GRENSELANDET, ST1 NORWAY GRID CONNECTION

Grid Connection Study Davvi Wind Farm

St1 Norway AS

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Table of contents

EXECUTIVE SUMMARY

Grenselandet AS is developing the 800 MW Davvi wind power plant project in Finnmark county, Norway. The company St1 Norway AS has requested a transmission system study regarding the connection of Davvi to the transmission grid, and the primary purpose of this study was to identify consequences of Davvi wind farm to the north part of the Nordic transmission grid. This study also investigated the results from a study of the future power production and grid in Finnmark by Statnett in their report "Vindkraft i Øst-Finnmark Muligheter og konsekvenser" from 2018.

The method of this study was to receive existing grids from the Norwegian and Swedish TSOs, Statnett and Svenska Kraftnät, and combining these into one grid. Then Davvi, as well as the wind farms and transmission lines that were identified to be important for this study and would be built until 2025, were added to the model to create a 2025 reference case. Then different scenarios and line trips were analyzed in order to determine how Davvi would affect the transmission grid.

The cross reference of Statnett's future scenario was made to the extent the details in Statnett's report allowed. The results from this analysis agreed with Statnett's results, which was that reactive power reserves and voltage limits in buses were bigger issues than thermal limits in lines.

Apart from the 2025 reference case, 3 different scenarios were analysed: maximum production, minimum local load; maximum production, maximum load; and minimum production, minimum local load. None of the scenarios showed issues for voltage levels in buses in the transmission grid, but the scenario with maximum production, minimum local load showed a breaching of the thermal limit of the 420 kV line between Vietas and Porjus, and was therefore deemed unacceptable.

The breaching can be combatted in different ways: curtailment of power production; increase in load; strengthening of lines; series compensation or line splitting of specific lines in order to direct the power; or a combination of some or all of the above. A curtailment in production could be done either by the wind farms in Finnmark, or by hydro power north of Vietas. Series compensation of the 420 kV line to Finland showed satisfactory results and greatly relieved the overloaded lines. The 132 kV regional line between Sildvik and Tornehamn was also overloaded which was resolved by making it radial. Some regional lines were overloaded because of some of the new wind farms, but these lines are being strengthened at the moment, and will be able to handle the increase in power.

Several different trips of lines were carried out to investigate how the grid handled (N-1) and (N-1-1) situations. The lines that were tripped were both close to Davvi, and further south along the corridors down both Norway and Sweden. The trips were applied to three scenarios: maximum production, minimum local load; maximum production, minimum local load but Davvi was restricted to 350 MW; and maximum production, maximum load.

As the first scenario already showed problems without tripping lines, trips of lines lead to many issues in the grid. As for the other scenarios, some trips still lead to overloading in the grid. The most critical trip was of the 420 kV line between Davvi and Adamselv. The lines that were subject to overloading were the 420 kV line between Vietas and Porjus, the 420 kV line between Porjus and Harsprånget and the 132 kV line between Lakselv and Adamselv.

Overall a connection of all the potential wind power (1400 MW) in Finnmark is feasible, as long as the 420 kV line between Skaidi and Pirttikoski is built. Certain scenarios and trips of lines will pose problems for some lines in the transmission grid, but measures to combat this have been identified. This study has not investigated how common or plausible these scenarios are.

1 INTRODUCTION

Grenselandet AS, a joint venture by energy company St1, Vindkraft Nord AS (VKN) and Ny Energi AS, is developing the 800 MW Davvi wind power plant project in Finnmark county, Norway. The company St1 Norway AS has requested a transmission system study considering the connection of the planned Davvi WPP to the Nordic transmission grid.

The primary purpose of the study is to identify consequences of Davvi wind farm to the north part of the Nordic transmission grid (NOR/SWE/FIN). Before the License application for Davvi WPP will be considered by the Norwegian Water Resources and Energy Directorate (NVE), the developer must conduct studies and surveys to satisfy the impact assessment program (NVE 1, 2018) as issued by NVE.

St1 Norway has appointed DNV GL to perform power system assessments. DNV GL has carried out stationary grid calculations to evaluate the consequences of the grid connection of Davvi wind farm to the Nordic transmission grid, including existing bottlenecks, capacity restrictions and interactions between the wind farm and existing hydro and nuclear/thermal production.

1.1 Davvi WPP and grid connection

Davvi wind farm is planned to be situated in Finnmark county, in the northern part of Norway. At this stage pre-studies are carried out to map the potential consequences that would arise if the park will be built, and suggestions for which full studies should be performed in order to be granted building and operating permissions. This report is part of the initial study.

Planned totally installed power in the park is 800 MW, and depending on which turbines are on the market at the time of construction there will be built between 100 and 267 wind turbines with a nominal power between 3 and 8 MW (Grenselandet AS, 2017). Estimated construction phase is 2025-2030 and the existing and decided transmission grid in close proximity to the park is shown in Figure 1.

Figure 1: Existing transmission grid near Davvi wind farm**.**

Grenselandet AS is planning for a grid connection of Davvi wind farm directly to the 420 kV line between Lakselv and Adamselv, in accordance with the map shown in Figure 2.

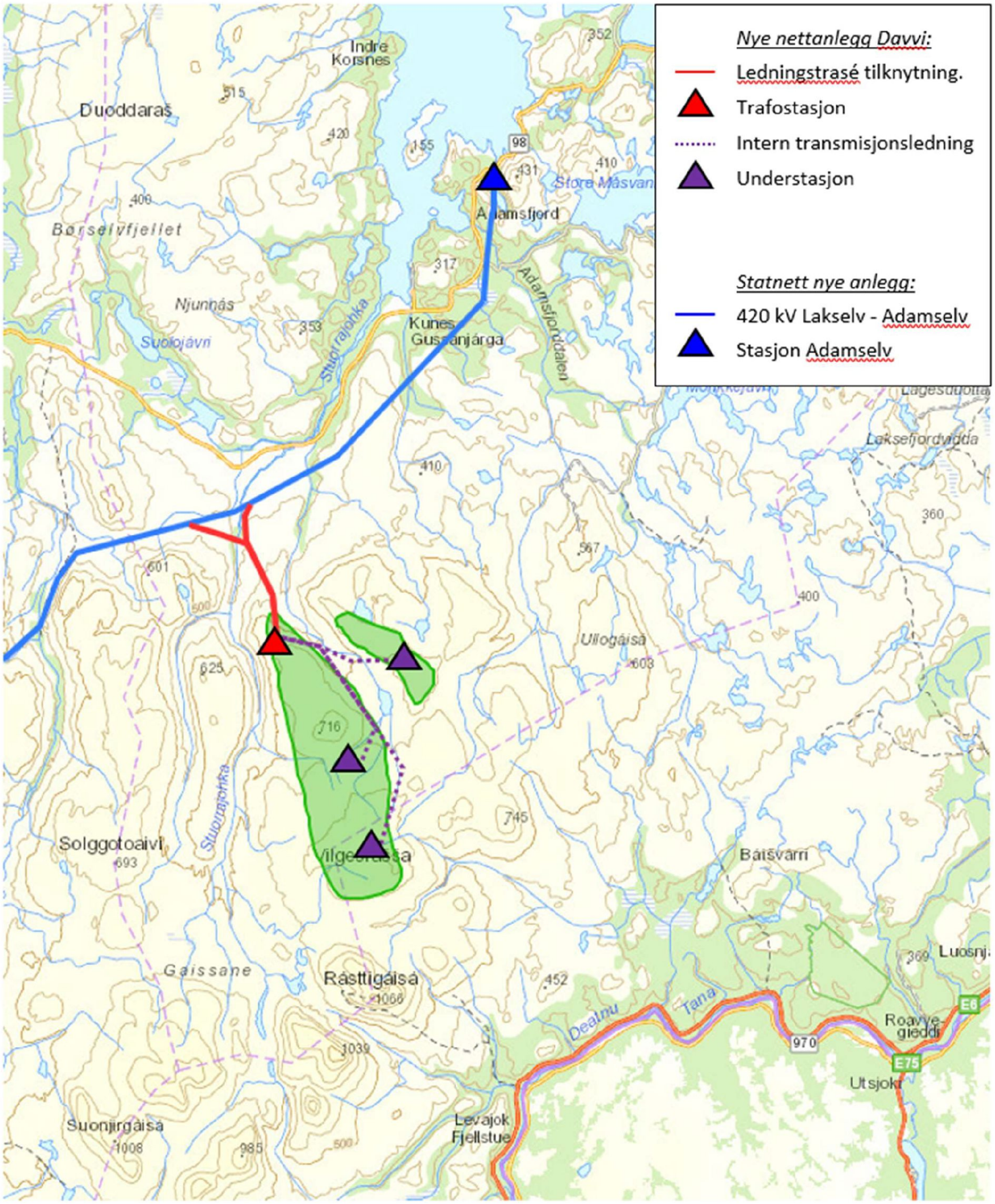

Figure 2: The whole park with its 800 MW is planned to connect towards the Norwegian Statnett planned 420 kV network Skaidi-Varangerbotn, which will have a transformer station at Davvi **(Grenselandet AS, 2017)**.

Only one grid connection alternative has been studied, see Figure 3, where the new 420 kV power line will go past Davvi wind farm on its way from Lakselv to Statnett's planned 420/132 kV Adamselv transformer station.

Figure 3: The planned 420 kV line Skaidi-Varangerbotn with a planned transformer station at Adamselv. Davvi will be connected to the line between Lakselv and Adamselv.

1.2 Statnett analysis of wind power in eastern Finnmark

Statnett has in the report «Vindkraft i Øst-Finnmark» analyzed the potential for installing new wind power in Finnmark. The report concludes that there is 175 MW wind power with concession in eastern Finnmark, and there is not grid capacity for all of the wind power to be installed. The report concludes that voltage limits will be breached long before thermal limits of lines will be reached mainly due to the long distances of the lines. Wind power poses also another challenge which is the rapidness of change in production which means that any reactive power compensation has to be rapid.

For the grid to be able to handle all the wind power, a 420 kV line from Skaidi to Varangerbotn is necessary, but this line is not socio economically profitable based on the information Statnett had at the time of the report (March 2018). The line would allow for 300 MW of additional wind power to be built. It would be possible for grid strengthening to be justifiable if even more wind power was to be built in Finnmark, and for that to be possible three possibilities were suggested: two 420 kV lines to Varangerbotn, an HVDC link or a 420 kV line to Varangerbotn together with a 420 kV line down northern Finland (Statnett, 2018).

A part of this study is to create a similar future scenario, taking place 2025, as Statnett deems possible without extending the 420 kV line from Skaidi, and compare the results.

1.3 Scope of work

This study is to form the basis for the developer's coverage of the following parts of the by NVE issued impact assessment program:

Nettilknytning

- *Kapasitetsforhold og behov for tiltak I overliggende nett skal beskrives og eventuelt omsøkes, herunder hvilke tiltak som eventuelt må gjøres på finsk side av grensen.*
- *Det skal redegjøres for hvordan tiltaket kan påvirke forsyningssikkerheten.*
- *Det skal beskrives hvordan økt kraftproduksjon i Finnmark kan påvirke kraftflyten i nettet. Herunder skal det redegjøres for tapskostnader, flaskehalskostnader og eventuelle systemdriftskostnader i transmisjonsnettet.*

This study has evaluated the following for the combined transmission system of the northern Nordic (NOR/SWE/FIN):

- Statnett's evaluation of grid capacity for connection of wind power in Finnmark.
- Existing bottlenecks/capacity restriction/limitations due to:
    - Thermal/rated limits of transmission components
    - Under- and overvoltages in buses
- Necessary measures (on system level, no detail engineering of solutions) to increase the transmission system capacity (if needed) and to accept the connection of Davvi wind farm at 800 MW, as well as MW from other wind farms with concession which cannot connect to the existing grid due to limited capacity.
- Reactions in the grid to transmission line failures.

The study and analysis has considered the development of the Davvi wind farm and its impact on the central grid (Transmission System Operator, TSO, networks) as well as all permitted wind farms in the Finnmark area. The study has not investigated costs or losses in the transmission grid.

2 BASIS FOR THE WORK

This chapter describes the basis for the work including methodology, preconditions, limitations, as well as description of the design of the assumed grid 2025.

2.1 Methodology

The following methodology was employed for the project:

- Collect and validate data both from employer and TSOs in Norway and Sweden.
- Build a unified model of the existing system as of 2018. If any data that is deemed necessary for the results is unattainable by DNV GL, then estimations are used. The program PSS/E version 34 was used for all simulations.
- Create a reference case similar to the one analyzed by Statnett in their report «Vindkraft i Øst-Finnmark», and compare results.
- Identify power lines, loads and production plants that will be built until 2025 and will have an impact on the result of this project.
- Add the findings from the previous post to the model according to the best of knowledge as of 2019 in order to create an estimated model of the power system, with loads and production, how it will look like in 2025. This will be used as a reference case.
- Analyze the created model and identify bottlenecks and potential weak cross sections.
- Run tests for different load scenarios.
- Set up different scenarios to be tested according to the (N-1) and (N-1-1) principle.

2.2 Technical preconditions

- A precondition for all analysis conducted as part of the study, is that the 420 kV power line "Arctic circle" Skaidi (NOR) – Varangerbotn (NOR) – Vajukoskki (FIN) is established at the time of connecting Davvi WPP.
- For the study, the single Point of Connection for Davvi WPP and a single grid connection solution has been assumed: Connecting to the 420 kV side of Adamselv (an existing 132 kV station that is likely included in the 420 kV "Arctic circle").
- Estimated construction phase for Davvi wind farm 2025-2030, and general grid development level 2025 has been assumed for the study.
- The study has considered existing power plants in the system, and included new (licensed) WPP in Troms and Finnmark Norway.
- All data used for the study was provided by the TSOs, the employer, taken from open sources, or estimated by DNV GL.

2.3 Limitations

The focus of the study has been on transmission system capacity and transmission system operation. Detailed analysis of WPP performance based on specific parameters/internal grid components, etc., were not conducted unless strictly necessary to clarify the aspects of the transmission grid capacity. This study has analyzed a steady state scenario and has not done a dynamic modeling or considered angle or frequency stability.

DNV GL has for this study assumed that:

- Davvi WPP will be equipped with sufficient technical capabilities of the wind power plant (like FRT capabilities, reactive power capabilities, SC rating, protection, breaker functionality, etc.) to meet:
  - Needs identified in the present study.
  - Normal grid compliance requirements for WPPs (as specified in Regulations (FEF/FoL) and TSO requirements (FIKS2012 in Norway))
- The dynamic properties and harmonic/flicker contribution from Davvi WPP Harmonic / THD has been similar or superior to the current state of art WTG technology of today.
- A simplified model of the wind power plant was used.
- No specific detailed studies or assessments of consequences in DNO networks (<132 kV) were conducted.
- Only components that are part of the transmission grid in Finnmark, Troms, northern Nordland, SE1 and northern Finland were subject to analysis.

2.4 Data

A grid model of the Norwegian high voltage power system was provided from the TSO Statnett in the form of a PSS/E model on the 6th of December 2018. A grid model of the Swedish high voltage power system was provided from the TSO Svenska Kraftnät in the form of a PSS/E model on the 6th of December. The Finnish TSO Fingrid did not provide any model of their power system as "the planned connection point is in Norway and Statnett will be the contact point regarding the connection of the wind park." Furthermore, Fingrid thinks that the responsibility of the main grid development and cross-border connection studies are with the TSOs" (Karlsson & Uusitalo, 2018).

The Finnish grid has been represented by a couple of buses on the border to the Swedish and Norwegian grid, as well as an equivalent that was provided in the model received by Svenska Kraftnät. The connections in the Finnish grid can be seen in Figure 4.

Figure 4: The buses and connections in Finland as received from Svenska Kraftnät. The 420 kV line from Varangerbotn to the Finland equivalent, and one of the 420 kV lines (there are now two) from Keminmaa to Sweden was added by DNV GL.

2.5 Setup of the PSS/E grid model for the existing grid

Both the grid of Norway from Statnett and the grid of Sweden from Svenska Kraftnät were high load cases and were solvable with a full Newton-Raphson method, however not from flat start. Both models contained 8 border buses that symbolized the borders between the three countries (7 between Sweden and Norway and 1 between Norway and Finland) where the lines cross the borders in reality. The buses had the same numbers and were connected to the same buses on each side for every instance except for one, which could be solved easily.

The model of Norway had a load equivalent connected to every border bus that symbolized the flow in and out of the country for that particular border line. The model of Sweden contained dummy nets of both Finland and Norway that worked as equivalents for those grids. When the two grid models were merged, all buses in Norway in the Swedish model were deleted, and the border buses were used as interface between the two systems. Load equivalents for the flows assumed in the different models were implemented for the two models to correspond to the power flow across the borders.

2.6 Statnett 2025 reference case

The case that was investigated as comparable to the possible future case in Finnmark, is a case where the 420 kV line from Balsfjord to Skaidi is built (see Table 2 for information regarding this line), and that the wind farms with respective power as seen in Table 1 are installed. The case takes place 2025 and does not include the 420 kV line Skaidi – Varangerbotn – Pirttikoski nor Davvi WPP. This case does not include the 420 kV between Jokkmokk and Messaure either as the case only investigated the grid in Finnmark and Troms.

Wind farm	Installed power today MW	Installed power 2025 MW
Hamnefjell	51.75	51.75
Rakkocearro 1	45	45
Rakkocearro 2	Under construction	50
Kjøllefjord	39.1	39.1
Havøygavlen	40.5	40.5
Dønnesfjord	Under construction	14.1
Fakken	54	54
Kvitfjell	Under construction	197.4
Raudfjell	Under construction	84
Nygårdsfjellet	32.2	32.2
Andmyran		100
Ånstadblåheia	50.4	50.4

Table 1: Wind power in Finnmark in a potential future scenario that is deemed possible by Statnett per their report «Vindkraft i Øst-Finnmark» where a 420 kV line is built to Skaidi, but not to Varangerbotn.

Since the report did not state which (N-1) scenarios were tested this study did not carry out any such scenarios.

2.7 2025 Reference case

In order to do analysis on how Davvi will affect the transmission grid in 2025, a 2025 reference case was built. This case was kept as alike the received grids as possible, with the addition of lines and wind power that were considered to be built by 2025 and have an impact on Davvi's interaction with the transmission grid. In this chapter, all lines and power production that were added are described, and they were added to the model of the existing grid that we created by connecting the received grids from Statnett and Svenska Kraftnät described in section 2.5. All other scenarios analyzed later were based on this 2025 reference case.

2.7.1 Planned grid developments

The power lines listed in Table 2 have been identified as being considered for construction by the Norwegian, Swedish or Finnish TSOs, and have been deemed as potentially important for this project. See also Figure 5 for location of listed power lines.

Object	Comment
420 kV power line Balsfjord (NOR) – Skaidi (NOR)	Statnett is extending the existing 420 kV grid in Norway and Sweden up into Finnmark by building a 420 kV line between Balsfjord and Skaidi. This line is being built at the moment, (NVE 2, 2018) and DNV GL has assumed that this line will be completed by 2025.
The 420 kV power line "Arctic circle" Skaidi (NOR) – Varangerbotn (NOR) – Vajukoskki (FIN)	This power line will be indispensable for the project Davvi WPP, and the whole project is dependent on it being built. DNV GL has assumed that this line will be built by 2025, and the Norwegian part has been notified (Skaidi – Varangerbotn) (NVE 3, 2018). According to an analysis done 13.03.2018 by Statnett, the part of the line Statnett would be responsible for, (Skaidi – Varangerbotn) would not be socio economically profitable based on the information at the time of the report. If the line is not built, then many of the wind farms in the area that have already been granted concession will not be able to be built, as there is not enough capacity in the grid (Statnett, 2018). Statnett has applied for concession for a strengthening of the 132 kV line from Lakselv and north, but this analysis has not taken into account any upgrades on that line. It is still unsure if the part of the line between Skaidi and Varangerbotn will be built, but for this analysis it is assumed that this line is built by 2025.
420 kV power line Varangerbotn (NOR) – Pirttikoski (FIN)	The northern end for the 420 kV net in Finland is Pirttikoski, and the current line between Pirttikoski and Varangerbotn is 220 kV. Fingrid's official statement for the development plans for the northern region is: "The possibility of increasing the current transmission capacity between northern Finland and northern Norway by means of a transmission line between Pirttikoski and Varangerbotn has been reviewed, but investigations currently remain on a conceptual level only. The possible need for transmission capacity is associated with the fact that the oil industry in northern Norway is expected to have a greater need for electricity and to utilize the outstanding wind generation potential in the region. Fingrid is preparing for future transmission needs by investigating the route for the required new transmission line. Fingrid's aim is to mark the indicative transmission line on the pending regional land use plan for northern Lapland.", (Fingrid) p.30. As the power transmission south is of critical importance for Davvi wind farm, and this line is a precondition for the farm to be built, it has been assumed that it is built for all analysis. As Pirttikoski does not exist as a bus in the received models, the

	line has been drawn between Varangerbotn and the Finnish equivalent bus.
Power line between Jokkmokk (SWE) and Keminmaa (FIN) 800 MW (Messaure – Keminmaa – Pyhänselkä)	Planned to be in use by the end of 2025 (Fingrid). DNV GL has assumed that this line will be built by 2025. As Pyhänselkä does not exist as a bus in the received models, the line has been drawn from Messaure to Keminmaa. Keminmaa was already connected to the Finnish equivalent bus.
400 kV Power line "The Forest Line" between Oulu (FIN) and Petäjävesi (FIN) 700 MW	This line is planned to be finished by 2022, and will help the transmission south in Finland (Fingrid, 2017). As DNV GL did not receive the Finnish net from Fingrid, we did not include this line in the model.
Kvarken DC line from Vaasa (FIN) across Kvarken to Sweden 800 MW	As one of the DC lines between Finland and Sweden will soon reach its end of operation, a new DC line is planned that will be finished at the end of 2020s (Fingrid, 2017). As this line is so far from being finished, and is far away from Davvi, DNV GL has not included this line in the model.

Table 2: Identified power lines that are planned to be constructed and will have an impact on Davvi wind farm.

Figure 5: The transmission grid in the Nordic and Baltic countries **(Svenska Kraftnät, 2013)**, where the key points for this project have been pointed out by DNV GL.

For the 420 kV lines that were added to the model, it was assumed that these would go parallel and use the same power line corridor as the 132 kV lines and 220 kV lines that they are supposed to relieve or replace. In order to ratings and impedance values for the lines, values from lines close to where the lines were to be built were used as references.

Buses corresponding to all the main connections on the 132 kV and 220 kV lines were added, but transformers to the 132 kV and 220 kV stations were added in Lakselv, and where the total installed power of the nearby production exceeded 100 MW. In Table 3 all the buses between Balsfjord and Varangerbotn are listed, and the connected total installed power in MW by 2025. According to the principle explained earlier only Skaidi, Adamselv and Varangerbotn will have transformation from the 420 kV level to the 132 kV grid.

Station	Total installed power MW after added planned production 2025
Skibotn	80.5
Goulasjåkka	85.2
Nordreisa	10
Kvænangen	80
Alta	62
Skaidi	362.1
Lakselv	1.6
Davvi	800
Adamselv	95.5
Varangerbotn	399.2

Table 3: Buses between Balsfjord and Varangerbotn and the total installed generation connected to them.

When the line between Balsfjord and Varangerbotn was added to the model, the voltage on the buses were more than 1.1 per unit of base voltage, which is too high. This is normal for new lines as they tend to not be heavily loaded. To compensate for this, two reactors were added to the bus Skaidi and Varangerbotn in form of switchable shunt reactors of 200 Mvar (in 2 steps of 100 Mvar) and 100 Mvar respectively.

The line that was added in Finland along the 220 kV line was connected directly to the Finnish equivalent bus as no buses existed along the way in the received grid.

2.7.2 Planned production developments

All wind power farms that have been built, are being built or have been given concession, within a 400-km radius from the Davvi wind power farm in the NVE map tool, are listed in Table 4. All these are expected to be built, or still exist in 2025 and are therefore kept, adjusted or added to the model per the client. Existing hydro power is assumed to not be subject to dismantling, and no hydro power is assumed to be built. As a comparison, the power assumed for the Statnett reference case from Table 1 is included in this table as well.

Name	Installed power MW	Statnett reference case MW	Planned power 2025 MW	Status	Grid status
Hamnefjell Vindkraftverk	51.75	51.75	120	Drift	In received grid, modified
Rakkocearro (Raggovidda) vindkraftverk	45	45	45	Drift	In received grid
Rakkocearro (Raggovidda) vindkraftverk Trinn 2	-	50	155		Added
Kjøllefjord vindkraftverk	39.1	39.1	39.1	Drift	In received grid
Havøygavlen vindkraftverk	40.5	40.5	45	Drift	In received grid
Davvi	-	-	800	Melding	Added
Dønnesfjord vindkraftverk	-	14.1	14.1	Under arbeid	Added
Fakken vindkraftverk	54	54	54	Drift	In received grid
Kvitfjell vindkraftverk	-	197.4	197.4	Under arbeid	Added
Raudfjell vindkraftverk	-	84	84	Under arbeid	Added
Nygårdsfjellet vindkraftverk trinn 2	32.2	32.2	32.2	Drift	In received grid
Andmyran vindkraftverk	-	100	100	Konsesjon gitt	Added
Ånstablåheia	50.4	50.4	50.4	Drift	Added
Sum	312.95	758.45	1736.2		

Table 4: Wind farms that already exist nearby Davvi, are planned or will be built nearby Davvi before 2025.

The following wind farms has been recognized as potential wind farms to be built, but have not been included in the 2025 reference case because they have been inactive for some time and/or have not come as far in the process as Davvi and have therefore been assumed unlikely to be built by 2025: Borealis, Digermulen, Laksefjorden, Skjøtningsberg, Nordkyn, Bjørnevatn, Snefjord, Maurneset and Kroken. Sandhaugen teststasjon lost its concession and was therefore not included either.

Most of the wind farms that are already in operation were present in the grid received from Statnett, and the rest were added at the most appropriate bus depending on their geographical position. Both Hamnefjell and Raggovidda which had a significant increase in their installed power were moved in the model to be directly connected to the 400 kV bus as the regional net could not handle the transmission of increased power. It was assumed that in case the parks were extended the regional net would be reinforced to handle the increased power.

Raggovidda phase 2 with 50 MW was not present in NVE but added on request from the customer. Planned installed power for the different wind farms have been updated as per information from the customer. For all added wind farms, a reactive capability in order to achieve PF=+/-0.95 at PCC was assumed. For the 2025 reference case, all wind farms were producing as they were in the received grid for the wind farms already present. All added wind farms were set to produce around 80% of their maximum capacity and Davvi was producing maximum installed power.

1900 MW wind power and 1200 MW nuclear power is planned to be built and connected to the grid in mid Finland [5]. Since DNV GL did not receive the Finnish grid from Fingrid this production has not been included in the model as it is assumed that the impact from these installations will be handled in the Finnish grid.

As the new wind farms were connected to the grid, the overall power in the system increased. To compensate, the power production from ten large hydro power plants was decreased. The power plants were chosen so that the transmission net would be minimally loaded. To regulate down the generation on the net in reality, one generator is turned off rather than lowering the generation on several generators as you want every generator that is running to run on its highest efficiency rate. For this analysis however, we have simplified the procedures to reduce generation rather than turning off generators.

2.8 Connection Davvi wind farm to Adamselv

The grid connection from Davvi wind farm will be on the 420 kV line between Lakselv and Adamselv, see Figure 3. The line from Lakselv is planned to go south east down to Davvi, and then up north east again to Adamselv. Davvi WPP will have an internal grid with a voltage of 33 kV (Grenselandet AS, 2017). Davvi will be directly connected to the 420 kV net.

3 ANALYSIS

The analysis of the assumed grid in 2025 focused on limit breaching of thermal limits of lines, and voltage limits of buses. Limit checks were done for different scenarios and different line trips, described in this chapter.

3.1 Limits that were investigated

For all cases, potential limit violations will be investigated. Limits to consider are:

- Equipment overload (based on the thermal limits) in the transmission grid.
- Under– or overvoltages (420 kV, 220 kV and 132 kV buses) in the transmission grid.

3.1.1 Limits for equipment overload

For every line, 3 rates of maximum MVA that is allowed on the lines are specified. The rates are set accordingly for the two systems:

Svenska Kraftnät:

Rate A: +20 °C normal operation including limiting devices

Rate B: +20 °C emergency operation including limiting devices

Rate C: +20 °C normal operation excluding limiting devices, i.e. solely the capacity of the line

This means that all 3 rates are set for summer temperatures (as the ambient temperature rises, the MVA capacity of the lines decreases, which means that less load can be transported). For this analysis, Rate A was used as it is desirable to include the limiting devices, typically located at the ends of the line. In case equipment overload would occur, scaling based on numbers from Statnett would be used to investigate if the same scenario would work during winter. Parts of the model from Svenska Kraftnät that is not owned by Svenska Kraftnät (lower voltage levels, radial net) used the following system for the rates:

Rate A: x °C winter, normal operation

Rate B: x °C winter, emergency operation

Rate C: x °C summer, normal operation

There are several different grid owners in Sweden, and they use slightly different line temperatures for the different rates.

Statnett:

Rate A: 0 °C normal operation including limiting devices

Rate B: +10 °C normal operation including limiting devices

Rate C: +20 °C normal operation including limiting devices

For the lines in Norway, Rate C was used as it represents summer during normal operation including limiting devices. The power limit during summer is lower than it is for winter, why it is most interesting to look at that limit.

For the parts of the grid received from Statnett that is not owned by Statnett, it was assumed that they use the same system as Statnett to set their rates.

In the models received, several lines were overloaded already. The lines that were overloaded were in the distribution system, and these lines are not owned by the TSOs and they are not of interest in this analysis. Only overloading of transmission grid lines in SE1 and north were considered in this analysis.

3.1.2 Limits for under- or overvoltages

All buses have set maximum and minimum allowed voltages both for normal and emergency operation. These vary typically between 0.9-1.1 per unit of base voltage, but depending on what is connected to the bus the limits can be set differently, as some buses are more sensitive to varying voltages. In the cases received from both Statnett and Svenska Kraftnät, some buses had higher or lower voltage levels than their normal and emergency operations limits. It is assumed that this was tolerable and a list of those buses and their limits were kept. Only breaching of limits of buses of the following buses were considered in this analysis: all 132 kV and higher buses in Finnmark, Troms and northern parts of Nordland; the 420 kV buses along the transmission line from Ofoten down in SE1 (Harsprånget, Ligga etc.); all 420 kV buses in Finland.

3.2 Scenarios that were investigated

4 scenarios were studied. All scenarios are described in the subsections below.

3.2.1 2025 reference case

The model that was built and used as a reference case represented how the net in Finnmark and northern Nordics would look like in 2025. The scenario had high wind farm production and high load, according to Table 5. This case was used as a reference for a likely high load scenario. “Other WPP” is referring to the wind farms investigated in Table 4, and were the ones changed in the different scenarios. This case did not change any loads or exports from received nets but adjusted the hydro power in order to receive balance in the net.

Davvi WPP production [MW]	Voltage level Davvi PCC [pu]	Other WPPs production [MW]	Other production (hydro)	Load Finnmark	Export	Load net
800 (max)	1.0175	As per the received net, or around 80%	Adjusted to fit the scenario	High	As per received net	High

Table 5: Conditions for the reference case.

3.2.2 Maximum production, minimum local load

This scenario was to investigate the transmission system bottle necks using a situation with high production in the north together with high load in the country as well as southern parts (export to Europe), but low load in the northern parts. It is based on the 2025 reference case with all its added wind power and lines, but changed loads and production according to Table 6.

In the reference case, the hydro power was adjusted to compensate for higher production in the north from wind power. In this case, the hydro power that had been regulated down was restored to the values they had in the received models, and instead the load on the HVDC links south was adjusted up to compensate for the surplus of power.

Davvi WPP production [MW]	Voltage level Davvi PCC [pu]	Other WPPs production [MW]	Other production (hydro)	Load Finnmark	Export	Load net
800 (max)	1.0175	Maximum	High	Minimum	Adjusted to fit the scenario	High

Table 6: Test conditions for scenario maximum production, minimum local load.

3.2.3 Maximum production, maximum load

This case was to investigate how the transmission system manages to handle the new flows due to maximum production from the Davvi wind farm, and maximum load in the net. The voltage level at the point of common coupling (PCC) will be set to the extreme values allowed in the grid codes. See Table 7 for parameters for this case.

Davvi WPP production [MW]	Voltage level Davvi PCC [pu]	Other WPPs production [MW]	Other production (hydro)	Load Finnmark	Export	Load net
800 (max)	1.0175	Maximum	High	Maximum	Adjusted to fit the scenario	High

Table 7: Test conditions for scenario maximum production, maximum load.

3.2.4 Minimum local production, minimum local load

This case was to investigate how the voltage levels in Finnmark will behave with minimum local power flows. The load in the rest of the net was kept high. The voltage level at the point of common coupling (PCC) will be set to the extreme values allowed in the grid codes. See Table 8 for parameters for this case.

Davvi WPP production [MW]	Voltage level Davvi PCC [pu]	Other WPPs production [MW]	Other production (hydro)	Load Finnmark	Export	Load net
0 (min)	1.0175	Minimum	High	Minimum	Adjusted to fit the scenario	High

Table 8: Test conditions for scenario minimum local production, minimum local load.

3.3 Faults that were applied

15 (N-1) and (N-1-1) (trip occurring in a situation already stressed by for example maintenance) situations will be studied, as well as Davvi wind farm being tripped. The faults are as follows:

- Trip 420 kV line Davvi – Lakselv (N-1)
- Trip 132 kV line Adamselv – Lakselv (N-1)
- Trip 420 kV line Davvi - Adamselv (N-1)
- Trip 132 kV line Adamselv – Varangerbotn (N-1) (there are 2 lines and these were tripped individually)
- Trip 420 kV line Davvi – Lakselv, when 420 kV line Davvi - Adamselv is out of service (N-1-1)
- Trip 420 kV line Davvi - Adamselv, when 420 kV line Davvi – Lakselv is out of service (N-1-1)

- Trip 420 kV line just north of Ofoten that is the corridor to the south (there are 2 lines and these were tripped individually)
- Trip 420 kV line just south of Ofoten
- Trip 420 kV line between Ritsem and Vietas
- Trip one of the 420 kV lines that goes from SE1 to SE2 (there are 4 lines and these were tripped individually)
- Trip Davvi wind farm

The cases were studied both when tap changers and shunt compensation were deactivated (to simulate a situation close in time to the line trip) and with tap changers and shunt compensation activated (a situation when the automatic adjustment of the compensating equipment have been made). See Figure 6 and Figure 7 for clarification regarding the positions of the tripped lines.

Figure 6: Local lines around Davvi, blue is 420 kV and green 132 kV or lower.

Figure 7: A map where the lines further south in Norway and Sweden that were tripped are pointed out.

3.4 Necessary measures

Dependent on the load flow studies of the cases, with and without line trips, necessary measures to increase the transmission system capacity will be identified. Potential mitigations could be suggestion of changed set points for existing shunt compensation, need of additional shunt compensation, disconnection of lines or reinforcement of lines or transformers.

4 RESULTS AND DISCUSSION

Results from the different analysis described in the previous chapter, as well as the comparison to Statnett's reference case is described in this chapter.

4.1 Statnett reference case

Our findings agree with Statnett's conclusion that voltage limits will be met before thermal limits in lines. This study also agrees with the following statement: "Høy resistans og mye produksjon i regionalnettet fører til høye spenninger ute ved vindkraftverkene, samtidig som spenningen i Varangerbotn og Adamselv blir lav på grunn av reaktive tap i regional- og transmisjonsnettet. Vindkraftverkene har spenningsregulatorer og vil arbeide for å opprettholde normale spenninger lokalt, slik at reaktiv kompensering i Varangerbotn kun vil føre til transitt av reaktiv effekt fra Varangerbotn til vindkraftverkene.

Dette er et velkjent problem ved tilknytning av produksjon på lavere spenningsnivå, typisk 22 kV, men på grunn av kombinasjonen av små ledningstverrsnitt og store avstander ser vi det samme på Varangerhalvøya" (Statnett, 2018).

We do not however see the same problems with low voltages at high wind power production, but it is unclear exactly what voltages Statnett expects and what reactive power capacity they require from the wind farms as the report is not detailed enough for that comparison. This study did not carry out any (N-1) analysis as it was not stated in the Statnett report if, or which (N-1) analysis had been carried out or what the grid expectations were from that.

The analysis found an overload on the regional line between Håkøybotn and Kvaløya because the installation of two new wind farms Kvitfjell and Raudfjell. This line is being strengthened at the moment to approximately 270 MVA and would therefore be able to carry the additional power in the future, if these two wind farms were built. This overload occurred for all scenarios, trips and analysis and does not have anything to do with Davvi or the transmission of power south. Since this line is being strengthened, this breaching has been omitted from all later tables of results. See Table 9 for details regarding the overload of the regional line close to Håkøybotn.

Network equipment	Limit value MVA	Simulated value MVA	Note
132 kV line between Håkøybotn and Kvaløya	109.2	167.3 (153.2%)	

Table 9: Overload of line at Håkøybotn because of newly built Kvitfjell and Raudfjell WPP.

4.2 2025 reference case

The transmission grid had no issues handling the new wind power. The lines that had been overloaded in the received net were still being overloaded and they were left that way. One new line in the regional net was overloaded due to the added wind power in Finnmark, which was the line crossing the border between Sildvik and Tornehamn. The line is situated just north of Ofoten, see Figure 7 for geographical position. This 132 kV line continues down in Sweden and helps with the provision of electricity to several towns and villages in this area, such as Kiruna for example. See Figure 8 for a schematic view of the grid around the line between Norway and Sweden at Sildvik - Tornehamn. Power flows from 420 kV to 132 kV both at Sildvik and Porjus.

One of the triple lines between Kivaar and Porjus goes straight but the two other has several buses along the way which have been left out in this picture. The connections between Kvandal and Sildvik, as well as between Ofoten and Sildvik are not direct but the buses along the lines have been omitted in the picture for simplicity reasons. The buses at the border only exists in this model and not in reality.

Figure 8: Schematic picture of buses and their connections around the line Sildvik - Tornehamn between Norway and Sweden. Blue corresponds to 420 kV and green 132 kV.

The line between Sildvik and Tornehamn continues down into Sweden, and the different segments have different lengths and thermal limits. See Table 11 for the details regarding these segments.

Buses	Length km	Limit value MVA	Note
Sildvik – border bus	13	117.5	
Border bus - Tornehamn	20	129	
Tornehamn - Stenbacken	46	99	
Stenbacken – Kivaar	59	99	

Table 10: Segments of the line from Norway to Sweden at Sildvik – Tornehamn.

See Table 11 for details regarding the overloaded lines. As can be seen, the breaching is very small and it was therefore not considered an issue.

Network equipment	Limit value MVA	Simulated value MVA	Note
132 kV line between Sildvik and Tornehamn	99	99.9 (100.9%)	

Table 11: Overloaded line in the regional net due to new wind power.

A check of the limit breaching of buses in the reference case was done. Of the buses that were of interest in this scenario only one new breach happened which was an undervoltage in the bus Båtsfjord, see Table 12 for details regarding the breach. This bus is very closely located geographically to where the wind farms Hamnefjell and Raggovidda are situated and it is assumed for this analysis that if, and when those wind farms are developed, they would contribute with enough reactive power to keep the surrounding grid in reactive balance.

Network equipment	Limit value (pu)	Simulated value (pu)	Note
132 kV bus Båtsfjord	0.9	0.8617	

Table 12: Breaching of an undervoltage limit in the bus Båtsfjord.

4.3 Maximum production, minimum local load

This scenario simulated the most stressed situation that could happen in the grid. The lines that had been overloaded in the received net were slightly more overloaded.

The 420 kV transmission line between Vietas and Porjus, see Figure 7 for location, was overloaded, which is unacceptable. Stora Lule älv (Big Lule river), which is the river where the hydro power plants Vietas and Porjus are situated, has been exploited for hydro power since the 50s. Harsprånget, which is the largest hydro power plant in Sweden, started its construction 1919 but was not completed until 1951, and all hydro power upstream as well as downstream were built in the decades to follow. The 400 kV line between Harsprånget and Hallsberg that was built 1952 was the first 400 kV line in the world (Kuhlin, 2018). During this time, the lines in this area were built without the knowledge or regard to the fact that several 1000 of MW wind power would potentially be built in Finnmark and transported down this line from Norway, so it is not surprising that this line is not dimensioned for this power and becomes overloaded.

The 132 kV line between Norway and Sweden at Sildvik and Tornehamn was also overloaded. This line is not part of the transmission grid, but because it runs parallel with the transmission line from Ofoten to Porjus, as can be seen in Figure 8, it gets overloaded as the transmission line also gets overloaded. The different segments of this line that are subject to overloading, get different overloads because they have different thermal limits. The lines past Kivaar does not get overloaded as there are 3 of them sharing the load. The reason why the line between Tornehamn and Stenbacken is the most overloaded line is because Tornehamn has a load which means that less power carries on towards Kivaar. See Table 13 for details regarding the overloaded lines.

Network equipment	Limit value MVA	Simulated value MVA	Note
132 kV line between Sildvik and border bus	117.5	119 (101.2%)	
132 kV line between Border bus and Tornehamn	129	149.2 (115.7%)	
132 kV line between Tornehamn and Stenbacken	99	124.5 (125.8%)	
132 kV line between Stenbacken and Kivaar	99	113.4 (114.6%)	
420 kV line between Vietas and Porjus	1091	1209.2 (110.8%)	

Table 13: Overloaded line in the transmission net between Vietas and Porjus, and overloaded lines in the regional net due to new wind farms.

Even though the line between Sildvik and Tornehamn is considered as regional, the breaching occurs due to increased wind power in Finnmark and therefore this analysis will address a solution to the issue. A meshed 132 kV net is desirable from a net operator's point of view as it offers better security. However, if it means that lines get overloaded, it might be more beneficial to make lines radial. Considering how the net is structured, this is done best between Stenbacken and Kivaar. Taking out that line could potentially be done only in situations when the line is on the brink of overloading, as a disconnection of that line results in an increase of overload between Vietas and Porjus from 1209.2 (110.8%) to 1292.3 (118.4%). Disconnection of the line between Stenbacken and Kivaar meant that it no longer belonged to the meshed grid, but instead acted as a radial grid and resulted in no overload on the 132 kV line anymore. Another option would be to strengthen the line all the way between Sildvik and Kivaar.

This study has not done an analysis on how likely the scenario maximum production, minimum local load is, or how often it would occur. Low loads typically happen during the summer, when wind power typically produce less, so it is reasonable to assume that this scenario is unlikely. Furthermore, in case this scenario does occur, electricity prices will be lower as the loads are lower which means that any potential production curtailments would mean lower income losses.

In case this scenario would happen, the problems could be combatted in different ways, such as: decrease in power production; increase of load in Finnmark; a combination of both; strengthening vulnerable lines; or series compensation or line splitting of specific lines in order to direct the power. A reduction in production would most likely be done either by the wind farms in Finnmark, collectively or only by Davvi, or by hydro power north of the line between Vietas and Porjus. An increase of load in Finnmark could be expected in Finnmark as electrification of petroleum installations, as well as building of new mines have been discussed, which could potentially lead to an increase in load of 1000 MW.

For the sake of the analysis, a simulation was run where Davvi wind farm was reduced to 350 MW in order to investigate this scenario in a steady state where the line between Vietas and Porjus was loaded up to 99%. The regional lines close to Raudfjell and Kvitfjell were still overloaded, but the line between Sildvik and Tornehamn was only overloaded to a maximum of 116% (without disconnecting the line between Stenbacken and Kivaar). This reduction in production could be split by all wind farms in Finnmark and thus spreading the losses.

Another simulation was run where a new load of 450 MW was added to the 420 kV bus Skaidi in order to simulate an electrification of a petroleum installation, which would increase the load in Finnmark. This simulation did not have an overload on the Vietas – Porjus line, but the 130 kV line between Stenbacken and Kivaar was not disconnected.

Another simulation was run where the production in Vietas was decreased to 110 MW from 275 MW (Vietas was producing 275 MW in the received net from SvK) out of 305 MW possible, which meant that the line from Vietas to Porjus was no longer overloaded. The line at Sildvik was still overloaded to a maximum of 123%, and when the line between Stenbacken and Kivaar was disconnected, the production at Vietas had to be decreased to 0 MW for the overloading on the 420 kV line to be avoided.

If the 420 kV line between Varangerbotn and Pirttikoski is built, it would be around 400 km long. For this long high voltage line, it is beneficial with series compensation. The degree of compensation in a 420 kV line is typically around 40-50% and a 50% degree was assumed for this line. This meant that the reactance was halved, and the transmission capacity increased. For this scenario, when the line was series compensated the amount of power flowing through the Finnish line increased from 886 MW to 1108 MW. The line between Vietas and Porjus was no longer overloaded, but the line at Sildvik was overloaded to a maximum of 115.9%. By disconnecting the line between Stenbacken and Kivaar, the overloading of the 132 kV line disappeared, but the line at Vietas became overloaded. By lowering Davvi to 500 MW, or Vietas to 180 MW all overloading was avoided.

Another way of directing power through the line to Finland is to split up the 420 kV line as south of Davvi as possible. This was done between Balsfjord and Skibotn which resulted in an increase of power to flow through Finland. Vietas – Porjus was not overloaded anymore, however the 132 kV line at Sildvik was still overloaded, and the 132 kV line between Balsfjord and Skibotn became overloaded. A disconnection between Stenbacken and Kivaar meant that Vietas – Porjus became overloaded, and a decrease in production in Vietas to 190 MW from 275 MW meant that the overloading disappeared. The 132 kV line between Balsfjord and Skibotn was still overloaded however, and a disconnection of that line meant overloads on several other lines as the 132 kV grid is highly meshed.

A check of the limit breaching of buses in the reference case was done. Of the buses that were of interest in this scenario only one new breach happened which was an undervoltage in the bus Båtsfjord, see Table 14 for details regarding the breach. This bus is very closely located geographically to where the wind farms Hamnefjell and Raggovidda are situated and it is assumed for this analysis that if, and when those wind farms are developed, they would contribute with enough reactive power to keep the surrounding grid in reactive balance.

Network equipment	Limit value (pu)	Simulated value (pu)	Note
132 kV bus Båtsfjord	0.9	0.8706	

Table 14: Breaching of an undervoltage limit in the bus Båtsfjord.

Some transmission grid buses had issues keeping up their voltages around southern and mid Sweden, and this was most likely due to the high load in the net at the same time as the export was high, and not Davvi, as the same issue was present in the case where wind power in Finnmark and Troms was set to

0. As it is possible for Sweden to keep a high load and high export without voltage limit breaches, it was assumed that this issue is solvable, but it was outside the interests of this analysis why it was left.

Reactive power contribution from all the wind farms in Finnmark and Troms, as well as the switched shunts at Skaidi and Varangerbotn, can be seen in Table 15. There are switched shunts in the area that turn on or off for the different scenarios, for example -100 Mvar in Varangerbotn to help lowering the voltages there for the scenario minimum production why the difference in contribution is not that great for some of the wind farms. A couple of them are controlling the same bus why they have the exact same contribution. Some are working on their maximum capacity for some of the cases and it is possible to change the desirable voltage level the controlled bus should have which will change the amount of reactive power the wind farm must produce.

Wind farm	Reactive power contribution maximum production (Mvar)	Reactive power contribution minimum production (Mvar)
Hamnefjell	39.4	38.7662
Rakkocearro	-3.3292	1.2065
Rakkocearro (Raggovidda) Vindkraftverk trinn 2	50.9	38.7662
Kjøllefjord	-1.4668	2.2025
Havøygavlen	13.739	11.2745
Dønnesfjord	4.6	4.6
Fakken	-3.2615	-2.6727
Kvitfjell	-11.6341	-11.1445
Raudfjell	-11.6341	-11.1445
Davvi	0.6337	-94.176
Nygårdsfjellet vindkraftverk trinn 2	-10.5840	-10.5840
Andmyran	-19.2159	-11.9125
Ånstadblåheia	-16.6	-11.9125
Skaidi switched shunt	-100 Mvar	-100 Mvar
Varangerbotn switched shunt	0	-100 Mvar

Table 15: Reactive power from wind farms and switched shunts at Skaidi and Varangerbotn in Finnmark and Troms for maximum production and minimum production, both during minimum local load.

Around Davvi there is already installed in the grid some reactive power, see Table 16 for details. The third column refers to the reactive power capability as stated in the received grid and is in steps for shunts, and ranges for generators. In the cases where there are several generators, each generator can contribute with reactive power according to the third column. The information is as given in the received grid, and some of them are SVC.

Reactive power contributions from lines or loads are not included. As the amount of production changes in Finnmark, the amount of reactive power produced by the different sources changes. The contributions from the new wind farms as well as the 420 kV line means that is it possible to hold the reactive balance in the system.

Bus	Type (switched shunts have fixed steps and generators are continuous)	Reactive power (Mvar) capability (positive means condensators and negative reactors)
Lakselv	Switched shunt	14.55 + 14.55
Tana	Switched shunt	3.6
Adam (2 generators)	Generator	-6 – 12
Kvalsund	Generator	-4 – 8
Lakselv22	Switched shunt	5 + 10
Saut G1	Generator	-12 – 24
Repvaag	Generator	-1 – 2
Skaidi22	Switched shunt	6
Goliat	Generator	-13.271 – 25.5
Melk (5 generators)	Generator	-39.7 – 40
Gandvik	Generator	-2.146 – 3.066
Melkef	Generator	-5 – 10.4
Skog (2 generators)	Generator	-6 – 12
Varanger	Switched shunt	-10 + 7.5
Vadsoy	Switched shunt	3.6
Smelror	Switched shunt	2.07

Table 16: Installed reactive power around Davvi.

Except for the potential new loads in Finnmark, the load in Finland can change. Finland imports a lot of electricity, and is connected through DC cables from north of Stockholm, AC lines across the border in the north both from Sweden and Norway, and through connections to Estonia and Russia. The import to Finland in a high load case can typically be around 2500 MW, with an import in the north of 1000 MW. The load in the north of Finland in the received net was 800 MW, and by increasing it to 1000 MW a slight increase in power going through Finland from Davvi instead of down in Norway was seen. By taking away the load in northern Finland the amount of power going from Davvi through Norway increased but not significantly (75 MW).

4.4 Maximum production, maximum load

This scenario did not see an overload of the line Between Vietas and Porjus as the local load was high enough to soak up enough power. Davvi was producing 1.06 Mvar of reactive power in this scenario. The 132 kV line between Norway and Sweden at Sildvik and Tornehamn was overloaded, see Table 17 for details. By disconnecting the line between Stenbacken and Kivaar the line was not overloaded anymore, however the line between Vietas and Porjus became overloaded to 1114.9 (102.2%) (see section 4.3 for discussion regarding this line). The overloading could be avoided by decreasing the wind power in Finnmark, hydro power at for example Vietas, or an assumption that more load will be present in Finnmark by 2025.

Network equipment	Limit value MVA	Simulated value MVA	Note
132 kV line between Border bus and Tornehamn	129	132.5 (102.7%)	
132 kV line between Tornehamn and Stenbacken	99	108.9 (110.0%)	

Table 17: Overloaded lines in the regional net due to new wind power.

By series compensation of the 420 kV line to Finland, the flow to Finland increased from 702 MW to 959 MW and the overloading of the 132 kV line at Sildvik decreased to a maximum of 101.8%. By disconnecting the line between Stenbacken and Kivaar all overloadings could be avoided.

A check of the limit breaching of buses in the reference case was done. Of the buses that were of interest in this scenario only one new breach happened which was an undervoltage in the bus Båtsfjord, see Table 18 for details regarding the breach. This bus is very closely located geographically to where the wind farms Hamnefjell and Raggovidda are situated and it is assumed for this analysis that if, and when those wind farms are developed, they would contribute with enough reactive power to keep the surrounding grid in reactive balance.

Network equipment	Limit value (pu)	Simulated value (pu)	Note
132 kV bus Båtsfjord	0.9	0.8586	

Table 18: Breaching of an undervoltage limit in the bus Båtsfjord.

Some transmission grid buses had issues keeping up their voltages around southern and mid Sweden. This was most likely due to the high load in the net at the same time as the export was high, and not due to Davvi, as the same issue was present in the case where wind power in Finnmark and Troms was set to 0. As it is possible for Sweden to keep a high load and high export without voltage limits it was assumed that this issue is solvable, but it was outside the interests of this analysis why it was left.

4.5 Minimum local production, minimum local load

This scenario did not see any new violated limits in neither the transmission nor the regional net.

A check of the limit breaching of buses in the reference case was done. Of the buses that were of interest in this scenario only one new breach happened which was an undervoltage in the bus Båtsfjord, see Table 19a for details regarding the breach. This bus is very closely located geographically to where the wind farms Hamnefjell and Raggovidda are situated and it is assumed for this analysis that if, and when those wind farms are developed, they would contribute with enough reactive power to keep the surrounding grid in reactive balance.

Network equipment	Limit value (pu)	Simulated value (pu)	Note
132 kV bus Båtsfjord	0.9	0.8739	

Table 19: Breaching of an undervoltage limit in the bus Båtsfjord.

Some transmission grid buses had issues keeping up their voltages around southern and mid Sweden, and this was most likely due to the high load in the net at the same time as the export was high, and not Davvi, as the same issue was present in the case where wind power in Finnmark and Troms was set to 0. As it is possible for Sweden to keep a high load and high export without voltage limits it was assumed that this issue is solvable, but it was outside the interests of this analysis why it was left.

4.6 Faults that were applied

All faults described in 3.3 were applied to the following scenarios: maximum production, minimum local load; the same scenario but with reduced power in Davvi to 350 MW; and the scenario maximum production, maximum load. All results presented are results from directly after the fault, tap changers and shunt compensations were deactivated. The difference in result for the loading on the lines between activated and deactivated tap changers and shunt compensation was negligible. All breaches were of thermal limits.

The overloading of the line between Norway and Sweden at Sildvik – Tornehamn was not included in the results. The line is considered regional and this breaching is a known problem. The highest breaching was obtained for the scenario maximum production, minimum local load when the 420 kV line between Davvi and Adamselv was tripped, and the overload was 143%. To combat the overloading of this line, as discussed in section 4.3, the line between Stenbacken and Kivaar could be disconnected. This would lead to a higher load on the 420 kV line from Ofoten down SE1.

The line between Stenbacken and Kivaar was not taken out of service for any of the trips, and it is reasonable to assume that for the cases where Sildvik-Tornehamn was overloaded the line between Stenbacken and Kivaar would be disconnected which would lead to a larger overload of the line between Vietas and Porjus. Another option is to assume that the line all the way between Sildvik and Kivaar would be strengthened in order to keep the 132 kV grid meshed. Series compensation of the 420 kV line to Finland has not been analysed for any of the trips, and it is assumed that this would greatly relieve both the line between Vietas and Porjus, and Sildvik and Tornehamn. The difference in result for the voltages on the buses was however more significant after tap changers and shunt compensation was activated.

The only new bus of interest that had its limit breached for the different trips was the bus at Båtsfjord. See section 4.3 for a discussion regarding this bus. Voltage levels for buses during the different trips were therefore not considered an issue.

4.6.1 Maximum production, minimum local load

In Table 20 the different overloadings of lines during different trips for the scenario maximum production, minimum local load can be seen. All violated limits were thermal limits. See Figure 7 for the geographical locations of the different lines

Network equipment	Limit value MVA	Simulated value MVA	Trip	Note
420 kV line between Vietas and Porjus	1091	1130.4 (103.6%)	Trip 420 kV line Davvi – Lakselv (N-1)	
420 kV line between Vietas and Porjus	1091	1130.9 (103.7%)	Trip 132 kV line Adamselv – Lakselv (N-1)	
420 kV line between Vietas and Porjus	1091	1435 (131.5%)	Trip 420 kV line Davvi - Adamselv (N-1)	As less power can go through Finland the line to Sweden is more overloaded than before.
420 kV line between Ritsem and Vietas	1091	1169.7 (107.2%)	Trip 420 kV line Davvi - Adamselv (N-1)	The amount of power going from Ofoten to SE1 is not so great that even the line between Ritsem and Vietas is overloaded.

132 kV line between Lakselv and Adamselv	199.5	265.4 (133%)	Trip 420 kV line Davvi - Adamselv (N-1)	As the 420 kV line to Adamselv is tripped, power goes from Davvi to Lakselv, and then down to 132 kV and then across the 132 kV line to Adamselv and then back up to 420 kV Adamselv and along towards Finland.
420 kV line between Vietas and Porjus	1091	1211.1 (111%)	Trip 132 kV line Adamselv – Varangerbotn (N-1) (line 1)	
420 kV line between Vietas and Porjus	1091	1211.1 (111%)	Trip 132 kV line Adamselv – Varangerbotn (N-1) (line 2)	
420 kV line between Hjälta and Kilforsen	1091	1138 (104.3%)	Trip 420 kV line Davvi – Lakselv, when 420 kV line Davvi - Adamselv is out of service (N-1-1)	Kilforsen is the system’s swing bus and this overload probably occurred because the swing bus has to compensate for the loss in production when Davvi is disconnected. This issue arises because of the way the software is built and will not be a problem in reality.
420 kV line between Hjälta and Kilfors	1091	1138 (104.3%)	Trip 420 kV line Davvi - Adamselv, when 420 kV line Davvi – Lakselv is out of service (N-1-1)	
420 kV line between Vietas and Porjus	1091	1196.9 (109.7%)	Trip 420 kV line just north of Ofoten that is the corridor to the south (line 1)	As there are two lines just north of Ofoten power still goes this way down from Finnmark through to Sweden, but less than before it was tripped.
420 kV line between Vietas and Porjus	1091	1197.2 (109.7%)	Trip 420 kV line just north of Ofoten that is the corridor to the south of Norway (line 2)	

420 kV line between Vietas and Porjus	1091	1263.1 (115.8%)	Trip 420 kV line just south of Ofoten	As the line down the Norwegian corridor is tripped, even more power takes the path down Sweden why this line becomes even more overloaded.
420 kV line between Harsprånget and Porjus	1091	1217.6 (111.6%)	Trip the 420 kV line that goes from SE1 to SE2 (line 1)	Line 1 goes from Porjus to Grundfors and when that line is tripped more power has to take the path down the other lines which means that all power has to go through Harsprånget which leads to an overloading on that line. With this trip, the corridor down Sweden becomes narrower why more power from Finnmark takes the route down Norway than before, and there we do not see an overloading between Vietas and Porjus.
420 kV line between Vietas and Porjus	1091	1162.0 (106.5%)	Trip the 420 kV line that goes from SE1 to SE2 (line 2)	As line 1 becomes available again the line between Porjus and Harsprånget is not overloaded anymore, however more power takes the path down Sweden again why there is an overloading again between Vietas and Porjus. The overloading is however smaller than when the line was in use.
420 kV line between Hjälta and Kilfors	1091	1196.8 (100.5%)	Trip the 420 kV line that goes from SE1 to SE2 (line 2)	As line 2 is tripped, the currents will take different paths around the swing bus and most likely cause a slight overloading. See Figure

				9 for geographical position of the swing bus.
420 kV line between Vietas and Porjus	1091	1113.4 (102.1%)	Trip the 420 kV line that goes from SE1 to SE2 (line 3)	
420 kV line between Vietas and Porjus	1091	1146.9 (105.1%)	Trip the 420 kV line that goes from SE1 to SE2 (line 4)	
420 kV line between Hjälta and Kilfors	1091	1225.9 (112.4%)	Trip the 420 kV line that goes from SE1 to SE2 (line 4)	As line 4 is tripped, more power has to go through all the buses around the swing bus instead of taking the route along the coast, see Figure 7 and Figure 9 for geographical position of line 4 and the swing bus.
			Trip 420 kV line between Vietas and Ritsem	This simulation blew up which means in real life black out.
420 kV line between Hjälta and Kilfors	1091	1229.7 (103.5%)	Trip Davvi wind farm	This overload probably occurred because the swing bus has to compensate for the loss in production when Davvi is disconnected.

Table 20: Overloaded lines during trips for the scenario maximum production, minimum local load.

Tripping the 420 kV line between Davvi and Adamselv poses most problems for the system as substantially more of the power now has to go through Ofoten and SE1. There is at the moment just one 132 kV connection between Lakselv and Adamselv which becomes overloaded as power takes that route from Davvi to get to Finland. By disconnecting that line the overload of the line disappears but the overloading further south increases. See Figure 9 for geographical position of the swing bus.

Figure 9: The geographical location of the swing bus, closely connected to the 4 transmission lines between SE1 and SE2.

The voltages of the buses along the 420 kV line between Balsfjord and Varangerbotn can be seen in Table 21. The trip analysed is the most problematic 420 kV one between Davvi and Adamselv. As can be seen, the voltage drops are not large and switched shunts as well as tap adjusters will rapidly restore the voltages to their initial value. The switched reactors at Skaidi and Varangerbotn are working well here, they contribute with the -100 Mvar each for the reference case, but the one at Varangerbotn is switched off for the maximum production, minimum local load in order to keep the voltage up.

The values in column two are after trips but before switched shunts and tap adjusters have changed. However, reactive contributions from continuous sources, such as wind power, have changed. For example, reactive power contribution from Davvi is 0.6 Mvar for column one, 93 Mvar for column two and 80 Mvar for column three. In a real life operative scenario, the shunts and tap adjusters would change in a closer collaboration with the continuous reactive power sources, and the inability to simulate this is a shortage in the steady state model. Ideally, it would be optimal if it was possible to control the shunts according to the reactive flow from the continuous source, but for that you would need to do a dynamic simulation. This study is however looking at the capacity rather than the details of the control why this does not have any significance for the results, but for a real operative case it would be handled in a different way. The system is designed to be able to handle faults and line faults in very short time periods.

Bus	Voltage (pu) before trip	Voltage (pu) after trip before switched shunts and tap adjusters	Voltage (pu) after trip and switched shunts and tap adjusters
Kvandal	1.0300	1.0237	1.0300
Bardufoss	1.0343	1.0299	1.0333
Balsfjord	1.0350	1.0320	1.0350
Skibotn	1.0401	1.0291	1.0319
Goulasjåkka	1.0415	1.0273	1.0300
Nordreisa	1.0419	1.0256	1.0281
Kvænangen	1.0413	1.0232	1.0255
Alta	1.0379	1.0190	1.0211
Skaidi	1.0291	1.0135	1.0152
Lakselv	1.0267	1.0143	1.0157
Davvi	1.0175	1.0175	1.0175
Adamselv	1.0151	1.0112	1.0113
Varangerbotn	1.0044	1.0175	1.0175

Table 21: Voltages of the buses along the 420 kV line from Balsfjord to Varangerbotn before and after trips as well as switch shunt and tap adjusters.

4.6.2 Maximum production, minimum local load, Davvi 350 MW

Table 22 shows the results for tripping different lines during the scenario maximum production, minimum local load but when Davvi is decreased to 350 MW. For a real scenario if all these wind farms and lines were built, it might be possible to decrease production in Finnmark overall with 450 MW, instead of having Davvi taking the whole reduction in order to spread the losses. Another option would be to assume an increase in load in Finnmark by 500 MW, or a decrease in hydro power production north of Vietas. All violated limits were thermal limits. The line between Norway and Sweden at Sildvik was overloaded for all trips, see section 4.6 for discussion around this topic.

Network equipment	Limit value MVA	Simulated value MVA	Trip	Note
420 kV line between Vietas and Porjus	1091	1196.6 (100.5%)	Trip 420 kV line Davvi – Lakselv (N-1)	
			Trip 132 kV line Adamselv – Lakselv (N-1)	
420 kV line between Vietas and Porjus	1091	1234.6 (113.2%)	Trip 420 kV line Davvi - Adamselv (N-1)	As less power can go through Finland, the line to Sweden is overloaded.
			Trip 132 kV line Adamselv – Varangerbotn (N-1) (line 1)	
			Trip 132 kV line Adamselv – Varangerbotn (N-1) (line 2)	
			Trip 420 kV line Davvi – Lakselv, when 420 kV line Davvi - Adamselv is out of service (N-1-1)	
			Trip 420 kV line Davvi - Adamselv, when 420 kV line Davvi – Lakselv is out of service (N-1-1)	
			Trip 420 kV line just north of Ofoten that is the corridor to the south (line 1)	
			Trip 420 kV line just north of Ofoten that is the corridor to the south of Norway (line 2)	
			Trip 420 kV line just south of Ofoten	

420 kV line between Harsprånget and Porjus	1091	1120.5 (102.7%)	Trip the 420 kV line that goes from SE1 to SE2 (line 1)	Line 1 goes from Porjus to Grundfors and when that line is tripped more power has to take the path down the other lines which means that all power has to go through Harsprånget. This leads to an overloading.
			Trip the 420 kV line that goes from SE1 to SE2 (line 2)	
			Trip the 420 kV line that goes from SE1 to SE2 (line 3)	
420 kV line between Vietas and Porjus	1091	1146.9 (105.1%)	Trip the 420 kV line that goes from SE1 to SE2 (line 4)	
420 kV line between Hjälta and Kilforsen	1091	1174.5 (107.7%)	Trip the 420 kV line that goes from SE1 to SE2 (line 4)	As line 4 is tripped, more power has to go through all the buses around the swing bus instead of taking the route along the coast, see Figure 7 and Figure 9 for geographical position of line 4 to the swing bus.
			Trip 420 kV line between Vietas and Ritsem	
			Trip Davvi wind farm	

Table 22: Overloaded lines during trips for the scenario maximum production, minimum local load where Davvi has been decreased to 350 MW.

For the sake of the analysis, Davvi was curtailed to 50 MW which meant that an overload between Vietas and Porjus at a trip of the 420 kV line between 420 kV Davvi – Adamselv was avoided.

4.6.3 Maximum production, maximum load

Table 23 shows the results for tripping different lines during the scenario maximum production, maximum load. The line between Norway and Sweden at Sildvik was overloaded for most trips, see section 4.6 for discussion around this topic. All violated limits were thermal limits.

Network equipment	Limit value MVA	Simulated value MVA	Trip	Note
			Trip 420 kV line Davvi – Lakselv (N-1)	
			Trip 132 kV line Adamselv – Lakselv (N-1)	
420 kV line between Vietas and Porjus	1091	1251.5 (114.7%)	Trip 420 kV line Davvi - Adamselv (N-1)	As less power can go through Finland, the line to Sweden is overloaded.
132 kV line between Lakselv and Adamselv	199.5	233.7 (117.1%)	Trip 420 kV line Davvi - Adamselv (N-1)	As the 420 kV line to Adamselv is tripped, power goes from Davvi to Lakselv, and then down to 132 kV and then across the 132 kV line to Adamselv and then back up to 420 kV Adamselv and along towards Finland.
			Trip 132 kV line Adamselv – Varangerbotn (N-1) (line 1)	
			Trip 132 kV line Adamselv – Varangerbotn (N-1) (line 2)	
420 kV line between Hjälta and Kilforsen	1091	1159.5 (106.3%)	Trip 420 kV line Davvi – Lakselv, when 420 kV line Davvi - Adamselv is out of service (N-1-1)	This overload probably occurred because the swing bus has to compensate for the loss in production when Davvi is disconnected.

420 kV line between Hjälta and Kilforsen	1091	1159.4 (106.3%)	Trip 420 kV line Davvi - Adamselv, when 420 kV line Davvi – Lakselv is out of service (N-1-1)	This overload probably occurred because the swing bus has to compensate for the loss in production when Davvi is disconnected.
			Trip 420 kV line just north of Ofoten that is the corridor to the south (line 1)	
			Trip 420 kV line just north of Ofoten that is the corridor to the south of Norway (line 2)	
			Trip 420 kV line just south of Ofoten	
			Trip the 420 kV line that goes from SE1 to SE2 (line 1)	
420 kV line between Hjälta and Kilforsen	1091	1094 (100.3%)	Trip the 420 kV line that goes from SE1 to SE2 (line 2)	
			Trip the 420 kV line that goes from SE1 to SE2 (line 3)	
420 kV line between Vietas and Porjus	1091	1146.9 (105.1%)	Trip the 420 kV line that goes from SE1 to SE2 (line 4)	
420 kV line between Hjälta and Kilforsen	1091	1200.8 (110.1%)	Trip the 420 kV line that goes from SE1 to SE2 (line 4)	As line 4 is tripped, more power has to go through all the buses around the swing bus instead of taking the route along the coast, see Figure 7 and Figure 9 for geographical position of line 4 to the swing bus.
			Trip 420 kV line between Vietas and Ritsem	

420 kV line between Hjälta and Kilforsen	1091	1153.8 (105.8%)	Trip Davvi wind farm	This overload probably occurred because the swing bus has to compensate for the loss in production when Davvi is disconnected.

Table 23: Overloaded lines during trips for the scenario maximum production, maximum load.

5 CONCLUSIONS

The cross reference of Statnett's plausible future scenario shows that we agree that in Finnmark reactive power reserves are a bigger issue than thermal limit breaching. The reason for this is that the lines connecting the different productions with loads must be very long to cover the distances present in this part of the country. In order to combat this issue, reactive power reserves have to be installed. A more detailed analysis could not be carried out as it was not clear from Statnett's report what reactive requirements were given new wind farms, or which tripping scenarios had to be acceptable.

The 2025 reference case that was built included Davvi and several other new as well as upgraded existing wind farms in Finnmark and Troms, as well as a new 420 kV line from Skaidi to Pirttikoski, and a 420 kV line between Messaure and Keminmaa. This reference case assumed high production and load and showed no issues for the transmission grid. The increase in power from the wind farms were compensated for by a decrease in ten large hydro power plants both in Sweden and Norway.

The regional grid around some of the new wind farms was overloaded because of the increase in power, which had nothing to do with Davvi. These lines are being strengthened at the moment which will mean that they will be able to handle the increase power in case those wind farms were built in reality.

The regional 132 kV line between Norway and Sweden at Sildvik and Tornehamn, just north of Ofoten, was also overloaded for the reference case and for almost all scenarios and trips. Even though this line is regional, the overloading occurs due to an increase in wind power in Finnmark, and the fact that it goes parallel to the 420 kV line from Ofoten to Porjus. There are two suggestions to combat this issue: strengthening the line, or making it radial. Strengthening the line would be expensive as the whole stretch that gets overloaded is over 138 km long. Making this line radial would be a cheap option and be best accomplished by disconnecting the line between Stenbacken and Kivaar. This however would lead to an increased overload for the 420 kV path from Ofoten down SE1 as more power must take that path.

3 scenarios that changed parameters on the reference case were analysed: one with maximum production and minimum local load; one with maximum production and maximum load; and one with minimum production and minimum local load. The only new bus of interest that was breached during any of the scenarios or trips was the 132 kV bus Båtsfjord that had an undervoltage. This bus is geographically close to Hamnefjell and Raggovidda and it was assumed that if these wind farms were expanded they would contribute with enough reactive power to keep the voltage up on the bus. Consequently, breaching of voltage limits on buses was not considered a problem for any of the scenarios nor trips of lines.

The scenario with maximum production and minimum local load showed problems for the transmission grid even without tripping any line and is therefore considered an unacceptable scenario. The line that was most stressed was the 420 kV line between Vietas and Porjus, which was not surprising considering its history. This study has not done any analysis on how likely this scenario is, or how often it would occur. It is reasonable to assume that minimum local load would happen during summer, when wind power typically produce less which means that this scenario is most likely uncommon.

If the scenario does happen, it could be combatted in different ways: higher load; lower production; a combination of both; or series compensation or line splitting of specific lines in order to direct the power. A reduction in production would most likely be done either by the wind farms in Finnmark, collectively or only by Davvi, or by hydro power north of the line between Vietas and Porjus. An increase in load could be expected in Finnmark as electrification of petroleum installations, as well as building of new mines have been discussed.

For the sake of the analysis, Davvi was lowered from 800 MW to 350 MW which meant that the breaching of the line between Vietas and Porjus was avoided. In a real case if this scenario arose, it might be possible to lower all wind farms to collectively achieve a decrease in power of 450 MW so that the losses are borne collectively. An alternative simulation was carried out where a load of 450 MW was added to Finnmark with also took away the overloading of the line Vietas – Porjus.

It is likely that the 420 kV line from Varangerbotn to Pirttikoski would be series compensated if it was built. An analysis was made for this possibility and for this study it was assumed to be compensated to 50%. The results were that significantly more power took the path through Finland and therefore relieved the line from Ofoten down SE1. The Sildvik – Tornehamn path was still overloaded, but not the Vietas – Porjus line. By disconnecting the line between Stenbacken and Kivaar the overloading of the 132 kV line disappeared, but the Vietas – Porjus line became overloaded. By decreasing the production at Vietas to 180 MW, or Davvi to 500 MW no lines were overloaded. Series compensation of the 420 kV line from Varangerbotn to Pirttikoski shows satisfactory results and consequently seems like a beneficial measure.

Another way of directing power is to splitting up lines. This was done by splitting the 420 kV line between Balsfjord and Skibotn, as well as disconnecting the 132 kV line Stenbacken - Kivaar. By reducing the production in Vietas to 190 MV, the overloading between Vietas and Porjus was avoided. However, this resulted in an overload on the 132 kV line between Balsfjord and Skibotn. Disconnecting that line resulted in an overload on other lines in the 132 kV grid as the grid was meshed. It might be possible to split the grid in a way that would be satisfactory, but from this analysis it would not be recommended as an option.

The other scenarios showed no problems for the transmission grid. The scenario maximum production, maximum local load showed an overload in the 132 kV line between Norway and Sweden at Sildvik and Tornehamn. By disconnecting the line between Stenbacken and Kivaar the line was not overloaded anymore, however the line between Vietas and Porjus became overloaded. The overloading could be avoided by decreasing the wind power in Finnmark, hydro power at for example Vietas, or an assumption that more load will be present in Finnmark by 2025.

15 different tripping scenarios were carried out on the following scenarios: maximum production, minimum local load; maximum production, minimum local load but Davvi decreased to 350 MW; and maximum production, maximum load. As line 1 between SE1 and SE2 was tripped, the line between Porjus and Harsprånget was overloaded for all scenarios except where Davvi was restricted to 350 MW. The breaching of the thermal limits between Vietas and Porjus was the most common breach and therefore considered to be the major problem for the different scenarios and trips. This study has not investigated how common or plausible the different scenarios and trips are, but if such a study would show that these situations are common and it could be shown that it was economically justifiable, a reinforcement of this segment, or the whole stretch between Ofoten and Harsprånget, could potentially be beneficial.

The tripping of the 420 kV line between Davvi and Adamselv showed worst consequences for the grid, not only between Vietas and Porjus but also for the 132 kV line between Lakselv and Adamselv. It might be suggested that should this line trip in reality when Davvi is producing more than 350 MW, then Davvi is disconnected or restricted down to 350 MW where the 132 kV line can handle the power. Alternatively the line is disconnected.

Overall a connection of all the suggested wind power is feasible, as long as the 420 kV line between Skaidi and Pirttikoski is built. Certain scenarios and trips of lines will pose problems for some part of the transmission grid as well as the regional grid. Different measures can be taken in order to avoid the overloading in the transmission grid such as: curtailment or disconnection of wind power, just Davvi or collectively in the whole of Finnmark and Troms; expected increase in load in Finnmark in the form of electrification of petroleum installations or building of new mines; curtailment of hydro power north of Vietas; strengthening of lines, both vulnerable 420 kV and 132 kV lines; disconnection of the 132 kV line between Stenbacken and Kivaar; series compensation of the 420 kV line between Varangerbotn and Pirttikoski; or a combination of some or all of the above.

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