic system is shown in Table 5-13. The south of Finland is in a surplus situation with 41 TWh/y of wind and 25 TWh/y of bioenergy integrated into the system. The high production results in an export of 22 TWh/y.

Based on 31 TWh/y of wind production and also some bio energy, SVER-SNO4 is in a surplus situation. SVER-SNO3 is in balance, and the surplus in production in northern Sweden is exported to SVER-SNO3 and SVER-SNO4 and further to in particular Poland and Lithuania.

Table 5-13 Power balances for each of the nodes in the Nordic region in 2050 in European Hub

TWh/year	Export	Import	Demand	Spillage	Hydro	Wind	Solar	Nuclear	Bio
BKK	6	9	11	1	9	1	0	0	0
DANM-OST	3	11	16	0	0	2	2	0	1
FIN-NORD	9	14	12	1	7	0	0	0	0
FIN-SYD	33	11	83	0	6	41	0	34	25
FINNMARK	3	3	4	1	3	1	0	0	0
FYN	2	4	3	0	0	0	0	0	1
HALLINGDAL	16	2	1	2	15	0	0	0	0
HELGELAND	12	4	7	1	11	4	0	0	0
INDRESOGN	4	1	3	1	6	0	0	0	0
JYLL-NORD	14	5	4	0	0	12	1	0	0
JYLL-SYD	16	12	16	0	0	16	2	0	3
MORE	14	7	13	1	8	12	0	0	0
NORDVEST	8	5	3	1	7	0	0	0	0
NORGEOST	7	43	51	4	16	0	0	0	0
NORGESYD	26	12	18	2	19	13	0	0	0
SKL	7	11	10	0	6	0	0	0	0
SORLAN-OWP	4	1	0	0	0	3	0	0	0
SVARTISEN	4	1	0	0	3	0	0	0	0
SVER-SNO1	26	8	10	0	20	7	0	0	0
SVER-SNO2	61	28	16	2	36	11	0	0	2
SVER-SNO3	76	75	101	0	10	13	3	72	6
SVER-SNO4	76	69	30	0	2	31	3	0	3
TELEMARK	23	20	8	1	12	0	0	0	0
TROMS	10	1	7	2	10	7	0	0	0
TRONDELAG	6	6	11	1	7	5	0	0	0
VESTSYD	35	27	1	1	9	0	0	0	0
Total	501	390	442	22	221	179	10	106	41

NORGEOST is in the same imbalance situation as in the other scenarios. NORGEOST is mainly importing from other regions in Norway like MORE and TELEMARK, and also from e.g. NORGESYD through TELEMARK.

Figure 5-25 shows the profitable increases in transmission capacities in the Nordic region in 2050 (to the left) and the power flows are shown to the right. As shown in Figure 5-25 there are large increases in Sweden: 4150 MW from SVER-SNO2 to SVER-SNO3 and 5750 MW from SVER-SNO3 to SVER-SNO4. The flow through Sweden is impacted by the increased renewable production in the northern Norway and Sweden is to some degree working as a transit country for the energy from northern Norway to regions further south. The capacity between TROMS and SVER-SNO1 is increased with 950 MW and between HELGELAND and SVER-SNO2 with 1250 MW.

Due to the power surplus in the south of Finland, large increases in transmission capacities are found profitable between FIN-SYD and Estonia (3350 MW). From SVER-SNO4 to Poland the increases are as much as 6250 MW.

Figure 5-26 shows the power flow in the four regions including the Nordic capitals and in four neighbouring countries.

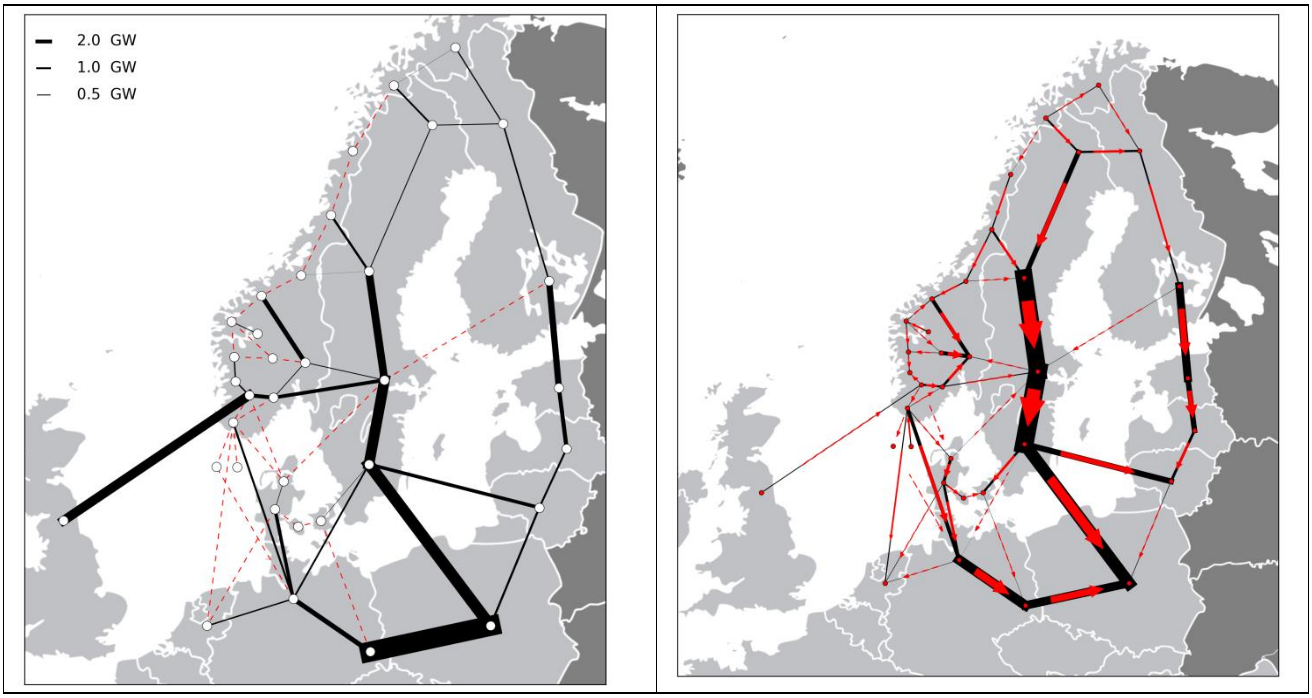

Figure 5-25 Profitable increases in transmission capacities in the Nordic region in European Hub (to the left) and net yearly power flow (to the right)

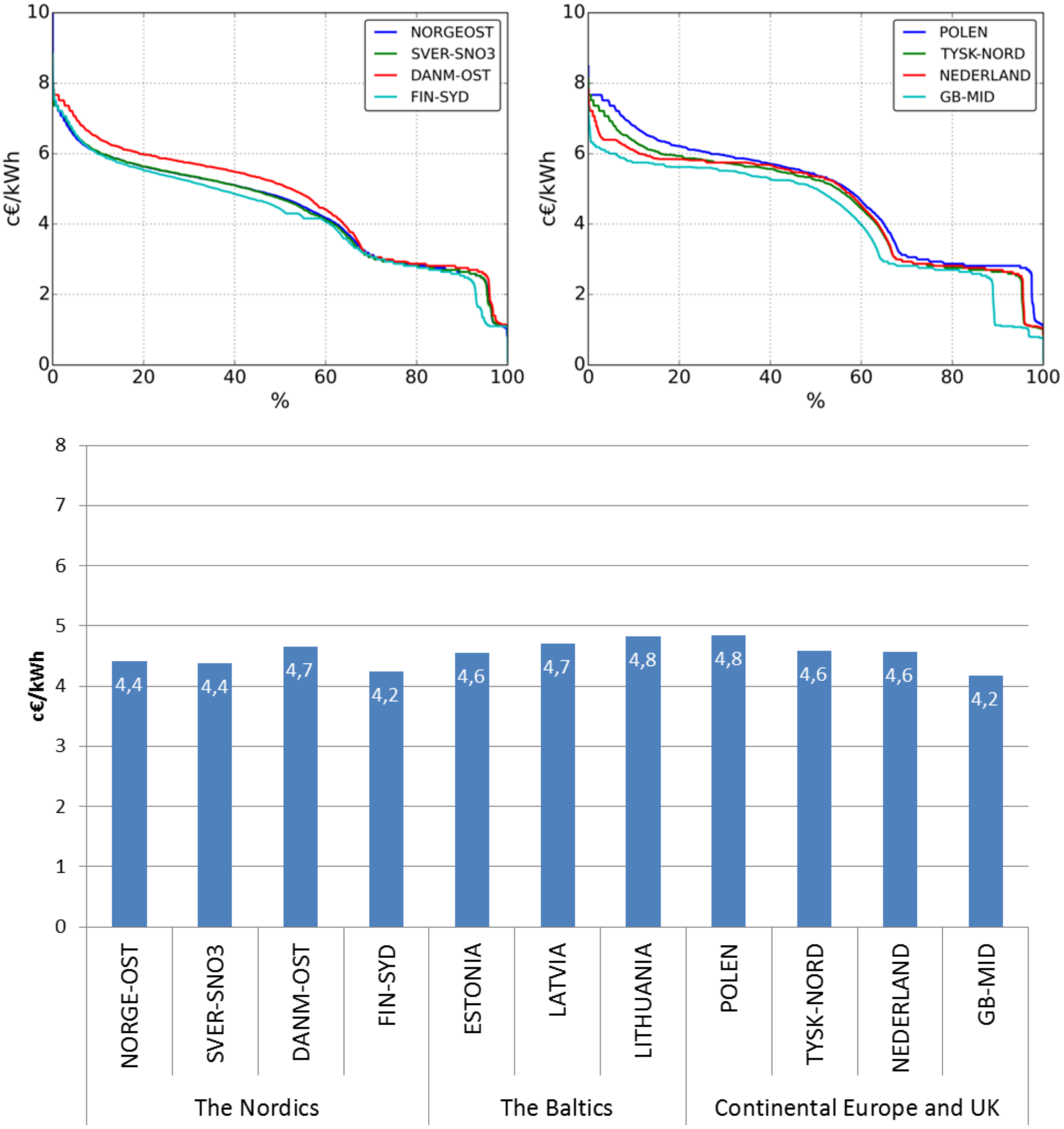

Figure 5-26 Power prices in the Nordic capitals and four neighbouring countries per simulation hour in European Hub [EuroCent/kWh]

5.6 Profitable increases in transmission capacities

Below there are several tables showing the profitable increases in transmission capacities for all four scenarios in 2050 compared to 2012.

5.6.1 Increases in internal Nordic transmission capacities

Table 5-14 Profitable increases internal in the Nordic region in all scenarios in 2050

[MW]		Starting point	Carbon Neutral	Purely RES	European Battery	European Hub	CN low demand	PR no nuc Sweden
FINNMARK	TROMS	500	0	550	0	100	0	50
FINNMARK	FIN-NORD	50	450	1000	450	650	400	600
TROMS	SVARTISEN	1200	0	0	0	0	0	0
TROMS	SVER-SNO1	600	0	550	0	950	0	800
SVARTISEN	HELGELAND	1200	0	0	0	0	0	50
HELGELAND	TRONDELAG	1500	0	0	0	0	0	0
HELGELAND	SVER-SNO2	350	100	1050	450	1250	0	1050
TRONDELAG	MORE	2000	0	0	0	0	0	0
TRONDELAG	SVER-SNO2	1000	0	0	0	50	0	0
MORE	NORDVEST	1500	0	0	0	0	0	0
MORE	NORGEOST	400	650	1800	650	2450	450	2100
NORDVEST	INDRESOGN	925	0	0	50	450	0	0
NORDVEST	BKK	1000	0	0	0	0	0	0
NORDVEST	HALLINGDAL	800	0	0	0	0	0	0
BKK	SKL	1500	0	0	150	700	0	200
BKK	HALLINGDAL	2000	0	0	0	0	0	0
SKL	VESTSYD	2500	0	0	250	750	0	0
VESTSYD	NORGESYD	2200	0	0	0	0	0	0
VESTSYD	TELEMARK	2000	0	1000	3450	2100	0	1000
VESTSYD	JYLL-NORD	0	0	0	0	0	50	0
HALLINGDAL	NORGEOST	3300	200	600	0	0	0	600
TELEMARK	NORGESYD	2000	350	2450	0	0	0	2450
TELEMARK	NORGEOST	3300	200	750	1650	400	0	900
NORGEOST	SVER-SNO3	2050	950	0	0	450	0	0
SVER-SNO1	SVER-SNO2	3300	0	0	0	500	0	950
SVER-SNO1	FIN-NORD	1500	300	1750	400	450	0	150
SVER-SNO2	SVER-SNO3	7300	850	2150	1150	4150	0	3600
SVER-SNO3	SVER-SNO4	6700	0	0	1500	5750	0	0
SVER-SNO4	DANM-OST	1700	550	0	0	200	600	300
FIN-NORD	FIN-SYD	2000	300	1900	150	850	0	1050
JYLL-NORD	JYLL-SYD	2600	0	350	0	300	0	0
JYLL-SYD	FYN	1600	0	0	0	0	0	0
NORGESYD	JYLL-NORD	1700	0	0	0	0	0	0
TELEMARK	SVER-SNO3	0	1400	3900	2000	1950	500	3450
SVER-SNO3	FIN-SYD	1350	0	800	0	0	0	800
SVER-SNO3	JYLL-NORD	720	150	2100	0	0	250	750
DANM-OST	FYN	600	0	50	0	0	0	0
Total internal Nordic region		**64 945**	**6 450**	**22 750**	**12 300**	**24 450**	**2 250**	**20 850**

As shown in Table 5-14 several increases appear in all scenarios and the capacity of several connections are never increased. The analysis indicates that it is possible to develop the Nordic power production to a carbon neutral region with limited increases in transmissions capacities. About 6500 MW is found profitable in Carbon Neutral and only 2250 MW in Carbon Neutral Low demand.

There is a high increase in all scenarios except Carbon Neutral Low demand on the connections from SVER-SNO2 to SVER-SNO3. The increases are profitable because several TWh/y of new wind production are built in region 1 and 2, and these regions have a surplus in production already in 2012. In Sweden region 3 and 4 the demand is increased because of population increase in the largest cities (Stockholm, Malmø and Gøteborg). The production is also increased, but region 3 is in a deficit situation in all scenarios except for the European Hub. In particular the region has a huge deficit in Purely RES where nuclear production is phased out. Figure 5-27 shows the flow in the channel between SVER-SNO3 and SVER-SNO4 for all four scenarios.

In Figure 5-27 to Figure 5-44 the flow on several of the channels in the Nordic power system are shown for all four scenarios. The figures show the flow in 2050 before and after increasing the transmission capacities to the levels found profitable by the investment algorithm. As shown in the figures, there will still be congestions on several channels after increasing the capacities. Since the algorithm do not find it profitable to invest more, the price difference between the two nodes connected by the channel, have to be limited.

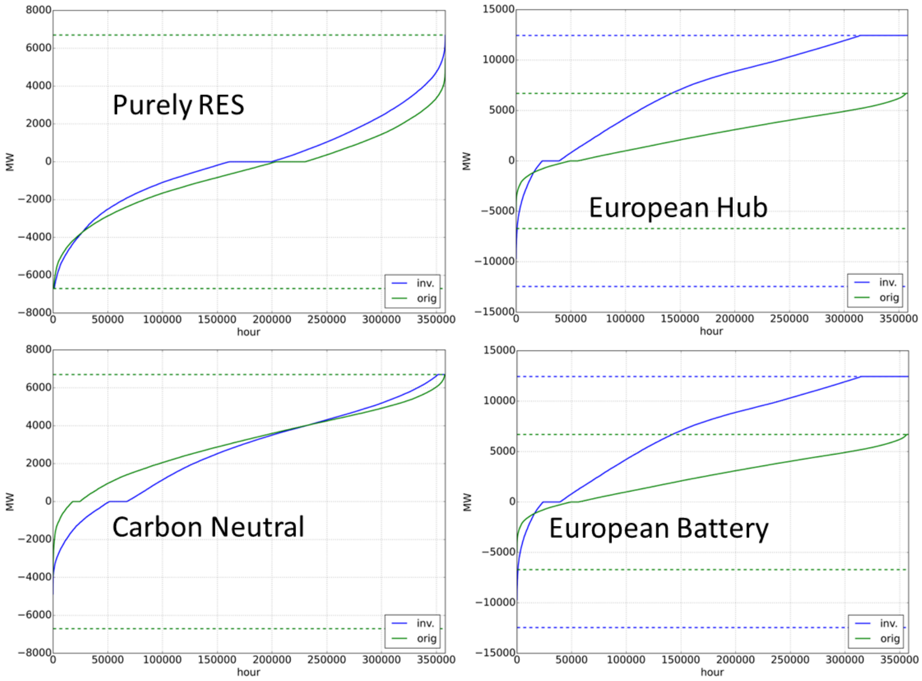

Figure 5-27 Flow SVER-SNO3 – SVER-SNO4 in all four scenarios in 2050 before and after increases in transmission capacities

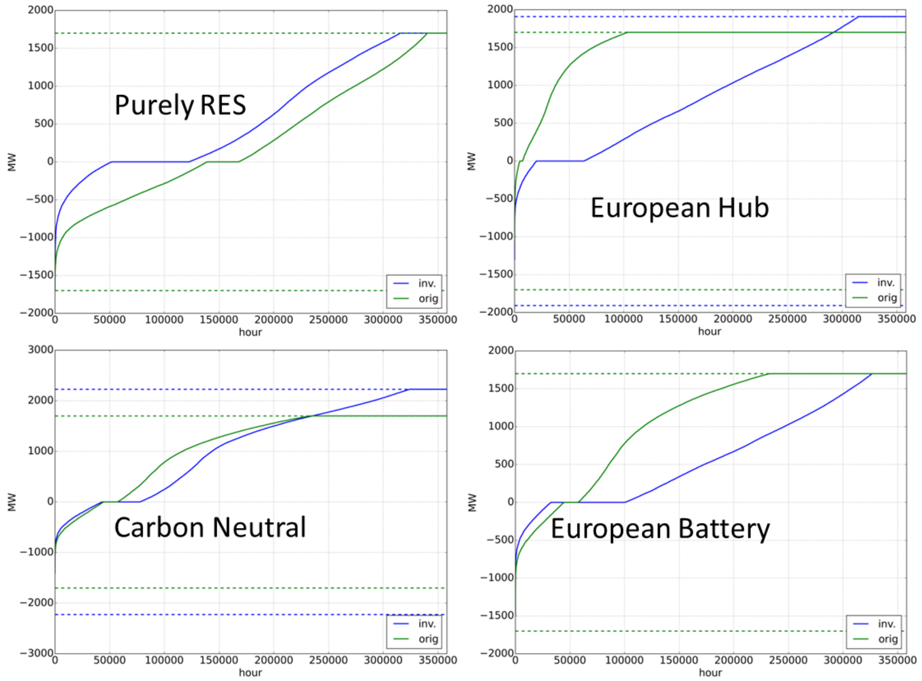

Figure 5-28 Flow between SVER-SNO4 and DANM-OST in all four scenarios in 2050 before and after increases in transmission capacities

Figure 5-28 shows the flow between SVER-SNO4 and DANM-OST in all 4 main scenarios. The main part of the time Sweden is exporting to Denmark. Denmark East (including Copenhagen) is in a deficit situation and needs to import from other regions. In European Battery (down to the right in the figure), less energy is exported (than in Carbon Neutral) after increasing transmission capacities, since the direct connections between south of Sweden and Germany and Poland are increased and Denmark is to a less extent a transit country.

Figure 5-29 shows the flow between NORGEOST and SVER-SNO3 in all four scenarios. NORGEOST is importing from SVER-SNO3 in three of four scenarios. However, the transmission capacity is only increased in Carbon Neutral (with 950 MW) and European Hub (450 MW). The import is highest in Carbon Neutral where NORGEOST is importing from SVER-SNO3 in about 250 000 of 350 000 hours with simulations. In Purely RES, the flow is going both directions, but to some degree more from NORGEOST to SVER-SNO3 than opposite.

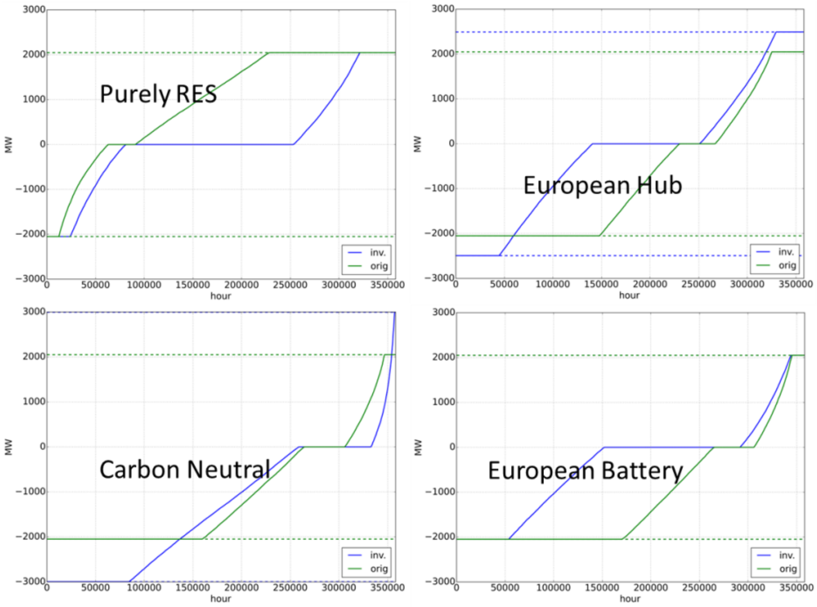

Figure 5-29 Flow between NORGEOST and SVER-SNO3 in all four scenarios in 2050 before and after increases in transmission capacities

Figure 5-30 shows the flow between TELEMARK and SVER-SNO3 in all scenarios. This connection does not exist today, but is found profitable in all cases. The capacity increase is highest in Purely RES with 3900 MW. In Carbon Neutral the connection is not used a main part of the time. Since it is still found profitable to establish the connection, it is probably utilised in periods with high prices (a kind of balancing purpose). Further investigations are necessary to study the utilisation of the connection. In Purely RES (nuclear power production in Sweden is phased out and there is an energy surplus in Norway) energy is exported from TELEMARK to SVER-SNO3 a main part of the time. Also in European Battery and in European Hub there is a total export from TELEMARK to SVER-SNO3. This is caused by the large export from SVER-SNO4 to Europe which causes energy to flow from Southern Norway and Northern Sweden through SVER-SNO3.

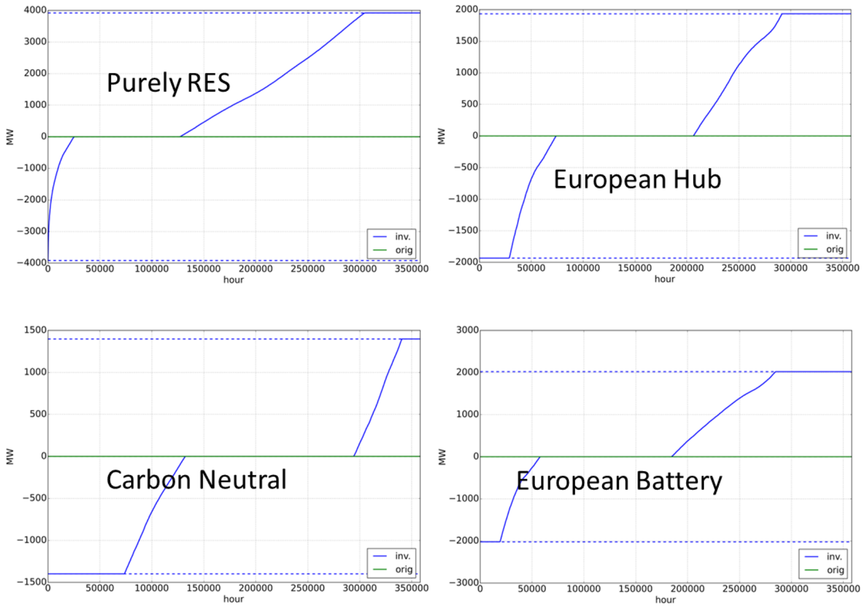

Figure 5-30 Flow between TELEMARK and SVER-SNO3 in all four scenarios in 2050 before and after increases in transmission capacities

Figure 5-31 shows the flow between MORE and NORGEOST in the four main scenarios. MORE has in Carbon Neutral and in European Battery 4 TWh/y in deficit. Anyway, there is a power flow from MORE to NORGEOST the main part of the time. In Purely RES and in European Hub the new renewable production in the region is increased and MORE has a surplus of about 7 TWh/y. The export to NORGEOST increases and there is hardly any power flow in the opposite direction, as shown in the figure.

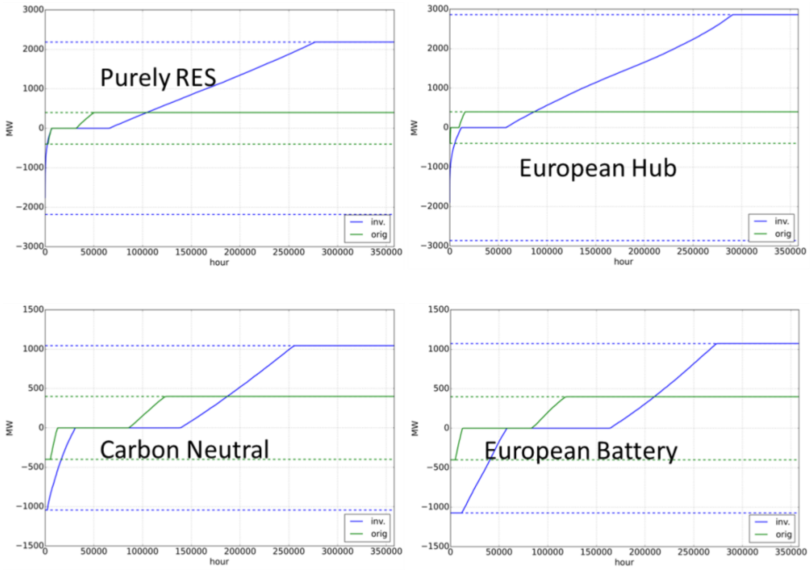

Figure 5-31 Flow between MORE and NORGEOST in all four scenarios in 2050 before and after increases in transmission capacities

The development of the flow between HELGELAND and SVER-SNO2 (Figure 5-32) and between TROMS and SVER-SNO1 (Figure 5-33) has very similar patterns. In Carbon Neutral and European Battery there are only small surpluses at HELGELAND (3 TWh/y) and in TROMS (3 TWh/y). In Purely RES and European Hub the surpluses have increased to 7 TWh/y and 9 TWh/y. In the latter two scenarios the transmission capacities to Sweden are increased and energy is exported from Northern Norway to Northern Sweden a main part of the time.

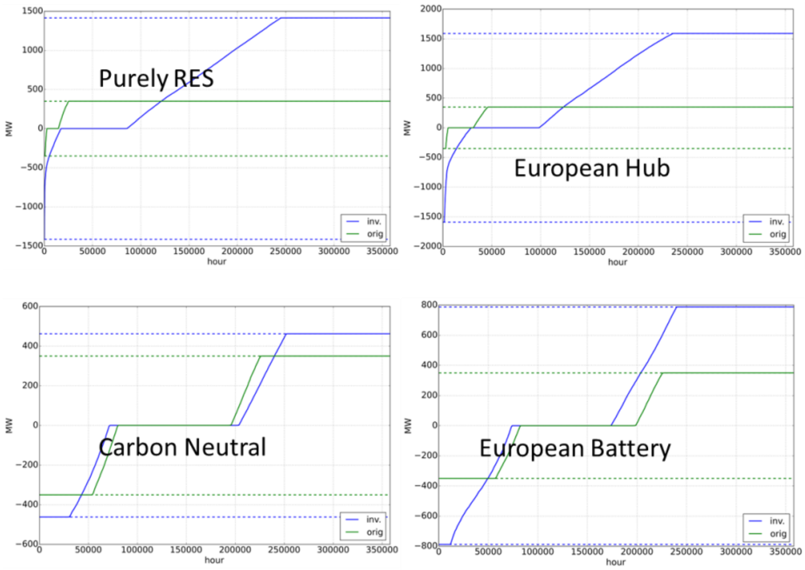

Figure 5-32 Flow between HELGELAND and SVER-SNO2 in all four scenarios in 2050 before and after increases in transmission capacities

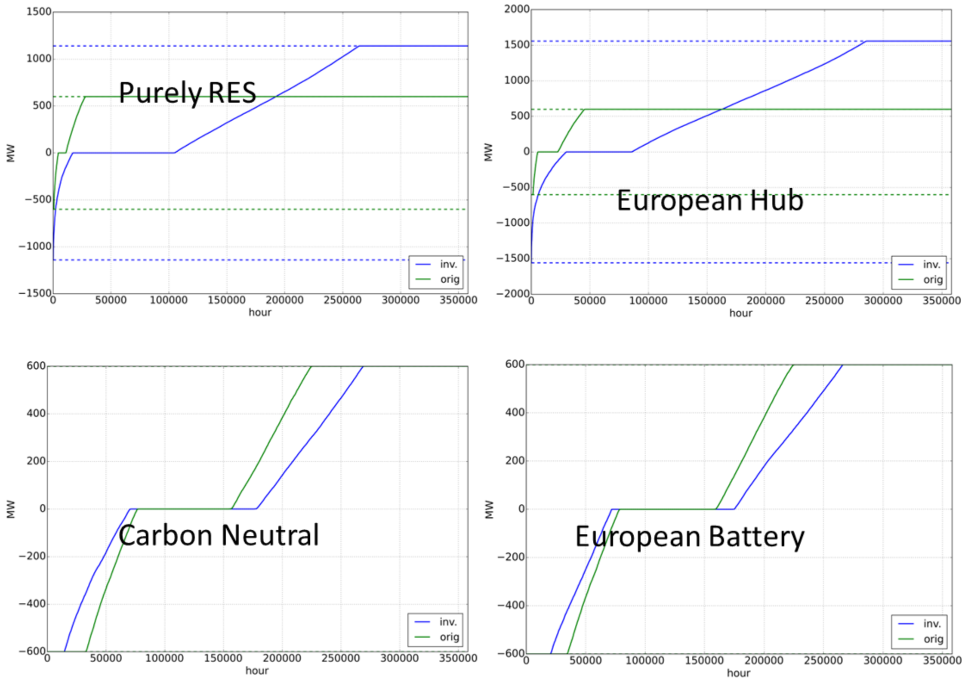

Figure 5-33 Flow between TROMS and SVER-SNO1 all four scenarios in 2050 before and after increases in transmission capacities

Figure 5-34 shows the exchange between SVER-SNO1 and FIN-NORD. Energy is exported from the north of Sweden to Finland in all scenarios. The largest export is in Purely RES where Finland has an energy deficit of 15 TWh/year due to phase out of the nuclear production. The lowest export from SVER-SNO1 to FIN-NORD is in European Hub where Finland is in a surplus situation.

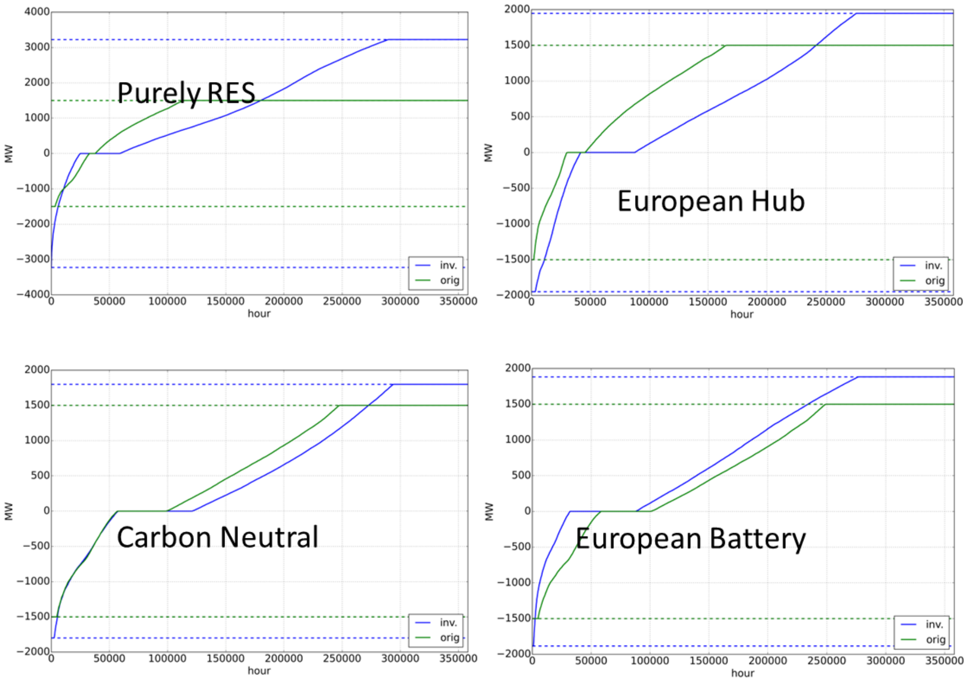

Figure 5-34 Flow between SVER-SNO1 and FIN-NORD all four scenarios in 2050 before and after increases in transmission capacities

Figure 5-35 shows the flow from FIN-NORD to FIN-SYD. In Purely RES the transmission capacity is increased and the flow from FIN-NOR to FIN-SYD is increased due to the decommissioning of the nuclear production.

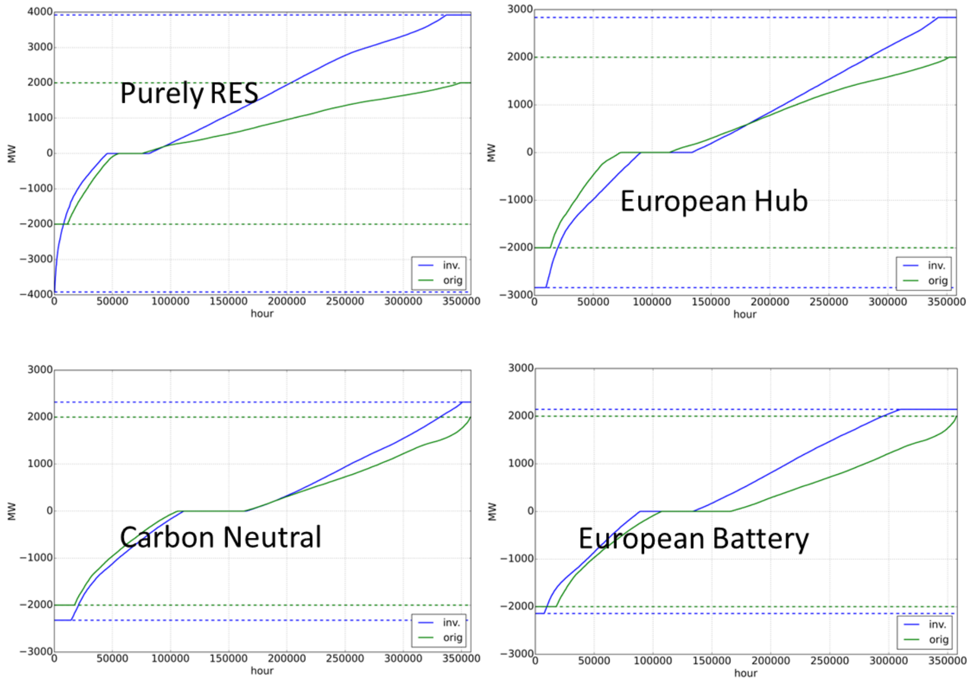

Figure 5-35 Flow between FIN-NORD and FIN-SYD all four scenario in 2050 before and after increases in transmission capacities

5.6.2 Transmission capacities between the Nordic region and Continental Europe

Table 5-15 shows the profitable increases in transmission capacities between the Nordic region and other European countries (Continental Europe). There is of course no increase in Carbon Neutral and Purely RES (since it was not allowed in the analysis). The increase is highest in European Hub (20 300 MW versus 12 550 MW in European Battery) which includes the highest surplus in the Nordic region and has the highest export to neighbouring countries.

Table 5-15 Profitable increases in capacities between the Nordic region and the rest of Europe in the four scenarios in 2050

[MW]		Starting point	Carbon Neutral	Purely RES	European Battery	European Hub	CN low demand	PR no nuc Sweden
DANM-OST	TYSK-OST	600	0	0	0	0	0	0
SVER-SNO4	LITHUANIA	700	0	0	1100	1850	0	0
FIN-SYD	ESTONIA	1000	0	0	1300	3350	0	0
JYLL-SYD	TYSK-NORD	1500	0	0	950	1800	0	0
NORGESYD	TYSK-NORD	1400	0	0	0	1100	0	0
NORGESYD	NEDERLAND	700	0	0	0	0	0	0
VESTSYD	GB-MID	1400	0	0	6200	5000	0	0
SVER-SNO4	TYSK-NORD	600	0	0	150	950	0	0
SVER-SNO4	POLEN	600	0	0	2850	6250	0	0
JYLL-SYD	NEDERLAND	700	0	0	0	0	0	0
Total Nordic - Europe		**9 200**	**0**	**0**	**12 550**	**20 300**	**0**	**0**

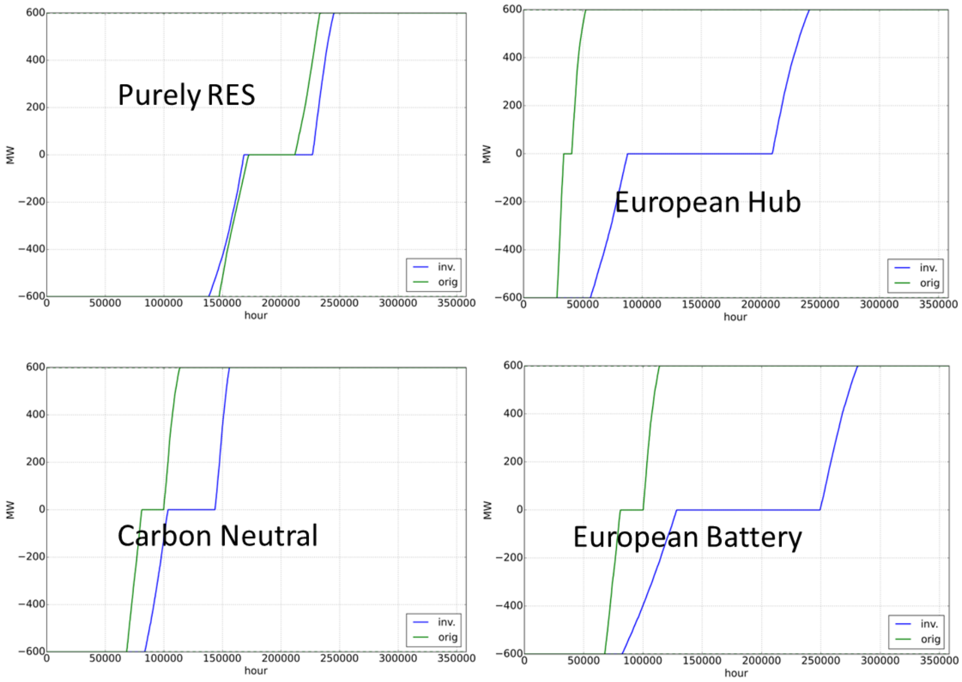

Figure 5-36 Flow DANM-OST – TYSK-OST in all four scenarios in 2050

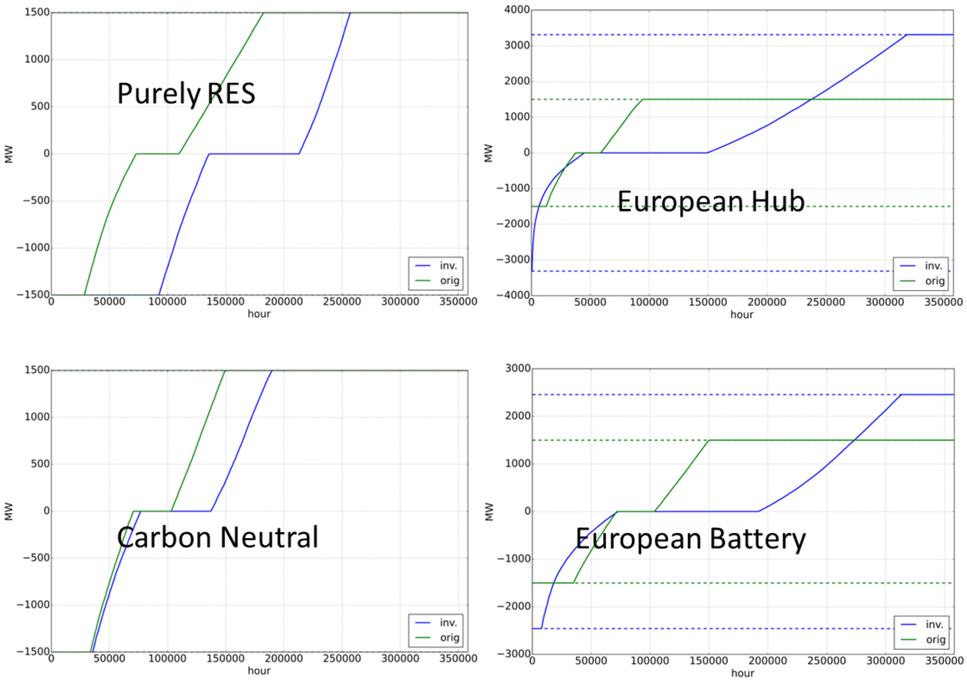

Figure 5-37 Flow JYLL-SYD – TYSK-NORD in all four scenarios in 2050 before and after increases in transmission capacities

Figure 5-36 and Figure 5-37 show the duration curves for DANM-OST to TYSK–OST and JYLL-SYD to TYSK-NORD. As shown in the figures, Denmark exports to Germany in all scenarios except for Purely RES where net power flow over the year is nearly zero.

Figure 5-38 shows the power flow from FIN-SYD to ESTONIA. In all four scenarios power flows from Finland to Estonia most of the time. In the two scenarios where it is allowed to increase the capacities between the Nordic region and other countries, the capacities between south of Finland and Estonia are increased with 1300 MW in European Battery and with 3350 MW in European Hub. In both these scenarios the energy is exported from Finland to Estonia all the time. In Purely RES where nuclear in Finland is phased out, there is some flow in the other direction as well. Energy is exported from Estonia to south of Finland approximately 25% of the simulated periods.

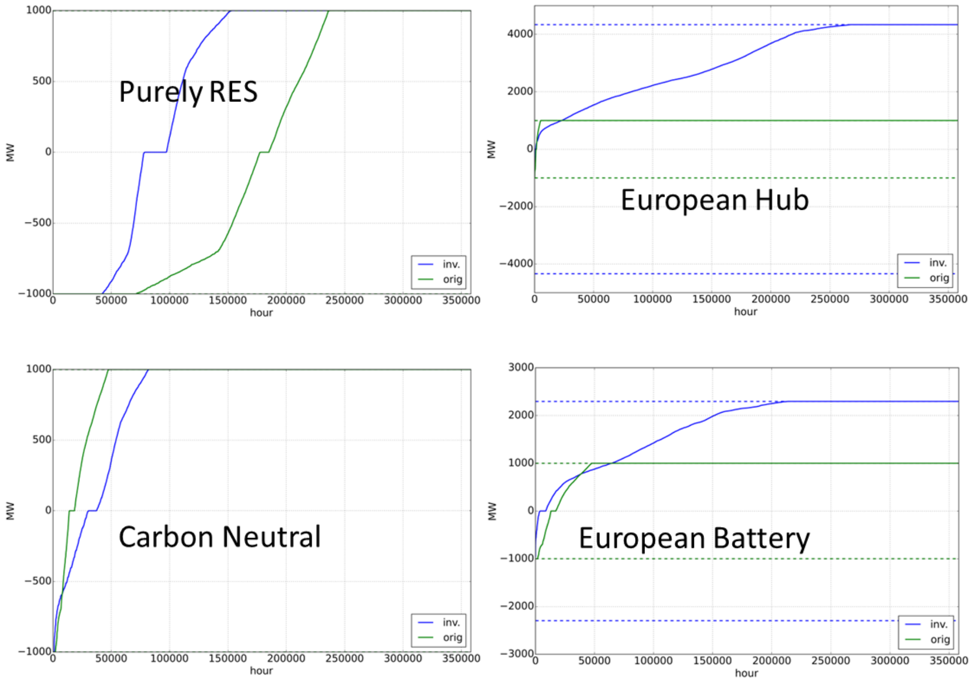

Figure 5-38 Flow FIN-SYD – ESTONIA in all four scenarios in 2050 before and after increases in transmission capacities

Figure 5-39 shows the utilization of the connection between the south of Norway and the North of Germany. This planned connection is included in the datasets before investments, but is not increased further in Carbon Neutral or Purely RES. It is found profitable to increase it compared to the staring capacity in the European Hub scenario. Norway is exporting to Germany a main part of the time in this scenario. Even in the European Battery scenario where Norway has an electricity deficit of 4 TWh/y in average, Norway is exporting to Germany a main part of the time. As already mentioned, Norway is probably working as a transit country in the simulations in this scenario.

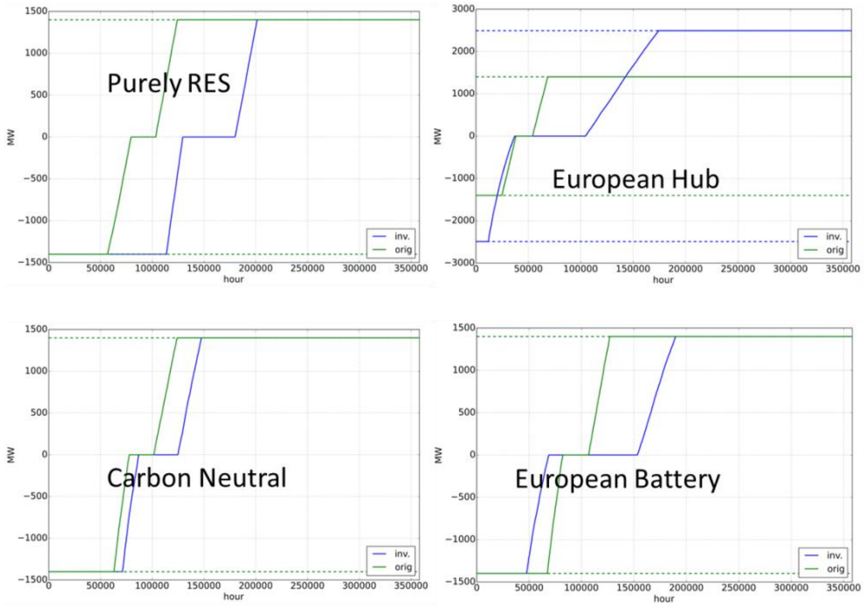

Figure 5-39 Flow NORGESYD-TYSK-NORD in the two scenarios European Battery and European Hub in 2050 before and after increases in transmission capacities

Figure 5-40 shows the duration curve for the connection between the south of Norway and the Netherlands. The transmission capacity of this link is not invested in, which means that the capacity is the same as today in all scenarios. As for the connection between Norway and the south of Germany, Norway is mainly exporting to the Netherlands in all scenarios even in the cases where Norway has a small electricity deficit (Carbon Neutral and European Battery). Particularly in Purely RES where nuclear is phased out in the Nordic region, power is also flowing from the Netherlands to Norway in long periods where Norwegian prices are high due to a large deficit in Sweden and Finland.

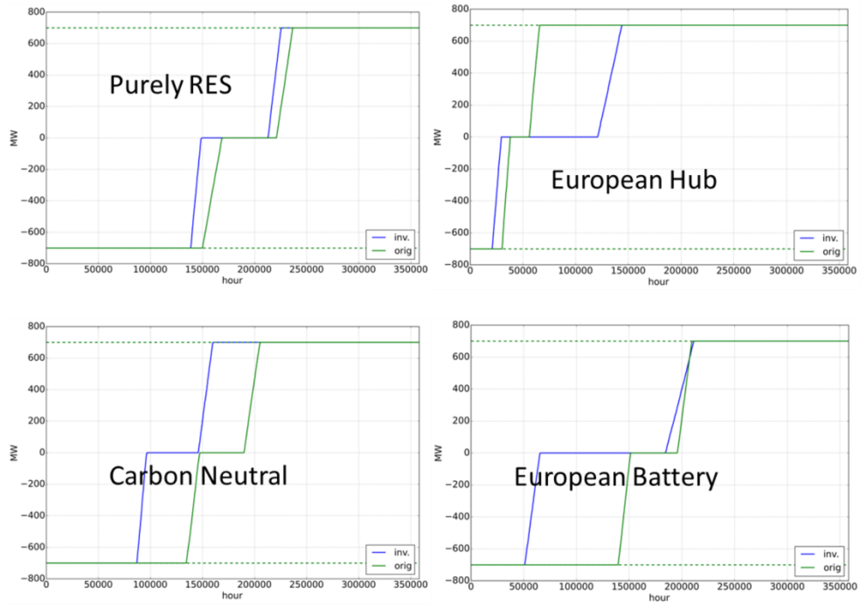

Figure 5-40 Flow NORGESYD – NEDERLAND for all four scenarios in 2050

Figure 5-41 and Figure 5-42 show the duration curves for the connections from the south of Sweden to the North of Germany and to Poland. Sweden is for all four scenarios exporting the main part of the time to

Poland. Even in Purely RES where Sweden is in a deficit situation, Sweden is exporting energy. The export increases in European Battery and European Hub where transmission capacities are allowed to increase.

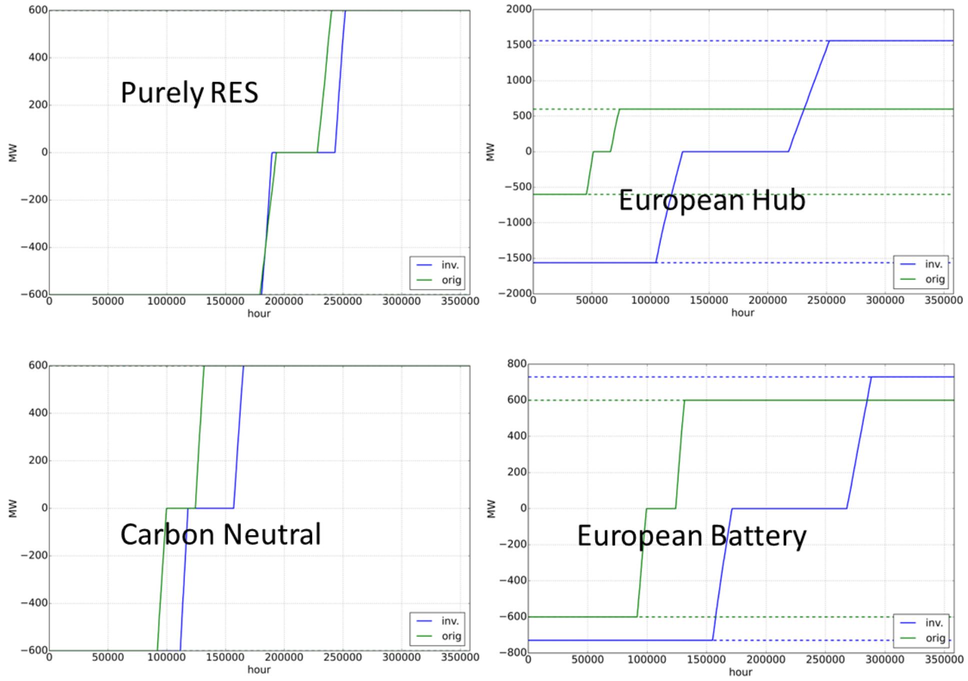

Figure 5-41 Flow SVER-SNO4 – TYSK-NORD for all four scenario in 2050 before and after increases in transmission capacities

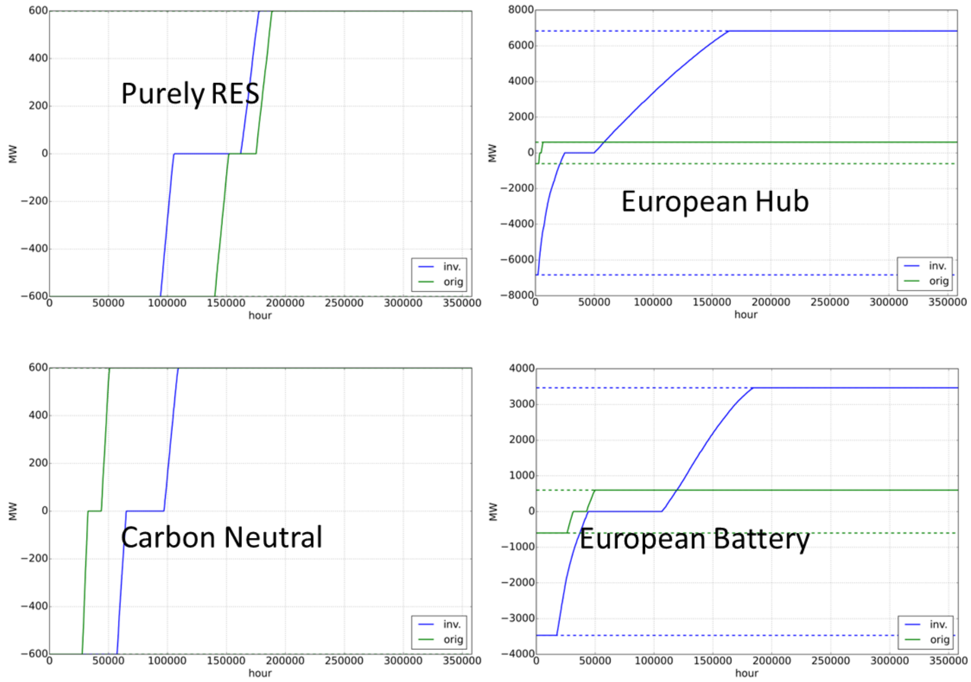

Figure 5-42 Flow SVER-SNO4 –POLEN for all four scenarios in 2050 before and after increases in transmission capacities

Figure 5-43 shows the duration curve for the connection between the south of Sweden and Lithuania. This connection, known as NordBalt, will be finished in few years, but is kept at a capacity of 700 MW in Carbon Neutral and Purely RES. An increased capacity of 1100 MW (European Battery) and 1850 MW (European Hub) are found profitable. Sweden is exporting to Lithuania almost all the time, except in Purely RES, where there also is some import in the winter.

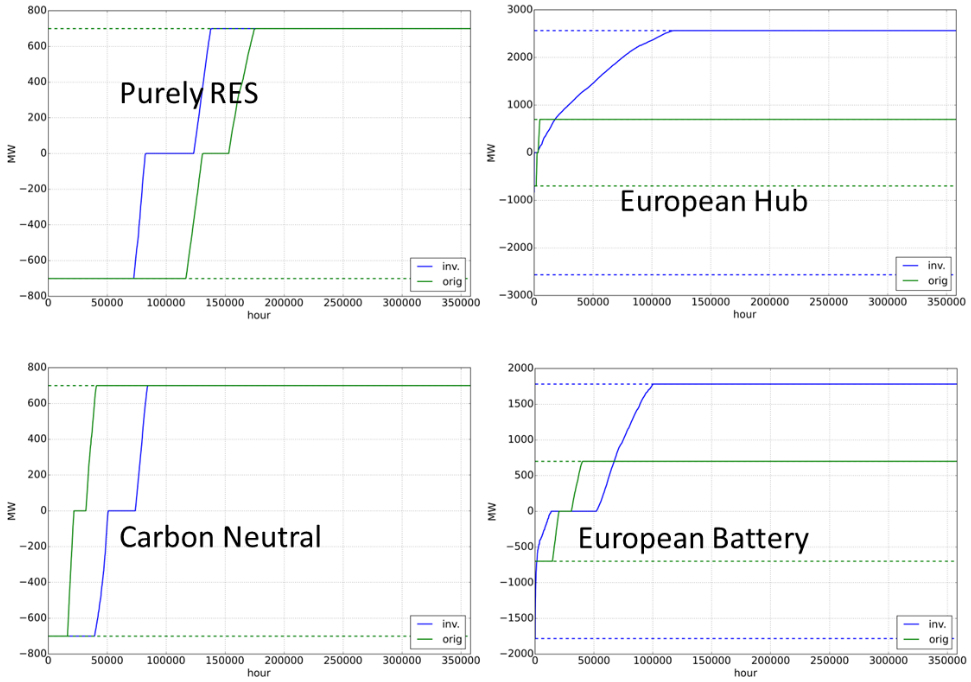

Figure 5-43 Flow SVER-SNO4- LITHUANIA in all four scenarios in 2050 before and after increases in transmission capacities

Figure 5-44 shows the duration curve for a connection between the west-south of Norway and the middle part of Great Britain. This connection will be finished in 2021, and therefore a capacity of 1400 MW exists in Carbon Neutral and Purely RES. As shown in the figure, the capacities are increased with 6200 MW in European Battery and 5000 MW in European Hub. The power is flowing in both directions, but the largest shares are from Great Britain to Norway, especially in Purely RES and European Battery.

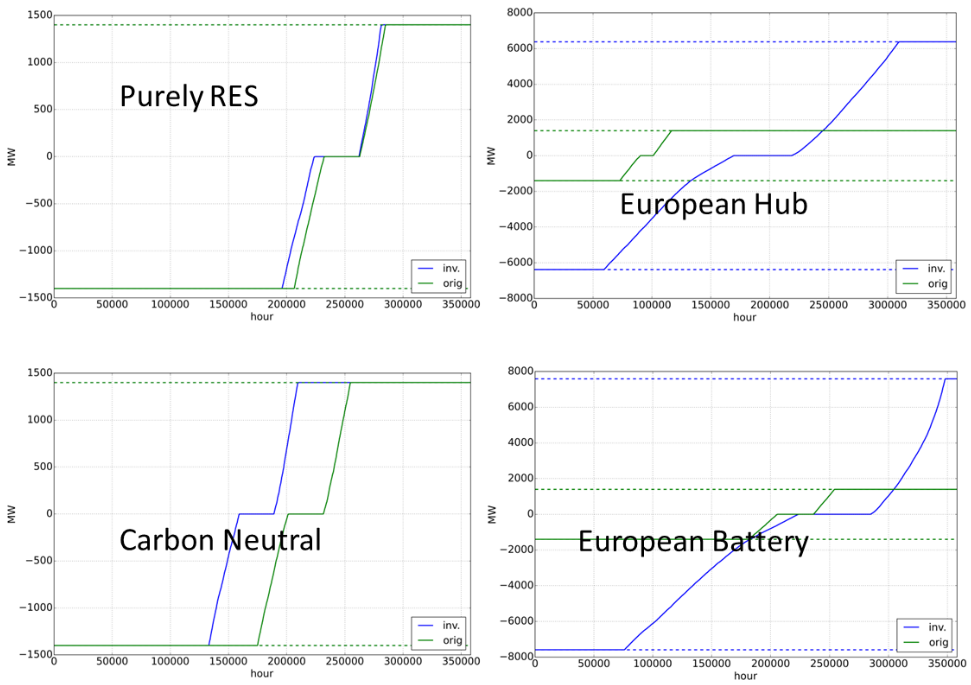

Figure 5-44 Flow VESTSYD (Norway) and GB-MID (Great Britain) in European Battery and European Hub in 2050 before and after increases in transmission capacities

Table 5-16 shows among other the profitable increases in transmission capacities in Europe minus the Nordic region (Continental Europe). The numbers represent profitable increases compared to the present transmission system for transformation of the production system from today's system to a system with a very high share of renewables (based on data from the EU FP7th project SUSPLAN). As shown in Table 3-7 the European transmission system is impacted from the investments between the Nordic region and the rest of Europe. In European Battery the capacities between the Nordic region and neighbouring countries are increased with 12 550 MW. In Continental Europe the increases of transmission capacities are 19 750 MW less than in Carbon Neutral. European Battery and Carbon Neutral are equal (in demand, production capacities etc.) except for the possibilities to increase capacities between the Nordic region and Continental Europe in European Battery. In both European Battery and European Hub there are less increases in capacities in the north of Germany, between Germany and Poland, in the south of Great Britain and between Great Britain and France than in Carbon Neutral and in Purely RES.

Table 5-16 Total numbers for profitable investments in the whole Europe for all scenarios in 2050

	Starting point	Carbon Neutral	Purely RES	European Battery	European Hub	Carbon Neutral low demand	Purely RES no nuclear Sweden
Total internal Nordic region	64 945	6 450	22 750	12 300	24 450	2 250	20 850
Total Nordic - Continental Europe	9 200	0	0	12 550	20 300	0	0
Total Continental Europe	295 100	205 750	210 250	186 000	180 600	202 900	206 450
Total Europe [MW]	**369 245**	**212 200**	**233 000**	**210 850**	**225 350**	**205 150**	**227 300**

6 Comparison with the Nordic Energy technology Perspectives (NETP)

The Nordic Energy Technology Perspectives were released in 2013 in cooperation between Nordic Energy Research and the International Energy Agency [Nordic ETP, 2013]. The study identifies pathways to a Carbon Neutral Energy System in a long term perspective. It includes three main scenarios: a 2DS (the global temperature increase is limited to two degrees), a 4DS (the global temperature increase is limited to 4 degrees) and a CNS (Carbon Neutral scenario). For the latter scenario two additional variants have been considered: the Carbon Neutral high Bioenergy scenario (CNBS) and the Carbon Neutral high Electricity Scenario (CNES). The final electricity demand is assumed to be between 430 TWh/y to nearly 450 TWh/y in the CNES scenario. Nearly all fossil production is phased out and increased consumption is covered by low-carbon electricity sources, mainly renewables. In all three scenarios nuclear generation grows by more than 40% between 2010 and 2050 reaching a level of 120 TWh in 2050. The expansion of nuclear energy is based on a capacity increase in Finland from the current level of 2.7 GW to 6.4 GW in 2050. The capacity in Sweden remains at the current levels.

Electricity generation capacity in both the 4DS and the 2DS increases from around 100 GW to 140 GW in 2050. Wind capacity reaching almost 40 GW by 2050, is the main factor behind the capacity growth. In addition to the storage capacity in the hydropower system, 8 GW of gas capacity is still operational in 2050 and provides additional flexibility.

In all the NETP scenarios, growth in electricity generation outpaces electricity demand, which implies net export from the Nordic region will rise to a level of roughly 80 TWh by 2050 in the CNS. In the CNES overall net export from the Nordic region in 2050 is roughly 100 TWh/y. Net export varies significantly among the Nordic countries in 2050 from 5 TWh in Denmark to 50 TWh in Sweden.

Comparing the NETP scenarios with the NORSTRAT scenarios show large similarities at a Nordic level. The demand in the NETP CNES is approximately the same as in the NORSTRAT scenarios. Wind power generation is the technology which is mainly growing in both studies, ending up with 108 TWh/y in European Battery and as much as 179 TWh in European Hub. In NETP the exact production per year is not given, but it is more than 100 TWh/y (40 GW in 2050). The export from the Nordic region in CNES is 100 TWh/y compared with 33 TWh in NORSTRAT European Battery and 111 TWh in European Hub. In both studies Sweden is a large exporter, and Denmark is almost in balance.

7 Discussion/conclusion

Possible development of the power system in the Nordic region is analysed for four main scenarios (Carbon Neutral, Purely RES, European Battery and European Hub) and for two sensitivity scenarios (Carbon Neutral – low demand and Purely RES – decommissioning only Swedish nuclear). All scenarios are based on a power system without use of fossil resources in 2050. Based on assumptions for development of power demand and integration of new renewable production, profitability of increases in high voltage transmission connections is analysed.

The NORSTRAT analyses are probably the most extensive analyses which are performed for the Nordic power system in a long term perspective both related to geographical and time resolution. The analyses are performed with a 26 node EMPS model for the Nordic region and an additional representation of each European country. Furthermore, Germany and Great Britain are modelled in great detail. 41 years with statistical data are used in the analyses with data about inflow to the hydropower system, wind and solar resources. Each week is analysed with 39 periods resolution resulting in 90 000 periods (or 358 000 hours) with simulations. Included in the data set are huge variations in the hydro, wind and solar resources.

The results give indication about profitable level/scale in the scenarios. However, the analyses cannot be regarded as plans. More detailed studies will be necessary before it is possible to conclude about specific connections. A weakness of the study is the use of fixed lengths for all transmission channels: 130 km for HVDC connections and 80 km for AC connections. The analyses do not include channels in the regional or distribution grids.

A Carbon Neutral Nordic power system

The NORSTRAT scenario studies show that there are more than enough new renewable resources in the Nordic region to phase out all fossil production (70-100 TWh/y), to cover possible increases in demand (assumed to be 58 TWh/y in 2050) and also to phase out nuclear production. NORSTRAT is mainly based on increases in wind and bioenergy production. In 2012 projects for 185 TWh/year new wind power production in the Nordic region are registered. The projects are in different phases and many of the projects will never be realized. However, they illustrate that the resources are available and can be exploited. Other resources such as more solar, tidal, wave, salt gradient power etc. may represent additional opportunities.

The profitable investments in the scenario "Carbon Neutral" are modest in the Nordic region: about 6500 MW (about 10 % of the total Nordic high voltage transmission grid in 2012). The scenario includes several major changes:

- All fossil production is phased out
- The demand is increased with approximately 58 TWh/y
- Demand is changed according to expected demographic changes
- Approximately 140 TWh/y of new renewable energy is integrated into the power system

The results are of course based on the assumptions: the fossil production is to a large degree substituted with renewable production in the same region and consequently the need for grid extension is limited.
Even though large changes of the Nordic power system are assumed, related to production, consumption and also considerable urbanization (people moving from rural areas to large cities), the analyses indicate that it is possible to obtain a secure power system without use of fossil resources. After increases in transmission capacities, a power system without rationing and with hardly any curtailment of non-dispatch-able production like wind and solar production is obtained in the analyses. However, technical/dynamic analyses of the grids must be performed before it is possible to finally conclude about the security of supply.

A purely renewable power system in the Nordic region

In the Purely RES scenario all nuclear production in Sweden and Finland is phased out and substituted with renewable production. About 23 000 MW of increased transmission capacity is found profitable in Purely RES. The channel between the north and south of Finland has its largest increase in this scenario. An increase of 1900 MW is found profitable. Furthermore, the capacity between north of Sweden and north of Finland is increased (1750 MW), and between north of Norway and north of Finland (1000 MW). Power is flowing from north of Norway and Sweden to the north of Finland almost all the year in this scenario.

When nuclear production is phased out in Sweden, it results in a large imbalance in SVER-SNO3. The imbalance is compensated with import from several regions to SVER-SNO3. Power is flowing from SVER-SNO2, SVER-SNO4, JYLL-NORD and TELEMARK into SVER-SNO3. In the PR no nuclear Sweden scenario, it is found profitable to increase the capacity between SVER-SNO3 and:

- SVER-SNO2 with 3600 MW
- JYLL-NORD with 750 MW
- TELEMARK with 3450 MW

Without any increases in the transmission capacities compared to the in 2020 level, there is rationing (curtailment of demand) in several regions in the Nordic countries in Purely RES. In particular there is rationing of up to 6.2 TWh in Sweden and 3.6 TWh in Finland in the most extreme year. The reason for this is a combination of high demand in winter, low wind power production and too little transmission capacity from areas with a surplus (Southern Norway and Northern Sweden). However, after increasing the transmission capacities, there is only a few periods with rationing in the power system.

The Nordic power system in a European perspective

One of the dimensions in the NORSTRAT scenarios is the integration between the Nordic power system and the neighbouring countries in the European power system. In Carbon Neutral and in Purely RES the connections to Europe are kept at the same level as in 2012. In European Battery and in European Hub the connections to the rest of Europe are increased according to profitability criteria.

Table 7-1 gives an overview of the interactions between the Nordic and the European power systems in the scenarios. As shown in Table 7-1 the Nordic region is in a net export position towards Europe in all four scenarios.

Table 7-1 Overview of the Nordic power system in interaction with the European system in the NORSTRAT scenario

Scenario	Net export [TWh/y]	Production in neighbouring countries compared with Carbon Neutral [TWh/y] **)	Increased grid capacity between Nordic region and the rest of Europe *) [MW]
Carbon Neutral	31	-	0
Purely RES	3	+ 22 gas	0
European Battery	33	-11 gas, + 1 bio,	12 550
European Hub	111	-57 gas, -1 coal, -1 nuclear, -4 bio	20 300

*) Does not include internal upgrade in the Nordic region
**) Great Britain, Germany, the Netherlands, Belgium, Poland, Estonia, Latvia, Lithuania and Russia. There will also be changes in other countries, so net export is not equal to changes in production in neighbouring countries.

From the table and the previous chapters we find:

- Both European Battery and European Hub are based on large increases in transmission capacities between the Nordic region and the rest of Europe compared to the present system. The present capacities including known plans are 9200 MW.
- Nordic energy substitute fossil based energy in neighbouring countries, dependent on the production portfolio in the neighbouring countries. In European Hub a main share of the increased export compared to Carbon Neutral substitutes gas production in Germany, Poland, Great Britain and the Netherlands.
- The largest export is in the European Hub scenario where 111 TWh/y is exported from the Nordic region in average. In European Hub the Nordic region has a nuclear production of approximately 106 TWh/y, but nuclear production in Germany is assumed to be phased out. It is more energy efficient to keep nuclear power closer to the consumption centres in Europe, instead of having to transport the power long distances since this involves a lot of network losses.
- Transmission capacities between the Nordic region and the rest of Europe seem to reduce the profitability of new transmission capacities in continental Europe, refer Table 5-16. E.g. Carbon Neutral and European Battery have very similar production portfolios. The capacities between the Nordic region and the rest of Europe are increased with 12 550 MW in European Battery, but not in Carbon Neutral. The profitable increases in capacities in Continental Europe are 19 750 MW less in European Battery than in Carbon Neutral. Increases in capacities internally in Germany and in Great Britain, between Germany and Poland, and between Great Britain and France are lower in European Battery than in Carbon Neutral.
- Power prices increase in the Nordic region with increased capacity towards neighbouring countries. The prices in neighbouring countries to the Nordic region are only limited impacted, see Table 7-2. Comparing Carbon Neutral and European Battery which have similar input data, we see that the output power prices from the EMPS model are increased with about10-15% in average in the Nordic capitals, increased only marginally in the Netherlands and Great Britain-mid and to some degree reduced in Estonia. On the other hand, periods with very high prices are reduced with increased connections to countries outside the Nordic region.

Table 7-2 Average power prices in 2050 for some of the regions/nodes in the NORSTRAT analyses

	Carbon Neutral	CN low demand	Purely RES	PR no nuc Sweden	European Battery	European Hub
NORGE-OST	4,6	2,8	7,3	5,0	5,0	4,4
SVER-SNO3	4,4	2,8	7,3	5,0	5,0	4,4
DANM-OST	4,6	3,0	7,3	5,1	5,2	4,7
FIN-SYD	4,3	2,8	7,3	4,7	5,0	4,2
ESTONIA	5,6	5,4	5,8	5,6	5,3	4,6
LATVIA	5,6	5,4	5,7	5,6	5,4	4,7
LITHUANIA	5,4	5,3	5,6	5,4	5,4	4,8
POLEN	5,3	5,1	5,4	5,3	5,3	4,8
TYSK-NORD	4,9	4,8	5,1	5,0	5,0	4,6
NEDERLAND	4,8	4,7	5,0	4,9	4,9	4,6
GB-MID	4,4	4,3	4,5	4,4	4,5	4,2

<u>The impact of demographic changes</u>

Based on data from the statistical offices in the four Nordic countries, it is assumed a growth in population from 2012 to 2050 of 4.2 million inhabitants. Furthermore, based on information from the same offices particularly the populations in the large cities like Oslo, Stockholm, Copenhagen etc are expected to increase. In NORSTRAT increase in power demand related to the population increase is assumed. For several of the Nordic regions including large cities, a growing power deficit is assumed. In particular, for the region NORGEOST (including Oslo), there are hardly any plans for new renewable power production, but a considerable growth in demand due to population increase. The demographic changes are to large extent impacting the profitability of new transmission capacities.

The main increase in capacity in Carbon Neutral is between Eastern Norway (NORGEOST and TELEMARK) and SVER-SNO3, in total 2350 MW increased capacity. Between NORGEOST and SVER-SNO3 the power is flowing westwards into the Oslo area most of the time and is a result of energy deficit in NORGEOST and energy surplus in SVER-SNO1 and SVER-SNO2. The surplus is exported from northern Sweden through SVER-SNO3 and to NORGEOST. The net energy flow between TELEMARK and SVER-SNO3 is nearly zero over the year, but is used for balancing purposes.

In Purely RES it is assumed a higher volume of new renewable production in Norway than in Carbon Neutral. None of the production is located in the demand centre NORGEOST, and the connection between NORGEOST and MORE needs to be increased (1800 MW). The connection between TELEMARK and NORGEOST is increased (750 MW) for the same reason. In Purely RES there is no increase in the capacity between NORGEOST and SVER-SNO3, but there is a large increase in capacity between TELEMARK and SVER-SNO3 (3900 MW) due to the large imbalance in Southern Sweden when nuclear reactors are de-commissioned.

The increases in transmission capacities

Some connections are found profitable to increase in several scenarios although to different levels. These connections are mainly:

Some connections are found profitable to increase in several scenarios. These connections are mainly:

- TELEMARK / SVER-SNO3 is a new connection not existing today, but represents the western branch of the South West Link between Tveiten in Norway and Barkeryd in Sweden which was cancelled in 2013. This connection is found profitable in all scenarios with capacities in the range (500 – 3900 MW). Although the link is not used a large part of the time in several of the scenarios it is profitable for several reasons:
    1. In case of a nuclear phase out in the SVER-SNO3 the link can provide power to Southern Sweden in times with high demand and low wind and solar power production.
    2. For the European Hub and European Battery scenarios, the link is invested in mostly because SVER-SNO4 increases its capacity towards Continental Europe. This causes large investments between SVER-SNO3 and SVER-SNO4 and raises the price in SVER-SNO3, making it profitable to increase capacity from TELEMARK and Northern Sweden (SVER-SNO3).
    3. In all scenarios, the link is important for balancing out wind and solar power variations in Southern Sweden with hydro power production in Southern Norway.
- SVER-SNO2 / SVER-SNO3 is increased in all scenarios (except for Carbon Neutral Low Demand), with the maximum increase of up to 4150 MW in European Hub. The investment algorithm finds the increase in this connection profitable due to the large surplus in Northern Sweden and Northern Norway which much be exported to the deficit areas SVER-SNO3 and NORGEOST, besides being exported further to Europe.
- MORE / NORGEOST has a capacity of 400 MW in 2015. This capacity is increased from 450 – 2450 MW depending on the scenario. The profitability of this investment is caused by the same drivers as the link between SVER-SNO2 / SVER-SNO3; a large transmission of power production surplus from the north to demand centres in the south.

Further work

This report shows the results from analyses of scenarios for power production without carbon emission in the Nordic region. Several aspects should be studied in more detailed in the next NORSTRAT report or in follow up projects:

- The analyses described in this report are based on a fixed length of transmission links. Further studies should be based on real lengths.
- The costs for developing the Nordic power system to be free of carbon emissions should be calculated at an overall level.
- More detailed studies of how the system is balanced in several situations should be performed. In all the NORSTRAT scenarios there is a large share of production from wind resources, and there will be periods with very low wind production. The EMPS model includes extensive dataset for simulation of such situations. It will in particular be interesting to study in more detail how the Nordic power system is balanced in situations where nuclear production is phased out. Furthermore, flexibility in demand should be considered. This will to some degree be covered in the next report from NORSTRAT, D3.2.
- The behaviour of the power system in extreme wet and dry years is not studied in this report. Such information is available in the results from the analyses and should be considered in further studies.
- Extended use of the Norwegian hydropower system for balancing purposes, e.g. pumping of hydro should be simulated with hourly resolution.
- The utilization of the hydropower system and its reservoirs in the NORSTRAT scenarios should be studied in more detail. The EMPS model includes information about the reservoir level in every time step in the analyses. It is observed that there is different development of the reservoir levels in the different scenarios. It should be studied in more detail what the differences are and why the development is different. It is in particular interesting to study how the hydropower system is used for regions (nodes) which are directly connected to the Continental Europe (e.g. the VESTSYD region).
- Some regions (e.g. the region around the Oslofjord – NORGEOST) show a large power deficit in a long term perspective due to expected population growth and limited growth in new production. The deficits around the Oslofjord and also to some degree around Stockholm impact the need for transmission infrastructures. It should be analysed if energy efficiency, new power production based on biomass etc could reduce the profitability of investments in infrastructures.
- Several channels should be studied for potential loops in the flow, e.g. TELEMARK–SVER-SNO3 and SVER-SNO3 – NORGEOST. Furthermore, the possibility of power flowing from Great Britain to Norway and further to Germany and the Netherlands should be studied.
- The focus in NORSTRAT has been to utilize a surplus from large scale deployment of new renewable production to either phase out nuclear production or to export it from the Nordic region to Continental Europe. A third alternative should be investigated: to develop new power consuming industries in the Nordic region and to utilize the surplus to supply such industries. Among others, environmental effects should be studied: what could the limitation of greenhouse gas emissions be based on "green" products in the Nordic region versus export of green electricity to Continental Europe?
- NORSTRAT is mainly based on large-scale renewable production and in particular wind power production. Solutions with higher shares of e.g. PV production could be considered.
- More sensitivity analyses related to localisation of demand would be useful. E.g. Eurelectric assumes another distribution of demand increase than NORSTRAT.
- Large investments between the Nordic region and Continental Europe seem to reduce the needs for grids in Continental Europe. This should be further studied.

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A.1 The EMPS model and the investment algorithm

The EMPS is an electricity market model that can handle systems with large shares of conventional and varying electricity generation as well as long- and short-term storage options such as hydropower. Basically it is a stochastic optimization model that maximizes the expected total economic surplus in the simulated system, and the solution coincides with the outcome in a well-functioning market. There are several nodes per country reflecting the present power production and transmission system in each country. Each node (or region) is characterized by an endogenously determined internal supply and demand balance with distinct import and export transmission capacities to the neighbouring nodes.

The inputs to the model include costs and capacities for generation, transmission and consumption of electricity, information about climatic variables in the past, among other things. Generation is separated into renewable production capacities like wind, solar, hydro, geothermal and bio. Further, it includes non-RES production capacities (coal, gas, oil, nuclear, etc.). Figure 2-2 is a graphical representation of the components that typically are modelled for each area. The hydropower system is modelled with complex river systems with multiple power plants in series or parallel.

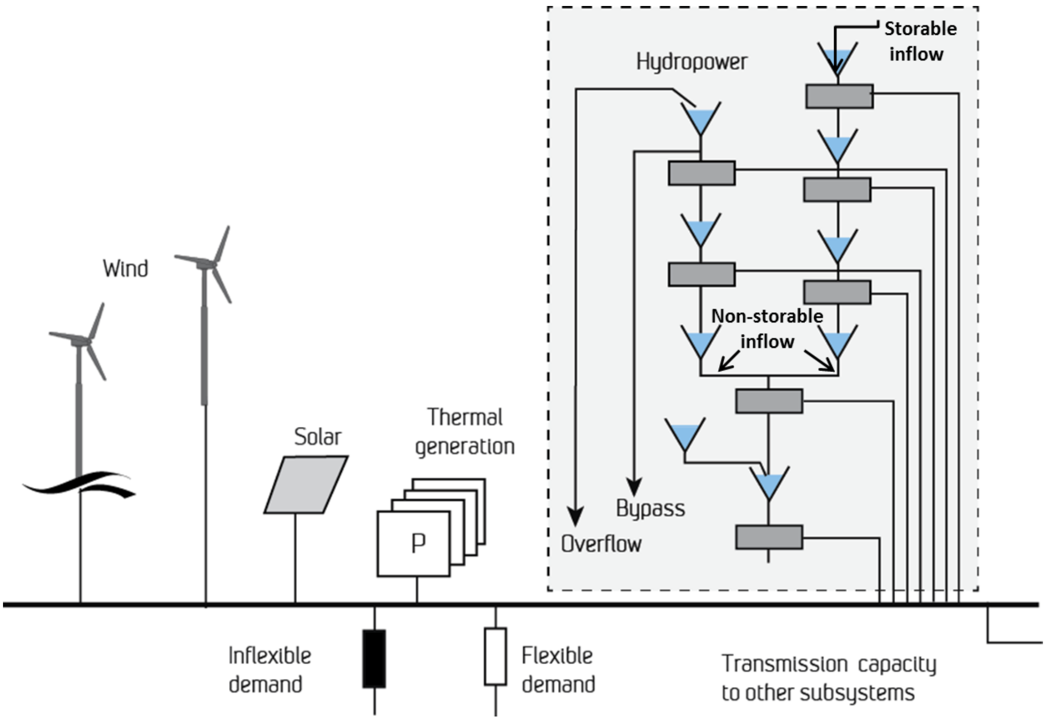

Figure A1 1 Typical components per area in model

The EMPS calculates an optimal strategy for hydropower generation. When creating a robust strategy in a situation where decisions made today impact on the ability to generate electricity several years ahead, the handling of uncertainty is important. Future inflow, wind and solar conditions are the most important uncertainties in a power system dominated by renewable generation. The goal is to find the strategy that minimizes the expected operation cost [Flatabø, 1998; Belsnes, 2009].

When strategies for hydropower have been calculated, the system is simulated for different stochastic outcomes. The optimal solution for market balance for each interval in week n is illustrated in Figure 2-3.

For each area, week, within-week time-step, and stochastic scenario, the endogenous variables determined by the model during simulation include power prices, reservoir levels, electricity consumption and generation, and power exchange with other areas. The optimization problem is stochastic because of the natural variation in climate variables such as temperatures and inflow to reservoirs and dynamic since the use of hydro reservoirs couple decisions in time. The model is described in more detail in [Wolfgang, 2009], including the mathematic formulation of the model.

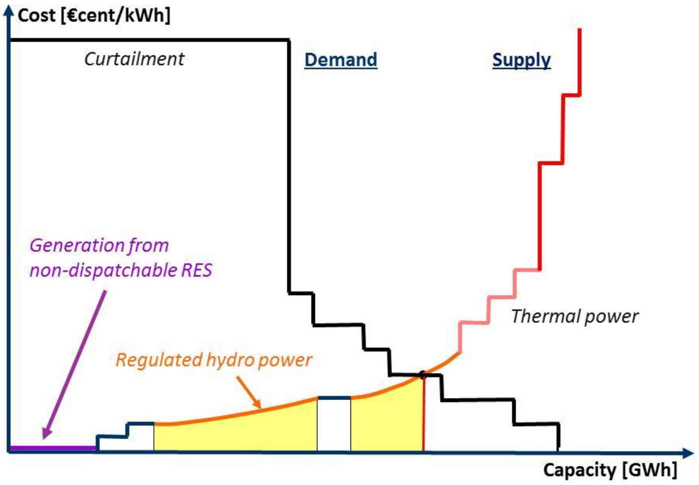

Figure A1 2 Optimal market balance for each interval in week n

The investment algorithm

The EMPS model can be combined with an algorithm for analysis of profitable investments in transmission and generation capacities [Wolfgang, 2008]. This is a one-stage investment analysis that finds profitable investments from a given start-year where capacities are known, e.g. 2012, to a given future year, e.g. 2020. It is however possible to combine several one-stage analyses into a sequence.

Before starting the analysis, all necessary inputs for the future year must be specified in the EMPS model, except for those capacities where the model shall derive profitable investments. First, the model is solved for the future year without any new investments, i.e. the capacities used for the future year are the remaining part of the capacities that existed in the start-year. This is illustrated in the upper part of Figure A1 3. In many cases this will lead to high power prices (mid part of Figure A1 3). Next, the model checks which investments that are profitable at simulated prices (lower part in Figure A1 3). This calculation includes a comparison between average annual operating profits over simulated climate years towards annualized investment costs. For *all* investments that are profitable at simulated prices, some new capacity is included before the next simulation (upward arrow in Figure A1 3.)

The EMPS model is now solved again using the adjusted capacities for the future year, and profitability for investments are checked again for the new power prices, and capacities are adjusted again. The algorithm converges when:

- All implemented investments are profitable
- No additional investments are profitable

This approach gives a reasonable suggestion for a balanced development of capacities, and simulated prices for the future year will reflect both operating- and investment costs. There are however not any guarantees that the model will find the global optimum for the combination of investments that should be carried out.

The marginal profit for investing in 1 MW extra transmission capacity is calculated by Equation 4.

$$\pi_k = \frac{\sum_{t\in T, i\in I, l\in L} \max\left\{0;\ \left[\mathrm{p}_{i,t,l,m_k}\left(1-t_{m_k n_k}\right)-\mathrm{p}_{i,t,l,n_k}\right];\left[\mathrm{p}_{i,t,l,n_k}\left(1-t_{n_k m_k}\right)-\mathrm{p}_{i,t,l,m_k}\right]\right\} h_l \cdot 10}{I^{numb}} - \mathrm{c}_k^{inv}, \quad \forall k \in K^{Trans} \qquad (4)$$

<u>Symbols</u>

I	Set of climate scenarios, e.g. {1931, …,2012}
L	Set of within-week time-steps, e.g. {1, …,100}
T	Set of weeks, {1, …,52}
I^{numb}	Number of climate scenarios, i.e. *card(I).*
K^{Trans}	Set of possible transmission capacity investments
c_k^{inv}	Annualized investment cost (in Euro/MW per year)
h_l	Number of within-week hours in time-step $l \in L$
m_k	Area-number for investment $k \in K^{Trans}$
n_k	2nd area-number for line-investment
p_{i,t,l,m_k}	Power price area m_k (in Eurocent/kWh)
$t_{m_k n_k}$	Transmission loss from m_k to n_k, 0,02
z_k	Needed excess profit to increase investment (as a share of investment costs)
π_k	Average annual profits (in Euro per MW per year)

The investment alternative k is for transmission between the areas m^k og n^k. If for instance the price in a given week is largest in the area m^k and the price difference is large enough to compensate for the losses in transmission, the marginal profit is calculated as $\mathrm{p}_{i,j,m^k}\left(1-t_{m^k n^k}\right)-\mathrm{p}_{i,j,n^k} > 0$. If the price is largest in area n^k, the opposite difference is utilized, cf. Equation 4.

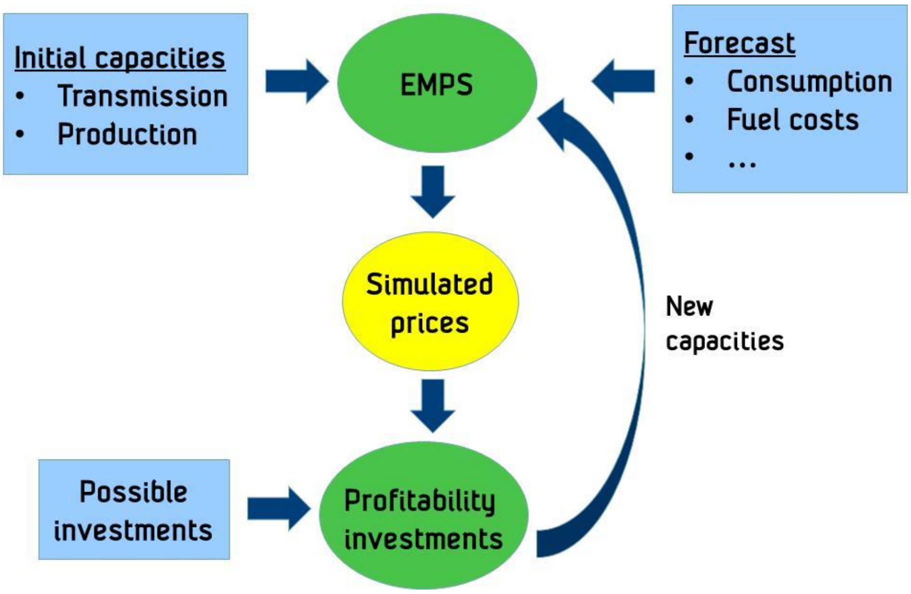

Figure A1 3 Investment algorithm in the EMPS model

For each time-step, the gains of having 1 MW extra capacity are checked. In the EMPS model, the full transmission capacity will always be utilized to send energy towards the high-price area if the price-difference is large enough to pay for the losses. Therefore, the average annual operating profits for transmission lines can be calculated by Equation 4. When the operating profits for all investment alternatives have been calculated the benefits of extra capacity are compared with investment costs. We now interpret the simulated average annual operating profits as the expected annual operating profits, account taken for uncertain climate variables. Then the expected annual profit of investing in 1 MW extra capacity for investment k is:

$$\pi_k^{tot} = \pi_k^{op} - c_k^{inv}, \quad \forall k \in K \tag{5}$$

In every round of the investment algorithm loop, we consider whether the capacity for a specified investment alternative should be increased, decreased or be unchanged. The capacity is increased if the following condition is satisfied:

$$\frac{\pi_k^{tot}}{c_k^{inv}} > z_k \tag{6}$$

A.2 Development of demand population and demographic changes

Denmark

Statistics Denmark has projected population development per region from 2012 to 2040 [DST, 2012]. Further, an estimation is given for the total population in 2050: 6 158 634 people. The estimations are shown in Table A2 1. Table A2 1 Development of population per region in Denmark to 2050 ([DST, 2012] + own projections)Based on the development per region between 2030 and 2040 and the total population in 2050, projections are made by SINTEF for development per region in 2050. The projections resulted in a total number in 2050 very close to the estimations from Statistics Denmark (but not equal). The population increases with 10.4% from 2012 to 2050. The largest increase is expected in the capital, its surroundings and in the eastern part of Jylland. Figures per municipality to 2040 are available on [DST, 2012].

Table A2 1 Development of population per region in Denmark to 2050 ([DST, 2012] + own projections)

	Statbank.dk					Change
	2012	**2020**	**2030**	**2040**	**2050**	2012-2050
Landsdel København by	704 108	793 436	875 992	921 667	951 356	247 248
Landsdel Københavns omegn	520 784	541 211	568 390	591 401	606 358	85 574
Landsdel Nordsjælland	448 291	447 440	451 045	460 075	465 945	17 654
Landsdel Bornholm	41 303	38 373	36 362	34 904	33 956	-7 347
Landsdel Østsjælland	236 429	235 679	236 723	240 399	242 788	6 359
Landsdel Vest- og Sydsjælland	581 478	567 239	559 448	555 631	553 150	-28 328
Landsdel Fyn	485 190	487 692	495 316	501 054	504 784	19 594
Landsdel Sydjylland	716 152	718 039	729 218	738 410	744 385	28 233
Landsdel Østjylland	839 710	887 243	943 681	987 065	1 015 265	175 555
Landsdel Vestjylland	426 972	427 332	433 389	438 942	442 551	15 579
Landsdel Nordjylland	579 996	581 471	590 326	595 846	599 434	19 438
Denmark	**5 580 413**	**5 725 155**	**5 919 890**	**6 065 394**	**6 159 972**	579 559

Finland

Statistics Finland has estimated population development per municipality to 2040 [STAT, 2012]. The figures are aggregated to regional level and shown in Table A2 2. The figures per region for 2050 are projected based on the development for 2030 and 2040 and adjusted according to the estimation from Statistics Finland for the total population in 2050. The estimation is 6 090 038 people in 2050 and the total population from the projected figures for 2050 is 6 093 563. The increase from 2012 to 2050 is 13.2 %. The largest increase is expected in the region Nyland which includes the capital. Further, a large increase is expected in Birkaland which among other includes Tammerfors. Many of the other regions have flat or decreasing population development.

Table A2 2 Development of population per region in Finland to 2050 ([STAT, 2012] + own projections).

	Statistics Finland						
	2010	2012	2020	2030	2040	2050	DIFF 50-12
Birkaland	486 814	495 470	527 799	560 150	582 774	600 873	105 403
Egentliga Finland	465 486	469 805	485 774	502 534	513 306	521 924	52 119
Egentliga Tavastland	175 626	178 181	188 160	199 208	206 563	212 447	34 266
Kajanaland	82 181	81 324	79 063	77 936	76 961	76 181	-5 143
Kymmenedalen	181 923	181 166	178 872	177 097	174 511	172 442	-8 724
Lappland	183 205	182 683	182 522	183 925	184 453	184 875	2 192
Mellerstad Finland	276 439	278 548	286 670	294 815	299 235	302 771	24 223
Mellersta Österbotten	68 253	68 569	70 081	71 820	72 698	73 400	4 831
Norra Karelen	165 286	164 534	162 485	160 874	158 184	156 032	-8 502
Norra Savolax	247 682	247 028	245 194	243 626	240 365	237 756	-9 272
Norra Österbotten	395 321	401 220	422 281	440 279	450 750	459 127	57 907
Nyland	1 533 123	1 563 973	1 679 050	1 794 877	1 877 882	1 944 286	380 313
Päijänne-Tavastland	202 379	203 979	211 064	219 062	223 799	227 589	23 610
Satakunta	226 568	225 678	223 309	221 378	218 318	215 870	-9 808
Södra Karelen	133 943	133 510	132 314	131 461	129 968	128 774	-4 736
Södra Savolax	154 708	153 053	148 252	144 637	141 119	138 305	-14 748
Södra Österbotten	193 530	193 729	195 937	199 331	201 056	202 436	8 707
Österbotten	177 645	179 299	186 007	193 073	197 237	200 568	21 269
Åland	28 053	28 643	31 104	34 014	36 177	37 907	9 264
TOTALT FINLAND	5 378 165	5 430 392	5 635 938	5 850 097	5 985 356	6 093 563	663 171

Norway

Information about possible population development and demographic changes is found at the web pages for "Statistics Norway" [SSB, 2012]. The population in Norway in beginning of 2012 was nearly 5 million inhabitants, and a rapid growth is likely for some time before it slows down. SSB has three projections for the further development of the population: low, medium and high. According to the medium alternative, the population in Norway will have passed 6 million people in 2029 and 7 million in 2063. There is great uncertainty in the figures, however, particularly in relation to future immigration.

The population growth is expected to be particularly strong during the first projection years. This is primarily due to increased immigration, especially from the EU area. The population will grow in all counties until 2040, according to the main (medium) alternative. The growth is expected to be strongest in Oslo, Akershus and Rogaland. Oslo will grow from 613 000 in 2012 to 833 000 in 2040.

The possible development for the population development in Norway per county is shown in Table A2 3. SSB has given total figures for the population in Norway for all years between 2012 and 2050 in the medium alternative and further figures per county for the years 2012 and 2040. The regional figures for the years 2020, 2030 and 2050 are constructed by SINTEF based on the figures given. The population in Norway increases with 34 % between 2012 and 2050 based on the middle alternative from SSB.
As shown in the table the population in Norway is expected to increase with about 800 000 inhabitants around the Oslofjord from 2012 to 2050 (the regions Oslo, Akershus, Østfold, and Vestfold and the largest

cities in Buskerud). This is an area of Norway with low electricity production and also low potential for new renewable production from either onshore or offshore wind.

Table A2 3 Population development per county in Norway to 2050 ([SSB, 2012] and own projections)

	SSB			SSB		Increase
County	2012	2020	2030	2040	2050	2012-2050
Østfold	278 352	308 721	338 798	360 115	376 468	98 116
Akershus	556 254	633 377	709 758	763 892	805 420	249 166
Oslo	613 285	695 166	776 259	833 733	877 823	264 538
Hedemark	192 791	206 073	219 227	228 550	235 702	42 911
Oppland	187 147	199 724	212 179	221 007	227 779	40 632
Buskerud	265 164	298 601	331 716	355 186	373 190	108 026
Vestfold	236 424	261 492	286 320	303 916	317 414	80 990
Telemark	170 023	180 273	190 424	197 619	203 138	33 115
Aust-Agder	111 495	126 584	141 528	152 119	160 244	48 749
Vest-Agder	174 324	196 977	219 412	235 312	247 510	73 186
Rogaland	443 115	504 023	564 345	607 097	639 893	196 778
Hordaland	490 570	549 772	608 405	649 961	681 839	191 269
Sogn og Fjordande	108 201	113 349	118 447	122 060	124 832	16 631
Møre og Romsdal	256 628	278 103	299 371	314 444	326 007	69 379
Sør-Trøndelag	297 950	328 319	358 397	379 714	396 067	98 117
Nord-Trøndelag	133 390	142 343	151 210	157 494	162 315	28 925
Nordland	238 320	246 918	255 433	261 468	266 098	27 778
Troms	158 650	165 478	172 240	177 032	180 708	22 058
Finnmark	73 787	75 979	78 150	79 689	80 869	7 082
NORWAY	4 985 870	5 511 270	6 031 618	6 400 408	6 683 316	1 697 446

Sweden

Estimated figures for population development per region in Sweden were not found. For Sweden there was not found any estimations per region for the population development. Possible development per region was instead projected based on historical development (2000-2011) and with adjustment to the estimations from Statistics Sweden for development of total population to 2050. The results are shown in Table A2 4.

A special calculation is done for Uppsala and Västmanlands län. The municipality Heby was moved from Västmans län to Uppsala län in 2007. Thus, the changes in population for the two läns from 2000-2011 could not just be projected to 2050. For the calculations Heby was kept in Västmanlands län to 2050 and then moved to Uppsala län.

Estimations for total population in Sweden in 2050 is 11 287 749 [SCB, 2012]. Projections made by SINTEF ended with 11 291 277 in 2050. The population in Sweden is increasing with 19% from 2011 to 2050 based on the total figures from Statistics Sweden. The increase is greatest in the regions with the largest cities, like in the Stockholm region, the Skåne region and in the Västre Gotalands län.

In [Rufs, 2010] there are estimates for development of the population in Stockholms län to 2030. In the report it is described a "high" development to 2030, where the population is increasing with 445 000 persons. It is also described a "low" increase of 260 000 persons to 2030. In NORSTRAT it is assumed a population increase in Stockholms län of 808 000 inhabitants from 2011 to 2050. With a linear development from 2011 to 2030, it implies an increase of 393 000 inhabitants in 2030, i.e. lower than the high development described above.

Table A2 4 Development population per region in Sweden to 2050 ([SCB, 2012] and own projections)

	Statistics Sweden			
	2000	2011	2050	2050-2011
01 Stockholms län	1 823 210	2 091 473	2 899 920	808 447
03 Uppsala län	294 196	325 249	431 248	105 999
04 Södermanlands län	256 033	272 563	322 378	49 815
05 Östergötlands län	411 345	431 075	490 534	59 459
06 Jönköpings län	327 829	337 896	368 234	30 338
07 Kronobergs län	176 639	184 654	208 808	24 154
08 Kalmar län	235 391	233 090	226 156	-6 934
09 Gotlands län	57 313	57 308	57 293	-15
10 Blekinge län	150 392	152 979	160 775	7 796
12 Skåne län	1 129 424	1 252 933	1 625 144	372 211
13 Hallands län	275 004	301 724	382 248	80 524
14 Västra Götalands län	1 494 641	1 590 604	1 879 802	289 198
17 Värmlands län	275 003	272 736	265 904	-6 832
18 Örebro län	273 615	281 572	305 552	23 980
19 Västmanlands län	256 889	267 638	287 615	19 977
20 Dalarnas län	278 259	276 565	271 460	-5 105
21 Gävleborgs län	279 262	276 130	266 691	-9 439
22 Västernorrlands län	246 903	242 155	227 846	-14 309
23 Jämtlands län	129 566	126 299	116 453	-9 846
24 Västerbottens län	255 640	259 667	271 803	12 136
25 Norrbottens län	256 238	248 545	225 361	-23 184
Total SWEDEN	8 882 792	9 482 855	11 291 227	1 808 372

The Nordic region

The total expected increase in population for the Nordic region in the period 2012-2050 based on the middle alternatives from the Statistical offices in each of the countries are shown in Table A2 5.

Table A2 5 Increase in population to 2050 based on middle alternatives from statistical offices in each Nordic country (1000 persons)

	2012	2050	DIFF
Danmark	5 580	6 160	580
Finland	5 430	6 094	664
Norge	4 986	6 160	1 174
Sverige *)	9 483	11 291	1 808
TOTAL	25 479	29 705	4 226

*) The figures for Sweden are from 2011 instead of 2012

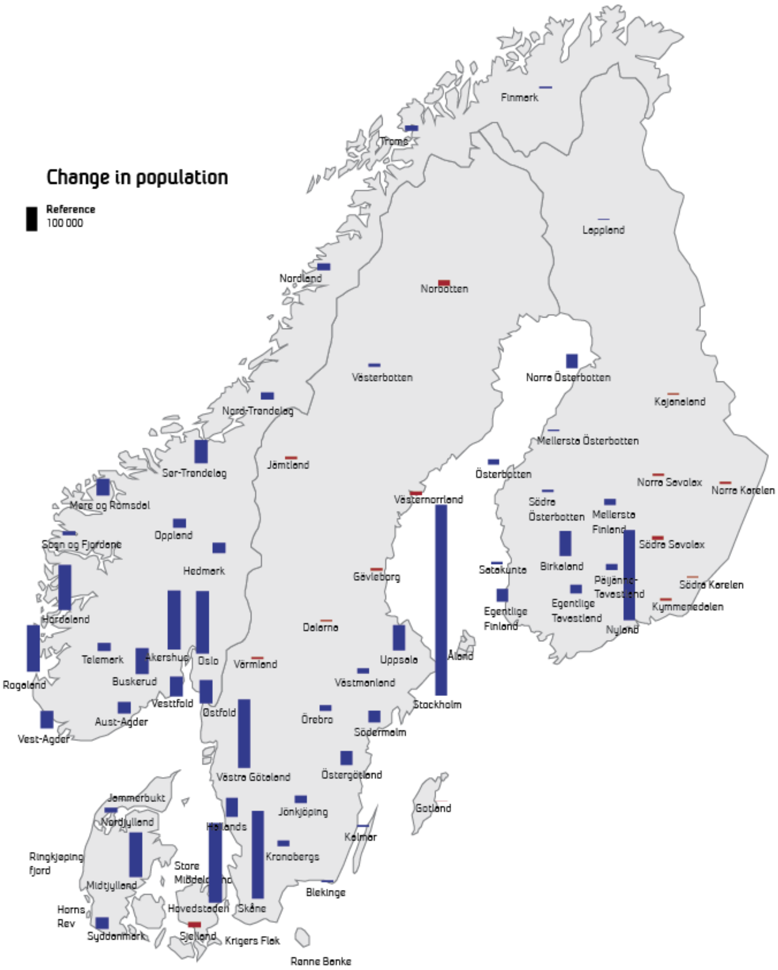

Figure A2 1 Location of population increase in the Nordic region to 2050 [Statistical offices in each country + own projections] (Blue is increase, Red is decrease)

In Figure A2 1 location of the increase in population is given. The regional increases for Denmark, Finland and Norway are based on figures from the statistical offices in each of the country and projected by SINTEF to 2050. For Sweden the distribution per region is projected based on historical data for population development per region for the period 2000-2011.

As shown in the figure, the population is expected to increase most of all in Stockholm, in the area around the Oslofjord, in the south-western part of Sweden (Malmø, Gøteborg) and around Helsinki and Copenhagen.

A.3 Development in demand and regional changes in demand

The expected increase in population will generate an increase in demand. A possible increase in demand is calculated based on the expected increase in population per region multiplied with current consumption per inhabitant in the specific region. The estimated demand increase per country is shown in Table A3 1.

The possible increase adds up to 58 TWh/y for the four countries together. The largest increases are in Norway (26 TWh/y) and Sweden (21 TWh/y). Figure 3-1 shows possible change in the demand based on the location of the expected increase/decrease in population multiplied with the current consumption in the region.

Table A3 1 Estimated demand increase due to expected increase in population

	TWh/y
Denmark	3,5
Finland	7,5
Norway	26,0
Sweden	21,0
Total	58,0

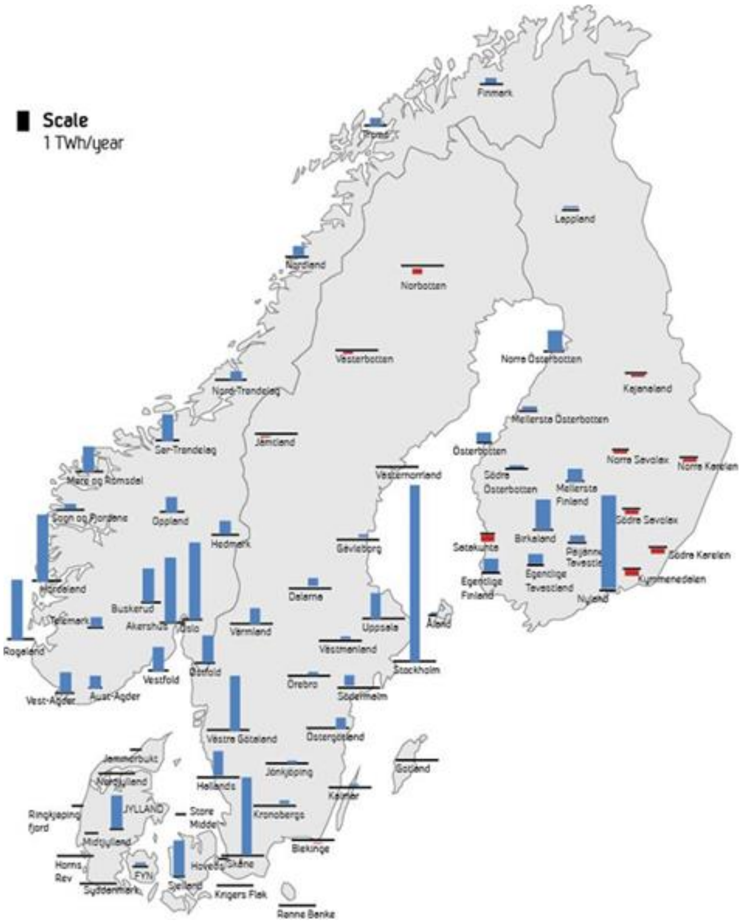

Figure A3 1 Location of increase in demand to 2050 based on expected population increase (Blue shows increase, Red shows decrease).

The estimation for increase in consumption per region/county in each country is shown below. The estimations are based on the excepted increase in population per region multiplied with the current power demand in the region. For Norway and Sweden the consumption in the power intensive industries is kept outside the calculations, since consumption in power intensive industries is assumed not to be impacted by changes in population. There was not available information about consumption in power intensive industries per region/county for Finland. Thus, the assumed increase in power consumption in Finland is the based on the total demand (including power intensive industries) multiplied with expected growth in population.

Table A3 2 to Table A3 5 shows an estimation of increase in consumption per county to 2050 for Denmark, Finland, Norway and Sweden. The estimations are based on an assumption that each inhabitant in each specific region/county will use the same volume of electricity as in 2010. Thus, the expected change in population in a region is multiplied with the current consumption per inhabitant in the same region.

Table A3 2 Increase in demand pr region in Denmark to 2050 due to population increase (consumption in 2012 from [statbank, 2012])

Region	Consumption 2012 [GWh/y]	% change in population 2012-2050	Consumption 2050, change based on population change [GWh/y]	Difference in consumption 2012-2050 [GWh/y]
Sjælland	13 800	12,7	15 550	1 750
Fyn	2 914	4,0	3 032	118
Jylland	17 387	9,3	19 007	1 620
Total	34 101		37 589	

Table A3 3 Increase in demand pr region in Finland to 2050 due to population increase (consumption in 2011 is from [energia.fi, 2012])

	Region	Consumption 2011 [GWh/y]	% change in population 2010-2050	Consumption 2050, based on % change in population [GWh/y]	Difference in consumption 2011-2050 [GWh/y]
Birkaland	Pirkanmaa	5 892	22,2	7 203	1311
Egentliga Finland	Varsinais-Suomi	4 836	11,5	5 393	557
Egentlige Tavastland	Kanta-Häme	2 092	20,0	2 510	418
Kajanaland	Kainuu	1 174	-6,7	1 095	-79
Kymmenedalen	Kymenlaakso	5 176	-4,9	4 922	-254
Lappland	Lappi	5 801	1,1	5 863	62
Mellersta Finland	Keski-Suomi	5 980	9,0	6 521	541
Mellersta Österbotten	Keski-Pohjanmaa	2 104	7,3	2 257	153
Norra Karelen	Pohjois-Karjala	2 472	-5,3	2 342	-130
Norra Savolax	Pohjois-Savo	3 162	-3,8	3 042	-120
Norra Österbotten	Pohjois-Pohjanmaa	6 024	15,2	6 939	915
Nyland	Uusimaa	15 962	25,5	20 027	4065
Päijänne-Tavastland	Päijät-Häme	2 155	11,9	2 412	257
Satakunta	Satakunta	6 043	-4,4	5 775	-268
Södra Karelen	Etelä-Karjala	5 647	-3,6	5 442	-205
Södra Savolax	Etelä-Savo	1 702	-9,9	1 533	-169
Södra Österbotten	Etelä-Pohjanmaa	2 016	4,5	2 107	91
Österbotten	Pohjanmaa	3 213	12,3	3 608	395
Åland	Ahvenanmaa	259	33,7	346	87
	Total	**81 711**		89 336	7625

Table A3 4 Increase in demand pr county in Norway to 2050 due to population increase (consumption in 2010 is from [NVE, 2011])

County	Consumption 2009, power intensive industries excluded [GWh/y]	% change in population 2012-2050	Consumption 2050, change based on % population change [GWh/y]	Difference in consumption 2009-2050 [GWh/y]
Østfold	3 863	35	5 225	1 362
Akershus	7 425	45	10 751	3 326
Oslo	9 120	43	13 054	3 934
Hedemark	3 082	22	3 768	686
Oppland	3 470	22	4 223	753
Buskerud	4 256	41	5 990	1 734
Vestfold	3 517	34	4 722	1 205
Telemark	2 657	19	3 175	518
Aust-Agder	1 527	44	2 195	668
Vest-Agder	2 466	42	3 501	1 035
Rogaland	6 929	44	10 006	3 077
Hordaland	8 855	39	12 307	3 452
Sogn og Fjorda	1 712	15	1 975	263
Møre og Roms	4 725	27	6 002	1 277
Sør-Trøndelag	4 129	33	5 489	1 360
Nord-Trøndela	2 003	22	2 437	434
Nordland	4 322	12	4 826	504
Troms	2 753	14	3 136	383
Finnmark	2 708	10	2 968	260
TOTAL	**79 519**		**105 749**	

According to Table A3 4 the consumption in Norway is increased with 26 TWh in 2050 compared to 2011. In [SSB, 2005] estimates are provided for the power development in Norway to 2030. In the analysis the Nordic power model Normod-T and the macro-economic model MSG-6 is used to study the future development of the Norwegian market. The other Nordic countries are also included in the analyses, but the main focus is the Norwegian market.

The power development is analysed in three scenarios with medium versus low and high price development. In the medium alternative the power prices are at the same level as today, in the high price alternative they are increasing with 20% and in the low price scenario they are decreasing with 30%. The different development of prices reflects different developments of primary costs for power producers like fuel costs and CO_2 prices. In the three scenarios the total power demand in Norway is increasing from the 2005 consumption of approximately 126 TWh to between 140 TWh to 159 TWh in 2030.

In the medium alternative the total power consumption is increased from 126 TWh in 2005 to 148 TWh in 2030. It is not assumed any electrification of the offshore oil and gas industry in any of the alternatives. The consumption in the power consuming industries is assumed to be at the same level as today. The consumption in general supply is increased from 80.4 TWh in 2005 to 108.5 TWh in 2030, which is an average increase of 1.1 TWh or 1.2 % per year.

Table A3 5 Increase in demand pr county in Sweden to 2050 due to population increase (consumption in 2010 is from [www.scb.se])

Region	Consumption 2010 [MWh/y]	% change of population from 2010-2050	Consumption 2050 based on % change in population [MWh/y]	Difference in consumption 2010-2050 [GWh/y]
01 Stockholms län	20 869 789	43,3	29 906 408	9 037
03 Uppsala län	3 003 710	43,2	4 301 313	1 298
04 Södermanlands län	3 568 638	14,4	4 082 522	514
05 Östergötlands län	6 631 028	8,6	7 201 296	570
06 Jönköpings län	4 526 620	2,9	4 657 892	131
07 Kronobergs län	2 074 233	7,8	2 236 023	162
08 Kalmar län	2 773 305	3,6	2 873 144	100
09 Gotlands län	882 223	0	882 223	0
10 Blekinge län	1 982 450	-2	1 942 801	-40
12 Skåne län	13 498 052	29,4	17 466 479	3 968
13 Hallands län	4 960 519	25,3	6 215 530	1 255
14 Västra Götalands län	19 426 673	14,3	22 204 687	2 778
17 Värmlands län	5 423 277	14,6	6 215 075	792
18 Örebro län	5 551 112	2,5	5 689 890	139
19 Västmanlands län	3 027 775	4,2	3 154 942	127
20 Dalarnas län	7 899 128	5	8 294 084	395
21 Gävleborgs län	4 523 327	3,1	4 663 550	140
22 Västernorrlands län	8 673 250	0	8 673 250	0
23 Jämtlands län	1 923 828	-2,41	1 877 464	-46
24 Västerbottens län	4 221 458	-2,2	4 128 586	-93
25 Norrbottens län	6 582 231	-4	6 318 942	-263
Total	132 022 626		152 986 101	20 963

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