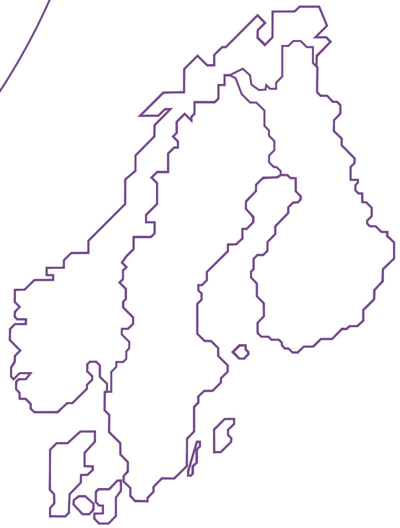
NORDIC GRID DEVELOPMENT PERSPECTIVE 2021



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EXECUTIVE SUMMARY

Development towards climate neutral Nordic society induces an unprecedented change in the energy sector. For example, consumption in the Nordic power system is growing due to electrification and new types of industry. On the other hand, the amount of renewables is growing at a rapid speed, and conventional generation is being phased out. The speed of the change is showing no signs of slowing, but instead, is continuously increasing. Consequently, the Nordic power system of 2030 and 2040 will be significantly different compared with the current system. A strong Nordic power grid is in the core of this system.

In this report Energinet, Fingrid, Statnett and Affärsverket svenska kraftnät (Svenska kraftnät) present a common perspective on the overall development of the Nordic power system. In addition, a more detailed outlook on certain selected focus areas is presented. The analyses are based on a common Nordic scenario, "Climate Neutral Nordics" for years 2030 and 2040, created by the Nordic TSOs. The key findings of the report are summarized below.

Climate neutral society needs more electricity - Significant investments to the grid and cross border connections are needed

Electricity consumption and production is expected to increase significantly in the future. Climate Neutral Nordics scenario assumes the annual Nordic electricity consumption to increase from the current approximately 400 TWh to 655 TWh by 2040. On the other hand, the scenario assumes the renewables generation capacity to more than double from 85 GW to 189 GW. The speed of the change in the energy system is faster than ever.

The Climate Neutral Nordics scenario also shows that the electricity transfer needs in the Nordic system are increasing. Furthermore, the existing flow patterns might change significantly in the future. As an example, the future dominant flow direction might be from bidding zone SE2 to SE1 instead of the opposite. The results of this report indicate that there is a need to reinforce the Nordic grid and large investments are needed to increase the grid capacities in several Nordic corridors. In many cases, building new lines or cables are needed. However, there exists also solutions to increase the capacities without traditional grid investments or solutions for more effective use of the existing transmission capacity, e.g. utilizing flexibility. The needs identified based on the Climate Neutral Nordics scenario are important input to more detailed planning processes.

Photo: Henrik Glette /Statnett

Fact Box 1:

Climate Neutral Nordics scenario assumes:

- Nordic yearly electricity consumption to grow from current 400 TWh to 530 TWh (33%) by 2030 and 655 TWh (65%) by 2040.
- Nordic renewable energy sources capacity to increase from current 85 GW to 145 GW (70%) by 2030 and 189 GW (122%) by 2040.

The Nordics are an excellent place for future investments

The Nordic electricity system is already a strong system with good possibilities to connect generation and consumption. In addition, the Nordic TSOs are making significant investments to the power grid to be able to connect the electricity production and consumption required in the climate neutral society of the future.

This means that there will be a lot of competitively priced and green electricity available in the Nordics in the future. The Climate Neutral Nordics scenario indicates an electricity surplus in the Nordics in the future, with average power prices lower than the prices in continental Europe. This combined with a strong power grid, makes the Nordics a great place for power intensive investments.

Future system is more volatile - flexibility is needed and will become increasingly profitable

The analyses shows that the volatility in the future system is increasing. This applies to all aspects of the power system - flows, balances, prices, adequacy questions, etc. As volatility increases, so does the need for flexibility throughout the whole power system. Furthermore, the energy transition and electrification increase the need for flexibility.

Available flexibility helps in optimal development and operation of the future system. Flexibility resources, such as demand-side response (DSR), power-to-X (P2X), storage, and electric vehicles will become increasingly important to even out the variations in the system and are needed to reduce the volatility. Due to higher variation in the power prices, it is expected that there are profitable ways to operate these resources in the future system. However, conventional generation and especially reservoir hydropower will remain to be important resources in the future system.

Future system is more complex and has new characteristics - new solutions and collaboration throughout the whole energy system are needed

The future system is becoming more complex and different sectors are becoming more interlinked. Furthermore, the future system is expected to contain large amounts of new resources and technologies such as offshore wind and P2X. The entire energy system should operate together seamlessly with the new resources, and this increases the need for collaboration between different actors. The grid, consumption, production, flexibility, and other resources should be developed together.

In addition, the characteristics of the future system will differ significantly from the current system. The future system has high amounts of converters, lower inertia, and high and volatile transfer needs. New solutions are needed to tackle these challenges in an optimal way. These challenges and solutions are discussed more thoroughly in the Nordic Solutions[1] report that will be published in 2022.

[1]Previous Solutions report can be found here: https://www.fingrid.fi/globalassets/dokumentit/fi/tiedotteet/sahkomarkkinat/2020/solutions-report-2020-3-april-2020-updated-figure.pdf

Regional grid plans and studies will be updated and developed

The Nordic Grid Development Perspective (NGDP) will be updated every second year and constitutes only one of many different regional grid development initiatives. The next NGDP report is planned to be published in 2023. The Nordic TSOs are also preparing a common Nordic strategy which will be published in the Solutions report of 2022. In addition to system planning aspects, the strategy will provide a broader view including markets and system operation. Moreover, the Nordic TSOs have identified the need of developing mid-term collaboration both in operational and planning aspects to complement the long-term collaboration.

In the European context, ENTSO-E is publishing the European Ten-Year Network Development Plan (TYNDP) every second year. A regional Baltic Sea investment plan is published as a part of the TYNDP.

Furthermore, each TSO is continuously updating their national grid development plans and publishing long term market and grid analyses. These reports focus more closely on the national aspects.

It is also important that the Nordic planning and collaboration processes are transparent and that stakeholders are involved at an early stage. Thus, involvement of stakeholders through workshops and consultations will continue to be an important part of the Nordic grid planning and other forms of collaboration.

Fact Box 2:

The Nordic TSOs are making significant investments to increase the future grid capacities during the ten-year period:

1. Energinet is building approximately 3,000 km of cables/lines, 8 new substations and making total investments worth approximately 7.8 billion euros (2021 value, values are not including Energy Islands).

2. Fingrid is building 3,700 km of lines, 41 new substations and making total investments worth approximately 2.1 billion euros (2021 value).

3. Statnett is building 2,500–4,000 km of lines, 30–35 new substations and making total investments worth approximately 6–10 billion euros (2021 value).

4. Svenska kraftnät is building 800 km of lines, 20–30 new substations and making total investments worth approximately 8.1 billion euros (2021 value).

5. In total, the Nordic TSOs are building over 10,000 km of lines, over 100 new substations and making total investments worth around 25 billion euros (2021 value).

All TSOs are also planning to reinvest in several substations and lines, make equipment upgrades, etc. These costs are also included in the total investment costs.

1 INTRODUCTION

The Nordic countries have a long-term history of cooperation in energy matters. The Nordic electricity system is highly interconnected, and the countries are frontrunners for example in renewables and sector-coupling. This creates an excellent platform to address the new challenges together – for example in the form of the NGDP2021 report.

The NGDP2021[2] is intended to function as a complementary bridge between the national planning processes and the ENTSO-E Ten Year Network Development Plan (TYNDP). Where TYNDP presents a high-level plan for the entire European grid and national plans focus more on local aspects in grid development, NGDP2021 presents a perspective for the Nordic energy system and highlights key focus areas that are relevant especially for the Nordic region. It is important to recognize that NGDP2021 presents an early-stage vision, and more detailed national or joint Nordic analyses are required before actual investment decisions are made. Thus, NGDP2021 is from this year called a perspective rather than a plan to underline that this report is more exploring the future rather than presenting a firm traditional investment plan.

The NGDP2021 report communicates a common Nordic view on the development of the future power system in the climate neutral Nordic society and investigates the future system needs. Furthermore, the report presents a Nordic view on selected focus areas: offshore wind, north-south power transfer and resource adequacy in the future system. In addition, the report updates the status of the five Nordic corridors of interest from the bilateral analyses from NGDP2019[3] (FI-NO, FI-SE, NO-SE, DK-SE, DK-NO).

An important part of the NGDP2021 work has been to prepare a common Nordic scenario for the years 2030 and 2040. The scenario Climate Neutral Nordics presents a path towards decarbonization of the Nordic society, and it is based on national scenarios and ENTSO-E's TYNDP2020 scenario Distributed Energy. The Climate Neutral Nordics scenario was also consulted with stakeholders[4] and updated based on the received feedback. The created scenario is not identical to all national TSO scenarios used for grid planning but will function as an important input to national planning processes. Most of the analyses of the NGDP report are based on the Climate Neutral Nordics scenario.

The Nordic TSOs are constantly collaborating to enable the clean energy system of the future and solve related challenges. There are also various other future challenges, which the NGDP2021 report is not aiming to analyse (i.e. reduced inertia, increasing dominance of converter connected generation, etc). These aspects have been recognized by the Nordic TSOs, but they are not the main focus of this report. There are several other Nordic reports available where different topics are considered, such as: Nordic Solutions Reports[5], Challenges and Opportunities for the Nordic Power System Reports[6], etc. Furthermore, the Nordic TSOs are currently preparing a common Nordic strategy on sector integration and wind power development which will be published in the Solutions report of 2022. Where the NGDP is focused on system planning related aspects, the strategy will provide a broader view including also markets and system operation.

[2] The Nordic electricity Transmission System Operators (TSO), Energinet, Fingrid, Statnett and Svenska kraftnät publish a common grid development report (NGDP) every second year, on request by the Nordic Council of Ministers. The aim of the NGDP2021 is to present a common Nordic view on selected key topics rather than presenting a technical grid development plan in purely traditional sense. Thus, NGDP2021 is named Nordic Grid Development Perspective (previously Plan).

[3] The previous NGDP can be found here: https://www.fingrid.fi/globalassets/dokumentit/fi/tiedotteet/lehdistotiedotteet/stet0126_nordic_grid_dp_2019.pdf

[4] https://www.fingrid.fi/en/pages/news/news/2021/feedback-on-the-climate-neutral-nordics-scenario/

[5] Latest Solutions report: https://www.fingrid.fi/globalassets/dokumentit/fi/tiedotteet/sahkomarkkinat/2020/solutions-report-2020-3-april-2020-updated-figure.pdf

[6] Latest Challenges and Opportunities for the Nordic Power System report: https://www.fingrid.fi/globalassets/dokumentit/fi/yhtio/tki-toiminta/report-challenges-and-opportunities-for-the-nordic-power-system.pdf

2 CLIMATE NEUTRAL NORDICS SCENARIO

All Nordic countries have ambitious climate targets. Electrification of different sectors, such as industry, transportation and heating, is seen as the main tool to reduce emissions and achieve climate targets. This extensive electrification calls also for new clean electricity generation.

By design, the scenario is ambitious with high electrification rates and thus rather high electricity demand in 2040. At the same time the grid is represented by the current national ten-year grid plans and has not been expanded further even if the scenario might indicate that to be beneficial. The purpose of this is that the scenario shall highlight potential system needs in a future power system with high electrification and demand and large volumes of renewable generation. Investigation of system needs is further discussed in Chapter 3.

The common Nordic scenario is not a forecast, nor a prediction of the future. As a scenario it presents one potential development path of many, for the Nordic power system.

2.1 Scenario building

This scenario has been developed in the collaboration with all the Nordic TSOs. For the scenario, the four Nordic TSOs have agreed on generation capacities and annual demand. The analyses have then been run in each TSOs own market simulation tool. This means not only that different software and modelling setup has been used, but also that each TSO has been using its own set of detailed data such as seasonal profiles, assumed availabilities, etc.

Despite these differences, the results are rather well aligned, which indicates a robustness of the modelling. Furthermore, given the large uncertainties in a scenario looking 20 years into the future, it will not add much certainty to the final result to harmonize every single bit of data in the models and tools.

The Nordic scenario was presented in a stakeholder webinar and a public consultation period was also included in the scenario building process. Certain changes were made based on the received stakeholder feedback[7].

2.2 Storyline of Climate Neutral Nordics

The scenario Climate Neutral Nordics delivers on the ambition of decarbonisation of the Nordic region. The scenario is based on national scenarios from the Nordic TSOs fulfilling the goal for decarbonisation in 2030–2050 and opens up a role for the Nordics of being a net exporter of green products such as electricity, steel, and to some extent hydrogen.

The Climate Neutral Nordics focuses on high direct and indirect electrification throughout the energy systems. With the increased electrification a large increase in electricity consumption is assumed, mainly from new consumption like electric vehicles (EVs), industry, heat pumps and P2X. In order to facilitate this electrification of the Nordic region, large amounts of renewable power production need to be built throughout the region, primarily wind, onshore and offshore and to a smaller extent photovoltaic (PV).

[7] https://www.fingrid.fi/en/pages/news/news/2021/feedback-on-the-climate-neutral-nordics-scenario/

The Climate Neutral Nordics will seek to benefit from the large onshore wind resources available in the northern regions as well as offshore potentials in the North Sea and Baltic Sea. The flexibility from hydro reservoirs in the Nordics and new types of demand-side response like P2X and batteries from EVs will benefit the electricity system and help balance production and demand when generation from renewable energy sources (RES) are extraordinarily high or low.

2.3 Key drivers

The key drivers for the scenario are to a large extent the same as in the previous version of the NGDP, but with a few clear changes. First, projections for future demand are showing higher and higher numbers, partly driven by electrolysers for production of green hydrogen. Second, the levelized cost of electricity (LCOE) of RES continue to fall thus enabling an increasing amount of installed capacity that can meet the increasing demand. Finally, the Swedish nuclear reactors are not assumed to all be decommissioned before 2040. The key drivers, and the assumed rate of change over time, are presented beneath and are summarized in Table 1.

Table 1 – Drivers of the Climate Neutral Nordics scenario

	Finland	Sweden	Denmark	Norway
Decarbonisation year (power sector/society)	2035/2035	2040/2045	2030/2050	2040/2050
Hydroelectric power	≈	≈	≈	+
Onshore wind power	+++	+++	+	+
Offshore wind power	+(+)	++	+++	++
Photovoltaics and energy storage	+	++	++	+
Nuclear power	≈	≈ (-)	n/a	n/a
Other thermal power	-	-	-	-
Electricity consumption	+++	+++	+++	+++
P2X	+++	+++	+++	+
Demand-side response (excluding P2X)	+	+	+	+
Electricity balance	2020: Import 2040: Balanced	2020: High export 2040: Low export	2020: Balanced 2040: Export	2020: Moderate export 2040: Moderate export

+ increase, - decrease, ≈ remain at similar level. The drivers show the development compared to today and are not directly comparable between countries.

Decarbonisation year of the society

All the Nordic countries are aiming to reach climate neutrality of the society in the coming decades. However, the decarbonisation year can vary between sector and society as a whole. In addition, EU is expected to become climate neutral by 2050.

Hydroelectric power

Norwegian annual hydropower generation is expected to grow somewhat during the next two decades, primarily in the form of additional small hydro plants and to some extent because of increased inflow due to climate change. In Finland and Sweden, however, it is assumed that no more large-scale hydro can be developed, and generation capacity is thus flat over the scenario period.

The hydropower is the main provider of flexibility in the power system of today, and its importance will be even greater in a future system with much larger volumes of intermittent generation.

Onshore wind power

Onshore wind continues to expand in Finland and Sweden, although for Sweden the growth rate might be declining. Onshore wind is the cheapest source of new green capacity in the Nordics, and is already competitive without subsidies. In Denmark and Norway, the growth of onshore wind is assumed to be very low, due to a rather strong public resistance towards onshore wind.

Offshore wind power

The LCOE of bottom-fixed offshore wind power is continuously decreasing and offshore wind is becoming commercially competitive. The Nordic countries have all somewhat different approaches to this, for instance regarding grid connection costs, but they all see a potential for a high growth of offshore wind. The status of offshore wind in the different countries is described in Chapter 4.3.

Photovoltaic

Photovoltaics is expected to grow in all Nordic countries, but with a slower rate compared to wind farms. The future capacity is assumed to be both roof top installations and commercial sites.

Nuclear power

Nuclear power is assumed to remain fairly stable during the scenario. Finland sees the commissioning of Olkiluoto 3 and Hanhikivi powerplants, while Loviisa plants are assumed to be decommissioned. In Sweden, Forsmark 1, the oldest of the six reactors is assumed to be decommissioned and there are currently no plans for new reactors, although there are discussions about potential lifetime extension of the reactors currently in operation.

Other thermal power

Thermal power, other than nuclear, is assumed to be reduced as wind and solar power grows. The increasing prices of emission rights and CO_2 are also contributing to the decommissioning of fossil-fuelled plants. The remaining plants will run on biofuel or waste. Some of the Combined Heat and Power (CHP) plants providing district heating may also change to heat only.

Electricity consumption

The EV share of new cars is continuously increasing as a result of development in several areas; cheaper and better batteries enable longer range, the infrastructure of charging points is improving, and there are political ambitions to phase out fossil fuels. Alternatively heavy transports can also be fuelled by green gas (methane or hydrogen) which would then require even larger volumes of electric energy.

The Nordic region continues to be an attractive area for location of data centres, due to good infrastructure and cheap, clean and reliable electricity supply. The demand for new data centres is driven by the increasing digitalization, e.g. cloud services, Internet of Things (IoT), 5G telecom, etc.

Both direct and indirect electrification of existing industry processes is also expected to take place in the future. This will have a significant effect on the electricity consumption.

P2X

Electricity consumption is also assumed to increase due to production of hydrogen. Hydrogen has during the few last years become a potential key element in the transition towards a climate neutral society. The increased use of green hydrogen is assumed in heavy transport, including air traffic, in replacing natural gas in existing gas grids, and as a result of electrification of industrial processes.

Demand-side response (excluding P2X)

Following the growing volumes of intermittent generation, it is assumed that the increasing price volatility will make DSR services more profitable. These resources are mainly expected from EVs and industry and they are expected to be important resources in the future system.

2.4 Scenario assumptions

The development towards a decarbonized Nordic region involves large changes in the Nordic power system, related to how electricity is produced, distributed and consumed. The scenario assumptions are presented below.

2.4.1 Electricity consumption

Electricity consumption is assumed to increase from around 400 in 2020 to around 655 TWh in 2040, i.e. by approximately 65 per cent. This development is illustrated in Figure 1.

The development of the general consumption, which consists of residential and service sector consumption, is slightly decreasing towards 2040 by 8 TWh.

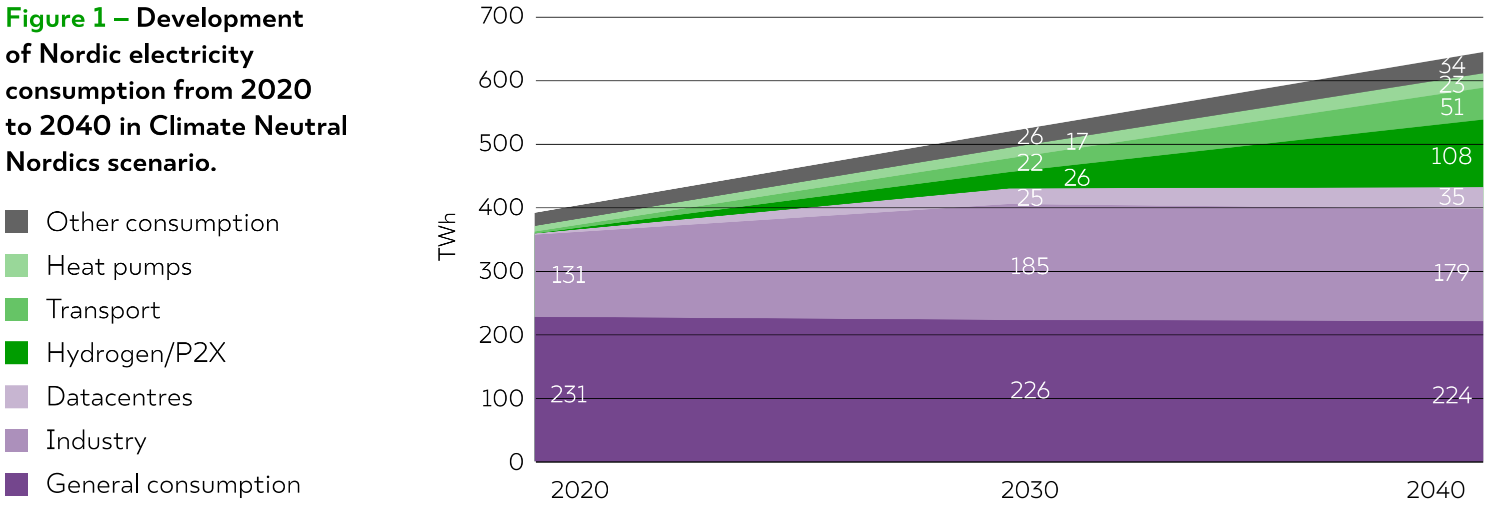
Hydrogen production/P2X accounts for the largest part of the development as it increases from 0 in 2020 to 108 TWh in 2040. Thereafter, electrification of existing and new industry, and direct electrification of transport have the largest impact respectively increasing by 49 and 48 TWh[8].

Data centres' consumption increases significantly by 33 TWh. Heat pump consumption is increasing by 14 TWh and other consumption increases from 21 to 34 TWh, which is mainly due to an increase in grid losses, which is included in the category (grid losses might be lower that this after investment to new capacity).

Development of consumption in each country is presented in the Appendix 7.1.

[8] There is no hydrogen production included in the industry category. It is all included in the hydrogen production/P2X category.

Figure 1 – Development of Nordic electricity consumption from 2020 to 2040 in Climate Neutral Nordics scenario.



2.4.2 Electricity generation capacity

Renewable electricity capacity

The total capacity of renewable generation is increasing from around 85 GW in 2020 to around 190 GW in 2040, i.e. by approximately 122 per cent. The increase in renewable generation is primarily due to changes in wind and PV. The development is illustrated in Figure 2.

Thermal capacity

The total capacity of thermal is assumed to decrease from 17 GW in 2020 to 14 GW in 2040, i.e. by approximately 22 per cent. The development is illustrated in Figure 3.

The decrease is mainly due to fossil fuels being phased out, but there is also a small decrease in the capacity of nuclear in the long run, which is decreasing by 1 GW.

Development of generation capacity in each country is presented in the Appendix 7.1.

2.4.3 Flexibility

High growth in consumption as well as a higher share of intermittent production increases the need for flexibility. Reservoir hydropower is an important source of flexibility in the Nordics today and will play an increasing important role in the future. Hydrogen is expected to emerge as a central, new source of flexibility, as well as a higher degree of consumption flexibility both in existing and new consumption. In addition, the power transmission grid will continue to be an important enabler for the exchange of sources of flexibility between regions.

Figure 2 – Development of Nordic renewable electricity capacity from 2020 to 2040 in Climate Neutral Nordics scenario.

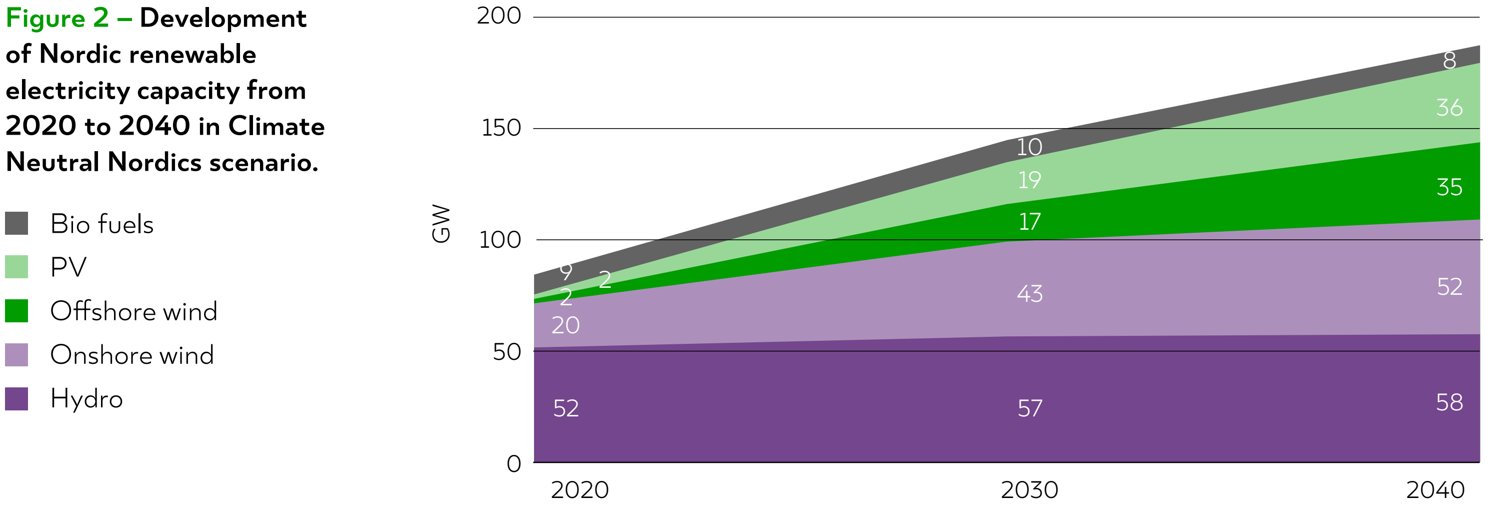
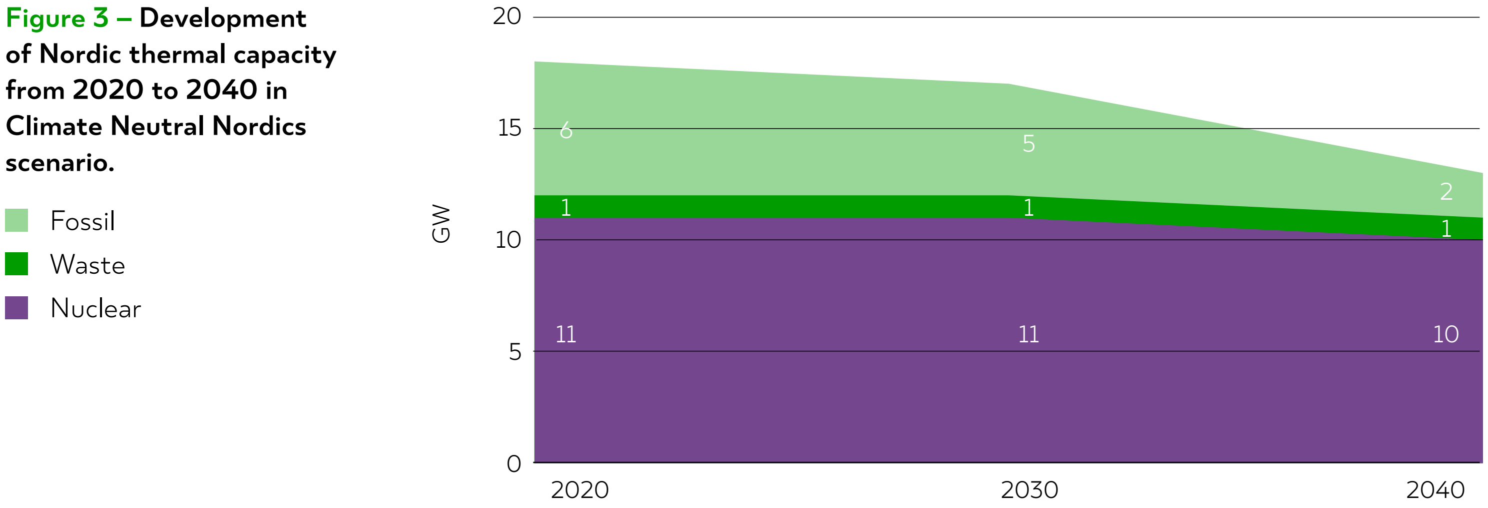


Figure 3 – Development of Nordic thermal capacity from 2020 to 2040 in Climate Neutral Nordics scenario.



Reservoir hydropower

Reservoir hydropower constitutes a high share of the Nordic power generation mix. As the share of intermittent power generation increases, and before other sources of flexibility have fully developed, reservoir hydropower will be the central source of flexibility. Reservoir hydropower has an advantage in being able to rapidly adjust the production at low cost, as well as being a seasonal storage. However, the existing reservoir hydropower system is not an abundant source of flexibility due to restrictions in storage capacity, installed capacity, as well as operational restrictions.

The generation capacity is expected to increase, in particular through reinvestments in existing hydropower plant, but also through some new investments. Pumped hydropower might become profitable as well, with increased price volatility in the future, however large-scale pumped hydropower is not considered in this scenario. In the long-term other sources of storage like hydrogen and batteries in EVs could compete with the storage in hydropower.

Demand flexibility

The potential for consumption flexibility in the Nordics is high, but the volume is uncertain, as there are no extensive historical data or standardized models available. However, as the price variation increases towards 2030 and onwards, the profitability in and incentives for avoiding high power prices is expected to increase, compared with today. Thus, the scenario assumes an increase in relatively cheap demand flexibility from EVs, as smart charging features will enable adjustments according to the power price. Also, new consumption from industry is assumed to be increasingly flexible. These industries include for instance P2X, as well as other industries such as data centres, etc.

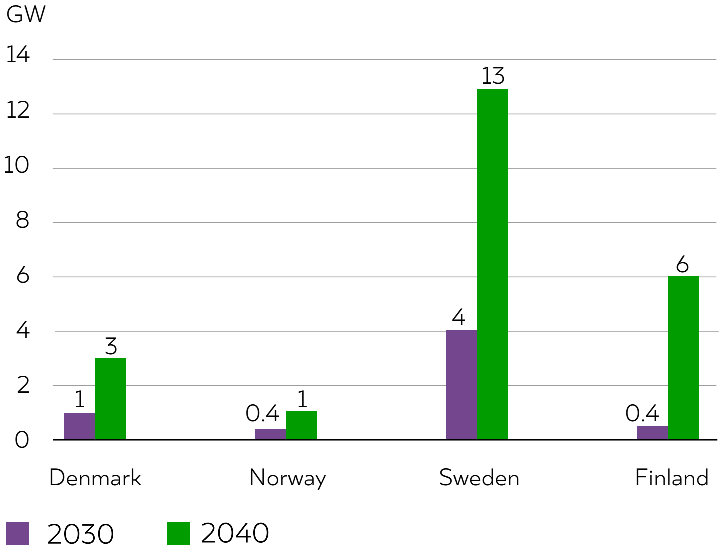
Hydrogen

Hydrogen is an enabler for the green transition in many sectors, and in the power system it provides flexibility in multiple ways. The production of hydrogen from electricity is a source of low-price flexibility, while hydrogen as a fuel, can be viewed as a source of high-price flexibility when used in power plants[9]. Hydrogen also serves as an energy storage, either stored directly as hydrogen, in the form of ammonia or as carbon-based synthetic fuels.

Provided that affordable hydrogen storage or transmission infrastructure is available, the production of hydrogen is relatively flexible and may be focused in the hours of large production from solar and wind, avoiding hours with high electricity prices. In the coming years hydrogen is assumed to be most relevant as a source of low-price flexibility in the Nordics, as there will be increasing need to produce hydrogen to decarbonize the industry and other hard-to-abate sectors. However, this requires that the production costs of green hydrogen become competitive with blue and grey hydrogen[10]. The potential for hydrogen as a source of high-price flexibility is assumed to be more limited due to the high share of reservoir hydropower in the Nordics.

To what extent the production of hydrogen in the power system will be flexible, depends on the access to infrastructure for transport, the storage options and the end-use of hydrogen. Production of hydrogen for direct use on-site

Figure 4 – Electrolyser capacity in the Climate Neutral Nordics scenario.



in an industry will, to a lesser extent be price flexible, than production of hydrogen for a hydrogen market. That is because an interconnected market will likely facilitate other, more competitive options for e.g. hydrogen storage and trade than relying only on local storage at an industrial site.

The two types of hydrogen production are modelled separately. Production of hydrogen to a hydrogen market is modelled as price flexible consumption, with cut-out prices for production at 40–60 €/MWh in 2030 and 30–45 €/MWh in 2040, resulting in a hydrogen price of approximately 2–3 €/kg in 2030 and 1.5–2.5 €/kg in 2040. This because the production will be most competitive when focused on the periods where power prices are low due to excess renewable power production.

Production of hydrogen for the industry is also assumed to be flexible to some extent, but less so than hydrogen production for a hydrogen market. These units are modelled with a storage of 2–3 days of supply, which enables that production of hydrogen is optimized dependent on the electricity prices and storage level.

There is high uncertainty related to how the hydrogen market will develop in general and in the Nordics. The cost of electrolyses and storage, as well as the development of renewables and infrastructure for hydrogen are key uncertainties. The demand for hydrogen from the Nordic industry is assumed to be met by hydrogen production units in the Nordic region, in the Climate Neutral Nordics scenario. Large-scale hydrogen production to a hydrogen market that is interconnected by hydrogen pipelines is not modelled explicitly in the scenario. However, if the future shows availability of a hydrogen export grid, the location of such grid-connected units would be dependent both on market dynamics in the new hydrogen market and the access to infrastructure.

[9] Low-price flexibility has low costs related to adjusting and is active on low power prices. High-price flexibility has higher costs and is active on higher power prices.
[10] Green hydrogen is produced by using zero-carbon electricity – such as that generated by wind turbines or solar panels – to split water into hydrogen and oxygen. The process is carbon-neutral. Blue hydrogen is produced from natural gas through steam methane reforming with carbon capture and storage (CCS). Grey hydrogen is produced from natural gas through steam methane reforming without CCS.

Power transmission grid

The extensive transmission grid within the Nordics and to the continental Europe has an important role in evening out variation between regions, through the exchange of production resources and other sources of flexibility. The transmission grid and trade are important to tackle local, short-term variation as well as seasonal variations. The transmission grid in the scenario is represented by the current national ten-year grid plans and has not been expanded further. This due to the purpose of the scenario; to highlight the potential system needs in a future power system.

2.5 Overview of electricity balance and power prices

The Nordics will have a positive electricity balance in all analysed years i.e. annual total consumption is less than the annual total generation of electricity. Thus, the Nordics will remain a net exporter of electricity.

The power surplus is increasing through 2030 and towards 2040, as the production in the region increases at a somewhat higher pace than the consumption. The rather large power surplus in 2040 of about 50 TWh in the Nordics, will likely serve to attract more consumption. This, as it is expected that the market development is balanced in the long run, as a power surplus attracts more consumption, and a power deficit attracts more production.

As the generation becomes more variable and weather dependent, the challenges of maintaining the instantaneous power margin will increase. More detailed analysis on resource adequacy is presented in Chapter 4.2

Figure 5 – Nordic electricity balance in the Climate Neutral Nordics scenario.

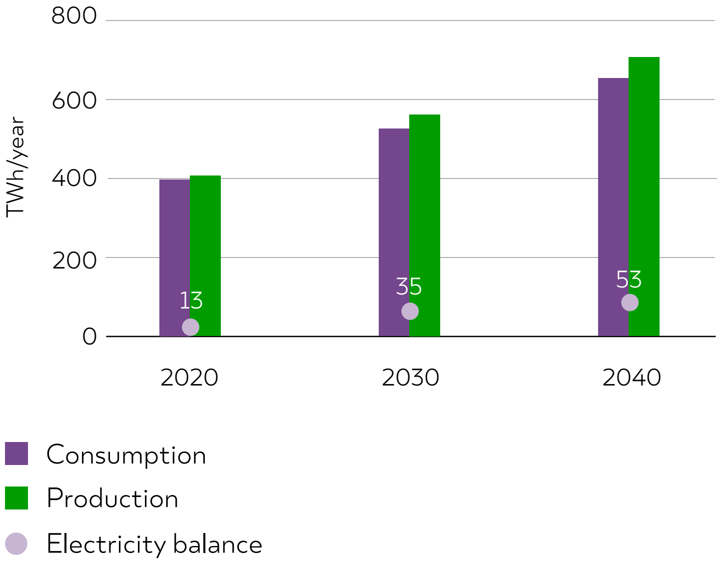
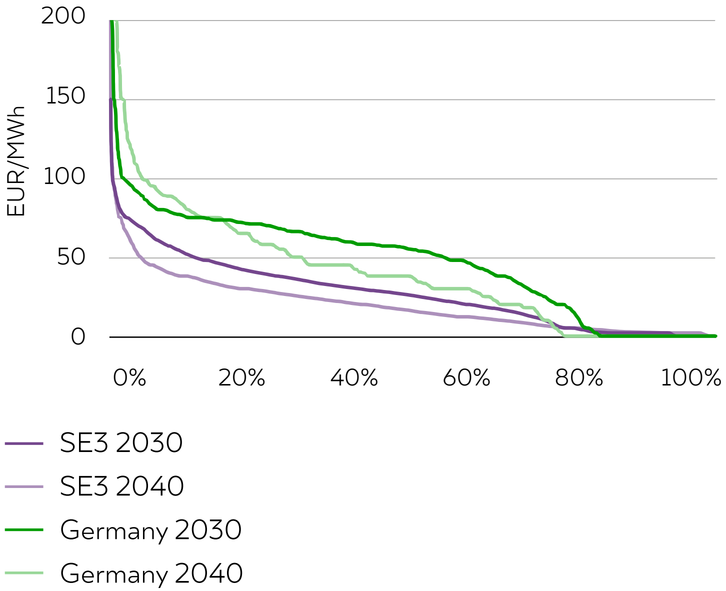


Figure 6 – Price duration curves in the Climate Neutral Nordics scenario in SE3 and Germany. (The y-axis has been cut off at 200 EUR/MWh)



2.5.1 Price levels

Figure 6 presents the simulated price duration curves for electricity from the Climate Neutral Nordics scenario in the Nordic SE3 bidding zone as well as the German price duration curves. The SE3 price can be considered generally as a proxy for the Nordic price levels. However, it should be noted that price differences and significant volatility are expected between the different Nordic bidding zones in the future.

The simulated German power prices are based on the ENTSO-E Distributed Energy Scenario, with an annual average power price between 40 and 50 EUR/MWh in 2030 and 2040. Also, the price duration curve indicates a substantial amount of power prices at 0 €/MWh. In a dynamic setting this would lead to increased consumption from flexible demand that can focus their demand on low price hours, such as P2X. This will in turn increase the prices in these hours.

In the Nordics, the annual average power prices are ranged between 20 and 30 EUR/MWh in 2030 and 2040, in the Climate Neutral Nordics scenario. However, the prices vary over a much larger range as the price volatility increases due to higher share of renewables combined with lower thermal and nuclear capacities. This gives a substantial amount of close-to-zero prices both in 2030 and 2040, and a number of hours with extremely high prices, especially in 2040. The Nordic average price levels decrease towards 2040 compared with 2030, due to the more integration of wind and photovoltaics.

Compared to the German price level, the Nordic average price level is expected to be somewhat lower (roughly half), due to an expected power electricity surplus in the Nordic region. This makes the Nordic countries a competitive option for power intensive industrial and P2X investments in the future. In turn, this might lead to even higher consumption than assumed in the Climate Neutral Nordics scenario, and hence, reduce the price differences between the Nordic region and the continent.

It should be noted that there are various uncertainties related to the assumptions, and thus, the simulated price levels of the Climate Neutral Nordics scenario. The next chapter presents the uncertainties more in detail.

2.6 Uncertainties

There are various uncertainties related to the assumptions of the Climate Neutral Nordics scenario. The uncertainties may, in certain cases, have a significant effect on the simulation and analysis results. For example, the following uncertainties should be considered when interpreting the results of the scenario work:

- Fuel and CO_2 prices
- Development of P2X, both capacities and how they are operated
- Development of electricity consumption
- Availability of flexible consumption and generation
- Role of batteries and other types of storage in the Nordics (EVs, large-scale storage, etc.)
- Development of wind power capacity, especially offshore wind, and offshore grids, and new connection types such as energy islands
- Phase-out of nuclear production
- Uncertainties related to building the necessary infrastructure: overhead lines, HVDC connections, etc.

In addition to these aspects, various other factors may increase the uncertainty related to scenario modelling and analysis results. The Climate Neutral Nordics scenario is showing one way of how the future Nordic energy system might develop. Given the ambitious targets for decarbonisation in the Nordics, the Climate Neutral Nordic scenario is the common “best guess” for a very ambitious decarbonisation scenario to illustrate the future challenges and possibilities for the Nordic system.

3 IDENTIFICATION OF SYSTEM NEEDS

This chapter presents an analysis which seeks to identify the need for increased grid capacity between the existing bidding zones in the Nordic region, by using a simple metric. The analysis was carried out using the Climate Neutral Nordics scenario, for the years 2030 and 2040. More detailed analysis on selected transmission corridors is presented in Chapter 5.

As this report is a perspective rather than an investment plan, the results shown in this chapter should be considered as preliminary starting points for future studies for grid investments. Before actual investment decisions can be made, more detailed studies must be carried out.

3.1 Methods

The analysis has used the absolute hour-by-hour price difference as a metric for the economic benefit of increased grid capacity between the existing bidding zones in the Nordic region. This metric is used as it reflects the marginal benefit of increased grid capacity between two bidding zones, that is, the benefit of increasing the grid capacity by 1 MW.

This study does not consider what an optimal capacity between bidding zones would be in the NGDP scenario, but rather whether there exists a marginal benefit for increasing the grid capacity on each of the bidding zone borders independently. Further, the analysis does not consider the costs of increased grid capacity, hence no cost-benefit analyses (CBAs) has been performed. The analysis also excludes other benefits of increased grid capacity, for instance related to renewables integration, security of supply, or improved functioning of reserve markets.

The modelled grid in the scenario consists of the current grid and each TSOs national ten-year development plans[11] including expected decommissions of interconnectors reaching their end of life. No additional lines or interconnectors have been added in the scenario-building process.

Furthermore, it is important to note that the direction of the price difference may vary from hour to hour, and calculation of absolute hour-by-hour price difference disregards the direction. Benefit for the interconnector exists regardless of which zone has the lower price, making absolute price difference a good metric for the benefits.

[11] Statnett's Grid Development Plan from 2019 was included in the reference grid in this analysis. The planned investments in the Grid Development Plan of 2021 will serve to further increase the north-south capacity. See also the appendix for the planned investments of Nordic interest and Statnett's Grid Development Plan for 2021: https://www.statnett.no/en/about-statnett/news-and-press-releases/news-archive-2021/grid-development-plan-for-the-green-change-of-pace/

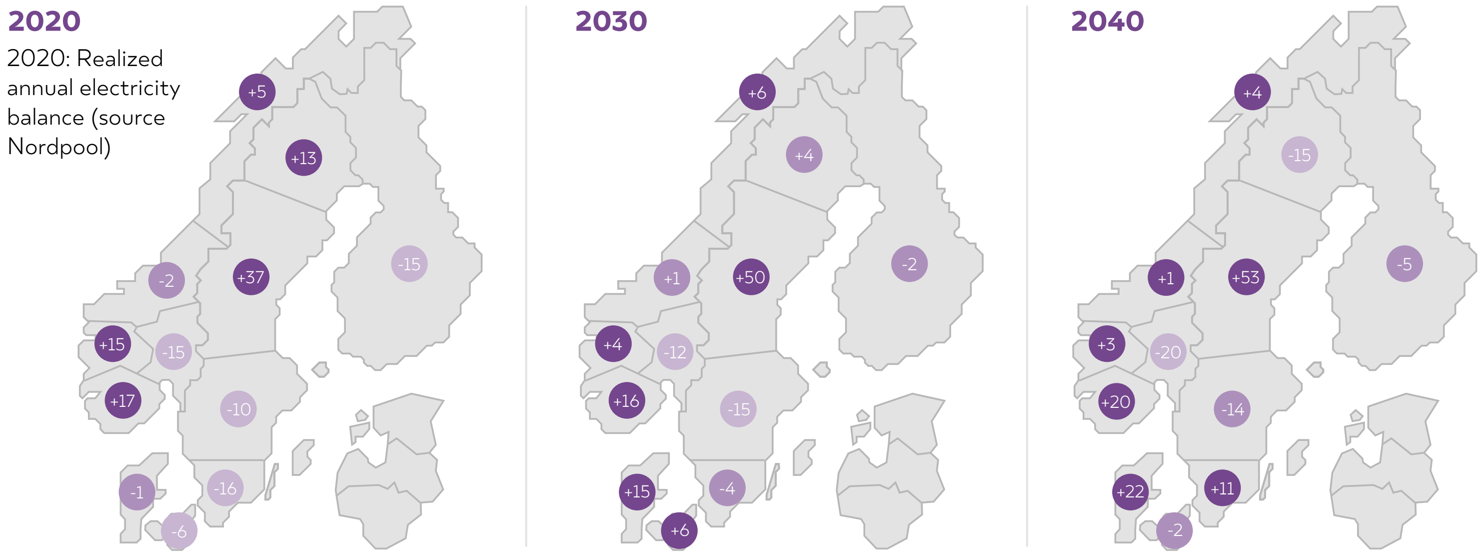
3.2 Results

3.2.1 Flows

In general, the power will flow from areas of electricity surplus to areas of electricity deficit. Figure 7 shows the electricity balance in the Nordic bidding zones. The northern part[12] of the Nordics is a large surplus area as it stands for about 30 per cent of the annual Nordic power production today and only 15 per cent of the annual consumption. The western part of Norway also has a considerable power surplus. Most of the consumption is in the southern part of the Nordics[13].

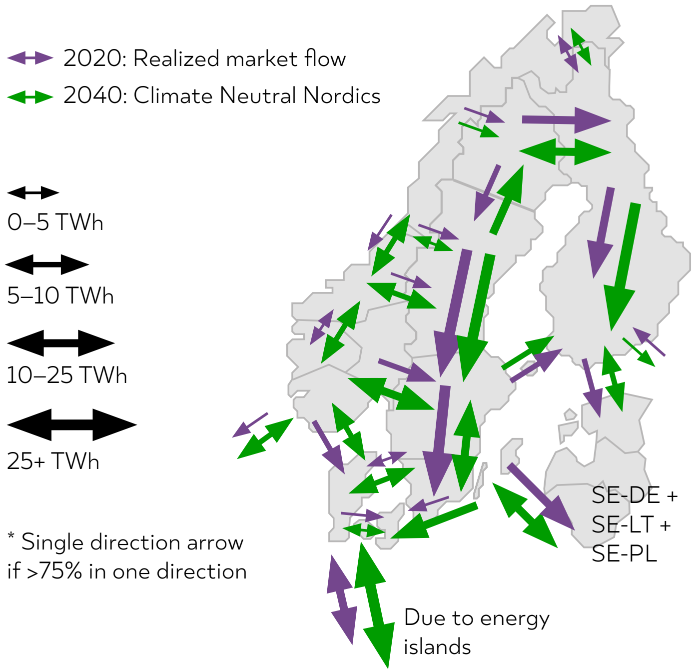
Hence, the main flow direction in the Nordic power system today is from the electricity surplus areas in the north, to the electricity deficit areas in the south, and further on towards the continent. To a smaller extent, the power also flows in the west-east direction in the Nordics. The power flows today and in 2040 in the Climate Neutral Nordics scenario are illustrated in Figure 8. The arrows indicate the net flow direction, and the size of the arrows also indicates the size of the power flows. Single direction of the arrows indicates that >75% of the electricity goes in one direction.

Figure 7 – Electricity Balance (TWh) in the Nordic bidding zones in 2030 and 2040 from the Climate Neutral Nordics scenario. The values for 2020 are historical values.



[12] Northern part refers to bidding zones NO4 (partly), SE1, SE2, northern part of bidding zone Finland.
[13] Southern part refers to SE3, SE4, Southern part of Finland and Denmark.

Figure 8 – Power flows (TWh) in 2020 and in the Climate Neutral Nordics 2040 scenario.



Towards 2040, a high consumption growth as well as a high share of intermittent production will affect the flow pattern, and the price differences between bidding zones. More consumption is expected to be situated in the northern parts of the Nordics, especially in the north of Sweden and in Norway. In the Climate Neutral Nordics scenario, the consumption in the northern part of the Nordics will increase to almost 25 per cent, up from 15 per cent today, and the production in the northern area will not be able to supply all of this. Hence, the surplus in the north decreases and the annual north-south flow is reduced compared with today. In Finland and Denmark, the annual flows from north to south will increase substantially towards 2040. Increased flow between Denmark and the continent is mainly due to energy islands.

The flows will also be increasingly dependent on the production from intermittent production. That is, the flow pattern may more often be in the opposite direction, depending on the wind power production. For instance, the new electricity consumption in the north will also lead to the flow going northwards, for instance between SE1 and SE2 and NO3 and NO4, especially in periods with high wind power production further south in Norway and Sweden.

The Nordic region is also expected to have increased export and import towards 2030 and 2040, as the interconnector capacity towards the continent and the UK increase, as well as the share of intermittent power production. Increased import and export will in general increase the bottlenecks and thus the hour-by-hour price differences in the Nordic system, if no investments to grid capacity are made.

More details on the flows in the Nordic system in Chapter 4.1.

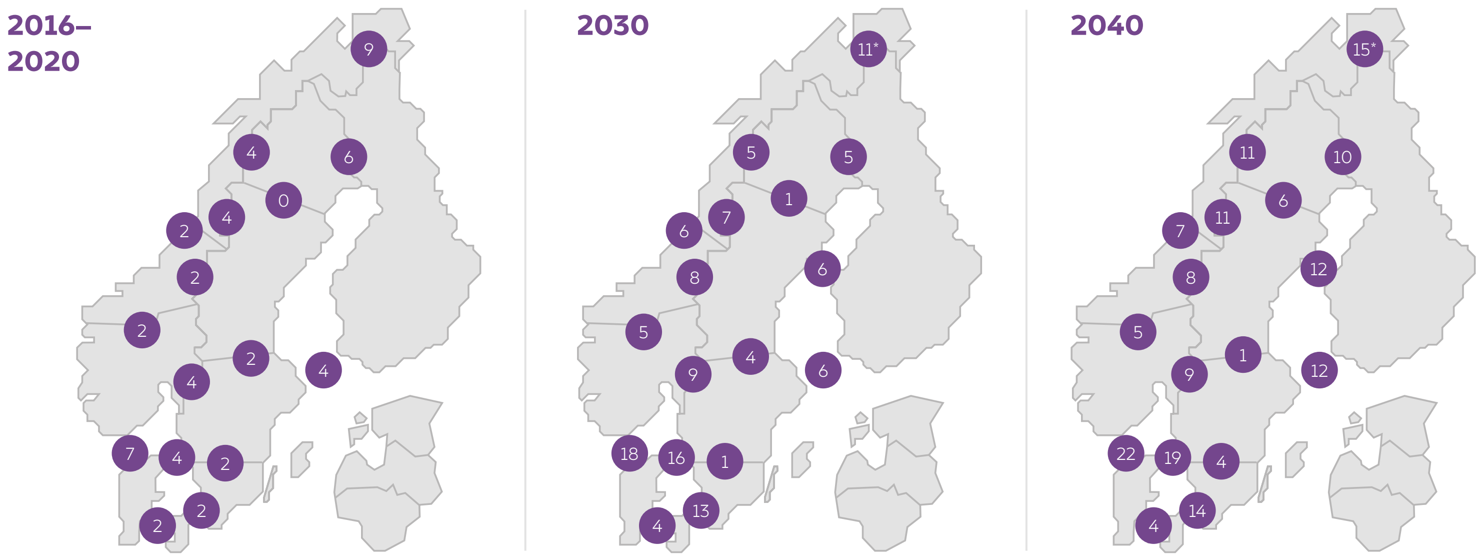
3.2.2 Price differences

The absolute hour-by-hour price differences between the Nordic bidding zones increases from today to 2030 and to 2040 in the Climate Neutral Nordics scenario, as illustrated in Figure 9.

The increase in price differences between 2030 and 2040 is an indication of an increased need for grid investments towards 2040. The price differences between bidding zones are increasing both due to increased electricity transport, as well as increased variation in production due to a higher share of intermittent production and less thermal capacity, as explained in the previous section. Reduced price difference between SE2 and SE3 is due to including the planned north-south grid reinforcements up to 2040 in the reference grid.

In addition, the continental power prices also vary more towards 2040, due to higher consumption and higher share of intermittent production. This increases the existing price differences in the Nordics.

Figure 9 – Average absolute hour-by-hour price differences (in EUR/MWh) in the Climate Neutral Nordics scenario for 2030 and 2040, as well as an estimate of the average price differences today, based on prices from 2016 to 2020. For Norway, NO1, NO2 and NO5 have been considered as one bidding zone.



* Investment cost (which is not included in the analysis) between Finland and Norway is expected to be high compared to benefit (see Chapter 5 for more information).

3.3 Summary

The analysis shows that the transmission needs are expected to increase in the future when the consumption increases, and large amounts of renewable generation is integrated in the Nordic power system. Hence, the analysis is indicating corridors which should be subject for further analysis and is important input to more detailed studies.

Even though the analysis illustrates large price differences in many corridors, it does not necessarily mean that there must be made investments in new grid. Over time the market dynamics may lead to more equal prices which will reduce the need for new grid investments. For instance, localisation of new consumption and production in line with the local price signals may lead to smaller price differences between bidding zones. Also, the higher price variation which is expected in the Climate Neutral Nordics scenario will increase the profitability of peak capacity and demand flexibility, both in power intensive industries and in individual households. In turn this could reduce the price variations which would lead to smaller price differences.

In addition to traditional grid investments, there are also other options for increasing grid capacity for the markets. These include for example: dynamic line rating, series compensation, static var compensator / static synchronous compensator devices (SVC/STATCOM), voltage control solutions, and system protection schemes. The Nordic TSOs are investing in the most cost-efficient options for increasing the grid capacity.

For more details on the specific bilateral corridors, see Chapter 5.

4 FOCUS AREA STUDIES

4.1 North-south transmission needs

The large consumption growth, balanced with mostly onshore wind power in the north and offshore wind power in the southern part of Scandinavia, will have major impacts on power flows and bottlenecks in the Nordic power system compared to today. This chapter analyses the North-South flows and needed capacity in the future Nordic power system. The analysis is based on the Climate Neutral Nordics scenario.

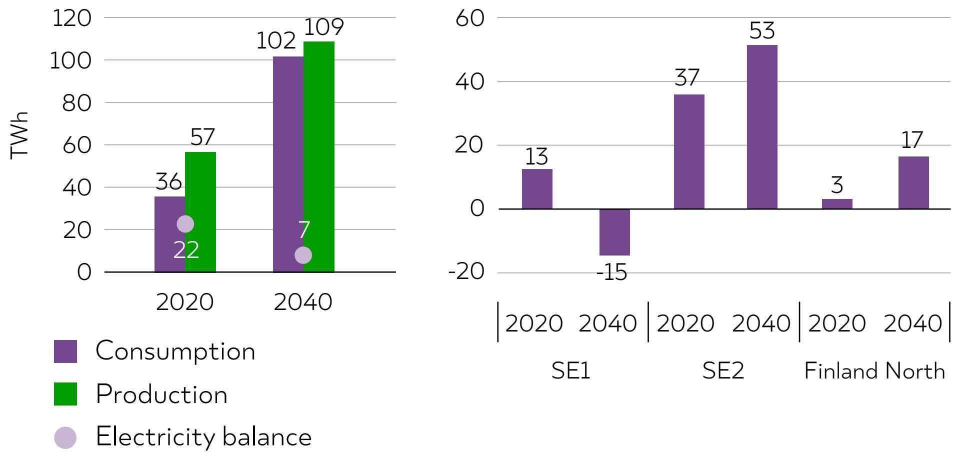
4.1.1 Future power balance compared to today

In the Climate Neutral Nordics scenario, the power system in the northern part of the Nordics will undergo major changes towards year 2040. This is related to both consumption and production growth. For the region comprising northern parts of Norway, Sweden and Finland, the consumption growth brings the region towards lower electricity balance in 2040 compared to the electricity surplus of today. This development is shown in the left part of Figure 10. This is mainly due to the consumption growth caused by P2X in bidding zone SE1.

The vanishing regional surplus occurs even though the investments are made in onshore wind power in Sweden and Finland. The added consumption from these developments is about 65 TWh for Sweden and Finland in total.

Even though the region has a positive electricity balance as a whole, consumption growth leads to a large electricity deficit in bidding zone SE1 and increases the need for import on all corridors into northern parts of Sweden by 2040. The right part of Figure 10 illustrate the development in the electricity balances. Both SE2 and the northern part of Finland increase the energy surplus towards 2040 whereas SE1 has a negative balance of about 15 TWh in 2040.

Figure 10 – Left: yearly electricity balances for 2020 and 2040 for the area comprising the northern part of Norway (NO4), Sweden's bidding zone 1 (SE1) and the northern part of Finland (northern part of Finland includes the part of the country north of the Kemi-Oulujoki cut). Right: yearly electricity balances for 2020 and 2040 for the bidding zones SE1, SE2 and northern part of Finland, respectively.



4.1.2 Changing north-south flow patterns in the system

The changed electricity balances in different parts of the Nordic system will subject the grid to partially new flow patterns. An overview of the present and future energy flows can be seen in Figure 8 in Chapter 3.2.1. The flows in the interconnected Nordic system are at present generally dominated by relatively steady energy flows from the north to the south, albeit with variations in the flow between regions, years and seasons. The projected changes to the production and consumption of electric energy in the Nordics will cause some of these flows to increase, decrease and even reverse. Bottlenecks can therefore become more constraining, alleviated or appear in new places. In the following, a per-country overview is given:

Denmark will experience an increased flow from southern Sweden (SE4) to eastern Denmark (DK2). This flow will keep its current north-south direction. All other flows between areas become more bidirectional. The main contributor to the bidirectional flows is the increase in offshore wind power in Denmark (especially in DK1, the western bidding zone) while P2X and electrification in Denmark will drive a higher flow from SE4 to DK2. Some of these flows will also extend through Denmark to the continent via new or existing interconnectors.

Finland will have a significantly increased north-to-south energy transfer. Increasing amounts of onshore wind power generated in northern Finland and increasing electricity consumption (electrification and P2X) in the south of Finland drives this change. The cross-border flow to northern Finland will become more bidirectional due to the electrification of heavy industry in northern Sweden (SE1).

Norway is experiencing increasing power flows from the north and central parts of the country to the southern parts. This trend will be reinforced in the next couple of years. After 2030 the flows will probably be more bidirectional, even if the main direction still will be southwards. The main reason behind this is increased industry consumption in the central- and northern parts of Norway and Sweden, combined with development of more offshore wind and PV in the south. Typically, the flows from south to north can be extensive in hours with large contribution from solar energy in the summer.

Sweden will have a deficit of energy in its northernmost part (SE1) that will make SE1 a net importer instead of an exporter. The border between SE1 and SE2 will be heavily utilized and subject to bidirectional flows, partly due to wind power development in northern Sweden and Finland and partly due to electrification in SE1. The border between SE2 and SE3 will continue to experience large north-south flows. Finally, the border between SE3 and SE4 will transfer less energy on average and become bidirectional. The main drivers behind this change is offshore wind power in the south of Sweden and increased imports on the HVDC-interconnectors that connect SE4 to continental Europe.

Photo: Statnett

4.1.3 Needs for grid capacity

As described above, there will be significant changes in Nordic demand-supply balance. Due to that development, there will be an increasing need for new grid capacity. Relevant issues are presented country-wise in the following:

Denmark is in a key position when developing connections between the Nordic countries and continental Europe. Denmark is in the process of expanding both onshore and offshore renewables connected in the southern and western part of the country. Compared to the other Nordic countries Denmark has a higher population density and a smaller land area. Despite this internal grid expansion is still possible, but to be able to handle a larger transfer capacity in the Danish grid this need to be combined with HVDC-projects, both onshore and offshore. Both internally and in the North Sea and the Baltic Sea new HVDC-projects are being planned to expand the capacity to the neighbouring countries to handle these new flows.

Finland will have most of the new onshore wind power in northern parts of the country, while majority of demand is expected to stay in southern Finland. That will require large investments in north-south transmission lines. Possible HVDC connections from southern Finland to Estonia and Sweden will further increase the need for internal grid investments. Finland is prepared for this situation, the development of power system is monitored and investment plans are updated frequently. Additionally, Finland has proven experience on developing new grid and there are available and environmentally acceptable routes for new overhead transmission lines. Therefore, developing onshore wind power with necessary new transmission lines will yield higher socioeconomic welfare than developing offshore wind power that might be located closer to power demand but would be more expensive to connect. Fingrid has also been given guidance by national legislation and customers to keep Finland as one bidding zone, a target that requires constant development of new north-south transmission lines.

Norway has a more decentralized power system compared to Sweden and Finland where consumption and production is spread across the whole country. Statnett is planning to upgrade all 300 kV lines to modern 420 kV lines by 2040. This will add capacity in the north-south direction and help reduce price difference between NO3 and the prices zones in the southern Norway. It will also to some degree relieve north-south flows in the Swedish grid. This is also necessary to meet the demand for grid capacity due to development of large industry units and offshore wind in the southern and western part of Norway. New large industry units can also create demand for new local power lines due to security of supply. This is especially the case in the northern parts with relatively few power lines today combined with very large distances. On a Nordic level this development combined with more industry and wind power in Sweden will contribute to more congestion between the countries both in north, mid and south. Internal reinforcement in the two countries will to a little degree relieve congestion between the two countries.

Sweden will face challenges to use mainly wind power to satisfy both consumption growth and replace the power production from decommissioned nuclear units. These developments could increase significantly the north-south transmission needs. However, demand increase in SE1 (e.g. fossil-free steel industry) can somewhat balance the situation. The onshore wind power in SE2 will need to be transmitted to both south (SE3) and north (SE1). Substantial grid investments are planned to reinforce the SE2-SE3 transfer capacity. Also, some of the offshore wind power will be located close to demand centres in bidding zones SE3 and SE4, which can help reduce the north-south flows. Due to its location in the middle of the Nordic power system, Sweden will have a large impact also on other countries. Therefore, the development of Swedish transmission grid needs to be taken into account also in other Nordic countries.

Generally, the increasing wind power will increase need for power transmission within and between countries, as there are always some wind variations between areas. The availability of hydropower and hydrogen solutions to balance the wind variations differs between areas. Therefore, there is an increasing need for common understanding how the power transmission grid could and should be developed in each Nordic country.

4.1.4 P2X's influence on the need of north-south capacity

In the Climate Neutral Nordics scenario it is assumed that P2X will expand its power consumption to 108 TWh by 2040. P2X is a technology that is rapidly developing and can be a major contributor to balancing renewable production. By storing and transporting energy, it can both be an alternative and a complement to electricity. To be able to have a positive or neutral effect on the need of capacity in the grid, a P2X rollout should consider:

1. The placement of P2X in the grid relative to placement of renewables
2. The P2X's ability to store and transport energy
3. The response time to grid events
4. The high reliability in operation

In **Denmark** the plans which are being explored by P2X entails placement both in the west and south of Denmark where the renewables are placed. At present, some of the first start-ups are placed near major cities, which might become a problem if they keep expanding. This is only the case if they are placed far away from production areas and no further market developments are done.

In **Finland** there are several potential areas with large industrial consumption centres, but at this point it is difficult to predict where or when the P2X solutions will be developed.

In **Norway** there are several concrete plans for producing P2X, both in the southern and northern parts of the country. The consumption growth can be extensive, and some of the concrete plans indicates several hundred MW in consumption related to P2X production.

In **Sweden** it is currently expected that P2X will mainly be established in the northern part of the country. P2X could help to reduce large north-south flows in Sweden when wind power production is large in the northern parts but too heavy concentration of P2X in one bidding zone might introduce new bottlenecks in to the electricity grid.

4.1.5 Summary

Changes to both electricity production and consumption will introduce changes to the overall north-south flow patterns in the Nordic grid. The grid will more often experience power flows in the opposite direction of what is predominant today. However, in the clear majority of corridors, the north-south flow will not decrease in magnitude and will be significant in many instances. The Nordic grid must therefore continue to have strong north-south connections and planned reinforcements to strengthen the north-south connections should be carried out. Cooperation between the Nordic TSOs is also needed in order to better understand the changing flow patterns in the interconnected grid. To avoid over-investments in grid capacity due to volatile wind power, P2X and other flexibility providers can have a role to play as a complement to grid reinforcements.

4.2 Resource adequacy

In a climate neutral society, the electricity generation mix as well as the electricity consumption side will differ significantly from the current. The consumption will increase due to electrification and the generation mix will be dominated by intermittent power sources as solar and wind power replaces most of the thermal capacity. This transformation gives a reason to examine the future development of resource adequacy and identify the risk of the situations when the lack of production capacity may, in extreme situations, lead to forced disconnection of consumption.

The adequacy analysis was carried out using the Climate Neutral Nordics scenario and by analysing the power margin in the Nordic countries, for the years 2030 and 2040. Detailed probabilistic analyses were not carried out in this study; however, the analysis considers uncertainty associated with weather, as several weather years is analysed.

The analysis shown in this chapter should be considered as an illustrative analysis of the future situation. More studies are needed to analyse the future situation in detail.

4.2.1 Methods

The adequacy situation in the Climate Neutral Nordics scenario was analysed in two different tools, BID3 and EMPS. Each TSO used their own tools for the analysis. The power margin has been used as a metric to get an overview over the adequacy situation in each country and in the Nordics.

The power margin is defined as the available production capacity hour-by-hour where the consumption in the corresponding hour has been subtracted. The available production capacity includes the available production from reservoir hydro, thermal and nuclear, as well as the expected production from wind, solar and run of river. On the consumption side the total input consumption is included in the calculation, meaning that demand-side flexibility (or demand-side response, DSR) is not considered. As the power margin is calculated for a country as a whole, or the Nordic region as a whole, the transmission capacity within the country or the Nordic region is not taken into account.

The power margin shows the margin in available production to what may lead to forced disconnection of consumption. A positive power margin indicates hours with excess available power production and thus available export capacity, whereas a negative power margin indicates a deficit in available power production to cover the consumption. As no flexibility in demand is included in this calculation, and there is no new peak capacity added in the Climate Neutral Nordics scenario, the negative power margin serves to illustrate the total need for additional flexibility, which could be met with imports, demand-side flexibility or peak capacity.

The metric was calculated hour-by-hour for several years[14], for each country as a whole, and for the entire Nordic region. The power margin is presented as a time duration curve, which means that each level of the power margin corresponds to a time duration, as a percentage, over the analysed weather years. The adequacy outlook in each country is also based on other internal and external reports.

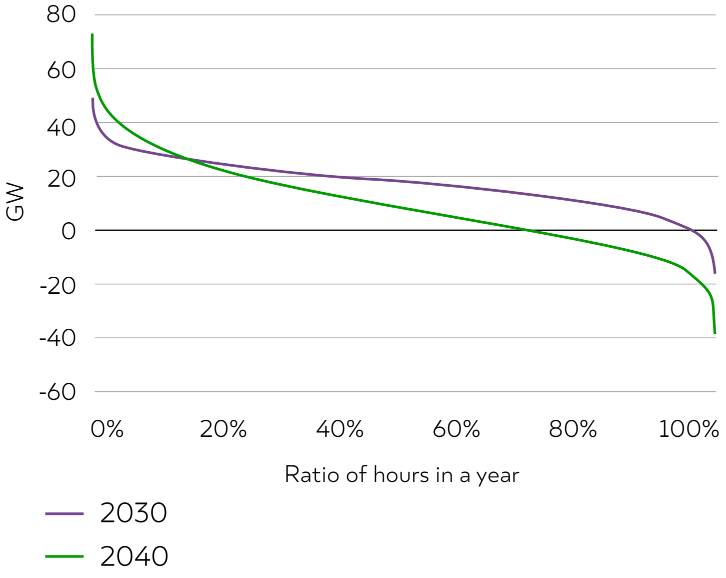
It should be noted that there are several uncertainties related to the power margin used as a metric in the adequacy analysis. First of all, the available generation capacity for each country is calculated for the country as a whole, which means that the internal transmission capacity is not taken into account. In reality, some of the available generation capacity might be in different bidding zones behind grid constraints, depending on the actual flow pattern in the system. Thus, the actual generation capacity might be lower than assumed on the country-level. Another uncertainty related to the available generation capacity is that the regulated generation capacity might not be fully available due to several factors. Lastly, the contribution from intermittent power production is uncertain, especially in the tightest hours.

[14] 29 weather years were used in the analysis for Norway and full Nordic area, and 35 weather years for Denmark, Finland and Sweden.

4.2.2 Status of the resource adequacy in the Nordics

The Nordics is a surplus area regarding annual energy production in 2030 and 2040, in the Climate Neutral Nordics scenario. However, the power margin at the Nordic level will become negative in an increasing number of hours towards 2040, as shown in the power margin duration curve in Figure 11.

Figure 11 – The power margin for the Nordic region as a whole in the Climate Neutral Nordics scenario for the years 2030 and 2040 (DSR not included).



The duration curve of the power margin illustrates a large variation in the power margin over time and shows how the variation will increase towards 2040 as the intermittent production plays a larger role. In hours where intermittent production is high and/or the consumption is low, the power margin is positive and there is high potential for export. In hours with low intermittent production and high consumption, the power margin is negative and there is a need for import or other additional measures, such as consumption flexibility and/or peak capacity. The figure shows that the amount of time with negative power margin increases substantially from 2030 to 2040.

Table 2 summarizes the ratio of time with negative power margin for the Nordics as a whole and for each country. The amount of time with negative power margin in the Nordics increases from 3% to 28%, from 2030 to 2040. And at the same time the power margin at the most negative falls from -16 GW to -38 GW (the most negative value during the analysed years). As the power margin is calculated for the Nordics as a whole, internal grid constraints are not considered. In reality, the actual power margin could therefore be even lower than this.

The transmission grid serves as a valuable enabler for exchange of resources between regions in the Nordics. The table shows for instance that the amount of time with a negative power margin at the Nordic level is much lower than the sum of the amount of negative power margin in the Nordic countries. That is, some adequacy issues at the country level are resolved on the Nordic level, thanks to the exchange of resources through the transmission grid. This

Table 2 – Ratio of time (%) with negative power margin for both 2030 and 2040 and maximum negative power margin (GW) without of consumption-side flexibility (i.e., the most negative value during the analysed years). Negative power margin indicates an import dependency or need of DSR.

	Nordics	Denmark	Finland	Norway	Sweden
2030	3%	14%	26%	<1%	<1%
2030	-16 GW	-6 GW	-7 GW	-2 GW	-10 GW
2040	28%	24%	42%	<1%	8%
2040	-38 GW	-10 GW	-13 GW	-3 GW	-10 GW

also illustrates that a negative power margin in some areas might be the socioeconomically best solution which leads to most effective utilization of resources.

However, in situations with similar weather conditions in the whole Nordic region, towards 2030 and 2040, there would be little potential for exchange of resources within the Nordic region, as the power production becomes more weather dependent. In these cases, other measures would be required to ensure the security of supply, such as imports from our surrounding countries on the continent or the United Kingdom, flexibility in consumptions or peak generation capacity.

The import capacity in 2030 in the Nordics is expected to be around 12 GW, and imports from surrounding regions will thus be important for the security of supply. But, since the import capacity is lower than the power margin at the most negative, there will be a need for additional measures as well. This is also related to the uncertainty in the availability of imports from the continent and the UK, in tight situations, as the same weather system may be present in both the continent and the UK and the Nordics.

The flexibility in consumption will become increasingly important to reduce the negative power margin and to ensure the security of supply. As the power margin was calculated to illustrate the total need for flexibility, before any new flexibility was added, the calculated power margin does not include flexibility in consumption. Adding flexibility in consumption would then reduce the power margin at the most negative and the number of hours with negative power margin. The flexibility in consumption is likely to span from flexible production of hydrogen, to flexible EVs and industry voluntarily disconnecting at certain price levels. Some flexibility in consumption is modelled in the scenario, however not included here in the power margin. More details on the consumption flexibility in Chapter 2.4.3.

Peak generation capacity such as peak plants on biofuels/hydrogen, fuel cells or increased capacity in reservoir hydropower, would serve to reduce the negative power margin. There are no assumed new investments in peak generation capacity in the Climate Neutral Nordics scenario, but the negative power margin on the Nordic and the country level, indicates that this might become profitable in the future.

The analysis shows that the development in the Climate Neutral Nordics scenario, with higher consumption and a higher share of intermittent power production, will lead to an increase in the hours with negative power margin. The results highlight the need for further cooperation between the Nordics TSO on adequacy issues, as there will be potential for national adequacy issues to be solved at the Nordic level.

Due to uncertainty related to the consumption growth, the volume of demand flexibility, weather patterns, etc., there is also large uncertainty related to the magnitude of the adequacy challenge. As such, the specific results presented here should be seen as indicative.

4.2.3 Status on the resource adequacy by country

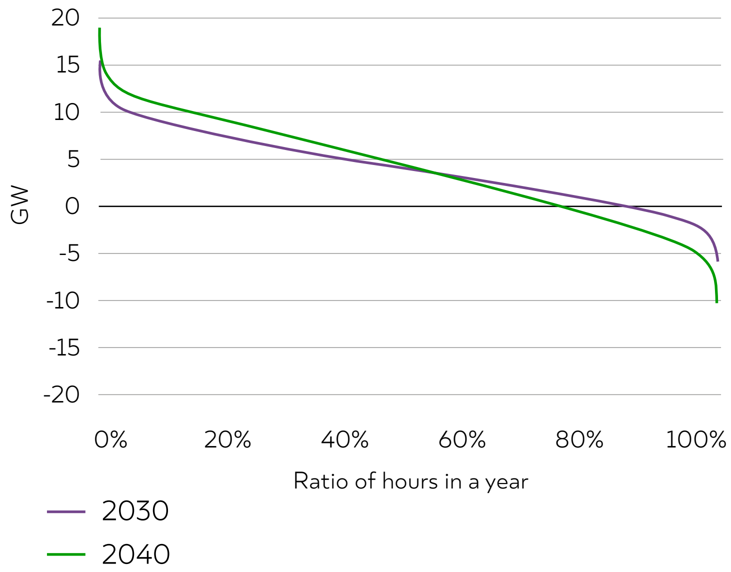
Denmark

In 2040, the estimated power margin in Denmark is at more than -10 GW, at the most negative. This is higher than the expected interconnector capacity in 2040. Thus, in the Climate Neutral Nordic scenario adequacy issues will occur in Denmark in 2040, as there is not enough import or generation capacity available.

The above tendency is characteristic to Denmark, as Denmark is dependent on interconnectors to balance national generation and consumption. Faster decommission of fossil fuelled power plants and thus stricter power margins in central Europe, most notably Germany, could restrict the available import and have consequences for the Danish adequacy situation in cold periods without wind.

Flexibility, whether it being consumer flexibility and/or batteries, could help move consumption from hours with low renewable power generation to hours with a surplus. Hydrogen peakers could also be implemented to be a backup in place

Figure 12 – The power margin for Denmark in the Climate Neutral Nordics scenario for years 2030 and 2040 (DSR not included).



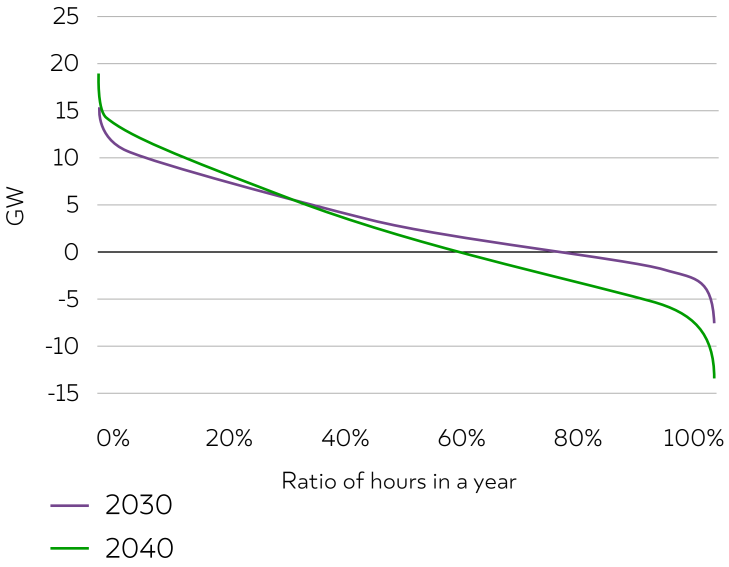
for today's oil peakers. This is not explicitly modelled in the scenario, but the analysis of the power balance above shows that the Danish adequacy on the long term is likely going to be dependent on most, if not all, of the above technologies.

More information can be found in the latest adequacy study made by Energinet[15]. The overall tendencies in the national study and in the Climate Neutral Nordics are somewhat the same, but are studied in more detailed in the national adequacy forecast.

Finland

For Finland, currently approximately 5–7 gigawatts of the power margin deficit can theoretically be covered by imports, assuming that all transmission capacity is available, and electricity is available from neighbouring countries. Thus, Finland will require strong connections and likely more capacity to the neighbouring countries also in the future.

Figure 13 – The power margin for Finland in the Climate Neutral Nordics scenario for years 2030 and 2040 (DSR not included).



Finnish import capacity is lower than the maximum assumed negative power margin when not including DSR in the analysis. Thus, flexibility of consumption is essential to ensure power adequacy in Finland. Fingrid is working with stakeholders and investigating different solutions to develop flexibility solutions for the future system. For example, sector coupling, P2X and possible flexibility markets are considered as important resources in the future.

Fingrid has recently published a Network Vision report[16]. That report investigates the adequacy from national perspective in four different future scenarios.

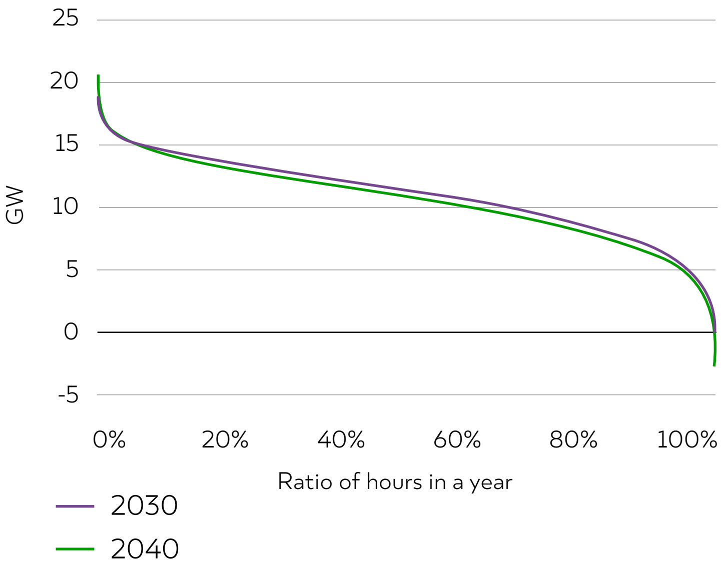
Norway

Norway has a positive power margin today, due to a high share of reservoir hydropower. Towards 2030 and 2040, the power margin is expected to be reduced because of a high expected growth in consumption in Norway, due to electrification, in combination with a higher share of intermittent power production. In the Climate Neutral Nordics scenario, the power margin in Norway becomes slightly negative in the tightest market situations. At the tightest the power margin is -1.7 GW in 2030 and -2.5 GW in 2040. However, this negative power margin only occurs at less than 1% of the analysed weather years.

[15] Current version RFE20: https://en.energinet.dk/About-our-reports/Reports/Security-of-electricity-supply-report-2020. The main publication is in Danish with an English executive summary available.
Consultation version of RFE21: https://energinet.dk/-/media/92160F33904F-42C8A5DD4DC640002E6B.PDF?la=da&hash=14AB1D0E8795865D40E7E18E16A-70C14A0438CDB Only in Danish. The final version is expected to be published November 15th, 2021

[16] Fingrid (2021) Network vision. URL: https://www.fingrid.fi/globalassets/dokumentit/fi/kantaverkko/kantaverkon-kehittaminen/fingrid_network_vision.pdf

Figure 14 – The power margin for Norway in the Climate Neutral Nordics scenario for years 2030 and 2040 (DSR not included).



Today, Norway has about 10 GW interconnector capacity which enables sufficient import in tightest hours with a negative power margin, in the years to come. In most hours, Norway will be an exporter of power surplus to the other Nordic countries and the continent, as Norway has a positive power margin during most hours, in the Climate Neutral Nordics scenario.

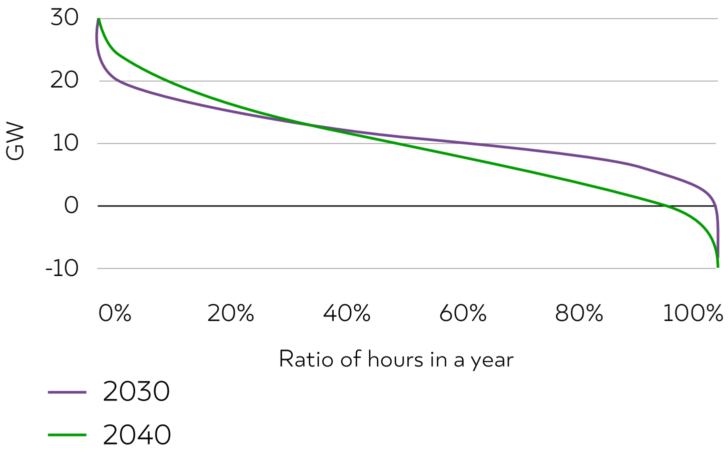
The amount of demand-side flexibility is a key uncertainty for the power margin, in Norway as well, however it is still expected to be the most efficient solution to decrease the power margin deficit in Norway. This due to the low expected profitability for peakers in Norway, due to the high Norwegian share of reservoir hydropower.

More information can be found in Statnett's Long Term Marked Analysis[17].

Sweden

In Sweden there will be larger variations in the power margin, in the coming decades. This due to more variation in the available power production and an increase in the power consumption due to massive electrification. The number of hours with a negative power margin will increase between 2030 and 2040 in Sweden and the power margin will be -10 GW at the most negative.

Figure 15 – The power margin for Sweden in the Climate Neutral Nordics scenario for years 2030 and 2040 (DSR not included).



To reduce the potential adequacy issues, the consumption needs to be increasingly flexible. In fact, a large portion of this electrification has potential to be flexible, as the large variation in available power production leads to large variation in electricity prices. Furthermore, the industrial activities such as hydrogen production is to a large extent dependent on avoiding the hours with high power prices, to ensure their own profitability. Energy storage could also help even out peaks in consumption, although the profitability for energy storage is still uncertain. In addition, interconnectivity with neighbouring countries will also likely play a greater role in ensuring adequacy.

More information can be found in the latest long-term market analysis[18] by Svenska kraftnät.

4.3 Offshore wind

Utilizing offshore energy resources is an important part in Europe's goal of becoming the world's first climate neutral continent by 2050. EU commission aims to have approximately 60 GW of offshore wind capacity in 2030 and 300 GW in 2050 in Europe[19] (and UK has a goal to integrate 40 GW by 2030 leading to 100 GW in total at the North

[17] https://www.statnett.no/for-aktorer-i-kraftbransjen/planer-og-analyser/langsiktig-markedsanalyse/ (in Norwegian)
[18] https://www.svk.se/siteassets/om-oss/rapporter/2021/langsiktig-marknadsanalys-2021.pdf (in Swedish)
[19] https://ec.europa.eu/energy/sites/ener/files/offshore_renewable_energy_strategy.pdf

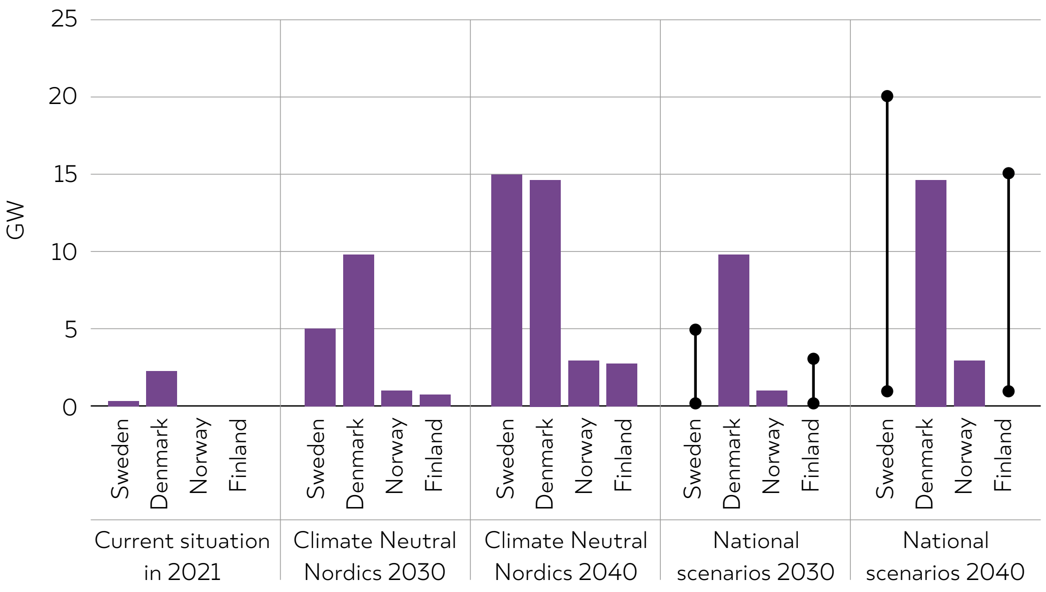
Sea region). Significant amounts of these new wind farms will be connected to the Nordics, on the Baltic Sea and North Sea, and the number and size of planned offshore wind farms are rapidly increasing in the Nordics. In addition to building radial lines, the massive offshore deployment might require new offshore grids that connect offshore wind farms located far from shore to hubs that can be connected to multiple countries (such as energy islands). These offshore grids are not technically mature enough but are needed to integrate offshore wind to multiple markets, meet the expected increase in electrification consumption and support the development of green fuel (P2X).

The Nordics have successfully integrated and continuously integrates an increasing share of renewable resources, especially onshore wind, into their resource mix. As the Nordics are moving towards climate neutrality, the wind integration and grid operation will become more challenging. This section of the NGDP2021 will explore the considerations and opportunities related to grid planning of offshore wind that this new transition will bring.

4.3.1 Overview of offshore status by country

As described in Chapter 1 of this report the Nordic TSOs expect a significant increase in connected offshore wind over the next 20 years. Today, the total capacity of connected offshore wind is approximately 2.5 GW. Climate Neutral Nordics scenario assumes the capacity to increase to 17 GW in 2030 and 35 GW in 2040. Figure 16 presents the amount of offshore wind in the different Nordic countries in the Climate Neutral Nordics scenario as well as different national scenarios.

Figure 16 – Status of offshore wind in the different Nordic countries, expected development in various scenarios and received applications. The black dots show the minimum and maximum in case there are various national TSO scenarios.



There are different approaches to determining where and how much offshore wind is expected in the Nordic waters. In Denmark and Norway, areas for potential new offshore wind parks are identified by the respective governments as available for tender. The Norwegian government opened in 2020 two areas for application; Sørlige Nordsjø II and Utsira Nord. Sørlige Nordsjø II is in the North Sea, approx. 200 km from shore and close to the border to Denmark. The application process for these areas will be decided in the autumn of 2021. The government has indicated a volume of 3 GW in Sørlige Nordsjø II and 1.5 GW in Utsira Nord. New areas can be available for tender in a few years depending on the interest from the developers. No subsidies have so far been planned for offshore wind in Norway.

The Danish legislature is planning for a 3.5 GW radial connected Danish wind capacity, including HesselØ, Thor, and Kriegers Flak, and has in addition decided to construct two energy islands, one in the North Sea with a starting capacity of 3 GW, with potential for expansion to 10 GW, and one in the Baltic Sea near Bornholm with a capacity of 2 GW.

In Sweden and Finland developers submit applications for potential wind farms. For example, Fingrid has received approximately 20 GW of offshore wind power connection inquiries at the time of writing this report. However, the main emphasis in Finland is still on onshore wind with approximately 100 GW of inquiries onshore. At the moment, all potential offshore wind projects in Finland are located on the western coast and around Åland islands.

In Sweden the developer also decides where to develop the offshore wind farm, and Svenska kraftnät has by the time of writing of this report received approximately 120 GW of offshore wind connection inquiries which is more than onshore wind related inquiries.

4.3.2 Offshore wind requires new methods and cooperation

Role and responsibility of TSOs in connecting offshore wind

TSOs have a crucial role in planning, building and operating the transmission grid which is needed to meet the climate targets and supporting the connection to offshore wind. Today, the four TSOs have different responsibilities related to connecting offshore wind. For traditional radial connections, the project developer pays the connection plus standard grid connection fees to connect to the grid in Finland and Denmark, but it is Fingrid's and Energinet's responsibility to develop and fund needed onshore grid reinforcements to support offshore wind. In Sweden, the developer finances the grid connection and those onshore reinforcements that only the developer benefits from. In Norway the government has published a parliamentary white paper that indicates that the developers should take the cost for connection to shore and necessary grid reinforcement onshore, but the details are subject for both political discussions and further investigation. Ownership on future hybrid connections is not decided but is one of the issues that will be further investigated. It is proposed by the former government that Statnett will be appointed as system operator offshore, equivalent to the role onshore.

However, renewable targets and the development of new hybrid offshore grids are resulting in new connection policies. The new hybrid projects can create opportunities for using offshore grids in a dual way: transporting produced wind power and enabling trade between two (or more) markets. In Denmark it has been determined that the wind developers will fund the radial connection to the new energy islands, however, Energinet will own and operate the critical infrastructure on the energy islands, onshore and Energinet and the TSO(s) involved will own the interconnectors. The actual island will be owned by a private/public ownership arrangement.

In Sweden, a new policy will be taken into force 1 of January 2022 where Svenska kraftnät will fund and be responsible for connections within territorial waters for those offshore connections that will be built to promote the fulfilment of the target of 100% renewable electricity production by 2040. For additional project connections in excess of what Svenska kraftnät will build, the project developer is still required to pay for the connection to the grid.

These differing roles and responsibilities will impact the future development of meshed and integrated offshore grids as the connection scheme and associated costs will impact the placement of future wind projects. If different countries have different regulations that affect the cost for offshore wind power, which is the case today, this may lead to a skewed distribution of offshore wind power in a sea basin and offshore wind gets built not where it would be most cost-efficient on Nordic level but where it is nationally subsidized most. However, one solution regarding the subsidies does not necessarily fit all.

Market setup for offshore grid

Market setup questions become relevant in the case of hybrid offshore connections (see the next chapter for details regarding hybrid offshore grids). There are two main alternatives[20] for market design offshore grid, the Offshore Bidding Zone model and the Home Market model. The Nordic TSOs and ENTSO-E are of the opinion that a market design based on the principle of offshore bidding zones is the most efficient. There is, in terms of market functioning, no difference between onshore and offshore bidding zones, in both cases congestions are efficiently handled by the bidding zones. Applying offshore bidding zones means that current electricity market regulations can be applied. The offshore bidding zone model supports an efficient market, a safer and simpler system operation and a levelled playing field for onshore and offshore production. Additionally, the offshore bidding zone solution ensures compliance with article 16.8 of EU (REG) 2019/943, the so-called 70% rule[21].

[20] ENTSO-E position paper on offshore development: https://www.entsoe.eu/2020/10/15/entso-e-position-paper-on-offshore-development-market-and-regulatory-issues/
[21] https://en.energinet.dk/-/media/8BB4875865F8451FB45B713D220EF929.pdf

Examining the cost and benefits of hybrid offshore grids
Hybrid offshore grid refers to a situation where there is an offshore hub connected to the interconnector(s) between different areas. The future hybrid offshore grid introduces the potential for more business partners than standard interconnectors. As such the issue of ownership and operations is one that needs to be resolved for each project and possibly needs newly evolved concepts. The ownership questions impact cost and benefit allocations, the complexity of contractual arrangement and the possibility of future expandability. For expandable hybrid hubs there is a need for harmonized rules in the EU[22].

The identification of benefits allocation associated with a (hybrid) offshore grid may also require new methodologies. The offshore grid combines offshore wind transmission and interconnection capacity into one project. The purpose of the offshore grid is to connect large offshore wind potentials far from shore to multiple individual energy markets. There is a strong cross-border nature by linking not only two, but possibly multiple individual energy markets. In addition, these hubs can potentially facilitate the integration of gas, electricity and heat sectors through e.g. P2X conversion, hydrogen, renewable gas and liquid fuels storage and Gas-to-Power. The interdependency between distant wind potential, multiple markets and green fuel is a unique aspect related to the recent development in offshore wind.

Market outlook for offshore wind
The cost for offshore wind production is predicted to drop substantially in the future. However, it is expected that future projects move further offshore and into deeper water, reducing some of the cost savings.

The weather dependent offshore wind production is expected to cause large volatility in power prices from very low prices to very high prices. Flexible hydrogen production and storage can have a stabilizing effect on the volatility of the power price and curb the cannibalizing effect as well as more classical solutions such as strong interconnectors between markets.

A large amount of the energy from the offshore wind farms will probably be converted into hydrogen, liquid energy carriers and green fuels. This could be done in the turbines, on a nearby platform or island or on the mainland which would reduce otherwise needed investments to the electricity grids.

Grid planning framework for hybrid projects
Integration of offshore wind to the Nordic power system is expected to challenge the current grid planning practices. Consequently, holistic planning and coordinated development of both on- and offshore grids are essential to enable the climate neutral Nordic electricity system of the future. From a grid planning perspective, the planning of grid connections for radially connected offshore wind farms is relatively straight-forward and national in nature. However, hybrid offshore solutions, with connections to several countries might require development of completely new or update of existing grid planning principles, such as dimensioning of the offshore grid, fault withstand, interoperability as well as system operation principles, etc. Several of these aspects have been assessed in ENTSO-E's position papers on offshore development[23].

In addition, to ENTSO-E work, the Nordic TSOs are actively investigating optimal grid planning practices for integration of offshore wind and development of offshore grids in the Baltic Sea region[24] as well as Nordic and national processes.

4.3.3 Summary
The long-established practice of close cooperation between the Nordic TSOs, leaves this region well equipped to respond to the needs of the offshore wind developers, consumers and the electricity market by developing a cost-efficient grid for the future. The Nordic TSOs, together with the other TSOs along the North Sea and the Baltic Sea continue to work closely on tools needed to integrate the expected capacity of offshore wind in the future, such as standardization, data sharing improved grid operation, effective use of reserves, and harmonization of balance service.

[22] ENTSO-E offshore position papers: https://www.entsoe.eu/publications/position-papers/
[23] See especially: https://www.entsoe.eu/2021/07/14/new-entso-e-paper-on-offshore-development-focuses-on-system-operation-governance/ and https://preview.entsoe.eu/news/2021/01/25/third-entso-e-position-paper-on-offshore-development-focuses-on-interoperability/
[24] https://www.fingrid.fi/en/pages/news/news/2020/tsos-agreed-to-strengthen-cooperation-for-the-future-of-offshore-grid-in-the-baltic-sea/

5 BILATERAL STUDY UPDATES

In NGDP2019 the five bilateral corridors: Norway-Sweden, Finland-Sweden, Finland-Norway, Norway-Denmark, and Denmark-Sweden were analysed. This chapter gives an update of the work done since the analyses and further development of the corridors. The work on the five corridors is at different maturity levels, therefore the content of the subchapters will differ.

5.1 Norway-Sweden

In NGDP2019, benefits of increased transmission capacity between southern Norway (NO1) and southern Sweden (SE3) were assessed. In this report, the previous analysis is updated. In addition, evaluations of the benefits associated with the increased transmission capacity in the remaining Norwegian-Swedish corridors is provided. The evaluations are based on Statnett's and Svenska kraftnät's long-term market analysis (LMA) scenarios and the Climate Neutral Nordics scenario.

There are four Norwegian-Swedish corridors: (1) the power line between Ofoten in Norway and Ritsem in Sweden (400 kV) connecting the northern bidding areas NO4 and SE1; (2) Rösspåga-Ajaure (220 kV) connecting NO4 and SE2; (3) Nea-Järpströmmen (400 kV) connecting NO3 in Mid-Norway with SE2; and (4) two 400 kV power lines connecting the southern bidding areas NO1 and SE3, the Hasle-corridor. All power lines between Norway and Sweden are AC overhead power lines.

Changed transfer patterns in the southern parts of Sweden

Three major changes in the Nordic power system have led to new transfer patterns: (1) the decommissioning of the Swedish nuclear power reactors Ringhals 1 and 2; (2) increased wind power in northern Sweden; and (3) a new cross-border interconnection from Norway to Germany.

These changes have increased electricity flows in the western part of Sweden, which has led to congestions between SE2 and SE3. In addition, there have been increased electricity flows from southern Finland to SE3 and onwards from Sweden to NO1 and Denmark leading to east-west-congestions in the Swedish transmission grid. In order not to risk operational security it has been necessary to reduce the capacity between NO1 and SE3. Since December 2020 the capacity between NO1 and SE3 has been significantly reduced for longer periods. In the coming years, these new flows are expected to increase, e.g. due to the planned commissioning of the Finnish nuclear power reactor Olkiluoto 3 and the North-Sea link between Norway and Great Britain. Svenska kraftnät investigates short-term and long-term transmission grid reinforcements to handle internal congestions. Svenska kraftnät currently analyses potential new power lines, which can provide the required east-west capacity in the Swedish transmission grid.

Short-term – utilize and increase today's market capacity

The reduced capacity in the corridor between NO1 and SE3 affects the power prices in the whole Nordic system. During the first half of 2021, a combination of reduced capacity between SE2 and SE3, reduced capacity between SE3 and NO1, and high continental prices due to high prices on CO_2, gas and coal, have led to very high price differences between the southern and the northern parts of Norway and Sweden.

The most important in a short-term perspective is to utilize today's maximum Net Transfer Capacity (NTC). To utilize the maximum NTC between the Norwegian and Swedish bidding zones, the capacity in the internal grid must be dimensioned for the capacities between the countries. Therefore, short-term investments of the internal grid, such as voltage control equipment or dynamic line rating, need to be prioritized.

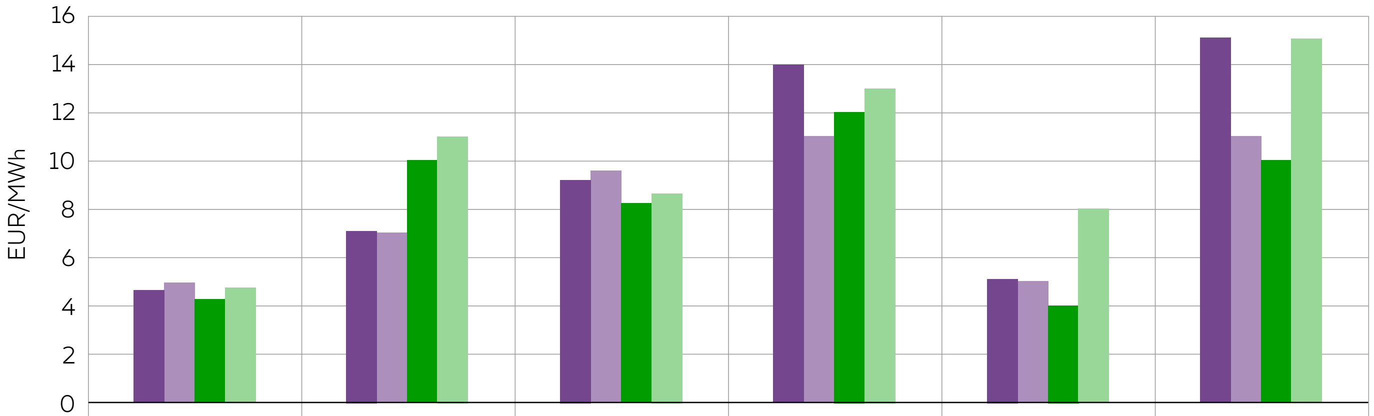
Long-term – increased capacity between Norway and Sweden can be profitable

Preliminary results based on the scenario Climate Neutral Nordics indicate that grid reinforcements on the Norwegian-Swedish corridors, in 2030, will lead to moderate benefits. Towards 2040, the results indicate that the benefits will increase significantly for the corridors NO4-SE1 and NO1-SE3.

However, the results vary between the scenarios, as shown in the Figure, due to the different assumptions in the scenarios. For instance, the consumption and production growth is smaller in Statnett's LMA scenario and in Svenska kraftnät's scenario SF2045, than in the Climate Neutral Nordics and in Svenska kraftnät's scenario EF2045[25]. In the two latter scenarios it is assumed a large increase of industrial consumption in the northern part of Sweden. For detailed results of the Climate Neutral Nordics Scenario, see Chapter 2.

A higher consumption growth in the north in Sweden in the Climate Neutral Nordics and in Svenska kraftnät's scenario EF2045, leads to more frequent congestions into SE1 because of the large need of import. Hence, there are higher benefits of increased transmission capacity in the Ofoten-Ritsem-corridor between NO4 and SE1, in the Climate Neutral Nordics and in Svenska kraftnäts's scenario EF2045. However, an increase in the capacity between NO4 and SE1 requires internal grid reinforcements in both countries.

Figure 17 – Average of absolute values of price differences in the Norwegian-Swedish corridors for 2030 and 2040, in the Statnett's LMA-scenario, the Climate Neutral Nordics and in two of Svenska kraftnät's LMA-scenarios for 2045. Note that the results of Climate Neutral Nordics are from Statnett's simulations, to be comparable to the other results. This means that the results differ from the ones presented in Chapter 3.



	Statnett's LMA scenario 2030	Climate Neutral Nordics 2030	Statnett's LMA scenario 2040	Climate Neutral Nordics 2040	Svenska kraftnät's LMA-scenario SF2045	Svenska kraftnät's LMA-scenario EF2045
NO4-SE1	5	7	9	14	5	15
NO4-SE2	5	7	10	11	5	11
NO3-SE2	4	10	8	12	4	10
NO1-SE3	5	11	9	13	8	15

[25] Småskaligt förnybart (SF2045) and Elektrifiering förnybart (EF2045).

The southern bidding zones in Sweden have lower power prices in Climate Neutral Nordics scenario because of large investments in offshore wind power and lifetime extension of the nuclear capacity. In the Climate Neutral Nordics scenario there are frequent congestions in the flows in the Hasle-corridor from SE3 to NO1. However, in Statnett's LMA scenario the congestions are less common because of different distribution of consumption and production, and due to assumptions of lower wind power and consumption growth.

A recent grid study shows that a third power line in the Swedish internal west-coast-corridor would enable an increased capacity from NO1 to SE3, from today's maximum NTC capacity of 2,145 MW to approximately 2,445 MW, provided that other internal congestions in the Norwegian and Swedish transmission grids are managed.

Next steps

Both TSOs recognize the benefits of having a closer collaboration on common market- and grid studies. Collaboration related to maintaining the capacities on the existing cross border corridors between the countries is the most important in a short-term perspective. Svenska kraftnät and Statnett aim to analyse potential reinforcements of cross-border interconnections between Sweden and Norway as well as necessary internal grid reinforcements.

5.2 Finland-Sweden

Finland and Sweden are currently connected in the European electricity market via AC overhead lines in the north and subsea DC cables Fenno-Skan 1 and 2 across the Gulf of Bothnia. Overhead lines connect bidding zones SE1 and FI, while Fenno-Skan cables connect bidding zones SE3 and FI. During recent years, the border between Finland and Sweden has been heavily congested, with congestion occurring roughly 40% of time in 2019.

Since the previous Nordic Grid Development Plan in 2019, Svenska kraftnät and Fingrid have continued to advance the Aurora Line[26], a 3rd AC interconnector between the countries, to be located between bidding zones SE1 and FI. The TSOs also conducted a technical investigation on the remaining lifetime of the Fenno-Skan 1 link (400 MW), commissioned in 1989. The investigation concluded that reliable operation of the link until 2040 is possible to achieve with extended monitoring of technical equipment, combined with refurbishments and renewals of certain equipment. Consequently, the lifetime of the link will be extended to 2040[27].

Within the last two years, the pace of the energy transition has accelerated and the role of electricity within it has increased. It is becoming increasingly clear that the fastest and most cost-efficient way to meet the climate targets is via electrification, including sector integration and the use of P2X solutions, especially in areas where direct electrification is difficult, such as certain industries and freight. This has resulted in the need to increase both consumption and generation of climate-neutral electricity substantially faster

[26] https://www.fingrid.fi/en/grid/construction/cross-border-connections/Aurora-Line-new-finland-sweden-interconnector/#18765e5b

[27] https://www.svk.se/en/about-us/news2/news/fenno-skan-1-lifetime-will-be-extended-until-2040/

and more broadly than previously considered. Interconnectors play a vital role in ensuring that this is possible.

The scenario created in NGDP2021 emphasizes the need of new interconnectors, and in this respect the results are aligned with recent studies completed by Fingrid and Svenska kraftnät individually. Fingrid completed its Network Vision in the beginning of 2021 for the years 2035 and 2045, including assessments on cross-border capacity needs[28]. Svenska kraftnät also updated its long-term market analysis for 2035 and 2045 during the first half of 2021. Like NGDP, these studies are reflecting the increased pace of the energy transition. All the analysis performed is pointing to the same direction: increasing electricity consumption, increasing share of intermittent renewables such as wind power, as well as simultaneous reduction in the amount of fossil fuels in the energy system, which trigger an increasing need for interconnector capacity, also between Finland and Sweden.

The options for further capacity reinforcement after the Aurora Line are 1) 4th AC line between Northern Sweden (bidding zone SE1) and Northern Finland i.e. Aurora Line 2; 2) DC submarine cable in “Kvarken” between bidding zones SE2 and Finland; 3) DC submarine cable between bidding zones SE3 and Finland. The results[28,29] indicate that any one of the connection options could be beneficial in the carbon-neutral future power system, but further studies are required to determine the way forward. AC interconnectors are typically cheaper to implement and have longer technical lifetime than DC-interconnectors, and they provide technical system benefits (such as reinforcing the synchronous zone) in addition to market benefits. On the other hand, DC alternatives could possibly be used to connect offshore wind power (“hybrid projects”) or, at the later stage, even be integrated to a larger offshore network should one eventually be built in the Baltic Sea.

Fingrid and Svenska kraftnät continue investigating the new possibilities through bilateral studies and as a part of European network planning processes. For example, Aurora line 2 between SE1 and Finland (in 2035) and a new HVDC connection between SE3 and Finland (in 2040) will be investigated in the European TYNDP process.

5.3 Finland-Norway

Statnett and Fingrid have investigated improvements on the cross-border connection between Northern Norway (NO4 - Finnmark) and Finland. The existing connection is a very long 220 kV AC line with limited capacity. Furthermore, the grid in Northern Finnmark consist of rather weak 132 kV connections. Consequently, controlling and limiting the flow on the line between Finland and Norway is very difficult, and it is a challenge for operations. Primary needs of improvement of this connection are related to

- controllable flow to match physical flow and market flow when the cross-section becomes a market border
- market benefits associated with having controllable flow and higher capacity
- improved security of supply
- growth in consumption and possibly wind power in Finnmark

Based on preliminary studies, the best option to improve the capacity seems to be a back-to-back (BtB) HVDC. The capacity of such a solution could be in the range of 100–150 MW and it could possibly be implemented earliest around 2025. A BtB gives full control over the flow and improves the damping of electromechanical oscillations that are restricting the flows in the current grid due to stability limitations. BtB would also make it possible to establish NO4-FI market border. Analysis so far indicates that a BtB could be an interesting investment, however, more detailed analyses of costs and benefits, especially the security of supply benefits are necessary to conclude anything. In addition to the relatively high per MW investment cost of the BtB, the cost of losses could be high due to the location of the interconnector and the long 132/220 kV voltage lines on both sides.

Based on previous studies, an AC loop connecting the 420/400 kV grids in Norway and Finland is not a feasible solution. Such line would have low capacity due to the length and would have little flow due to the shorter electrical route between the countries through Sweden. The cost of the necessary reinforcements would be high. It is a clear conclusion that a 420/400 kV connection is not a feasible solution – and very large changes in the power system in Northern Norway and northernmost Finland would be necessary to change that conclusion.

[28] https://www.fingrid.fi/globalassets/dokumentit/fi/kantaverkko/kantaverkon-kehittaminen/fingrid_network_vision.pdf
[29] https://www.svk.se/siteassets/om-oss/rapporter/2021/langsiktig-marknadsanalys-2021.pdf (in Swedish)

5.4 Norway-Denmark

Today, the net transfer capacity between Norway and Denmark is 1,700 MW, distributed on four interconnectors, Skagerrak 1, 2, 3 and 4. The Skagerrak 1 and 2 (SK12), with a total capacity of 500 MW, are beginning to reach the end of their expected technical lifetime[30].

Development in the corridor since NGDP19

The corridor was investigated in the NGDP19 using the Nordic reference scenario. From the results of this early assessment, it seemed beneficial to maintain or increase the capacities between Norway and Denmark.

Statnett and Energinet carried out a joint study in autumn/winter 20/21 "Updated lifetime assessment of Skagerrak 1 and 2" which conducted technical and economic evaluations of the SK12 capacity. SK12 are now the oldest HVDC converter valves in the Nordic countries. They have both exceeded the estimated lifetime of HVDC systems which is 40 years. The technical assessments concluded that SK12 can most likely operate several years with normal maintenance. The conclusion from the economic evaluation was that extending the lifetime is expensive and it does not reduce the technical risks of failure. In general, the results indicate that the cost of lifetime extensions is too high compared to an alternative with a new cable set and onshore installations. The report also recommended further discussions to decide upon the possibility of entering a potential collaboration on a new interconnector replacing SK12 between Denmark and Norway.

The results show that the market benefit increases over time, and the main driver for this is more volatility in the Danish prices, mostly due to higher consumption and production growth of wind power, and more volatile prices on the continental markets.

The main driver for increasing benefits is the big increase in the capacity from Jutland in Denmark (DK1) to the continent and the United Kingdom in the coming years. In addition, the capacity given to the market between DK1 and Germany is expected to increase compared to historical levels. Consequently, the Danish prices are expected to become more linked to the continental prices and less to Nordic prices.

There are some uncertainties that needs to be further assessed. The grid development progress in Germany and the internal grid capacity is one of the most important uncertainties.

Noticeable price differences in Climate Neutral Nordics scenario

The preliminary results from the simulations with the Climate Neutral Nordics scenario indicate high price differences and therefore high benefit for capacity between Norway and Denmark. National analysis done with Statnett's Long term market analysis (LMA) concludes the same.

The increasing price difference is also a result of the assumptions of higher CO_2 prices. The final decision to cut emissions by 55% by 2030 has contributed to a doubling of the CO_2 price in the EU ETS between November 2020 and May 2021. The increase in the CO_2 price is expected to continue and the CO_2 prices in the scenarios are between 75 – 100 €/ton in the Climate Neutral Nordics scenario and Statnett's LMA towards 2040. The impact of the CO_2 prices is higher in the 2030 scenario than 2040, where most of the thermal production capacity is phased out. Higher CO_2 prices result in higher marginal costs in fossil power plants and thus also higher power prices both on the Continent and in Norway. However, the Continental price-level increases more than the Norwegian, leading to higher price differences between Norway and Denmark and thus also higher benefits.

Next steps

The expected high price differences between Norway and Denmark indicates high socio-economic benefits of renewal of the SK12. Also, possible synergies between the Danish offshore energy island in the North Sea and the and the Norwegian offshore wind (Sørlige Nordsjø II) might be considered. In addition, the grid development both in Norway, Denmark and Germany is important for the NO-DK-capacity and needs to be further investigated.

5.5 Denmark-Sweden

Today Denmark and Sweden are connected between several bidding zones. Konti-Skan 1 and 2 which is connecting Jutland in Denmark (DK1) to Sweden (SE3) with a net transfer capacity of 715 MW, and Öresund cables which is connecting Zealand in Denmark (DK2) to the southern part of Sweden (SE4) with a total net transfer capacity of 1,300 MW import to Denmark and 1,700 MW export from Denmark. Konti-Skan 1 and 2 has an estimated end of life-

[30] The HVDC links SK12 were commissioned in 1976 and 1977, respectively.

time between 2030 and 2036, and the northern Öresund cable has an estimated lifetime around 2030. The corridor between Denmark and Sweden is important as it links areas with hydropower with areas with high dependencies on wind and solar power.

Development in the corridor since NGDP19

The corridor was investigated in the NGDP19 using the Nordic reference scenario. From the results of this early assessment, it seemed beneficial to maintain or increase the capacities between Sweden and Denmark. Therefore, it was suggested to study the possible alternatives in more detail.

Since the NGDP19 the reinvestment of the northern Öresund cable has mainly been analysed by Energinet as the cable is owned by Energinet. Energinet expects to present a business case in mid-2022 with a recommendation of the northern Öresund cable being reinvested with commissioning in the end of 2029.

Further, a full study on renewal of Konti-Skan 1 and 2 was started in spring 2021. Capacities of 0 MW to 1,400 MW (in both directions) are being investigated. So far there have been done some sensitivities on increasing the capacity between DK2-SE4 and different combinations of connecting to Bornholm Energy Island (connecting it to DK2, Germany and SE4) have been analysed. The socio-economic net welfare, calculated with rough investment costs, shows positive results for all cases. The sensitivities affect the welfare, but it remains positive. However, the study is still in an early phase and real costs, and accessibility and system studies are yet to be completed.

Noticeable price differences in Climate Neutral Nordics scenario

The IoSN study shows noticeable price differences between DK1-SE3 and DK2-SE4 in both 2030 and 2040. The price differences are among the highest in the Nordics and they are increasing from 2030 to 2040. The results from the IoSN study support the results from NGDP19 and the studies done on national analysis assumptions.

Next steps

Further work needs to be done to complete the business case for the northern Öresund cable and to complete the full study on renewal of Konti-Skan 1 and 2.

6 FURTHER WORK

The Nordic Grid Development Perspective will continue to be updated every second year. The next report will be published 2023. The exact scope of the next report has not yet been decided. However, updated Nordic scenario(s) and the overall need for more grid capacity are relevant topics for further studies. Also, synchronous area specific issues, such as development of inertia and converter connected generation will need to be jointly studied further.

The Nordic Solutions process is also a continuous work, and a solutions report is published every second year. Furthermore, the Nordic TSOs are also preparing a common Nordic strategy which will be published in the Solutions report of 2022. In addition to system planning aspects, the strategy will provide a broader view including markets and system operation. Moreover, the Nordic TSOs have identified the need of developing mid-term collaboration both in operational and planning aspects to complement the long-term collaboration.

In addition to Nordic collaboration, all Nordic TSOs are participating in European TSO processes. ENTSO-E is publishing the European Ten-Year Network Development Plan (TYNDP) every second year. A regional Baltic Sea investment plan is also published as a part of the TYNDP. The next TYNDP is published in 2022.

Furthermore, each Nordic TSO is continuously updating their national grid development plans and long-term network visions. These reports focus more closely on national grid investments and long-term aspects in each individual country.

A significant part of the Nordic cooperation is about sharing knowledge and data on the overall future system and market development, both in the Nordic area and in Europe as a whole. It is important that the processes are transparent and that stakeholders are involved at an early stage. Involvement of stakeholders through workshops and consultations will continue to be an important part of the Nordic grid planning and other collaboration. Thus, stakeholders are invited to give feedback on which topics the future collaboration should cover and how the collaboration processes should be improved.

7 ANNEXES

7.1 Consumption and generation in each country for Climate Neutral Nordics scenario

Nordic countries

	Type	2020	2030	2040
Electricity consumption (TWh)	General consumption	231	226	224
	Industry	131	185	179
	Datacentres	2	25	35
	Hydrogen/P2X	0	26	108
	Transport	3	22	51
	Heat pumps	9	17	23
	Other consumption	21	26	34
	Total	399	527	655
Renewable electricity capacity (GW)	Hydro	52	57	58
	Onshore wind	20	43	52
	Offshore wind	2	17	35
	PV	2	19	36
	Bio fuels	9	10	8
	Total	85	145	189
Thermal capacity (GW)	Nuclear	11	11	10
	Waste	1.2	0.8	0.8
	Fossil	6	5	2
	Total	17	17	14

Denmark

	Type	2020	2030	2040
Electricity consumption (TWh)	General consumption	30	32	34
	Industry	0	0	0
	Datacentres	0.4	7	10
	Hydrogen/P2X	0	5	15
	Transport	0.1	3	10
	Heat pumps	2	5	7
	Other consumption	3	4	5
	Total	35	55	80
Renewable electricity capacity (GW)	Hydro	0	0	0
	Onshore wind	5	6	5
	Offshore wind	2	10	15
	PV	1	6	9
	Bio fuels	2	2	1
	Total	9	25	30
Thermal capacity (GW)	Nuclear	0	0	0
	Waste	0.4	0.2	0.2
	Fossil	3	2	2
	Total	3	3	2

Finland

	Type	2020	2030	2040
Electricity consumption (TWh)	General consumption	36	38	37
	Industry	36	43	48
	Datacentres	0	9	9
	Hydrogen/P2X	0	2	28
	Transport	0.1	2	7
	Heat pumps	7	12	16
	Other consumption	3	3	4
	Total	83	109	150
Renewable electricity capacity (GW)	Hydro	3	3	3
	Onshore wind	2	12	17
	Offshore wind	0	1	3
	PV	0.2	1	4
	Bio fuels	3	3	3
	Total	9	21	30
Thermal capacity (GW)	Nuclear	3	4	5
	Waste	0.2	0.2	0.2
	Fossil	3	2	1
	Total	6	6	5

Norway

	Type	2020	2030	2040
Electricity consumption (TWh)	General consumption	87	83	80
	Industry	45	66	65
	Datacentres	1	5	8
	Hydrogen/P2X	0	3	8
	Transport	2.8	10	15
	Heat pumps	0	0	0
	Other consumption	4	5	6
	Total	140	172	183
Renewable electricity capacity (GW)	Hydro	33	38	39
	Onshore wind	4	6	7
	Offshore wind	0	1	3
	PV	0	4	8
	Bio fuels	0.005	0	0
	Total	37	49	57
Thermal capacity (GW)	Nuclear	0	0	0
	Waste	0.1	0	0
	Fossil	0.07	0.13	0.11
	Total	0.16	0.13	0.11

Sweden

	Type	2020	2030	2040
Electricity consumption (TWh)	General consumption	79	73	73
	Industry	50	76	67
	Datacentres	1	5	8
	Hydrogen/P2X	0	16	57
	Transport	0.4	7	18
	Heat pumps	0	0	0
	Other consumption	11	14	19
	Total	141	191	243
Renewable electricity capacity (GW)	Hydro	16	16	16
	Onshore wind	9	18	23
	Offshore wind	0.2	5	15
	PV	1	7	15
	Bio fuels	4	4	4
	Total	31	50	72
Thermal capacity (GW)	Nuclear	8	7	6
	Waste	0.5	0.5	0.5
	Fossil	0.1	0.7	0
	Total	8	8	6

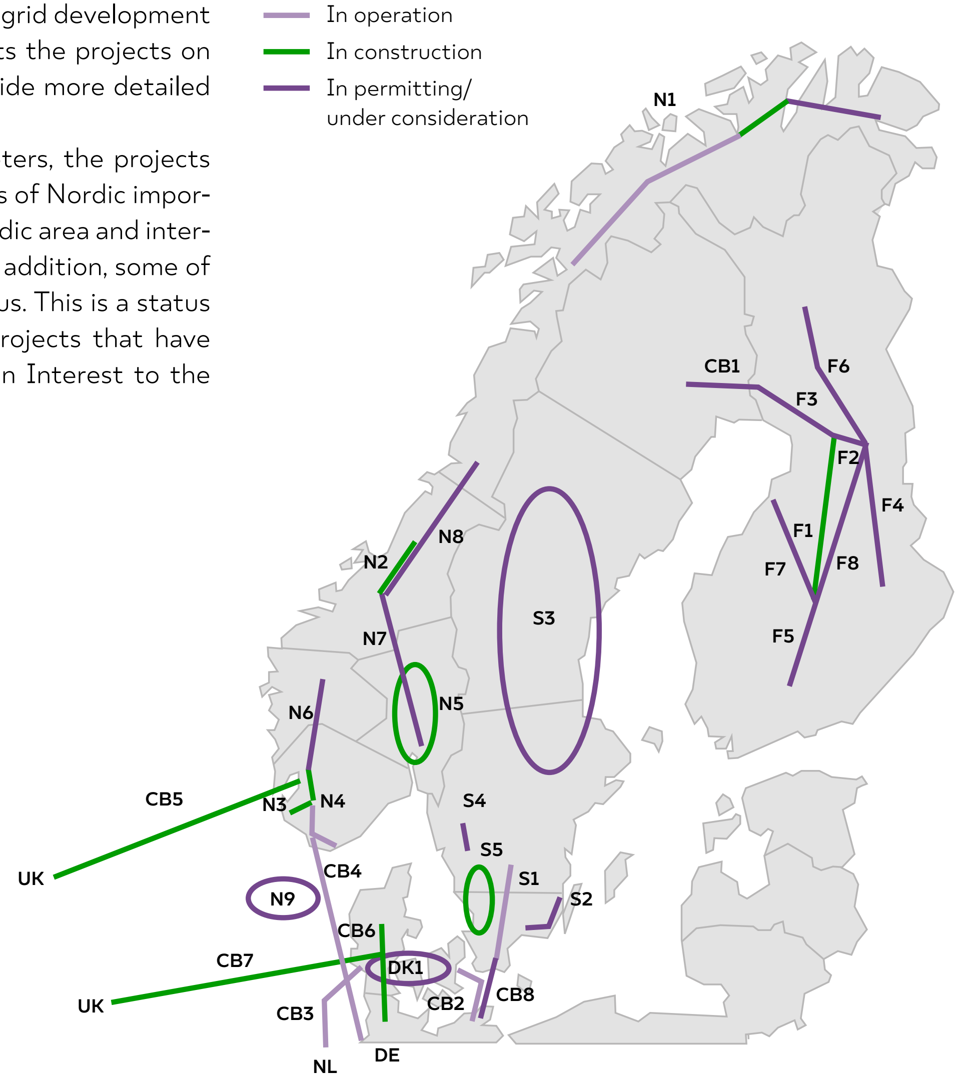
*Heat pumps are not modelled separately in Sweden.
**For Sweden, P2X includes new steel industry that uses hydrogen.

7.2 Status of grid development projects in the Nordics

This chapter presents the most significant grid development projects in the Nordics. Figure 18 presents the projects on a map and Subchapters 7.2.1 to 7.2.3 provide more detailed descriptions of the projects.

In the reporting of the following chapters, the projects have been categorised as: national projects of Nordic importance, cross border projects within the Nordic area and interconnectors to other synchronous areas. In addition, some of the projects have a reference to PCI-status. This is a status given by the European Commission to projects that have been deemed to be a Project of Common Interest to the European Union.

Figure 18 – Map of projects of Nordic significance.



7.2.1 National projects of Nordic significance

Each Nordic TSO has a large number of internal grid investments including reinvestments. Some of these investments have a more direct impact on the Nordic and European system as they are needed in order to use the cross-border interconnectors efficiently. The most important internal investments from a Nordic perspective are listed below.

Denmark

The grid developments in Denmark includes projects for connection of new consumption (data centres), new generation (offshore wind farms) and domestic reinforcements due to connection of new interconnectors. Some of the most important investments are summarized in the table.

	Project	Status	Description
DK1	**Endrup-Idomlund**	Decided The last section of the line is expected in operation 2024	Endrup-Idomlund and Landerupgaard-Revsing are both 400 kV domestic transmission lines. It is still uncertain what is needed in the Bjæverskov-Hovegaard project, but a 400 kV domestic transmission line is considered.
	Landerupgaard-Revsing	Under consideration Expected in operation 2026	The purpose of the investments is to integrate on-going and planned connections of renewable generation (offshore wind farms) and to connect new interconnectors to the domestic grid.
	Bjæverskov-Hovegaard	Under consideration Expected in operation 2026–2030	

Finland

The grid development in Finland is mainly characterised by several projects in the north-south-direction. The north-south reinforcements will facilitate integration of new renewables, power transmission from surplus areas to the deficit areas, and allow further integration with Sweden securing coverage of national consumption. In addition, there are also some important local grid reinforcement projects for example in Southern and Western Finland.

	Project	Status	Description
F1	**Pyhänselkä and Petäjävesi (Forest line)**	Under construction Expected in operation 2022	New 400 kV AC single circuit OHL of 300 km between Pyhänselkä and Petäjävesi. Built to increase the north-south transmission capacity thus enabling the integration of new renewable, new connection to Sweden and conventional generation and RES in Northern Finland and to compensate dismantling of obsolescent existing 220 kV lines.
F2	**Pyhänselkä-Nuojuankangas**	Under construction Expected in operation 2022	New 400 kV + 110 kV AC OHL of 45 km between Pyhänselkä and Nuojuankangas. Built ahead to compensate dismantling of obsolescent existing 220 kV lines.
F3	**Keminmaa-Pyhänselkä**	Planned/Under consideration Seeking permission Expected in operation 2024	This transmission line is part of the third 400 kV AC connection between Finland and Sweden (Aurora line). Aurora line project has PCI-status.
F4	**Nuojuankangas-Huutokoski. (Lake line 2)**	Planned/Under consideration Seeking permission Expected in operation 2026	New 400 kV AC single circuit OHL of 300 km between Nuojuankangas and Huutokoski. Enables integration of renewables and increases transfer capacity from north to south.
F5	**Petäjävesi-Hikiä**	Planned/Under consideration Seeking permission Expected in operation 2030	Continuation of the Forest line (F1) to the south to transport electricity to the consumption centers of southern Finland. Possibly 2 x 400 kV lines.
F6	**Petäjäskoski-Nuojuankangas**	Planned/Under consideration Seeking permission Expected in operation 2027	New 400 + 110 kV AC OHL between Petäjäskoski and Nuojuankangas.
F7	**Jylkkä-Alajärvi-Toivila**	Planned/Under consideration Expected in operation 2028	New 400 kV + 110 kV OHL (possibly partly 2 x 400 kV) between Jylkkä and Toivila. The line will enable connection of new wind power to the western coast and increase north south transmission capacity.
F8	**Nuojuankangas-Petäjävesi (Forest line 2)**	Planned/Under consideration Expected in operation 2030	New single circuit 400 kV OHL is planned to be built from Nuojuankangas to Petäjävesi. Enables integration of renewables and increases transfer capacity from north to south.

Norway

The grid development in Norway is characterised by several projects in the north-south-direction which will facilitate new renewables, facilitate increased interaction with other countries, prepare increased consumption and at the same time secure an adequate security of supply level.

	Project	Status	Description
N1	**Ofoten–Balsfjord–Skillemoen-Skaidi**	Under construction First two parts (Ofoten–Balsfjord and Balsfjord–Skillemoen) where taken into operation in 2017 and 2020 respectively Third part (Skillemoen-Skaidi) expected in operation 2022	New 420 kV-line (ca.450 km) will increase the capacity in the north of Norway, mainly to serve increased petroleum-related consumption, as well as increase the security of supply. In addition, the project will prepare for some new wind power production. A line further east (Skaidi-Varangerbotn) is planned. The first part, Skaidi–Lebesby, has applied for a permit. Lebesby-Varangerbotn is under consideration.
N2	**Fosen**	First part was taken into operation in 2019 Second part (Åfjord-Snilldal and Surna-Viklandet) expected in operation in 2027	New 420 kV-lines in Mid-Norway (Fosen) in order to facilitate new wind production and increased consumption.
N3	**Lyse - Fagrafjell**	Under construction Expected in operation in 2024	New 420 kV-line (ca. 70km) will increase the capacity in the Southwestern part of Norway. The project will increase the North-South capacity as well as facilitate high utilisation of the interconnectors.
N4	**Western corridor**	Under construction Final step expected in operation in 2021	Voltage upgrades in the Southwestern part of Norway. The project will increase the North-South capacity as well as facilitate high utilization of the planned interconnectors. Most of the project is set into operation.
N5	**Greater Oslo**	Under construction Planned/under consideration Expected to seek permission in 2023	Voltage upgrades in the Oslo region. The project will serve increased consumption in the Oslo region, as well as increase the capacity North-South in Norway and facilitate high utilisation of the interconnectors. A new 420kV-line (Fåberg-Oslo) is being planned.

	Project	Status	Description
N6	**Sogndal-Sauda**	Planned/ under consideration	Statnett is planning voltage upgrades (420 kV) that will increase the north-south capacity, facilitate increased consumption and facilitate high utilisation of the interconnectors.
N7	**Sunndalsøra - Oslo**	Planned/ under consideration	Statnett is planning voltage upgrades (420 kV) that will increase the north-south capacity and facilitate high utilisation of the interconnectors.
N8	**NO3 – south in NO4**	Planned/ under consideration	Statnett is planning an additional 420 kV line from NO3 to the southern part of NO4. This will increase the north-south capacity.
N9	**Hybrid Connection**	Planned/ under consideration	Statnett is planning a hybrid connection in the Norwegian sector of the North Sea, connecting Norway, an offshore wind farm and a second country. The hybrid will provide interconnector capacity in hours with low wind production.

Sweden

The grid development in Sweden is characterised by several large projects to increase grid capacity as well as studies on requests for connection of renewable power production, new industrial consumption and organic consumption growth.

During the past few years increasing efforts have been made to enable further consumption growth of city areas, since the often long permission process conflicts with city growth and the needs of new businesses.

	Project	Status	Description
S1	**SouthWest Link** 2*600 MW	In operation since July 2021	Will increase the internal Nordic capacity in a north – south direction between areas SE3 and SE4. This will make it possible to handle manage an increased amount of renewable production in the north part of the Nordic area as well as an increase in trade on Nord-Balt and the planned Hansa Power-Bridge with less risk for limitations. The project has been delayed due to difficulties in the implementation phase.
S2	**Ekhyddan – Nybro - Hemsjö**	Ekhyddan-Nybro (Seeking permission) Nybro-Hemsjö (permission granted) Expected in operation 2027	This is currently a PCI-project and has reapplied for continued status. New 400 kV AC single circuit OHL of 70 km between Ekhyddan and Nybro and a new 400 kV AC single circuit OHL of 85 km between Nybro and Hemsjö. The reinforcements are necessary to fully and securely utilize the NordBalt interconnection that is connected in Nybro. The projects will also facilitate the connection of offshore wind in the area. The project has been delayed due to longer than expected time to receive permission.
S3	**North-South** SE2 – SE3	Planned/Under consideration Expected in operation between 2025 and 2040+	A set of almost 50 different projects which will increase the capacity between bidding zones SE2 and SE3. In the near term, new shunt compensation, upgrades of existing series compensation and station components are planned for installation between 2026 and 2028. Three of the oldest of the 400 kV lines and the three 220 kV lines are expected to be replaced with new 400 kV lines with a higher transfer capacity. The first replacement is planned for 2033. These reinforcements will together significantly increase the north–south capacity in the internal Nordic transmission grid, from current 7,300 MW to more than 10,000 MW.

	Project	Status	Description
S4	**Skogssäter – Ingelkärr** **Ingelkärr - Stenkullen** Swedish west coast	Planned/Under consideration Seeking permission Expected in operation 2028–2030 and 2025 respectively	New 400 kV single circuit overhead line that will increase capacity on the Swedish west coast. This will lead to better trading capacity between Sweden, Denmark and Norway. The project has been delayed due to longer than expected time to receive permission.
S5	**Sweden southwest**	Planned/Under construction Expected in operation between 2021 and 2028	Replacement and thermal upgrade of several old 400 kV overhead lines on the west-ern coast of Sweden, along a line from Trollhättan (SE3) to Malmö (SE4). This corridor is highly important for the exchange of power between Norway-Sweden-Denmark. The upgrade program is required to maintain high availability and internal capacity of the Swedish west coast corridor. A high operational security on these power lines is crucial for trading capacities SE3-NO1, SE3-SE4, SE3-DK2 and SE3-DE.

7.2.2 Cross border projects within the Nordic area

	Project	Status	Description
CB1	**Aurora line** Sweden - Finland	Planned/Under consideration Seeking permission Expected in operation 2025	This is currently a PCI-project. New 400 kV AC-line cross the northern border between Sweden and Finland. The line will increase trading capacity and the possibility to exchange system services as well as increase the power adequacy in Finland. The project F3 (Keminmaa-Pyhänselkä) in the Finnish project list is a part of this cross-border connection and has also PCI-status.

7.2.3 Interconnectors to continental Europe/Great Britain

	Project	Status	Description
CB2	**Kriegers Flak CGS** 400 MW Denmark East – Germany	The Combined Grid Solution was taken into operation in December 2020	Secure connections to shore are vital for the Kriegers Flak offshore wind farm. The offshore interconnector was developed in collaboration with the German TSO (50Hertz Transmission GmbH). The new interconnector takes advantage of the proximity of Danish and German wind farms by adding short cables and thus connecting the wind farms to both Germany and Denmark.
CB3	**COBRA** 700 MW Denmark West – The Netherlands	Taken into operation in September 2019	The purpose of the COBRA cable is to improve the cohesion of the European transmission grids by increasing the exchange of excess wind power to neighbouring countries and strengthening the electrical infrastructure, the security of supply and the European electricity market. The interconnector goes from Endrup in Denmark West to Eemshaven in Holland.
CB4	**NordLink** 1,400 MW Norway – Germany	Commisioned 2020	HVDC subsea interconnector between southern Norway (Tonstad) and Northern Germany (Wilster). The interconnector will improve security of supply both in Norway in dry years and in Germany and Continental Europe in periods with negative power balance (low wind, high demand etc.). Additional the interconnector will be positive both for the European market integration, for facilitating renewable energy and also for preparing for a power system with lower CO_2-emission.
CB5	**North Sea Link** 1,400 MW Norway – Great Britain	Commissioned Q4-21 (Expected in operation Q4-2021)	720 km long HVDC subsea interconnector between western Norway (Kvilldal) and eastern England (Blyth). The interconnector will improve security of supply both in Norway in dry years and in Great Britain in periods with negative power balance (low wind, high demand etc.). In addition, the interconnector will be positive both for the European market integration, for facilitating renewable energy and also for preparing for a power system with lower CO_2-emission.
CB6	**The West Coast project** 1,000 MW Denmark West - Germany	Under construction Expected in operation in 2023	The West Coast project is a project of a double 400 kV line from Endrup to Klixbüll where it is to connect with the two 400 kV lines being build up along the German western coastline in Schleswig Holstein. This project increases the possibility of exporting and importing electricity on the border from 2,500 MW to 3,500 MW in 2023. The project has currently PCI-status (List IV), but has not reapplied for continued status.

	Project	Status	Description
CB7	**Viking Link** 1,400 MW Denmark West – Great Britain	Under construction Expected in operation 2023	The Viking Link project was approved by the Ministry, the 30th of October 2017. The project aims at integrating the electricity markets of GB and DK to increase the value of wind power as well as improving security of supply in GB in the long term. The project is closely connected to an expansion of the internal western Danish grid as well as additional interconnection to Germany, in the so-called West Coast project. This is currently a PCI-project (List IV), but has not reapplied for continued status.
CB8	**Hansa Power-Bridge** 700 MW Sweden - Germany	Planned/Under consideration Seeking permission Expected in operation 2025/26	A HVDC subsea interconnector between Hurva in southern Sweden and Güstrow in Northern Germany. A decision to start further project work on permissions has been taken in early 2017.

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