Cross-border capacity study between Finland and Sweden
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# Table of Contents

1 Summary .................................................................................. 5

2 Introduction .............................................................................. 6
  2.1 Background ........................................................................ 6
  2.2 Scope .................................................................................. 7
    2.2.1 Studied alternatives ..................................................... 7
    2.2.2 Assumptions and limitations ........................................ 9
  2.3 Outline ................................................................................. 10

3 Grid studies ............................................................................... 10
  3.1 Introduction .......................................................................... 10
  3.2 Alternative SE1-FI, 400 kV AC overhead line ....................... 11
    3.2.1 Thermal constraints ..................................................... 12
    3.2.2 Dynamic constraints .................................................... 15
    3.2.3 Summary of alternative SE1-FI, 400 kV AC overhead line 16
  3.3 Alternative SE2-FI, 220 kV AC cable .................................. 17
    3.3.1 Initial screening ............................................................ 17
    3.3.2 Summary of alternative SE2-FI, 220 kV AC cable .......... 18
  3.4 Alternative SE2-FI, 800 MW HVDC connection ................. 18
    3.4.1 Thermal constraints ..................................................... 18
    3.4.2 Dynamic constraints .................................................... 21
    3.4.3 Summary of alternative SE2-FI, 800 MW HVDC
           connection ................................................................. 21
  3.5 Alternative SE3-FI, 800 MW HVDC connection ................. 21
    3.5.1 Thermal constraints ..................................................... 22
    3.5.2 Dynamic constraints .................................................... 25
    3.5.3 Summary of alternative SE3-FI, 800 MW HVDC
           connection ................................................................. 28
  3.6 Combinations of different alternatives ............................... 28
    3.6.1 Thermal constraints ..................................................... 28
    3.6.2 Dynamic constraints .................................................... 28
  3.7 Conclusions from the grid studies .................................... 29

4 Technical review of the HVDC alternatives ............................ 30
  4.1 Scope of the review ............................................................. 30
  4.2 The main differences between the two HVDC alternatives .. 30
  4.3 Technical risks and opportunities ....................................... 32
  4.4 The different main configurations ....................................... 32
    4.4.1 The main configurations for alternative SE2-FI HVDC .. 32
    4.4.2 The main configurations for alternative SE3-FI .......... 33
  4.5 Assessment of the main cost components ........................... 34
  4.6 Preferred alternatives ......................................................... 35
  4.7 Recommended next actions ................................................ 36

5 Routing and permissions ....................................................... 36
  5.1 Routing and environmental aspects ..................................... 36
    5.1.1 Finland ................................................................. 37
5.1.2 Sweden ........................................................................... 40
5.2 Permit processes in Finland and Sweden ....................... 43
5.3 Conclusions regarding routes and permits .................... 45

6 Market studies ..................................................................... 46
6.1 General approach ................................................................. 46
6.1.1 Net present value calculation ........................................ 47
6.2 Scenarios and basic assumptions ....................................... 48
6.2.1 Scenarios ...................................................................... 48
6.2.2 Sensitivities ................................................................. 54
6.3 PINT study ........................................................................ 54
6.3.1 Introduction ................................................................. 54
6.3.2 Results ......................................................................... 56
6.3.3 Conclusions from the PINT study ................................. 57

7 Socio-economic evaluation ................................................... 57
7.1 Methodology and assumptions .......................................... 57
7.1.1 Aspects to evaluate ....................................................... 58
7.1.2 Investment and maintenance cost ................................. 59
7.1.3 Sensitivity analysis ....................................................... 61
7.2 Results .............................................................................. 63
7.2.1 Socio-economic welfare ............................................... 63
7.2.2 Grid losses ................................................................. 65
7.2.3 Net present value ........................................................ 68
7.2.4 Impact on reserves and balancing services .................. 71
7.2.5 System adequacy ........................................................ 72
7.2.6 Environmental impact ................................................. 74
7.2.7 Integration of renewables ............................................. 77
7.2.8 Multi-criteria analysis .................................................. 77
7.2.9 Sensitivity ................................................................. 79
7.2.10 Consistency check and confirmation of the PINT results .80
7.3 Conclusions from the socio-economic evaluation .......... 82

8 Summary and conclusions .................................................. 83
8.1 Comparison of the connection alternatives ..................... 83
8.1.1 Alternative SE1-FI, 400 kV AC overhead line .............. 83
8.1.2 Alternative SE2-FI, 800 MW HVDC connection .......... 84
8.1.3 Alternative SE3-FI, 800 MW HVDC connection .......... 84
8.2 Summary and conclusion .................................................. 84

Appendix ................................................................................. 86
Appendix 1 Routing Finnish side ............................................. 86
Appendix 2 Routing Swedish side .......................................... 89
Appendix 3 Investment cost ...................................................... 93
Appendix 4 Comparison to TYNDP2016 results ................. 94
Appendix 5 Percentages of congestion hours ..................... 97
1 Summary

Large price differences between Sweden and Finland combined with the approaching end of the technical lifetime of the Fenno-Skan 1 connection are driving factors behind this joint Svenska kraftnät and Fingrid study. The study was carried out to investigate the socio-economic benefits and overall feasibility of increasing the transmission capacity between Sweden and Finland. Four different connection alternatives were examined.

- SE1-Fi, 400 kV AC overhead line
- SE2-Fi, 220 kV AC cable
- SE2-Fi, 800 MW HVDC connection
- SE3-Fi, 800 MW HVDC connection

Grid studies were performed to investigate the feasibility of integrating the different alternatives into the system. An AC line between SE1 and Finland and an HVDC connection between SE2 and Finland were considered feasible. A new HVDC connection between SE3 and Finland with a higher capacity than Fenno-Skan1 was found to require reinforcements in both Sweden and Finland, but further studies were required to determine the most advantageous grid solutions. The study showed that even an import capacity at a level of 550 MW, as Fenno-Skan 1 was originally designed for, would require reinforcements on the Swedish side. An AC cable between SE2 and Finland was rejected due to poor utilisation of the cable. However, if a connection point between SE2 and Finland is desired an AC cable together with a phase shifting transformer could be a viable alternative compared to an HVDC connection.

A technical review identified the need for a new metallic return path for Fenno-Skan 2 as a crucial factor after the decommissioning of Fenno-Skan 1. This reduces the additional overall cost of the SE3 to FI HVDC alternative since this HVDC connection can be used in a bipole configuration with Fenno-Skan 2 eliminating the need for a new return current cable. On the other hand, the SE2-Fi HVDC connection alternative was considered to be a more straightforward technical solution.

The routing, environmental aspects and permissions for the three alternatives remaining after the grid studies have been investigated. All alternatives were found to be feasible in this respect, based on current information.

In the market studies, the socio-economic benefits of the three grid alternatives were evaluated from a Nordic perspective. In an initial screening the net present values were calculated for the grid alternatives both individually and in combinations. A new AC line
between SE1 and Finland as a standalone alternative, and as an alternative coupled with an HVDC connection between either SE2 or SE3 and Finland indicated the highest benefit and was chosen for further study. Next, the aforementioned combinations of alternatives were evaluated for different socio-economic aspects, both in monetary and qualitative terms. The results indicated that increased capacity between Sweden and Finland is highly beneficial. Apart from a relatively high net present value and short pay-back time, the evaluation of the grid alternatives also indicated improved possibilities for trading reserves and balancing services, enhanced system adequacy, decreased environmental emissions and increased potential for integrating renewable energy sources. All in all, the market studies proved that the most beneficial alternative was a new AC line between SE1 and Finland and the next most beneficial alternative an HVDC connection between SE3 and Finland.

Finally, advantages and disadvantages of the remaining alternatives were compiled and summarised. This study shows that a new AC line between SE1 and Finland is the most advantageous. When comparing the two HVDC alternatives the connection between SE2 and Finland is technically more advantageous, but due to return current issues with Fenno-Skan 2 the SE3-FI HVDC results in a higher socio-economic benefit.

From the issues addressed in this report, it was concluded that a new AC connection between SE1 and Finland increases socio-economic welfare as well as improves the technical performance of the system. While a new HVDC connection between SE2 or SE3 and FI also is socio-economically beneficial there are some technical and system related issues, especially for the SE3 to Finland alternative, that need to be further assessed.

2 Introduction

2.1 Background

During recent years there have been significant changes in the Nordic power markets. Subsidised renewable power production has increased significantly in both Sweden and Denmark, as well as in continental Europe. This has led to lower day-ahead electricity market prices that in turn have reduced the competitiveness of Finnish and Danish condensing power. As a result, several condensing power plants have been decommissioned. Lately, even CHP and nuclear power plants have been reported to face diminishing profitability. For example, four Swedish nuclear units will be decommissioned and Finnish utilities have published plans to replace outdated CHP power plants with heat-only boilers. Security of supply in Finland has been threatened especially during the winter season.
Finnish power imports from Sweden have increased during recent years, partly due to a new pricing structure in Russian power markets which has limited the power flow from Russia to Finland and the Baltic countries. This, combined with the shift from conventional thermal power to subsidised renewables, has increased the congestion of the existing power lines between Sweden and Finland, causing large and frequent price differences between these countries.

In addition to this, the HVDC connection Fenno-Skan 1, built in 1989 is expected to reach the end of its technical lifetime by 2029. Fenno-Skan 1 has since April 2013 been running at a reduced capacity because of long-term damage sustained during operation. How this cross-border link might be replaced is also an issue which is examined in this study.

This project has been performed as a joint study between Fingrid and Svenska kraftnät.

2.2 Scope

2.2.1 Studied alternatives

The goal of this analysis is to investigate the benefits of increased transmission capacity between Sweden and Finland, and to provide a basis for decisions about future investment projects.

The scope of the analysis is to investigate new interconnectors between Finland and Sweden in a technical and socio-economic evaluation.

The northern parts of Finland and Sweden are mainly connected by land, and the most economical solution for increasing the capacity between Finland and SE1 would be an overhead AC line. A project of this type has been examined earlier ("the third AC") and is already incorporated in the grid development project portfolios of Fingrid and Svenska kraftnät. However, this connection has been re-evaluated in this study with the purpose of investigating if the AC line is still beneficial compared to other alternatives.

A connection between Finland and SE2 could be achieved by using sea cable. HVDC connections are the preferred option for long ocean distances. However, the shortest distance between the Finnish and Swedish shore is approximately 100 km making a 220 kV AC cable a possible option. In this study both AC and HVDC alternatives were investigated as connection between SE2 and Finland.

Currently there are two HVDC connections between Finland and SE3, Fenno-Skan 1 (FS1) and Fenno-Skan 2 (FS2). FS1, commissioned in 1989, 1

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1 CIGRE technical brochure 649 (February 2016) provides a reference showing a 35-40 year lifetime for an HVDC converter station, implying an end of life for FS1 between 2024-29.
is expected to reach the end of its technical lifetime by 2029. Due to recent issues, concerns have been raised that its life-time may actually be shorter than previously expected. In this study FS1 was assumed decommissioned and a new HVDC connection between SE3 and Finland was investigated.

To summarise, the following four grid investment alternatives have been investigated in this study:

- SE1-Fi, 400 kV AC overhead line
- SE2-Fi, 220 kV AC cable
- SE2-Fi, 800 MW HVDC connection
- SE3-Fi, 800 MW HVDC connection

**Figure 1** Schematic presentation of the three main grid investment alternatives in the study

In addition, there are also options for some of the alternatives regarding routes and technology that will be presented later on in the report.
2.2.2 Assumptions and limitations

The most important assumptions and limitations are listed below:\(^2\):

- To make the analysis of the grid alternatives comparable all were assumed to be commissioned at the beginning of 2028, even if the actual commissioning dates may be different.
- In this study the Fenno-Skan 1 link was assumed to be decommissioned by the year the investigated grid alternatives would be commissioned which means the transmission capacity between SE3 and Finland was reduced from the current level of 1200 MW to 800 MW. A new metallic return path for Fenno-Skan 2 is assumed to be built.
- In the alternative from SE3 to Finland a bipolar configuration with Fenno-Skan 2 is assumed and the cost for a separate metallic return path for Fenno-Skan 2 has been deducted from the project cost.
- The net transfer capacity from SE1 to Finland was decreased from the current level of 1500 MW to 1200 MW due to changed conditions after the commissioning of Olkiluoto 3.
- The net transfer capacity from Finland to SE1 was set to 1100 MW.
- In the grid studies there is a margin of 100 MW between the net transfer capacity and the total transfer capacity.
- The net transfer capacities within Sweden were set to 3300 MW between SE1 and SE2, 8800 MW between SE2 and SE3, 6500 MW from SE3 to SE4 and 4800 MW from SE4 to SE3.
- The net transfer capacity between northern and southern Finland was set to 3500 MW southwards and 2500 MW northwards for 2025. For the 2035 scenario the net transfer capacity was increased by 1000 MW in both directions after the commissioning of the additional sixth line of the north south cross section (P1).
- Hansa Power Bridge (between Sweden and Germany), Viking link (between Denmark and UK), North Sea Link (between Norway and UK) and Nordlink (between Norway and Germany) were assumed to be commissioned prior to 2025.
- The day-ahead energy-only market was simulated, i.e. other markets such as capacity markets and ancillary service markets were not included in the simulations.

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\(^2\)The cross-border and internal capacities which have been used in this study are planning assumptions and should not be regarded as future trade capacities. For studies of this magnitude it is important to ensure that the investments proposed are robust, and are not sensitive to external factors or future network developments. For this reason potential cross-border and internal capacities have been used in various sections of this study.
The commercial network transfer capacities were assumed to be fully available, with the exception of the market border between Denmark (DK1) and Germany which was set to 1500 MW southwards and 1780 MW northwards to account for the historically poor availability of this connection.

Power system simulations were performed for the year 2025. Fingrid also looked at a 2035 production mix for grid studies.

Market simulations were performed for 2025 and 2035.

Some of these assumptions and limitations were tested by sensitivity analysis throughout the study. For specific details about certain assumptions and scenarios see chapter 6.2.

2.3 Outline

This study examined the alternatives listed in section 2.2.1. For each alternative, grid studies were performed in order to determine suitable connection points and reinforcements required in order to realise the alternatives. For alternative SE1-FI, a net transfer capacity of at least 2000 MW between SE1 and Finland was investigated in both directions, corresponding to an increase of 800 MW towards Finland and 900 MW towards Sweden, compared to reference capacities. For SE2-FI AC cable alternative, the possible transfer capacity was to be estimated during the initial screening. To simplify the comparison, an increase of 800 MW for the HVDC alternatives SE2-FI and SE3-FI was assumed.

The grid alternatives were then simulated in market models, one at a time, to estimate the impact on socio-economic welfare, which is the consumer and producer surplus as well as the congestion rent. The socio-economic welfare was set against the estimated investment costs to get an indication of which grid alternative was the most beneficial. Different combinations of the grid alternatives were also considered, until no additional benefit could be seen. The most beneficial grid alternatives were further analysed in both quantitative and qualitative terms.

Other factors such as geographical conditions and technical requirements were considered in the evaluation.

3 Grid studies

3.1 Introduction

The different alternatives from section 2.2.1 were studied from a grid and power system perspective in order to determine if the alternatives were feasible and which reinforcements or other measures would be required in order to realise them.

For the grid alternatives, thermal loading and stability issues were examined in order to determine the reinforcements required. The
investment cost for the needed reinforcements were estimated to be incorporated in the total cost for each grid alternative. Fingrid determined the requirements for establishing these connections on the Finnish side, while Svenska kraftnät determined the requirements for the connections on the Swedish side.

A shared database of the Nordic system based on operating conditions in 2014 was updated to include planned investments and production changes in Finland and Sweden up to 2025 (Stockholm area up to 2028), and in Norway up to 2022. This database was used in the network calculation tool PSS/E to evaluate feasibility and necessary reinforcements.

3.2 Alternative SE1-Fi, 400 kV AC overhead line

Today there are two 400 kV AC lines connecting Sweden and Finland in the north. The SE1-Fi grid alternative would constitute a third AC-line between the two market areas and is therefore referred to as the “third AC” in this chapter. For this alternative two Swedish connection points were studied:

- SE1-Fla: Svartbyn-Keminmaa-Pyhänselkä
- SE1-Flb: Messaure-Keminmaa-Pyhänselkä

In Figure 2 and Figure 3, a schematic of the routing options SE1-Fla and SE1-Flb are presented. More specific information regarding routing options can be found in chapter 5. Both options include lines which are series-compensated to approximately 72 percent. This corresponds to the same level of compensation as used for the two existing AC lines, Letsi-Petäjäskoski and Svartbyn-(Djuptjärn)-Keminmaa.

![Figure 2 Schematic of the route for option SE1-Fla, Svartbyn - Keminmaa - Pyhänselkä](image-url)
3.2.1 Thermal constraints

**Swedish side**
In this study four operating conditions with varying wind power production and flow were examined:

- high wind power production in SE1 (Markbygden)
- no wind power production
- high transfer from NO4, 700 MW
- high transfer to NO4, 1350 MW

By 2028, when the third AC line can be commissioned, all relevant 400 kV stations in Sweden have been refurbished. This implies that equipment in the stations is rated for 3150 A and that the stations Letsi and Ligga have been rebuilt with double-breaker busbar configurations.

The two existing AC lines between Finland and SE1 have been upgraded to withstand an 80 °C conductor temperature. The rating of the two lines is presented in Table 1.

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<tbody>
<tr>
<td>Svarbyn - Keminmaa</td>
<td>2338</td>
<td>2694</td>
<td>1800</td>
<td>2880</td>
</tr>
<tr>
<td>Letsi-Petäjäskoski</td>
<td>2338</td>
<td>2694</td>
<td>1800</td>
<td>2880</td>
</tr>
</tbody>
</table>

The two series-compensators (SCs) in Isovaara and Keminmaa set the thermal limits of the lines during normal operation. During emergency
operation the lines are limited by the conductors. The SCs have an emergency rating of 1.6 p.u. for 15 minutes.

The thermal loading was examined both with and without the third AC line in operation, in order to examine which network reinforcements would be required for establishing the connection, and which could be considered as necessary to fulfil the requirements for the assumptions.

In some of the scenarios the parallel 130 kV grid was overloaded but the overloads were related to the transfer between SE1 and NO4 and could be handled with system protection.

Contingencies that were examined on the Swedish side were:

- Tripping of 400 kV and 220 kV lines in SE1 and SE2
- Major faults in SE3 and SE4
- Major faults in Finland

Alternative SE1-Fi a: Svartbyn-Keminmaa-Pyhänselkä:

In the SE1 to FI direction the distribution of power flow between the three AC lines was found very uneven in this routing option. Letsi-Petäjäkoski (LE-PE) took approximately 55-60 percent of the total transfer and the third AC only 25 percent.

In normal operation, the line between Letsi and Petäjäkoski is limited by the 1800 A current capacity of the SC Isovaara. When transferring 2100 MW it was loaded to 97 percent (1750 A). Under emergency conditions the line is limited to 2694 A. During a fault on the line between Messaure and Svartbyn, Letsi-Petäjäkoski was loaded to 100 percent (2688 A) indicating that the maximum capacity was reached for the studied configuration. It was however possible to further increase the capacity between SE1 and Finland if the level of compensation was lowered on the Letsi-Petäjäkoski line.

In the FI to SE1 direction the distribution of power flow between the three lines is fairly even. The loading varied between 30 and 40 percent on the three lines. There were no problems with overloading during normal or emergency operations. For normal operation the voltages were low in the stations along the eastern lines in Sweden, Svartbyn-Råbäcken-Högnäs-Stornorrfors, indicating that a shunt capacitor was needed in the area to keep the voltages above 400 kV. In the high wind scenario the voltages were very low in the eastern stations. The total transfer capacity could be increased to at least 2600 MW. The capacity is however limited by dynamic constraints.

Alternative SE1-Fi b: Messaure-Keminmaa-Pyhänselkä:

For the Messaure routing option, in the Sweden to Finland direction, the third AC was closer connected to the production in Luleälven and therefore took more of the total transfer, between 45 and 50 percent. The capacity between the SE1 and Finland could be increased by 1500 MW, up to 2800 MW, before any constraints in Sweden were
reached. During normal operation the transfer has a margin to the capacity of the lines. During emergency operation two critical faults were identified. A fault on the third AC resulted in 89 percent loading (2393 A) on the Letsi–Petäjäskoski line and in the scenario with high transfer from NO4, a fault on Harsprånget–Letsi line led to 100 percent loading (2670 A) on the Ligga–Messaure line.

In the Fl to SE1 direction, during normal operation, Djuptjärn–Keminmaa took between 55 and 60 percent of the loading. With a transfer of 2100 MW the SC in Keminmaa was loaded to 95 percent (1712 A). The voltage in Svartbyn sank to 395 kV indicating that a shunt capacity was needed. If the series-compensator is refurbished, the total transfer capacity from SE1 to Finland could be increased to at least 2600 MW, but dynamic restraints limit this capacity.

**Finnish side**

Due to thermal limitations of the 400 kV lines north of Pikkarala and Pyhäselkä substations, a new transmission line between Keminmaa and Pyhäselkä is needed to achieve the 800 MW additional capacity with the SE1-FI AC overhead line.

Thermal constraints were mainly identified with numerous snapshots of reference scenario 2025 and 2035 by simulating single 400 kV contingencies in Northern Finland and other dimensioning faults in the Finnish system. The thermal capacities of the cross-border AC connections were harmonised with Svenska kraftnät’s capacities in such a way that a 20 °C ambient temperature was assumed for capacity calculation.

The most limiting constraints are the aforementioned cross-border lines and their SCs, but the old 400 kV overhead lines with 2-Finch conductors in northern Finland follow soon after. The uneven loading of parallel circuits could be somewhat relieved by adjusting the degree of series compensation or even by-passing series capacitors during some operational situations. This, however, was not investigated in this study.

The reference scenario for 2025 and 2035 for the market studies showed mostly transfers from Sweden to Finland. Achieving more than an 800 MW increase was only investigated in the direction from Sweden to Finland, and at this level thermal and voltage violations were observed. By applying current operational criteria it was estimated that a transmission capacity increase of 800 MW assumed in market studies could be achieved. The average capacity increase calculated with numerous snapshots was around 1100 MW but the variation in increase was quite large. A more in-depth capacity analysis would be necessary to confirm this.
3.2.2 Dynamic constraints

**Sweden to Finland**

The transfer capability from northern to southern Finland could be limited by the voltage stability. Low voltages were observed especially after the loss of Olkiluoto 3 unit, as indicated in Figure 4.

![Figure 4](image)

*Figure 4 An example of voltage at Alapitkä after 100 ms AC fault followed by trip of Olkiluoto 3. The lowest acceptable post-fault voltage is 370 kV and the lowest acceptable momentary voltage during oscillations is 320 kV, corresponding to 0.925 and 0.8 p.u., respectively.*

With the planned fifth 400 kV connection from northern Finland to southern Finland, a transfer capacity of 3500 MW could be achieved. This might however require changes in SC for the north-south connections, or additional reactive power compensation to provide necessary voltage support during normal operation. The issue with low voltages is not solely related to the third AC connection to Sweden, but also to the increased transfer requirements due to increased power production in northern Finland and the uneven loading of the parallel lines of north-south cross-section P1. These reinforcements are therefore not considered in the grid alternative project cost.

**Finland to Sweden**

Different scenarios were used with different flows within in Sweden and between SE3 and NO1. The following faults were studied:

- A three phase fault on each of the three cross-border lines
- A 100 ms AC grid fault followed by the loss of FS2

When power is transferred from Finland to Sweden through the northern AC connections, the transfer is limited by the damping of electro-mechanical oscillations. The damping factor is required to be at least 3 percent, which means that amplitude would be approximately halved after four cycles. As shown in Figure 5, the damping was adequate with
a third AC overhead line between SE1 and Finland, and a capacity increase up to 900 MW is feasible. The net transfer capacity would thus be 2000 MW.

After approximately 15 seconds the damping is very poor as seen in Figure 5. With a transfer of 2100 MW these oscillations were acceptable but the damping was getting worse with increased transfer. These oscillations are not within the scope of this study but need to be investigated further if the net transfer capacity should be increased beyond 2000 MW.

![Figure 5 An example of transfers on cross-border AC lines after 100 ms AC fault at Rauma followed by FS2 trip at full power (800 MW) towards Sweden.](image)

### 3.2.3 Summary of alternative SE1-Fi, 400 kV AC overhead line

Implementing a third AC line between SE1 and Fi was shown to be a good grid alternative for increasing the net transfer capacity between the countries by 800 MW in the SE1 to Fi direction and 900 MW in the Fi to SE1 direction to at least 2000 MW in both directions. In many power flow situations the new AC connection gave even more additional capacity in SE1 to Fi direction. On the Swedish side there were some problems with low voltages which could be solved with shunt capacitors. On the Finnish side transfer capacity increase was limited by both low voltages and, in some scenarios, overloaded lines. With a new line between Kemimaa-Pyhänselkä the extra capacity could be achieved and the investment cost of the reinforcement was included in the cost analysis.

The Swedish side connection point Svartbyn is better for the Fi to SE1 direction and Messaure for SE1 to Fi direction. Provided that the
prevailing flow direction is SE1 to FI, Messaure is the preferable alternative.

3.3 Alternative SE2-FI, 220 kV AC cable

3.3.1 Initial screening
As described in section 2.2.1, two cross-border connection options were considered for connecting SE2 to Finland – an AC and an HVDC alternative.

To examine the AC alternative, calculations were performed on a large number of scenarios generated by a market modelling tool. These scenarios showed the effect of including a 220 kV AC cable between points Stornorrfors and Tuovila.

![Figure 6 Duration curve of SE1-FI flow compared to SE2-FI AC flow](image)

Figure 6 shows that compared to its 500 MVA capacity the AC cable is only lightly loaded, due to the relative difference in the impedances between SE1 and Finland, and the impedance of the new AC connection between SE2 and Finland. It also shows that the correlation between the transfers on these links is poor, such that the AC cable does not always contribute to increased transfer between Finland and Sweden. For this reason the AC option for the SE2-FI connection was removed from further studies.

By installing a phase shifting transformer at either end of the AC cable it is possible to achieve better control over the power flow. With a proper control strategy the power flow could be adjusted correlate with the existing AC lines or to minimise losses. Preliminary tests indicate that a solution with a phase shifting transformer could be feasible.

A connection with a capacity of 800 MW which is comparable to the other alternatives has an investment cost in the same range as an
HVDC connection. The high cost is explained by the need for three parallel cables in order to achieve the required capacity.

3.3.2 Summary of alternative SE2-FI, 220 kV AC cable
This alternative gave very little extra to the capacity between Finland and Sweden, and it was decided that this alternative should not be investigated further.

If, however, a connection between SE2 and Finland is desired, this alternative in combination with a phase shifting transformer could be a viable alternative.

3.4 Alternative SE2-FI, 800 MW HVDC connection

3.4.1 Thermal constraints
For the HVDC connection between SE2 and Finland, the stations Hjälta on the Swedish side and Tuovila on the Finnish side have been considered for reasons described below. See Figure 7 for an overview.

![Figure 7 Overview of Alternative C, an HVDC connection between SE2 (Hjälta) and Finland (Tuovila).]

**Swedish side**
In this study four operating conditions were examined by varying wind power production such that:

- Future wind power is evenly distributed
- There is no wind power production
- Future wind power is located in the east of Sweden
- Future wind power is located in the west of Sweden

These were implemented in the shared network database.

The thermal loading was examined both with and without the cross-border connection in operation, in order to investigate which network reinforcements were required for establishing the connection, and
which could be considered as necessary to fulfil the requirements for the assumptions.

The substation Hjälta was chosen as the connection point on the Swedish side the substation Hjälta was studied. Hjälta is an important node in eastern SE2, meshing several 400 kV lines in the area. The fact that the grid is well meshed around Hjälta was viewed as an important factor making Hjälta a feasible choice compared to neighbouring substations.

The results from the load flow simulations show that there were two 400 kV branches near Hjälta whose thermal capacities are exceeded regardless of the cross-border connection. These two branches are Kilforsen-Ramsele and Kilforsen-Hjälta. Both branches are parts of a series of lines connecting the eastern and western parts of SE2. The results show that an uneven distribution of generation, load and export could lead to high flows from east to west or vice versa, especially coupled with high transfer from SE2 to SE3. With grid alternative SE2-Fi, the thermal capacities of the previously mentioned branches were further exceeded, indicating that reinforcements are needed. See Table 2 for a comparison of the loadings before and after the new grid alternative between SE2 and Fi.

Table 2 Comparison of branch loadings for alternative SE2-Fi

<table>
<thead>
<tr>
<th>Branch</th>
<th>Contingency</th>
<th>Worst loading before the connection [%]</th>
<th>Worst loading with SE2-Fi alternative [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hjälta-Kilforsen</td>
<td>Vargfors-Tuggen-Nortjärn</td>
<td>103</td>
<td>119</td>
</tr>
<tr>
<td>Kilforsen-Ramsele</td>
<td>Långbjörn-Storfinnforsen</td>
<td>120</td>
<td>135</td>
</tr>
</tbody>
</table>

There was also an issue with transit of power through the 220 kV grid that runs parallel to the line between Kilforsen and Hjälta. When the Hjälta-Kilforsen branch was faulted or taken out of service the power found a path through the parallel 220 kV branches with large overloads as a result. The issue exists even without the implementation of grid alternative SE2-Fi but was further worsened by it.

Svenska kraftnät is in the process of carrying out a grid study that aims to address internal limitations in SE1 and SE2. The issues with thermal overloads described above are addressed in that study. A new branch between Betåsen and Hjälta/Nässe and an upgrade of the Kilforsen-Ramsele branch are proposed together with a number of upgrades of individual switchyard components. With the proposed reinforcements the described issues, including the transit through the 220 kV grid, would be resolved and the transfer capacity of 800 MW for alternative SE2-Fi would be achievable.
All of the thermal issues that were described above exist regardless of whether alternative SE2-FI is established. The necessary reinforcements should thus be realised regardless. No investment costs associated with the reinforcements should therefore be included for alternative SE2-FI.

In order to avoid having to limit the capacity of the new HVDC connection it is important that the proposed reinforcements are commissioned before the link is taken into service. The time frame to commission a new 400 kV line in Sweden is approximately 10 years.

The voltage levels around Hjälta were also studied with alternative SE2-FI modelled as a conventional HVDC link, i.e. without additional capacity for reactive power support. The voltage levels were within acceptable limits in all the studied scenarios and contingencies. Very little difference could be seen with the new HVDC connection. This indicates that there is no major need for additional voltage support in the area and a VSC link cannot be motivated purely from the perspective of its capacity for voltage support.

**Finnish side**
The HVDC connection to Tuovila would integrate smoothly into the Finnish transmission system in the studied reference scenario for 2025 and 2035. In Figure 8, transmission duration curves for the 400 kV AC lines from Tuovila are presented.

![Figure 8 Duration curves of power flows of the outgoing AC lines from Tuovila with alternative SE2-FI HVDC connection in reference scenario 2035.](image)

Based on this figure, a preliminary assessment has been made that no additional local AC reinforcements would be necessary since the maximum flows for the 400 kV lines connecting Tuovila are modest,
even in the 2035 reference scenario where the new Hanhikivi generating unit is in operation.

3.4.2 Dynamic constraints

In terms of dynamic constraints, the HVDC connection between SE2 and Finland would not significantly alter the oscillations in the power system. As shown in Figure 9, the loss of the HVDC connection between SE2 and Finland would clearly have a less severe impact on the system than FS2, as it is located further north than FS2, and is further away from generators which are inclined to swing against each other.

![Figure 9 Comparison of transfer on AC border connections after trip of FS2 (solid lines) and trip of SE2-FI HVDC connection (dashed lines).](image)

3.4.3 Summary of alternative SE2-FI, 800 MW HVDC connection

Alternative SE2-FI could be implemented in the grid without any additional reinforcements. On the Swedish side there are some projects that have to be implemented before the HVDC-link can be used without risking having to limit the capacity after certain faults.

3.5 Alternative SE3-FI, 800 MW HVDC connection

By 2029 it is expected that FS1, which connects Swedish station Dannebo and Finnish station Rauma, has reached the end of its technical life, and must be decommissioned. A natural placement for an HVDC connection from Finland to SE3 would therefore be between Dannebo and Rauma, as shown in Figure 10.
3.5.1 Thermal constraints

**Swedish side**

In this study the same four operation conditions that have been examined by Svenska kraftnät for alternative SE2-Fi have also been examined for alternative SE3-Fi.

The thermal loading is examined both with and without the cross-border connection in operation, in order to determine which network reinforcements are required for establishing the connection, and which can be considered as necessary to fulfil the requirements for the assumptions.

The station Dannebo, north of Stockholm, was studied as a connection point on the Swedish side, for the SE3-Fi alternative. This was a natural starting point as it is the connection point for the aging FS1. Finnböle was not considered as it would lead to the risk of losing two HVDC connections simultaneously after a fault at the substation. Connections to neighbouring substations lead to similar loading patterns in the network.

Transfer of power from SE3 to Finland does not lead to any complications in the Swedish network.

Transferring 800 MW power from Finland to Dannebo results in a number of overloads, especially if there is a lot of wind power produced in the east of Sweden. This production loads the long lines in the east of Sweden, several equipment upgrades are required to accommodate the extra power, in some cases upgrades to 4000 A are needed, which
is higher than Svenska kraftnät’s current standard. Additional 150 Mvar reactive power is also required near Ångsberg in order to maintain stable operation when Forsmark 3 trips or when Finnböle-Hamra CL5 is tripped.

Even once equipment has been upgraded a number of lines still require measures to relieve them. These are listed in Table 3.

**Table 3 Overloads for lines with alternative SE3-Fi for wind in the east**

<table>
<thead>
<tr>
<th>Branch</th>
<th>Contingency</th>
<th>Loading [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hamra-Finnböle CL5</td>
<td>Hamra-Finnböle CL33</td>
<td>103</td>
</tr>
<tr>
<td>Hamra-Åker</td>
<td>Hall Hedenlunda</td>
<td>101</td>
</tr>
<tr>
<td>Hedenlunda Glan CL3</td>
<td>Hedenlunda Glan FL9</td>
<td>107</td>
</tr>
</tbody>
</table>

Even with an import capacity at a level of 550 MW, overloads are still present for Hedenlunda-Glan CL3.

An alternative connection point in Hall, or alternatively Hedenlunda, south of Stockholm has been considered to alleviate the problems seen by feeding in 800 MW into Dannebo. This connection point however has the issue that for export from Sweden to Finland, overloads occur in the area around Finnböle, Stackbo and Ångsberg, shown in Figure 11.

**Figure 11 Network near Finnböle, Stackbo, Ångsberg**

By not exporting power through via Dannebo and letting current continue from Stackbo to Ångsberg to Finnböle, the lines become overloaded. This area is already strained, and by 2025 the network requires upgrading to equipment rated for 4000 A. For this reason a connection point south of Stockholm has been deemed unacceptable.
Dannebo is therefore the chosen point of connection for alternative SE3-Fi, but leads to extensive reinforcements required in order to realise the 800 MW capacity from Finland to Sweden. These need to be dealt with before high import capacities can be achieved. There are, however, no limitations to export with this alternative.

While the line reinforcements required to realise a 800 MW import capacity to Sweden through Dannebo are extensive, it is the combination of not only the increased import capacity but also a large transfer of power from SE2 to SE3 which leads to the extreme line loading in east of Sweden. Svenska kraftnät is currently conducting a study for the transfer capacity between SE2 and SE3, which will examine the division of power between the east and west sides of Sweden. For this reason the costs associated with the increased import capacity from Finland for alternative SE3-Fi will be examined in Svenska kraftnät’s own study, and have not been added to the cost of a new connection between SE3 and Finland.

**Finnish side**

The West Coast cross-section of Finland is quite heavily loaded already in the base scenarios without new transmission capacity between SE3 and Fi. Therefore even a quite modest cross-border capacity increase would trigger the need to reinforce the 400 kV AC network in southwestern Finland. The lines Rauma–Lieto and Huittinen-Forssa are heavily loaded in situations where there is transfer from SE3 to Fi. If one of those lines trips the loading on the remaining lines is not kept within an acceptable range. This is illustrated in Figure 12 and Figure 13.

![Figure 12 Consequences of Rauma-Lieto fault, low voltages and high loadings.](image)
A new transmission line between Rauma and Lieto was included in the investment costs as it was clearly required to achieve increased HVDC import capacity from Sweden.

3.5.2 Dynamic constraints

**Critical clearing times**

An issue with feeding in a large amount of power towards Dannebo is that the line Forsmark-Odensala becomes more loaded, leading to large changes in angles, and voltages, when the line is tripped.

Svenska kraftnät’s grid codes allow for a modified requirement for fault ride through. This says that a machine must remain connected to the network after a 180 ms three phase short circuit at the nearest meshed transmission network point after a line is tripped. The voltage at this point must not go below 0.7 p.u. after the fault is cleared.

This requirement reflects the time for protection equipment to trip lines, and the voltage at which nuclear power units can trip. For the case in which there is a 8800 MW transfer from SE2 to SE3, and a 800 MW import to Dannebo, the critical clearing times in Table 4 are required before voltages dip below 0.7 p.u. at FT47, where the nuclear reactor Forsmark 3 is located.
Table 4 Critical clearing times for Forsmark 3 for different Alternative SE3-FI capacities

<table>
<thead>
<tr>
<th>Disconnected line</th>
<th>0 MW</th>
<th>550 MW</th>
<th>800 MW</th>
<th>SE2-SE3 transfer</th>
<th>Wind scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>FT47- Odensala</td>
<td>150 ms</td>
<td>90 ms</td>
<td>70 ms</td>
<td>8800 MW</td>
<td>east</td>
</tr>
<tr>
<td>FT47-Ängsberg</td>
<td>150 ms</td>
<td>150 ms</td>
<td>140 ms</td>
<td>8800 MW</td>
<td>east</td>
</tr>
<tr>
<td>FT47-Dannebo</td>
<td>210 ms</td>
<td>190 ms</td>
<td>170 ms</td>
<td>8800 MW</td>
<td>east</td>
</tr>
<tr>
<td>FT47- Odensala</td>
<td>180 ms</td>
<td>120 ms</td>
<td>120 ms</td>
<td>8800 MW</td>
<td>base</td>
</tr>
<tr>
<td>FT47- Odensala</td>
<td>140 ms</td>
<td>140 ms</td>
<td>130 ms</td>
<td>8000 MW</td>
<td>east</td>
</tr>
<tr>
<td>FT47- Ångsberg</td>
<td>150 ms</td>
<td>150 ms</td>
<td>150 ms</td>
<td>8000 MW</td>
<td>east</td>
</tr>
</tbody>
</table>

It is clear that even for variations in transfer from SE2 to SE3, import to Dannebo, and wind distributions, the system is unable to fulfil the modified requirement for fault ride through.

The probability of different transfers from SE2 to SE3 and different import values to Dannebo is depicted in Figure 14. These results come from market simulations.

Figure 14 Correlation between SE3-FI and SE2-SE3 transfers
Given that high transfers from SE2 to SE3 and high imports to Dannebo can occur simultaneously, this operating condition needs to be accommodated. Determining the appropriate solution should be coordinated with further studies for reinforcements between SE2 and SE3.

Inter-area oscillations
When power is transferred from Finland to Sweden through the northern AC connections, the studied contingency was a 100 ms AC fault at Rauma followed by loss of the new HVDC connection. Due to the AC fault, FS2 is assumed to experience a short-term drop to zero-power, followed by ramping back to full power of 800 MW. Thus, the combination of two 800 MW HVDC links at Rauma will have a bigger impact on the system compared to the present configuration of FS1 and FS2. Simultaneous tripping of both HVDC connections has not been studied, as this contingency is considered to fall outside of the regular N−1 criteria for system dimensioning. It is likely that the risk of bipole failure can be managed with proper design of the possible new HVDC connection, but the effect of bipole failure and related reasonable risk level should be assessed to justify proper level of countermeasures required to address this risk.

As with the previously examined alternatives, the transfer from Finland to Sweden is constrained by the damping of the electro-mechanical interarea oscillations, as shown in Figure 15. The damping of oscillations remains adequate and a transfer capability of 2500 MW from southern Finland to northern Finland can be maintained. The damping can further be improved by utilising the damping control function in the remaining HVDC connection between SE3 and Finland.

![Figure 15 Transfer on AC border connections after 100 ms AC fault at Rauma followed by trip of alternative SE3-Fi. Both FS2 and alternative SE3-Fi transfer full power, 1600 MW towards Sweden before the fault.](image)
3.5.3 Summary of alternative SE3-FI, 800 MW HVDC connection

This alternative is constrained by internal thermal limitations on both the Swedish and the Finnish sides, and reinforcements would be required on both sides to take advantage of the full capacity of the HVDC connection.

On the Swedish side there were both thermal and dynamic problems. Overhead lines need to be upgraded, or other reinforcements built. Reactive power compensation is required, and power needs to be diverted from the area near Forsmark to solve the problems with short clearing times. Further studies are needed to determine which reinforcements are needed.

The HVDC connection alternative between SE3 and Finland would also require reinforcements in south-western Finland.

3.6 Combinations of different alternatives

3.6.1 Thermal constraints

The proposed grid alternatives, SE1-FI, SE2-FI and SE3-FI, were constrained by independent thermal limitations. Thus, the combination of different alternatives would not cause new thermal constraints in addition to those discussed with the individual alternatives in sections 3.2.1, 3.4.1 and 3.5.1.

3.6.2 Dynamic constraints

If alternative SE1-FI, the third AC line, were paired with either of the HVDC connection alternatives, the constraining factors would be the same as discussed in the previous sections for the individual alternatives. When transferring power from Finland to Sweden through AC connections, the transfer was limited by the damping of electro-mechanical oscillations, as shown in Figure 16.
From a system perspective, the combination of alternatives SE1-Fi and SE3-Fi would be less favourable than the combination of alternatives SE1-Fi and SE2-Fi, due to the fact that establishing alternative SE3-Fi means that both SE3-Fi and FS2 are both affected by AC faults near Rauma, and the fact that more import into Dannebo causes transient stability issues around Forsmark. These issues are discussed previously in section 3.5.2. However, this combination is still feasible, but more studies are required to find a solution to realise it.

It is also worth noting that additional 800 MW capacity between SE2 and Finland or SE3 and Finland would decrease transfer need through northern AC connections, which could in practice have a positive effect on the damping compared to the alternative with a third AC only.

3.7 Conclusions from the grid studies

**Alternative SE1-Fi, 400 kV AC overhead line**, provides a capacity increase of at least 800 MW. When transferring power from Sweden to Finland, the transfer capacity was constrained by thermal limits, and a new transmission line between Keminmaa and Pyhänselkä would be needed. When transferring power from Finland to Sweden, the capacity was limited by the damping of electro-mechanical oscillations. The results indicate that alternative SE1-Fi b connected to Messaure on the Swedish side is preferable to SE1-Fi a, connected to Svartbyn, as it provides a higher overall capacity increase and a better loading profile when the transfer is from Sweden to Finland.

**Alternative SE2-Fi, 220 kV AC cable**, was discarded due to poor utilisation and correlation with the flows on the existing SE1-Fi AC lines.
Alternative SE2-FI, 800 MW HVDC connection, was found to be feasible. The alternative required some reinforcements near Hägta on the Swedish side due to thermal limitations. These reinforcements would, however, be needed regardless of the new connection and was not included in the cost for the alternative. On the Finnish side no reinforcements were required. From a system perspective this was found to be the best location for a new HVDC connection.

Alternative SE3-FI, 800 MW connection, would require reinforcements in south-western Finland. A new 400 kV transmission line between Rauma and Lieto in Finland would be needed. In order to utilise the full capacity, this alternative must be studied further with respect to both thermal and dynamic aspects on the Swedish side. Dynamic studies also showed that a contingency involving an HVDC connection trip would have a bigger impact on the system if another 800 MW HVDC connection was connected to Rauma.

Combinations of the alternatives mentioned above do not require any additional reinforcements on top of the individual alternatives.

4 Technical review of the HVDC alternatives

4.1 Scope of the review

The main scope of the technical review was to provide a high level cost assessment for the main different technical solutions of the HVDC connection alternatives described in chapter 2.2.1:

- SE2-FI, HVDC connection 800 MW
- SE3-FI, HVDC connection 800 MW

In addition to the high level cost assessment, the target of the technical review was to identify the key factors affecting the overall feasibility of the different HVDC configurations. These factors include, but were not limited to, aspects which may have major impact on operational security, reliability, system technical performance and complexity of the technical solution. At this stage of the assessment, it is practically impossible to give these factors a monetary value, but their impact on system availability, reliability and safety should be taken into account in assessment of the most cost-effective solution.

4.2 The main differences between the two HVDC alternatives

As described in chapter 2, this study assumes that the FS1 HVDC system is not in operation and only FS2 connects SE3 and Finland. Decommissioning FS1 presents a major factor considering the technical and financial feasibility of the connection alternatives because simultaneous availability of both FS1 and FS2 allows for operation in a bipolar configuration. In the context of this study, the main benefit of
bipolar operation is the fact that it inherently eliminates the need for continuous use of sea electrode with high current levels.

In order to avoid operation at high electrode currents, there is great need of alternative measures to limit high continuous electrode currents. In practice this implies that a metallic return path for FS2 current must be provided. This could be obtained basically by two different approaches. One option is to invest in a new HVDC system in parallel with FS2 to facilitate bipole operation after FS1 is taken out of service. Another option is to establish a metallic return path adequate to operate continuously at the nominal current equal to the nominal current of FS2. The first option is feasible only in case of a new SE3-Fi HVDC connection, while the second one is the option that shall be applied in case of SE2-Fi HVDC connection or if no new HVDC connection is built. The need for a new return current path is the difference that has the most significant financial impact on the alternatives.

There are also two additional fundamental differences which have significant overall impact on both the technical and financial feasibility of the grid alternatives. The major differences are summarised in Table 5.

<table>
<thead>
<tr>
<th>Table 5 The main differences between the two HVDC alternatives</th>
</tr>
</thead>
<tbody>
<tr>
<td>SE2-Fi</td>
</tr>
<tr>
<td>Inherently more expensive due to the need for three new HVDC</td>
</tr>
<tr>
<td>circuits (two for SE2-Fi, new return for FS2)</td>
</tr>
<tr>
<td>No risk of bipole failure because there is no bipole</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>SE2-Fi as a greenfield project provides a straightforward technical solution and project</td>
</tr>
</tbody>
</table>

Considering the total cost of each HVDC configuration, the first item in Table 5 results in crucial differences between capital costs of the options requiring a new FS2 metallic return current circuit and the options where a new metallic return current circuit is not required. The other two factors present features that cannot be directly monetised, but are significant with regard to the technical quality of the options. In this case, one of the options is more cost-effective while the other provides better technical robustness and performance.
4.3 Technical risks and opportunities

An HVDC connection consists of several subsystems and can therefore be implemented using various different configurations. These configurations involve different risks, challenges and opportunities depending on technical choices i.e. the design of the subsystems or related technical solutions. During the review four key technical items impacting the possible HVDC configurations applicable for the studied HVDC alternatives were identified.

1. Continuous or temporary use of sea electrode
2. Use of FS1 cable either as return circuit of FS2 monopole or as neutral return circuit of FS bipole
3. Bipole as main circuit configuration
4. Converter technology selection

4.4 The different main configurations

In the following two sections the configurations that were considered as feasible are presented. The configurations for alternatives SE2-Fi and SE3-Fi are described in chapter 4.4.1 and chapter 4.4.2 respectively.

4.4.1 The main configurations for alternative SE2-Fi HVDC

For the SE2-Fi HVDC alternative, only configurations based on VSC converter technology are presented, because LCC based configuration provided essentially the same outcome. For alternative SE2-Fi the overall configuration, and specifically the need to arrange a new metallic return current path for FS2, as indicated in previous sections, has a decisive impact on the total cost and feasibility. Therefore, the difference between the two main options related to the SE2-Fi HVDC connection are actually different only with respect to the technical solution for the return cable of FS2 which alone defines the cost-effectiveness of this alternative.

An overview of the main technical configurations for alternative SE2-Fi is provided in Table 6 and Figure 17. The configuration with the existing FS1 cable serving as FS2 return cable is referred to as option A, and the configuration with a new FS2 sea return cable is referred to as option B.
Table 6 Summary of the main configurations for alternative SE2-Fi

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>New VSC at SE2-Fi FS2 with FS1 cable serving as return cable</td>
<td>Lower cost than SE2-Fi Option B</td>
<td>Highest reliability and asset risks Highest losses</td>
</tr>
<tr>
<td>B</td>
<td>New VSC at SE2-Fi FS2 with new sea return cable</td>
<td>New, standalone, state-of-art HVDC connection</td>
<td>Highest cost</td>
</tr>
</tbody>
</table>

Figure 17 Overview of the technical options most relevant for alternative SE2-Fi.

4.4.2 The main configurations for alternative SE3-Fi

Overview of the main technical configurations for alternative SE3-Fi is provided in Table 7 and Figure 18. For SE3-Fi four main options are presented as a combination of two different converter technologies and two different solutions available to arrange neutral metallic return circuit for the bipole. Unlike for SE2-Fi HVDC connection, the converter technology presents significant difference in case of SE3-Fi due to required bipole configuration. Options 1A and 1B are based on LCC technology. Option 1A considers the existing FS1 cable serving as a neutral return circuit and option 1B considers the investment of a new cable for the neutral return. Options 2A and 2B are based on VSC technology, and refer to the solutions applied to address the need for a neutral return cable.
### Table 7 Summary of the main configurations for alternative SE3-FI

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>1A</td>
<td>new FS as a greenfield LCC FS1 cable as a neutral return</td>
<td>Reduced bipole failure risk, lowest cost</td>
<td>Status of LCC technology in 2020s, weaker performance than VSC, minor risk concerning feasibility of FS1 cable</td>
</tr>
<tr>
<td>1B</td>
<td>new FS as a greenfield LCC New neutral return</td>
<td>Reduced bipole failure risk</td>
<td>Status of LCC technology in 2020s, weaker performance than VSC, higher cost than 1A</td>
</tr>
<tr>
<td>2A</td>
<td>new FS as a greenfield VSC FS1 cable as a neutral return</td>
<td>Lowest bipole failure risk, low cost as compared with 2B</td>
<td>Bipole with VSC and LCC not a standard solution, higher losses that option 1A/B, minor risk concerning feasibility of FS1 cable</td>
</tr>
<tr>
<td>2B</td>
<td>new FS as a greenfield VSC New neutral return</td>
<td>Lowest bipole failure risk</td>
<td>Bipole with VSC and LCC not a standard solution, highest cost, higher losses that option 1A/B</td>
</tr>
</tbody>
</table>

---

**Figure 18 Overview of the "greenfield" technical options 1 and 3 most relevant for alternative SE3-FI**

4.5 Assessment of the main cost components

Table 8 and Table 9 present the cost (capital cost and losses) estimates for the HVDC subsystems. The values were based on the best information available, and most of the figures were based on actual realised investment costs and losses determined during recent HVDC projects.
Table 8 Estimate of the capital costs of the main HVDC subsystems

<table>
<thead>
<tr>
<th>Key technical data</th>
<th>Cost estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>LCC converter 500 kV, 800 MW</td>
<td>80 MEUR</td>
</tr>
<tr>
<td>VSC converter 300 kV, 800 MW</td>
<td>80 MEUR</td>
</tr>
<tr>
<td>XLPE cable, main circuits 300 kV, 1400 A</td>
<td>0.6 MEUR / km</td>
</tr>
<tr>
<td>MI cable, main circuit 500 kV, 1700 A</td>
<td>1.2 MEUR / km</td>
</tr>
<tr>
<td>XLPE cable, return circuit 20 kV, 1700 A</td>
<td>0.95 MEUR / km</td>
</tr>
<tr>
<td>MI cable, return circuit 20 kV, 1700 A</td>
<td>1.2 MEUR / km</td>
</tr>
</tbody>
</table>

Table 9 The loss estimates for the main HVDC subsystems

<table>
<thead>
<tr>
<th>Key technical data</th>
<th>Loss estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>LCC converter 500 kV, 800 MW</td>
<td>0.7% per converter</td>
</tr>
<tr>
<td>VSC converter 300 kV, 800 MW</td>
<td>1% per converter</td>
</tr>
<tr>
<td>XLPE cable, main circuits 300 kV, 1400 A</td>
<td>32 W / m</td>
</tr>
<tr>
<td>MI cable, main circuit 500 kV, 1700 A</td>
<td>28 W / m</td>
</tr>
<tr>
<td>XLPE cable, return circuit 20 kV, 1700 A</td>
<td>47 W / m</td>
</tr>
<tr>
<td>MI cable, return circuit 20 kV, 1700 A</td>
<td>28 W / m</td>
</tr>
<tr>
<td>FS1 as return 20 kV, 1310 A</td>
<td>50.5 W / m</td>
</tr>
</tbody>
</table>

The investment cost for a cable handling the return current of FS2 was estimated to be 189 MEUR utilising the XLPE cable unit cost of 0.95 MEUR/km and a cable length of approximately 200 km. The operating cost for the return cable at maximum transfer capacity for FS2 was calculated by using the loss estimate for the XLPE cable in Table 9 multiplied with the cable length.

4.6 Preferred alternatives

Based on the high level assessment, the following preferred alternatives were identified:

- Alternative SE2-FI installed as a greenfield HVDC system and FS2 as a monopole with new return cable (option B in Table 6).

Alternative SE2-FI was considered the most technically sound, but it is heavily burdened by the need of two metallic return circuits: one between SE2 and Finland and one as a return circuit.
for FS2. In this case FS2 would be modified as monopolar system with new cable as return circuit, because the risks and the consequences related to failure of the FS1 cable while serving as the only metallic return current path for FS2 current are considered unacceptable.

- Alternative SE3-Fi installed as a greenfield HVDC system to setup a bipole with the FS2 and FS1 cable would be used as a metallic neutral return circuit (option 2A in Table 7).

Maintaining bipole configuration provides significant cost benefits as compared to independent, monopolar HVDC systems. The FS1 cable is considered as feasible for this use of purpose as it will be loaded beyond its nominal current only if either FS2 or alternatively SE3-Fi is out of operation. Neither of the two converter technologies has a major advantage over the other and in this context their cost can be estimated to be close to equal. The selection of the converter technology and identification of technical issues requiring special attention can be done at the stage of pre-specification studies to be conducted before the possible project.

4.7 Recommended next actions

The following four actions are recommended in the case that at least one of the two HVDC alternatives is proposed as a future cross-border capacity investment:

1. An assessment of the technical feasibility of using the FS1 cable either as a return circuit for FS2 or a neutral return circuit for a new FS bipole should be launched.

2. The extent of the refurbishment of Fenno-Skan sea electrode shall be evaluated in case the preferred configuration benefits from use of the FS1 cable.

3. Necessary technical clarification to determine the measures for managing system security risks (ensuring technical quality) should be started in case the preferred configuration is based on bipolar use of FS2 and alternative SE3-Fi.

4. Clarification about the different approaches affecting the availability of FS1 as a back-up connection for the period of commissioning, trial and warranty of new possible HVDC connection should be started.

5 Routing and permissions

5.1 Routing and environmental aspects

In this chapter, the routing and environmental aspects for the grid alternatives listed in chapter 2.2.1 on the Finnish and Swedish sides are
described. The AC cable SE2-FI was not evaluated as it was discarded during the grid studies.

5.1.1 Finland

The basics of the interconnector route options are shown in Table 10 and in Figure 19 and Figure 20. In Appendix 1 more specific information regarding the essential features within and nearby the suggested Finnish corridors can be found. The studied routes are to be considered preliminary and are based on a map study. The presented environmental data is based on regional land use plans and geographic information systems.

<table>
<thead>
<tr>
<th>Alternative</th>
<th>In total</th>
<th>Onshore part</th>
<th>Submarine part</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Length (km)</td>
<td>Length (km)</td>
<td>Parallel to an existing transmission line (km)</td>
</tr>
<tr>
<td>SE1-FI (Kukkolankoski)</td>
<td>179</td>
<td>179</td>
<td>93</td>
</tr>
<tr>
<td>SE1-FI (Vuennonkoski)</td>
<td>205</td>
<td>205</td>
<td>119</td>
</tr>
<tr>
<td>SE2-FI</td>
<td>129</td>
<td>60</td>
<td>27</td>
</tr>
<tr>
<td>SE3-FI</td>
<td>238</td>
<td>117</td>
<td>117</td>
</tr>
</tbody>
</table>

3 Fingrid 2016, "New interconnection Finland to Sweden preliminary assessment_Fingrid summary text_Final_9.6.2016"
Figure 19 General map of the route alternatives

SE1-Fi Pyhänselkä-Kortejänkkä-Kukkolankoski/Vuennonkoski – territorial border of Sweden
SE1-Fi starts at Pyhänselkä in Oulu region and ends at the territorial border of Sweden in Tornio region. The total length of the transmission...
line route is either 179 km (Kukkolankoski) or 205 km (Vuennonkoski). The route is situated onshore.

A new infrastructure corridor is needed for 86 km from Pyhänselkä to Tuomela. From Tuomela to Kukkolankoski or Vuennonkoski the route is parallel with the existing transmission lines. The land area required for a new transmission line is approximately 550 ha for the Kukkolankoski alternative, and 600 ha for the Vuennonkoski.

**SE2-FI Tuovila-Korsnäs-EEZ Finland/Sweden**
SE2-FI is comprised of a transmission line route between Tuovila and Korsnäs and a submarine power cable route between Korsnäs and the Exclusive Economic Zone (EEZ) Finland/Sweden.

The onshore length of the route is 60 km and the length of the submarine cable is 69 km, making the total length of SE2-FI 129 km.

From Tuovila to Murtoinen the route is parallel with existing transmission lines for 27 km. A new infrastructure corridor is needed for 33 km between Murtoinen and Korsnäs. The submarine power cable route is in a new infrastructure corridor. The land area required for this is approximately 200 ha.

**SE3-FI Lieto-Rauma-Rihtniemi-EEZ Finland/Sweden**
SE3-FI is comprised of transmission line route from Lieto via Rauma to Rihtniemi and a submarine power cable route from Rihtniemi to the EEZ Finland/Sweden.

The onshore length of the route is 117 km and the length of the submarine cable is 121 km, making the total length of SE3-FI 238 km.

The onshore transmission line route is parallel with existing transmission lines. The submarine power cable route is roughly parallel with FS1 connection. The land area required for this is approximately 240 ha.
5.1.2 Sweden

In Appendix 2 more specific information regarding the essential features within and nearby the Swedish suggested corridors can be found. The routes, described in the following chapters, are the result of a desktop study based on available geographic information about land use, infrastructure, environment, archaeology, terrain and geology.

**SE1-FI Messaure/Svartbyn – territorial border of Finland**

The alternative SE1-FI is located in the Swedish region Tornedalen. Tornedalen is situated in the county of Norrbotten in the north eastern part of Sweden. The area is characterised by large forests and wetlands in an undulating landscape. The river systems of Råneälven, Kalixälven and Torneälven flow from north to south through the landscape. In the western parts of the area the terrain consists of bouldery moraine and areas of peat and stratified drift. Further east the moraine gets less bouldery with areas of peat and stratified drift. The route options are presented in the text below, Figure 21.

**SE1-FI (Messaure-Vuennonkoski)**

The corridor starts at the Messaure station and ends at the northern connection point at the territorial border of Finland. The corridor

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4 Svenska kraftnät 2016, “New interconnection between Finland and Sweden preliminary feasibility study”
measures approximately 185 km in length. About 10 percent of the corridor runs parallel with existing transmission lines. This will take approximately 800 hectares of land.

SE1-Fi (Messaure-Kukkolankoski)

The corridor starts at the Messaure station and ends at the southern connection point at Kukkolankoski at the territorial border of Finland. The corridor measures approximately 210 km in length. About 15 percent of the corridor runs parallel with existing transmission line. This will take approximately 900 hectares of land.

SE1-Fi (Svartbyn-Kukkolankoski)

The corridor starts from the Svartbyn station east of Boden and runs parallel with existing transmission line UL21 S1-2 A1 for 91 km and thereafter UL 21 S3-4 A1 for the last 19 km. Parallel with UL21 S3-4 A1 is a power line corridor from the former transmission line AL9 A1. The connection point with the territorial border of Finland is the southernmost point in the map below, at Kukkolankoski. The corridor is chosen with consideration of running parallel with existing transmission line, and not like the other corridors that consider environmental features and buildings. That means the adjustments due to environmental or other aspects might be needed even though it runs parallel with existing corridors. This will take approximately 330 hectares of land.

Figure 21 Map showing the three alternative route corridors at SE1-Fi.
SE2-Fi Hjälta-EEZ Sweden/Finland
The area of Hjälta is situated in the counties of Västernorrland and Västerbotten by the east coast in the middle part of Sweden and reaches to the EEZ (Sweden/Finland) about 50 km from the coast in the Sea of Bothnia. The land area is characterised by forests in an undulating terrain with many lakes and watercourses. The terrain consists of rock and moraine and various soil conditions. The marine geology consists of sedimentary rock covered by postglacial and glacial masses of soft clay, sand and bouldery moraine.

The corridor starts with an overhead line from Hjälta power station outside Sollefteå and runs south of the existing transmission line. The route on land is approximately 120 km long, whereof approximately 20 percent runs parallel with an existing transmission line. The alternative has a connection to a submarine power cable at the proposed landfall Grundsunda. The submarine power cable measures 55 km and ends at the EEZ. This route option is a combination of different corridors (Hjälta 1 and Hjälta 2) as shown in Figure 22. This will take approximately 500 hectares of land.

Figure 22 Map showing the alternative route corridor SE2-Fi

SE3-Fi Dannebo-EEZ Sweden/Finland
The area of Dannebo is situated in the county of Uppsala on the eastern coast of Sweden. The marine geology consists of sedimentary and crystalline rock partially covered by glacial and postglacial clay. The surface substrate contains of boulders and gravel. Rocks are visible at several places. The route is chosen north of the existing submarine
power cables. Due to terrain, national interests and protected areas a route south of the existing cables has been ruled out. The alternative starts at Dannebo power station and runs as a cable on the onshore part. It measures approximately 1.8 km and goes mostly parallel with existing land cables. This will take approximately 2 hectares of land. The route follows a road towards northwest and connects to the submarine power cable north of the existing landfall for XL7 S3 A2 and XL8 S4 A2. The submarine power cable, within Swedish waters, measures about 80 km and ends at the EEZ. In open water the route goes parallel with existing submarine power cables (XL7 S3 A2 and XL8 S4 A2), as shown in Figure 23.

![Figure 23 Map showing the alternative route corridor of SE3-FI.](image)

### 5.2 Permit processes in Finland and Sweden

The permission processes in Sweden and Finland are complex, time-consuming and require the involvement of a variety of authorities. A complete list of permits required in Finland and Sweden are shown in Table 11 and Table 12. The ESPOO convention has to be followed for cross-border projects in the Baltic Sea that may have environmental impacts on other countries. The overall Swedish permit process takes approximately seven to ten years, while the Finnish process is estimated to take three to five years.
<table>
<thead>
<tr>
<th>Process</th>
<th>Permits</th>
<th>Authorities</th>
<th>Timescale</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bottom survey permits</strong></td>
<td>Exploration of the sea bottom</td>
<td>Finnish Government</td>
<td>3-6 months</td>
</tr>
<tr>
<td></td>
<td>Right to perform surveys in Finnish waters</td>
<td>The Finnish Defence Forces</td>
<td>1-2 months</td>
</tr>
<tr>
<td><strong>Construction permit process</strong></td>
<td>Construction permit</td>
<td>Energy Market Authority</td>
<td>3-6 months</td>
</tr>
<tr>
<td></td>
<td>Cross-border permit</td>
<td>Ministry of Employment and Economy</td>
<td>9 months</td>
</tr>
<tr>
<td><strong>Land acquisition process</strong></td>
<td>Survey permit</td>
<td>National Land Surveying</td>
<td>3-4 months</td>
</tr>
<tr>
<td></td>
<td>Expropriation permit incl. EIA</td>
<td>Finnish Government</td>
<td>2-3 years</td>
</tr>
<tr>
<td><strong>Permission to build in water process</strong></td>
<td>Water permit</td>
<td>Finnish Regional State Administrative Agency</td>
<td>6 months</td>
</tr>
<tr>
<td></td>
<td>Economic Zone Permit</td>
<td>Finnish Government</td>
<td>6 months</td>
</tr>
<tr>
<td><strong>Permission to build on substations</strong></td>
<td>Building permit</td>
<td>Municipality</td>
<td>1-2 months</td>
</tr>
<tr>
<td><strong>Permission to build on important conservation areas</strong></td>
<td>Change of degree or Act</td>
<td>Finnish Government</td>
<td>2-3 years</td>
</tr>
</tbody>
</table>
Table 12 Permits in Sweden

<table>
<thead>
<tr>
<th>Process</th>
<th>Permits</th>
<th>Authorities</th>
<th>Timescale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bottom survey permits</td>
<td>Exploration of the continental shelf</td>
<td>Ministry of Enterprise and Innovation</td>
<td>4-8 months</td>
</tr>
<tr>
<td></td>
<td>Right to perform surveys in Swedish waters</td>
<td>Swedish Defense Authority</td>
<td>1-4 months</td>
</tr>
<tr>
<td>Concession process</td>
<td>Concession incl. consultation and EIA</td>
<td>Energy Markets Inspectorate, Ministry of the Environment and Energy</td>
<td>6-9 years</td>
</tr>
<tr>
<td>Land acquisition process</td>
<td>Right of way</td>
<td>Cadastral Authority</td>
<td>6 months</td>
</tr>
<tr>
<td>Permission to build in water process</td>
<td>Permit incl. consultation and EIA</td>
<td>Land and Environment Court</td>
<td>2-4 years</td>
</tr>
<tr>
<td></td>
<td>Right to lay cables in the territorial sea</td>
<td>The Legal, Financial and Administrative Services Agency</td>
<td></td>
</tr>
<tr>
<td>Building permit process</td>
<td>Building permit</td>
<td>Municipality</td>
<td>1-2 years</td>
</tr>
<tr>
<td>Continental Shelf process</td>
<td>Permit according to the Continental Shelf Act</td>
<td>Geological Survey of Sweden, Ministry of Enterprise and Innovation</td>
<td>1-4 months</td>
</tr>
</tbody>
</table>

5.3 Conclusions regarding routes and permits

The Finnish part in SE1-FI (the northernmost transmission line route either via Kukkolankoski or Vuennonkoski) requires a long new infrastructure corridor and several possible conflicts with Natura 2000 and conservation areas. There is a possible need for more detailed route planning and/or law reform and several Natura Assessments, which may result in scheduling risks. The same is true of the Swedish side. On top of that conflicts will arise due to the fact that there are military areas with restrictions in building heights.

The Finnish part in SE2-FI to Tuovila has a submarine cable and the shortest onshore part. Re-routing or permitting risks are identified mainly related near one Natura 2000 area on the onshore part. Several Natura 2000 areas are located on the Swedish onshore part, along the 120 km overhead line.

The Finnish part in SE3-FI to Lieto has a submarine cable and an onshore part parallel to existing transmission lines, where there is plenty of dense inhabitation. There are major risks regarding implementation and
timetable concerning Perämeri National Park, which the new submarine cable route crosses, leading to the need for a law reform. On the Swedish side the onshore distance is only 2 km long and runs parallel with existing cables. Even though it runs parallel with existing cables, and only for a short distance, it runs through areas of national interests which can cause conflicts. The offshore part crosses areas of interest for the Commercial Fishery.

It is difficult at this stage to compare the alternatives other than in a general way. For the SE1-FI AC alternative there are no permit processes related to sea cables, for example, bottom surveys. Sea cables can be more risky when it comes to estimate the time required to obtain the required permits.

All three alternatives are considered feasible based on current information. A more detailed analysis, in which the routes should be much more deeply investigated, is required in the next phase.

6 Market studies

6.1 General approach

In the market studies the AC line alternative SE1-FI, as well as the HVDC connection alternatives; SE2-FI and SE3-FI listed in 2.2.1 were evaluated in a socio-economic perspective. The AC cable SE2-FI was not evaluated as it was discarded during the grid studies. The market studies were divided into two parts:

- PINT studies (Put IN one at a Time)
- Socio-economic evaluation

In the PINT-studies, a net present value (NPV) was calculated for each alternative. The aim of the PINT study was to sort out and promote the most promising grid alternative or alternatives for the socio-economic evaluation phase where the grid alternatives were further evaluated in both qualitative and quantified terms. The PINT studies are described in chapter 6.3 while the socio-economic evaluation is mainly covered in chapter 7. The findings from the technical review, presented in chapter 4, were not yet available when the PINT studies were performed and were incorporated first in the socio-economic evaluation. However, in chapter 7.2.10 a consistency check was performed to confirm the PINT result.

Two market models were utilised in the studies: “Better Investment Decision” (BID) and “EFI’s Multi-area Power-market Simulator” (EMPS). The BID model is better adapted to capture the behaviour of thermal production whilst the hydro modelling is more thoroughly developed in EMPS. The differences in the model methodology provided additional robustness and reliability to the results.
The simulation years 2025 and 2035 were selected. A reference scenario was constructed for 2025 and 2035. In addition three alternative scenarios were built for 2035.

In the market simulations 51 historical weather years ranging from 1962 to 2012 were utilised to capture possible variation of hydro inflow, wind and temperature. In the BID model an hourly time resolution was used and for the EMPS model each week was divided into ten non-sequential price periods. Svenska kraftnät conducted the BID simulations and Fingrid the EMPS simulations. For economical evaluation an average of the output from the two models was used while BID results were applied where hourly output was needed.

Prior to the PINT simulations, an important part of the study was to setup and harmonise the two market models. The inputs were discussed thoroughly and realistic developments outlined with the help from national plans, the ENTSO-E’s Ten Year Network Development Plan (TYNDP), World Energy Outlook (WEO) and other applicable sources. The simulation output was evaluated in order to have harmonised and comparable results between the models. It was important to understand the market outcome (energy balances, power flows and day-ahead market prices) in order to be certain of the usability of the result. The evaluation was performed for all simulated scenarios. Both models provided very similar results with no significant differences, and could therefore be used for the study.

6.1.1 Net present value calculation

In both the PINT studies and in the socio-economic evaluation, NPVs were calculated to assess the different grid alternatives. In this chapter the methodology and the assumptions for the calculations are described.

In the NPV calculation the future expected costs and revenues over a given period of time were converted into a NPV using a real discount rate of 4 percent, a valuation period (economical life time) of 25 years and a residual value of 0. These parameters are proposed by the European Commission and ACER, and accepted by ENTSO-E for Project of Common Interest (PCI) assessment. These assumptions were concluded to be reasonable and applicable in this study.

Both AC overhead lines and HVDC connections were investigated and compared. Although the expected technical lifetime of sea cables

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built today has not been tested in practice, AC lines are assumed to have a significantly longer lifetime. The 25-year analysis period was applied for all alternatives irrespective of the technology used, but the life expectancy was evaluated as an extra advantage for the AC line alternative.

The costs of grid investments were estimated by utilising typical unit costs (in MEUR or MEUR/km) for different types of power lines and other equipment. The length of each alternative was estimated based on expected routing. The cost for necessary equipment and other required internal reinforcements were included based on grid studies. The unit costs for AC lines and related equipment can be estimated fairly accurately due to several recent projects. However, for the HVDC connections, the unit costs can vary significantly depending on e.g. the supply/demand situation at the time of investment or the development of different technical solutions. Therefore, a price range of unit costs was estimated based on available data from recently commissioned and upcoming projects. As mentioned earlier the technical review presented in chapter 4 was not yet available at the time the PINT study was performed and the findings were first incorporated in the socio-economic evaluation. How the recommendations from the technical review impacted the cost assessment in the socio-economic evaluation is described in chapter 7.1.2.

Socio-economic welfare (SEW), which is the consumer and producer surplus as well as the congestion rent, is regarded as the revenue for the grid alternatives. The SEW calculations for all studied alternatives were performed for years 2025 and 2035, as described earlier, due to the possibility to use several data sources that were available for these years. There are only a few data sources describing the development of the electricity market beyond 2035 so this was assumed to be the best choice for the latter simulation year.

The NPV calculations were performed assuming that all alternatives are commissioned at 1.1.2028, thus the annual SEW values for 2028-2034 were interpolated from the 2025 and 2035 SEW results, and for the further years the 2035 results were used. Additionally, a construction period of four years prior to the commissioning was assumed for all alternatives. The NPVs were discounted to the year 2016. Costs and socio-economic welfare are described in more detail in chapter 7.1.2 and 7.2.1 respectively.

6.2 Scenarios and basic assumptions

6.2.1 Scenarios

Investigated scenarios in the study included the reference (best estimate) scenario and three alternative scenarios.

The reference scenario for 2025 and 2035 was constructed by combining estimates of future development by Fingrid and Svenska
kraftnät, as well as data collected in Baltic Sea Market Modelling Group and the Baltic Sea Green Vision (BSGV) scenario created within ENTSO-E. Three alternative scenarios for 2035 were then built by grouping interdependent uncertainties in an attempt to capture possible future developments with regards to fuel prices, policies and technologies.

For continental Europe, focus lay on updating data for Germany, France and the United Kingdom as the future electricity balance of these countries could have a significant impact on the Nordic energy system. For this purpose, national development plans describing the future possible development for each country, were utilised. The different paths in the national plans were matched with the storylines for the reference and alternative scenarios and incorporated in the market models.

The scenario set-up is outlined in Figure 24 and key differences with regards to fuel and CO₂-prices are shown in Table 13.

![Figure 24 Scenario set-up](image)

### Table 13 Coal, gas and CO₂ prices [€/MWh] used in the scenarios (excluding inflation).

<table>
<thead>
<tr>
<th>Type</th>
<th>Ref2025</th>
<th>Ref2035</th>
<th>Price Pressure</th>
<th>CO₂-focus</th>
<th>New Tech</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>9</td>
<td>11</td>
<td>9</td>
<td>12</td>
<td>11</td>
</tr>
<tr>
<td>Gas</td>
<td>24</td>
<td>28</td>
<td>26</td>
<td>40</td>
<td>28</td>
</tr>
<tr>
<td>CO₂</td>
<td>23</td>
<td>46</td>
<td>3</td>
<td>90</td>
<td>46</td>
</tr>
</tbody>
</table>

As a part of the scenario development process, all scenarios were quantified with EMPS and BID tools. Table 14 presents the overall market simulation results in different scenarios compared with the historical year of 2013.

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6 France: Réseau de transport d’électricité (Rte) (2014), “Generation adequacy report on the electricity supply and demand in France

Germany: Netzentwicklungsplan 2025, Version 2015, zweiter Entwurf

The United Kingdom: National Grid (2015), Electricity Ten Year Statement 2015, UK electricity transmission
Table 14 Annual key figures in reference scenario and alternative scenarios, and compared to historical values. Source for 2013 numbers: ENTSO-E statistical factsheet7.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Historical</th>
<th>Reference</th>
<th>Price</th>
<th>CO2 focus</th>
<th>New Tech</th>
</tr>
</thead>
<tbody>
<tr>
<td>[TWh/y]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Year</td>
<td>2013</td>
<td>2025</td>
<td>2035</td>
<td>2035</td>
<td>2035</td>
</tr>
<tr>
<td>Nordic demand</td>
<td>383</td>
<td>411</td>
<td>434</td>
<td>381</td>
<td>462</td>
</tr>
<tr>
<td>Nordic wind production</td>
<td>23</td>
<td>59</td>
<td>85</td>
<td>97</td>
<td>95</td>
</tr>
<tr>
<td>Nordic solar production</td>
<td>0</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Nuclear production SE+FI</td>
<td>86</td>
<td>85</td>
<td>84</td>
<td>45</td>
<td>84</td>
</tr>
<tr>
<td>Annual balance Nordic countries</td>
<td>±0</td>
<td>+13</td>
<td>+15</td>
<td>+31</td>
<td>+15</td>
</tr>
<tr>
<td>Annual balance Sweden</td>
<td>+10</td>
<td>+18</td>
<td>+24</td>
<td>+5</td>
<td>+17</td>
</tr>
<tr>
<td>Annual balance Finland&lt;sup&gt;a&lt;/sup&gt;</td>
<td>-16 (-11)</td>
<td>-17 (-14)</td>
<td>-18 (-17)</td>
<td>-8 (±0)</td>
<td>-18 (-20)</td>
</tr>
<tr>
<td>Nordic system price (EUR/MWh)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>38</td>
<td>46</td>
<td>61</td>
<td>24</td>
<td>99</td>
</tr>
<tr>
<td>Share of RES generation</td>
<td>65 %</td>
<td>73 %</td>
<td>77 %</td>
<td>86 %</td>
<td>78 %</td>
</tr>
<tr>
<td>Share of CO2-free generation</td>
<td>88 %</td>
<td>93 %</td>
<td>95 %</td>
<td>96 %</td>
<td>95 %</td>
</tr>
</tbody>
</table>

<sup>a</sup>Balance including net flow between Russia and Finland given in parenthesis

<sup>b</sup>Average price for Sweden and Norway (normal hydro year) used to represent the system price for the scenarios, excluding inflation

In the reference scenario, continued climate policy has strengthened the emission trading system, but with renewable subsidies still playing a role. CO2 prices increase to 23 EUR/ton by 2025 and 46 EUR/ton by 2035.

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Fuel prices increase from 2015 levels. Electricity demand in the Nordic countries grows moderately at approximately 0.6 percent p.a. between 2013 and 2035, as growth in new demand types such as data centres, heat pumps and transportation offsets demand reduction via increased efficiency.

The Nordic wind output more than doubles between 2013 and 2025. Between 2013 and 2035, it almost quadruples driven by energy policies and higher electricity and CO₂ prices. No new nuclear plants are built in Finland or Sweden after completion of Olkiluoto 3 and Hanhikivi 1. Oskarshamn 1 and 2 as well as Ringhals 1 and 2 are decommissioned by 2020, while the remaining six units are operational in 2025 and 2035. Lovisa 1 and 2 are decommissioned by 2030. Between 2025 and 2035, the increase of production from Hanhikivi 1 and decrease in production from the Lovisa units balance each other, therefore the total generation from Finnish nuclear units is roughly the same in 2025 and 2035. Conditions for reinvestments in ageing CHP plants become profitable in the 2030s.

Conditions for electricity trade between Finland and Russia does not change significantly from the present – capacity payments and inflexible trading arrangements continue to limit the trade. For the year 2035, the three oldest HVDC interconnectors between Finland and Russia are decommissioned, leaving only 320 MW commercial transmission capacity between the countries.

The Swedish annual electricity balance remains significantly positive, as wind generation offsets the decline in nuclear generation and growth in demand. The Finnish annual balance remains in deficit, even when nuclear and wind generation increase significantly. Growth in demand and reduction in fossil-based thermal generation keep the annual balance negative. Consequently, the exchange between Sweden and Finland is primarily from Sweden to Finland. The wholesale electricity price rises to a level where unsubsidised generation investments are feasible.

In general, the assumptions in the reference scenario are in line with the latest political agreement in Sweden⁸ regarding support for renewables and policies towards nuclear energy, as well as the political targets and assumptions regarding energy and climate strategy published in Finland⁹.

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⁸ Available at http://www.regeringen.se/contentassets/b88f0d28eb0e48e39eb4411de2aabe76/energioverenskommelse-20160610.pdf
⁹ Assumptions in reference scenario of Energy and Climate Strategy (first draft, in Finnish). Available at: http://tem.fi/documents/1410877/2148188/Perusskenaarion+taustaotukset+%28luonnos+16.5.2016%29/1f44a515-66f2-477f-bfd0-ac6d7a9fc1c3
In the **price pressure** scenario the continued climate policy has a strong focus on direct renewable subsidies, which continue to keep the wholesale electricity prices relatively low. Given that climate action is effected through subsidies, CO₂ prices develop poorly and remain at 3 EUR/ton by 2035. Fuel prices remain at 2015 levels. Electricity demand in 2035 is at the same level as in 2013, as new demand due for increased electrification is offset by decrease in industrial demand.

Subsidies increase wind power output significantly compared to the reference scenario. Wind power covers 25 percent of the annual Nordic electricity demand and becomes the second largest source of electricity (after hydro) in terms of annual production. A considerable share of the increase between 2025 and 2035 is located in Finland. Several nuclear plants are closed by 2035 in the scenario due to low wholesale prices and only three units in Finland and two units in Sweden remain. Consequently, Nordic nuclear generation almost halves compared to reference scenario.

Low fuel prices and insignificant CO₂ trading together with strongly subsidised wind power keeps the wholesale electricity prices at a low level, with Nordic prices averaging between 25 and 30 EUR/MWh for an average weather year. In Russia, the wholesale electricity prices are also low. Together with the elimination of capacity payments and reconstruction of the Vyborg HVDC facility, there is an increase of electricity imports from Russia to Finland.

The wholesale price level does not support investment in unsubsidised generation such as CHP, resulting in decreased CHP generation compared to the reference scenario. However, due to simultaneous weak demand growth, strong wind power development and higher imports from Russia, the Nordic region has a higher surplus compared to the reference case.

Swedish surplus is significantly decreased in the scenario due to decommission of nuclear generation. Meanwhile, Finland is in balance if Russian imports are included. The electricity price in Russia is generally lower than the price in the Nordics, leading to significant export from Russia to Finland and the Baltic countries. Consequently, the exchange between Finland and Sweden becomes balanced on annual level. An objective of creating this scenario was to assess a case where the exchange between Finland and Sweden would be balanced, given that in other scenarios, and the current situation in the market, power flow is mainly from Sweden to Finland. Therefore, increase in wind generation is especially high in Finland in this scenario (+9 TWh compared to reference scenario 2035).

In the **CO₂ focus** scenario a significantly stronger global CO₂ reduction framework compared to the reference scenario was considered. Consequently, the CO₂ price climbs to 90 EUR/ton by 2035, driven by the global effort to reduce CO₂ emissions and maintain the long-term rise of global temperature between 1.5-2 °C. Overall, Nordic electricity
demand in 2035 is six percent above the reference case level and 21 percent above the 2013 level. Global CO₂ trading blocks “carbon leakage”, which occurs when industrial production is located to countries outside the emission trading schemes. Consequently, electricity demand in the Nordic countries increases due to a higher level of industrial activity in the region. In addition, the high CO₂-price also facilitates new technologies replacing fossil fuels with electricity in industrial processes, such as the CO₂-free steel initiative currently investigated by Vattenfall, SSAB and LKAB. Adoption of such technologies supports electricity demand growth. Fuel prices are higher than in the reference case.

Due to high CO₂ prices, wholesale electricity prices are at high level, averaging close to 100 EUR/MWh. Such prices effectively facilitate investment in new emission-free power generation without subsidies. Consequently, wind capacity is on a higher level compared to the reference scenario, especially in Norway. In Finland, additional investments in biomass-based CHP are feasible compared to the reference scenario. Despite the higher wholesale price level, the number of nuclear reactors is the same as in the reference scenario. In Sweden, changes in climate policy after 2025 do not affect the decision to decommission the four oldest units as that is set to happen by 2020. In Finland, two new units were assumed in the reference case, and no further units were assumed feasible before replacement investments would be needed due to the scheduled decommissioning of Olkiluoto 1 and 2 in the late 2030s. While no additional nuclear is built in the Nordic countries in this scenario, Visaginas nuclear power plant was assumed to be built in Lithuania, therefore increasing nuclear generation in the region compared to the reference scenario.

Prices for CO₂ and domestic natural gas in Russia were assumed to increase to the same level as in Europe. Consequently, Russian wholesale electricity prices increased significantly compared to reference scenario, making capacity payments unnecessary and facilitating the renovation of the Vyborg HVDC facility. Due to relatively poor efficiency of Russian power plants compared to European ones, the main direction of the power flow is from Finland to Russia.

Swedish surplus is slightly lower in CO₂ focus scenario compared to reference scenario, due to higher consumption. Finnish balance is roughly on reference scenario level, as increase in bio-CHP generation is offset by increasing demand.

The New Technology scenario was constructed to examine the effects that significant growth of residential solar capacity, electric vehicles and increased (intra-day) flexibility have on interconnectors between
Finland and Sweden. Nordic electricity demand is two percent above the reference scenario due to a higher number of electric and hybrid vehicles. Nordic solar capacity increases to 16 GW in the scenario, roughly 0.6 kWp/capita. This is a similar penetration to the one presently observed in Germany. The intra-day generation profiles of solar resemble the residential electricity intra-day demand profile, meaning that “prosumers”, with the help of batteries balance their own demand with their own generation, to a greater extend. Furthermore, there is no commercial electricity trade between Finland and Russia or the Baltic countries and Russia. Otherwise, the assumptions are as in reference scenario.

Despite the significant increase of capacity, annual electricity from solar power only covers three percent of the Nordic electricity demand. Therefore, its effects on the annual key results are relatively low, and consequently the annual balances and generation mix in the New Technology scenario is relatively similar to the Reference scenario.

6.2.2 Sensitivities

In addition to alternative scenarios, a set of sensitivities were also studied. These sensitivities were factors that were considered relevant to be studied independently, i.e. not merging them in to a selected alternative scenario. These sensitivities included:

- Low Nuclear sensitivity, which consists of
  - decommissioning of nuclear units in Sweden sooner than assumed in the reference scenario
  - less new nuclear capacity or decommissioning of nuclear units in Finland sooner than assumed in the reference scenario
- Lower capacity and availability on the border between price areas SE2 and SE3
- Lower capacity and availability of the interconnectors between Nordic countries and the Continent / United Kingdom

These sensitivities are further described in chapter 7.1.3 and the result presented in chapter 7.2.9.

6.3 PINT study

6.3.1 Introduction

PINT is a methodology used by ENTSO-E in TYNDP, that “…considers each new item grid element on the given network structure one-by-
one and evaluates the network flows over the lines with and without the examined network reinforcement\textsuperscript{11}.

In the market studies the PINT simulation was performed in several rounds which are described in the following sections.

**Round 1:** The SE1-Fi AC line and the two HVDC connections SE2-Fi and the SE3-Fi were separately simulated in the reference scenario 2025 and 2035.

- The change in socio-economic welfare, associated with each grid alternative was calculated.
- The NPV was estimated by the change in social economic welfare and the roughly estimated investment and maintenance costs.
- The most beneficial grid alternative, i.e. the grid alternative with greatest positive NPV, was selected to continue to PINT round 2.
- To reduce the risk of missing a potentially solid combination of grid alternatives the next beneficial grid alternative in round 1, the so called “runner up”, was also promoted to round 2.

**Round 2:** The grid alternatives determined in round 1 were incorporated into the reference scenario and a second grid alternative was then added.

- The same steps as for round 1 were performed to determine the most beneficial combination of two grid alternatives to continue to round 3.

**Round 3:** The grid alternatives determined in round 2 were incorporated into the reference scenario and the third (and last) grid alternative was then added.

- The same steps as for round 1 were performed to determine if a combination of three grid alternatives was beneficial.

**Round 4:** The most beneficial combinations of grid alternatives found in the previous rounds were simulated in the alternative scenarios and the NPV calculated.

- The combinations of grid alternatives that were most beneficial in the reference scenario, as well as robust for future development were determined. These were then promoted to the socio-economic evaluation-phase.

\textsuperscript{11} https://www.entsoe.eu/Documents/TYNDP\%20documents/TYNDP\%202016/150331_TYNDP\_2016\_FAQs\_application\_for\_projects.pdf)
6.3.2 Results

The grid alternatives for each PINT round are illustrated in Figure 25. Grid combinations in pale boxes were not simulated as they are duplicated of other combinations.

![Figure 25 Simulated alternatives in PINT study](image)

In Table 15 the calculated NPVs for each grid alternative and PINT round are summarised.

**Table 15 Net present values [MEUR] for grid configuration in reference and alternative scenarios**

<table>
<thead>
<tr>
<th>Grid alternative</th>
<th>Ref scenario</th>
<th>Alt scenarios</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Round 1</td>
<td>Round 2</td>
</tr>
<tr>
<td>SE1-FI</td>
<td>+ SE2-FI</td>
<td>+ SE3-FI</td>
</tr>
<tr>
<td>SE2-FI</td>
<td></td>
<td>+ SE3-FI</td>
</tr>
<tr>
<td>SE3-FI</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

For the first PINT round the alternative SE1-FI was the most beneficial. The AC alternative rendered the highest NPV for the analysis period (25 years) and is expected to have a significant longer lifetime relative the HVDC connection options.
In the second PINT round the SE1-Fi alternative was combined with each of the two HVDC alternatives. Both combinations rendered high NPVs relatively close to one another. The combination of SE2-Fi and SE3-Fi was simulated as “runner up” alternative but the resulting NPV was significantly lower than the combinations including the AC line between SE1 and Fl.

In the third PINT round all three alternatives were combined but the NPV for adding a third interconnector was negative and the combination was dismissed. There were still some price difference between Sweden and Finland after two alternatives were implemented, but the difference was not large enough to justify the investment and maintenance costs of the third alternative.

The most beneficial grid configurations – SE1-Fi, SE1-Fi + SE2-Fi and SE1-Fi + SE3-Fi proceeded for simulation in the alternative scenarios. The NPVs were slightly negative in the Price Pressure scenario but greater than the reference in the two remaining alternative scenarios, implying robust results.

6.3.3 Conclusions from the PINT study

Based on the results from the PINT studies, the following investment combinations are suggested for further studies in the socio economic evaluation:

- SE1-Fi
- SE1-Fi + SE2-Fi
- SE1-Fi + SE3-Fi

The SE1-Fi alternative rendered the single highest NPV and could also be expected to have an increased lifetime in regards to the SE2-Fi and SE3-Fi HVDC connections. SE1-Fi was also clearly beneficial in two out of three alternative scenarios and close to neutral in the third scenario. Adding an HVDC connection, either SE2-Fi or SE3-Fi, to the SE1-Fi grid alternative gave the highest total NPV in the reference scenario and was beneficial in two out of three alternative scenarios.

7 Socio-economic evaluation

7.1 Methodology and assumptions

In the socio-economic evaluation, the grid alternatives promoted from the PINT studies, were further assessed in a cost-benefit analysis (CBA) as well as in a multi-criteria analysis. CBA is a methodology commonly used to calculate the public welfare of policies or projects, for example infrastructure developments. The aim of the CBA is to evaluate different socio-economic aspects in monetary terms. NPVs are calculated to conclude if a project is beneficial or not and to be able to compare different solutions. In this study a set of aspects were identified to be
assessed in the socio-economic evaluation. The aspects are presented in chapter 7.1.1. Only some of the aspects were possible to monetise in the CBA with current methods. The non-monetised aspects were evaluated with the help of qualitative reasoning and simulation results in a multi criteria analysis.

To investigate the robustness of the result a set of sensitivity analyses were performed which are described in chapter 7.1.3. The socio-economic aspects were evaluated for all four scenarios described in chapter 6.2.1 while the sensitivity analyses were only simulated in the reference scenario.

In order to calculate the NPVs for different grid alternatives, certain assumptions concerning investment and maintenance cost needed to be made. These assumptions were briefly described within NPV methodology in chapter 6.1.1 but a more thorough presentation is included in chapter 7.1.2.

Two options regarding the Swedish connection point for the SE1-Fi AC line, either Messaure or Svartbyn was presented in chapter 3.2. The two options differ slightly in investment cost and grid losses while the SEW is the same due to the identical transfer capacity used. The Messaure routing option has been used for the SE1-Fi grid alternative in the socio-economic evaluation as the grid studies indicated this to be the most preferable connection point, see chapter 3.7. However, the NPV for both the Svartbyn and Messaure options are presented in chapter 7.2.3.

The assessment of the combination of grid alternatives SE1-Fi + SE2-Fi and SE2-Fi + SE3-Fi have generally been done assuming that the HVDC connection is added to the case already including the SE1-Fi AC line. However, it is stated throughout the report if the incremental or aggregated results are presented.

7.1.1 Aspects to evaluate

In Table 16 the socio-economic aspects evaluated in this study are listed and the methodology broadly described. It is also shown if the aspect has been monetised and included in the NPV calculation or not. Further descriptions of the aspects as well as the conclusions can be found in chapter 7.2.
### Table 16 Description of socio-economic aspects to be assessed in the socio-economic evaluation

<table>
<thead>
<tr>
<th>Aspect</th>
<th>Methodology</th>
<th>NPV?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Socio-economic welfare</td>
<td>Socio-economic welfare for the Nordic countries simulated in BID and EMPS. Average result between the models utilised. The result from the market simulation scenarios for 2025 and 2035 were interpolated between the years and kept constant from 2035 and onwards.</td>
<td>Yes</td>
</tr>
<tr>
<td>Grid losses</td>
<td>Hourly market result were extracted from BID model and implemented in PSS/E-model (grid model) to calculate the grid losses (MWh/y). The cost for the losses induced in the FS2 return cable was also derived based on market simulation results.</td>
<td>Yes</td>
</tr>
<tr>
<td>Impact on reserves and balancing services</td>
<td>Change in congestion hours on the borders between Finland and Sweden as well as internally in Sweden.</td>
<td>No</td>
</tr>
<tr>
<td>System adequacy</td>
<td>1. Monte Carlo simulation in the BID model’s “capacity margin module”. Stochastic treatment of weather-dependent variables and probabilistic sampling of outages. Studied indicator: energy not served (MWh/y) 2. Qualitative assessment from a system perspective</td>
<td>No</td>
</tr>
<tr>
<td>Environmental impact</td>
<td>1. Life cycle analysis of three environmental aspects (climate change, eutrophication and acidification) of building, operating and decommissioning the grid alternatives. 2. Change in carbon emissions from electricity production with and without grid alternatives. 3. Environmental impact from grid losses by multiplying the estimated losses with the average carbon emission from Nordic electricity production.</td>
<td>No</td>
</tr>
<tr>
<td>Integration of renewables</td>
<td>Change in transmitted energy over the borders between Finland and Sweden.</td>
<td>No</td>
</tr>
</tbody>
</table>

#### 7.1.2 Investment and maintenance cost

As briefly described in chapter 6.1.1 the grid investments were estimated by utilising typical unit costs (as MEUR or MEUR/km) for different types of power lines and other equipment. The power line investments were calculated by multiplying the expected distances with the typical unit costs.

For the AC connection SE1-FI, the unit costs for Finland (0.3 MEUR/km) and Sweden (0.6 and 0.9 MEUR/km) differ mainly due to the use of different power pylons. For Sweden the unit cost variation was a consequence of challenging terrain depending on the connection point to either Svartbyn (0.9 MEUR/km) or Messaure (0.6 MEUR/km). In the NPV calculations the cost has been based on the Messaure option but a comparison of the NPV for the two connection points has been carried out in chapter 7.2.3. The SE1-FI AC line from Messaure has two suggested routing options (either to Vuennonkoski or Kukkolankoski in
Finland) and the average costs of the different routes were used when calculating the NPV. The additional costs of required equipment in substations etc. were included as well as the cost of necessary internal reinforcements. The largest of those reinforcements is the Keminmaa-Pyhänselkä line with an estimated cost of 45 MEUR. The construction of that line may, however, be necessary in any case due to large amount of new wind power in northern Finland, which is the case especially in the Price Pressure scenario. Nevertheless, the cost of the reinforcement was included for all scenarios.

The HVDC investment costs were estimated based on recently finalised projects, available information for planned future projects as well as assumptions made about technical development. Realised costs can vary significantly depending on the project. There are only a limited number of cable providers, which each have limited installation capacity, so in high demand situations with short notice, costs might be higher than otherwise expected. Sea-cable costs were estimated to a range of 0.7-1.2 MEUR/km, and for the land-based part of the connection a unit cost of 0.6 MEUR/km for Sweden and 0.45 MEUR/km for Finland was used. The costs of the HVDC-converters were estimated to be 80 MEUR per unit which is roughly the same as current price levels.

For the SE3-FI option, an internal reinforcement in Finland, from Rauma to Lieto, was concluded to be necessary and included with the estimated cost of 60 MEUR. In chapter 3.5.1 it was stated that internal reinforcements in Sweden would also be needed in case of realising the SE3-FI alternative. However, the required reinforcements and associated cost will be investigated in further studies and have therefore not been included in the total cost for this alternative. Although, an impact of an additional cost of 65 MEUR has been examined in the consistency check in chapter 7.2.10.

The maintenance costs for the SE1-FI AC line were estimated to be very small (i.e. close to zero). The consequence of faults was not taken into consideration due to comparatively low risks and the possibility to repair the faults at short notice. For the HVDC connections the maintenance costs as well as reinvestments in the control systems were estimated based on data for operating HVDC-links. Additionally it was estimated that a major fault would occur that would stop the power transmission for two months once every ten years, reducing the SEW for those years.

The existing Fenno-Skan HVDC system is implemented as a bipole consisting of FS1 (commissioned 1989) and FS2 (commissioned 2011). Bipole configuration allows the current to flow in one direction in FS1 and in the other direction in FS2. When the current required by the power transmission of FS1 and FS2 is not balanced, the unbalanced current between the poles flows through the ground and sea through the sea electrodes. If one of the Fenno-Skan cables is unavailable, the full return current of the operating Fenno-Skan cable flows through the sea electrodes, as was the case for FS1 before FS2 was commissioned.
With the addition of FS2, a bipole configuration was established allowing effective limitation of the current flowing through the sea, and this was actually one of the aspects highlighted in the environmental permission of FS2.

FS1 has been expected to approach the end of its technical life by 2029 and due to recent issues, concerns have been raised that the lifetime may actually be shorter than expected. Experts from both Svenska kraftnät and Fingrid have performed a high level feasibility study on the possible solutions for handling the return current of FS2 when FS1 is decommissioned. The results of the study are presented in chapter 4. Based on the findings, the continuous use of sea electrodes might violate the environmental permits, while temporary use is still considered feasible and in accordance with permits. Therefore, the continuous use of electrodes is not a recommended option and in the market studies the return current is assumed to be handled by a new metallic return cable which does not increase the capacity of FS2. If the SE3-FI alternative is built, the return current cable would not be necessary as the new connection would be configured as a bipole with FS2, and the return current taken care of. The cost of a return cable, estimated to 189 MEUR as described in chapter 4.5, is therefore deducted from the total cost of the SE3-FI HVDC connection.

The investment costs for the grid alternatives used in the NPV calculations are presented in Table 17.

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Route</th>
<th>Inv cost [MEUR]</th>
<th>Cost span [MEUR]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SE1-FI</td>
<td>Messaure-Keminmaa-Pyhänselkä</td>
<td>179</td>
<td>175-182</td>
</tr>
<tr>
<td>SE2-FI</td>
<td>Hjälta-Tuovila</td>
<td>377</td>
<td>346-408</td>
</tr>
<tr>
<td>SE3-FI</td>
<td>Dannebo-Rauma-Lieto</td>
<td>237</td>
<td>187-286</td>
</tr>
</tbody>
</table>

A comprehensive investment cost table for each grid alternative is presented in Appendix 3.

7.1.3 Sensitivity analysis

A sensitivity analysis was conducted to further test some of the assumptions made when constructing the scenarios. The sensitivity analysis was performed for the reference scenario for 2025 and 2035. Three uncertain or simplified input parameters were identified that presumably could have an impact on the utilisation and necessity of the investigated alternatives. The sensitivity analyses are described in the following sections.

In the Nuclear closure sensitivity scenario four additional reactors in Sweden were assumed to be decommissioned in the early 2020s leaving only two remaining units. In Finland the nuclear production was
decreased due to either the Hanhikivi 1 reactor not being built or earlier decommissioning of existing units. The development was assumed to be a consequence of low electricity prices in the late 2010s and 2020s in combination with relative high production cost of nuclear power. The purpose for this sensitivity analysis was to further investigate how the energy balance in Sweden and Finland respectively could impact the need for new transmission capacity between the two countries.

In the transmission capacity sensitivity scenario the capacity between SE2 and SE3 was assumed to be lower than in the original reference scenario. Svenska kraftnät plans to increase the transmission capacity and ongoing grid studies will show the feasible level. In the reference scenario a capacity of 8800 MW was assumed and in this sensitivity analysis the capacity was decreased to 7800 MW. While a flat 100 percent availability profile was utilised in the reference scenario, the actual availability profile for 2015, as shown in Figure 26 was used in this sensitivity to represent a more modest net transfer capacity.

![Figure 26](image)

**Figure 26** Availability for transmission capacity between SE2-SE3 (southwards direction) in sensitivity and reference scenario.

The purpose of this sensitivity analysis was to investigate how the transmission capacity between SE2 and SE3 would impact the placement of a new cable between Finland and Sweden. A lower transfer capacity would block more of the surplus production in SE2, and the SE2-Fi HVDC connection may relieve the tie lines between SE2 and SE3. On the other hand the deficit area SE3 would be able to import more electricity if the transfer capacity between SE3 and Finland was increased.

In the Continental capacity sensitivity scenario the transfer capacities between the Nordic and the external countries, including continental Europe, the Baltic countries and the United Kingdom, were altered to represent a less integrated European electricity market. The planned interconnectors “Viking link” (between Denmark and England) and “Hansa Power Bridge” (between Sweden and Germany) were assumed
to not be built. For the existing interconnectors actual availability profiles for 2015 were applied instead of the flat 100 percent profiles used in the reference scenario. Availability profiles were approximated as in Table 18 for cables not yet taken into operation by 2015.

<table>
<thead>
<tr>
<th>Interconnector</th>
<th>Interconnector used for approximating the availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO-UK “North Sea Link”</td>
<td>NO-NL “NorNed”</td>
</tr>
<tr>
<td>NO-DE “Nordlink”</td>
<td>NO-NL “NorNed”</td>
</tr>
<tr>
<td>SE-LT “Nordbalt”</td>
<td>FI-EE “Estlink 2”</td>
</tr>
</tbody>
</table>

Table 18 Approximated availability profiles

The purpose of this sensitivity was to test the relatively optimistic assumptions in the reference scenario regarding market integration which could be impacted by several events, for example political processes such as Brexit and the ongoing discussion regarding the division of Germany in bidding zones. The ability of the Nordic countries to import and export electricity could have a large impact on the Nordic power flows and the demand for new internal Nordic interconnectors.

7.2 Results

7.2.1 Socio-economic welfare

The revenues from the new grid investments can be seen as an increase in SEW. SEW is calculated for each bidding area and divided into consumer and producer surplus as well as congestion rent. All scenarios and sensitivities were simulated in the BID and EMPS-models, which were able to provide comparable SEW values. The NPV calculation was performed by using the average SEW values for the 51 historical weather years simulated in each of the two models. As the simulation was performed for the years 2025 and 2035, the SEW for the years 2026-2034 were interpolated and then kept constant at the 2035 level for the further years.

In this study the comparison between alternatives was made based on the total Nordic SEW. The division of SEW between countries and interest groups for the reference scenario in 2025 and 2035 as well as for the promoted alternatives is presented in Table 19 and Table 20. Note, that for the SE1-Fi + SE2-Fi and the SE1-Fi + SE3-Fi grid alternatives, the figures represent the incremental change when adding the HVDC connection to the case already including the SE1-Fi AC line. Due to the large deficit in energy balance, Finland will gain the largest benefit from the new connections. Sweden has negative SEW due to a significant reduction in congestion rent, but Swedish producers benefit more from the new
connections than the Swedish consumers lose. The impact on Norway and Denmark is less significant on a total level.

Table 19 Change in socio-economic welfare for reference scenario 2025 [MEUR/y]. For grid alternatives SE2-FI and SE3-FI the figures show the incremental change.

<table>
<thead>
<tr>
<th>Grid alternative</th>
<th>Country</th>
<th>Consumer surplus</th>
<th>Producer surplus</th>
<th>Congestion rent</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>SE1-FI</td>
<td>Finland</td>
<td>403</td>
<td>-304</td>
<td>-40</td>
<td>59</td>
</tr>
<tr>
<td></td>
<td>Sweden</td>
<td>-92</td>
<td>108</td>
<td>-38</td>
<td>-22</td>
</tr>
<tr>
<td></td>
<td>Norway</td>
<td>-68</td>
<td>68</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Denmark</td>
<td>-9</td>
<td>9</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Nordic</td>
<td>233</td>
<td>-119</td>
<td>-72</td>
<td>42</td>
</tr>
<tr>
<td>SE1-FI + SE2-FI</td>
<td>Finland</td>
<td>180</td>
<td>-132</td>
<td>-22</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td>Sweden</td>
<td>-37</td>
<td>47</td>
<td>-25</td>
<td>-15</td>
</tr>
<tr>
<td></td>
<td>Norway</td>
<td>-22</td>
<td>20</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Denmark</td>
<td>-4</td>
<td>4</td>
<td>-1</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Nordic</td>
<td>117</td>
<td>-61</td>
<td>-43</td>
<td>13</td>
</tr>
<tr>
<td>SE1-FI + SE3-FI</td>
<td>Finland</td>
<td>181</td>
<td>-133</td>
<td>-22</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td>Sweden</td>
<td>-34</td>
<td>42</td>
<td>-23</td>
<td>-15</td>
</tr>
<tr>
<td></td>
<td>Norway</td>
<td>-20</td>
<td>26</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>Denmark</td>
<td>-4</td>
<td>4</td>
<td>-2</td>
<td>-1</td>
</tr>
<tr>
<td></td>
<td>Nordic</td>
<td>124</td>
<td>-61</td>
<td>-45</td>
<td>17</td>
</tr>
</tbody>
</table>
Table 20: Change in socio-economic welfare, reference scenario 2035 [MEUR/y]. For grid alternatives SE2-Fi and SE3-Fi the figures shows the incremental change.

<table>
<thead>
<tr>
<th>Grid alternative</th>
<th>Country</th>
<th>Consumer surplus</th>
<th>Producer surplus</th>
<th>Congestion rent</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Finland</td>
<td>1 149</td>
<td>-880</td>
<td>-89</td>
<td>180</td>
</tr>
<tr>
<td></td>
<td>Sweden</td>
<td>-187</td>
<td>229</td>
<td>-92</td>
<td>-51</td>
</tr>
<tr>
<td></td>
<td>Norway</td>
<td>-141</td>
<td>145</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Denmark</td>
<td>-16</td>
<td>16</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Nordic</td>
<td></td>
<td>805</td>
<td>-489</td>
<td>-176</td>
<td>139</td>
</tr>
<tr>
<td>SE1-Fi + SE2-Fi</td>
<td>Finland</td>
<td>565</td>
<td>-415</td>
<td>-61</td>
<td>89</td>
</tr>
<tr>
<td></td>
<td>Sweden</td>
<td>-120</td>
<td>145</td>
<td>-67</td>
<td>-42</td>
</tr>
<tr>
<td></td>
<td>Norway</td>
<td>-89</td>
<td>84</td>
<td>11</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Denmark</td>
<td>-11</td>
<td>11</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Nordic</td>
<td></td>
<td>345</td>
<td>-175</td>
<td>-116</td>
<td>54</td>
</tr>
<tr>
<td>SE1-Fi + SE3-Fi</td>
<td>Finland</td>
<td>566</td>
<td>-416</td>
<td>-60</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>Sweden</td>
<td>-114</td>
<td>131</td>
<td>-60</td>
<td>-44</td>
</tr>
<tr>
<td></td>
<td>Norway</td>
<td>-82</td>
<td>78</td>
<td>10</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Denmark</td>
<td>-10</td>
<td>10</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Nordic</td>
<td></td>
<td>359</td>
<td>-197</td>
<td>-110</td>
<td>52</td>
</tr>
</tbody>
</table>

A similar division of SEW can be seen with most of the other scenarios and assessed grid alternatives. The only exception is the price pressure scenario where the Finnish energy deficit has been balanced with large amount of new wind power and the SEWs for new grid alternatives are generally much lower.

The results are quite different compared to results obtained in ENTSO-E’s TYNDP. This is due to several factors related to scenarios, the modelling methodology and input data. The differences are further discussed in Appendix 4. The results obtained in this study are considered representative for the studied alternatives.

### 7.2.2 Grid losses

New transfer capacity between Finland and Sweden will impact the total grid losses in the system.
In this study, the grid losses were approximated both on a system level and explicitly for the FS2 return cable. As described in chapter 4.6, a cable handling the return current from FS2 is recommended when FS1 is decommissioned. The usage of the return cable would induce losses. The investment in a return cable and hence its losses, could be avoided if the SE3-Fi connection was built. Therefore, the cost for these losses has been deducted from the SE3-Fi alternative in the NPV calculation.

Two approaches were used to estimate the grid losses:

- PSS/E calculations – system grid losses as well as losses in return cable
- Mathematical derivation – losses in return cable

As the utilised market models do not have a grid topology, the first method was to extract hourly simulation data from the market study and incorporate it in the PSS/E model where the system grid losses could be estimated. As this methodology was relatively time consuming the approach was used only for the reference scenario. The method of combining market model data with the PSS/E data is new and therefore the result should be seen as a rough approximation.

The induced losses in the FS2 return cable were calculated and included in the result from the PSS/E grid loss simulation. However, to have an estimation of the return cable losses for the alternative scenarios as well as provide an additional approach, the losses induced in the return cable were also calculated with the help of simulation results and approximation from the technical review.

The two methodologies and the result are presented in the following sections.

**PSS/E simulation with data from market simulation**

The grid losses were approximated by extracting hourly market data for production, consumption and market flows between bidding areas - from the BID model for a normal weather year, 2004, and simulating that data using the Nordic network database in PSS/E. The losses were calculated assuming that the HVDC connection alternatives were built with VSC technology. The results are presented in Table 21. Note that for the SE1-Fi + SE2-Fi and the SE1-Fi + SE3-Fi grid alternatives, the figures represent the incremental change when adding the HVDC connection to the case which already includes the SE1-Fi AC line.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>No new projects (total grid losses)</th>
<th>SE1-Fi</th>
<th>SE1-Fi + SE2-Fi</th>
<th>SE1-Fi + SE3-Fi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference 2025</td>
<td>6615</td>
<td>-67</td>
<td>+59</td>
<td>-59</td>
</tr>
<tr>
<td>Reference 2035</td>
<td>7152</td>
<td>+81</td>
<td>+24</td>
<td>-114</td>
</tr>
</tbody>
</table>
The change in grid losses were then multiplied with the average annual electricity price for Sweden and Finland during the weather year 2004 and for each grid alternative to estimate the yearly increase or decrease in cost of losses. The estimated annual cost of the grid losses is presented in Table 22.

Table 22 Estimated annual cost [MEUR/y] for grid losses for the reference scenario and the grid alternatives. For grid alternatives SE2-FI and SE3-FI the figures show the incremental change.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>SE1-FI</th>
<th>SE1-FI + SE2-FI</th>
<th>SE1-FI + SE3-FI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference 2025</td>
<td>-3.3</td>
<td>+2.9</td>
<td>-2.9</td>
</tr>
<tr>
<td>Reference 2035</td>
<td>+5.3</td>
<td>+1.5</td>
<td>-7.2</td>
</tr>
</tbody>
</table>

The hydro inflows have a great impact on the flows and the amount of grid losses in the Nordic system. The losses approximated from only one weather year therefore leads to in an uncertainty in the result. Nevertheless the cost of the losses was included in the NPV calculation in chapter 7.2.3 to give an indicator of how it could impact the result, but the result was also shown without the PSS/E estimated losses.

Mathematical derivation of losses in return cable

As described in the technical review in chapter 4.5, the losses in the return cable were estimated to be 9.4 MW when assuming that the maximum transfer capacity was utilised on FS2. To approximate the cost of the losses in the return cable the average electricity price in Finland and Sweden for each scenario and the average utilisation of FS2 was used. The estimated costs are shown in Table 23.

Table 23 Cost of losses [MEUR/y] for the return current from FS2

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Average price(a) [EUR/MWh]</th>
<th>Utilisation FS2(b)</th>
<th>Losses return current [MWh](c)</th>
<th>Cost of losses return current [MEUR/y]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ref2025</td>
<td>49</td>
<td>76%</td>
<td>62 600</td>
<td>3.1</td>
</tr>
<tr>
<td>Ref2035</td>
<td>65</td>
<td>82%</td>
<td>67 900</td>
<td>4.4</td>
</tr>
<tr>
<td>Price Pressure</td>
<td>27</td>
<td>63%</td>
<td>52 200</td>
<td>1.4</td>
</tr>
<tr>
<td>CO2-focus</td>
<td>109</td>
<td>93%</td>
<td>76 900</td>
<td>8.4</td>
</tr>
<tr>
<td>New Tech</td>
<td>67</td>
<td>85%</td>
<td>69 600</td>
<td>4.7</td>
</tr>
</tbody>
</table>

\(a\)Average price in Sweden and Finland for no investments, SE1-FI and SE1-FI + SE2-FI grid alternatives.

\(b\)Average utilisation of FS2 with no investments, SE1-FI and SE1-FI + SE2-FI grid alternatives.

\(c\)Losses for the return current= 9.4 [MW] x 8760 [h/y] x “Utilisation FS2”
7.2.3 Net present value

The calculated NPVs for each scenario and each grid alternative are presented in Table 24. The figures represent the total NPV for the grid alternatives. In other words, the NPV for the SE1-Fi + SE2-Fi and the SE1-Fi + SE3-Fi are the aggregated NPV for both the AC line and each of the HVDC connections respectively. The following additions have been made to the initial NPV calculations in the PINT studies:

- 189 MEUR, corresponding to the cost of a return cable, has been deducted from the investment cost for the SE3-Fi alternative (see chapter 7.1.2)
- The cost of the total annual grid losses in Finland and Sweden calculated with PSS/E has been included in the reference scenario and is presented in a separate column headed “Ref/a”
- The mathematically derived cost of the losses in the return cable has been deducted from the operational cost for the SE3-Fi alternative for all scenarios (excluding column “Ref/a” as the losses already is included within the PSS/E simulation results).

Table 24 Net present value [MEUR], including investment and maintenance cost, socio-economic welfare as well as grid losses. The cost of building and operating a return cable is deducted from the SE3-Fi alternative. For the grid alternatives SE2-Fi and SE3-Fi the figures show the aggregated values of the SE1-Fi AC-line and the HVDC connection.

<table>
<thead>
<tr>
<th></th>
<th>Ref</th>
<th>Ref/a</th>
<th>Price Pressure</th>
<th>CO2-focus</th>
<th>New Tech</th>
</tr>
</thead>
<tbody>
<tr>
<td>SE1-Fi</td>
<td>1123</td>
<td>1084</td>
<td>-33</td>
<td>1928</td>
<td>1561</td>
</tr>
<tr>
<td>SE1-Fi + SE2-Fi</td>
<td>1318</td>
<td>1222</td>
<td>-225</td>
<td>2552</td>
<td>1916</td>
</tr>
<tr>
<td>SE1-Fi + SE3-Fi</td>
<td>1447</td>
<td>1393</td>
<td>-86</td>
<td>2732</td>
<td>2073</td>
</tr>
</tbody>
</table>

aIncluding the roughly estimated cost of annual grid losses calculated with PSS/E and described in chapter 7.2.2.

As mentioned in chapter 7.1.2 the cost of the sea cables were estimated to have a range of 0.7-1.2 MEUR/km. The cost of the SE1-Fi alternative also had some variation due to two different routes. In Figure 27 the impact that the cost variations have on the NPVs from Table 24 are presented as error bars.
In Figure 28 the accumulated NPVs for each year of the analysis period are shown for the grid alternatives in the reference scenario. For the SE1-FI + SE2-FI and SE1-FI + SE3-FI alternative the figures show the aggregated NPV for both the AC line and the HVDC connections. The break-even time (BET), the time period when the cost and revenues are equal, is already reached in two years in case of the SE1-FI AC line and in 7-12 years for the HVDC connections after the commissioning date. The aggregated BET for the alternatives SE1-FI + SE2-FI and SE1-FI + SE3-FI is thus four to six years.

In Table 25, the NPV for the total costs and total revenues over the calculation period (2016-2052) are shown as well as the BET for the investments. Note, that for the SE1-FI + SE2-FI and the SE1-FI + SE3-FI grid alternatives, the figures represent the incremental change when
adding the HVDC connection to the scenario already including the SE1-Fi AC line.

Table 25 NPV of the total cost and revenues as well as the break-even time (BET) for each investment and each scenario. For grid alternatives SE2-Fi and SE3-Fi the figures show the incremental change.

<table>
<thead>
<tr>
<th>Connection</th>
<th>Ref/α</th>
<th>Price Pressure</th>
<th>CO2-focus</th>
<th>New Tech</th>
</tr>
</thead>
<tbody>
<tr>
<td>SE1-Fi</td>
<td>-130</td>
<td>-170</td>
<td>-127</td>
<td>-127</td>
</tr>
<tr>
<td>NPV costs</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[MEUR]</td>
<td>1253</td>
<td>1253</td>
<td>94</td>
<td>2055</td>
</tr>
<tr>
<td>NPV revenues</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BET [Years]</td>
<td>2</td>
<td>2</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>SE1-Fi + SE2-Fi</td>
<td>-280</td>
<td>-337</td>
<td>-280</td>
<td>-280</td>
</tr>
<tr>
<td>NPV costs</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[MEUR]</td>
<td>475</td>
<td>475</td>
<td>88</td>
<td>904</td>
</tr>
<tr>
<td>NPV revenues</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BET [Years]</td>
<td>12</td>
<td>14</td>
<td>-</td>
<td>7</td>
</tr>
</tbody>
</table>

a Including the roughly estimated cost of annual grid losses calculated with PSS/E and described in chapter 7.2.2.

It can be seen that all grid alternatives have a positive NPV, except in the Price Pressure scenario. The SE1-Fi + SE3-Fi alternative has a higher NPV than the SE1-Fi + SE2-Fi alternative due to the decreased investment and operation cost of the return cable.

Two different options regarding connection points were suggested for the Swedish side for the SE1-Fi alternative, either by the station Svartbyn or by the station Messaure. In Table 26 the NPVs for the two routing options have been calculated. The difference in NPV arises from various investment costs and the cost of grid losses. The Messaure option is more beneficial even though the route is a bit longer because it located on more accessible terrain and has less grid losses.

Table 26 Net present value [MEUR], including investment and maintenance cost, socio-economic welfare as well as grid losses, for two different routing option for SE1-Fi alternative.

<table>
<thead>
<tr>
<th>Connection point option</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>SE1-Fi, via Svartbyn</td>
<td>1048</td>
</tr>
<tr>
<td>SE1-Fi, via Messaure</td>
<td>1084</td>
</tr>
</tbody>
</table>
7.2.4 Impact on reserves and balancing services

New transfer capacity between Finland and Sweden could impact the possibilities for trading balancing resources and reserve energy between bidding areas. If the market flow on a border reaches its maximum net transfer capacity on the day-ahead market, it cannot be used to exchange balancing power on the intraday market. Hence, congested borders increase the risk of blocking available balancing power inside price areas. Currently the borders between Finland and Sweden are frequently congested and increasing the transfer capacity could relieve the tie lines. The transmission capacity between SE2 and SE3 is also currently congested at times. To investigate how the grid alternatives would impact the number of congestion hours and the ability to trade balancing resources, the market flows on the borders between Finland and Sweden as well as on the internal Swedish borders was extracted from the simulation result.

In Appendix 5 the share of congestion hours on these borders are presented for the three grid alternatives as well as for the four scenarios. In Figure 29 and Figure 30 duration diagrams for the market flow on the tie lines between SE2 and SE3 and for the total transfer capacity between Finland and Sweden is shown for the reference scenario in 2025 and 2035.

![Figure 29 Duration diagram of market flow on the tie lines between SE2 and SE3 for the reference scenario 2025 (to the left) and 2035 (to the right) as well as for the grid alternatives.](image-url)
It can be seen that the amount of hours with congestion on the borders between Finland and Sweden decrease with all three grid alternatives. Also the congestion on the tie lines between SE2 and SE3 is reduced slightly. The result also shows that the SE2-FI alternative relieves congestion between SE2 and SE3 more than the SE3-FI alternative. Placing the new connection in SE2 is therefore better than placing it in SE3, from a reserves and balancing services point of view.

### 7.2.5 System adequacy

System adequacy refers to the ability for an electric system to supply the energy demanded by customers at all times. In general, new connections contribute positively to system adequacy.

In this study, the impact on system adequacy from new connections between Finland and Sweden was evaluated by estimating the power shortage volume with and without the investigated grid alternatives. Additionally, the grid alternatives were assessed from a system perspective, where their contribution to the system adequacy in the Nordic synchronous area was considered.

Both system adequacy and system contributions are described in the following chapters.

**Power shortage volume**

The effect of cross-border connections on system adequacy was assessed in the study with a methodology developed at Fingrid\(^\text{12}\), which

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\(^{12}\) Jarkko Tulensalo (2016): Utilisation of a Power Market Simulator in Power Adequacy Assessment
combines Monte Carlo simulations using market simulation tools and statistical analysis. Studies were carried out with the BID model. The overall results are summarised in Table 27. Note, that for the SE1-Fi + SE2-Fi and the SE1-Fi + SE3-Fi grid alternatives, the figures represent the incremental change when adding the HVDC connection to the case already including the SE1-Fi AC line.

**Table 27** Change in power shortage volume [MWh/y] for Nordic countries and average year. For grid alternatives SE2-Fi and SE3-Fi the figures shows the incremental change.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>No new projects (total shortage volume)</th>
<th>SE1-Fi</th>
<th>SE1-Fi + SE2-Fi</th>
<th>SE1-Fi + SE3-Fi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference 2025</td>
<td>1750</td>
<td>-1280</td>
<td>-140</td>
<td>-140</td>
</tr>
<tr>
<td>Reference 2035</td>
<td>4300</td>
<td>-3320</td>
<td>-530</td>
<td>-530</td>
</tr>
<tr>
<td>CO₂ focus</td>
<td>2130</td>
<td>-390</td>
<td>-30</td>
<td>-80</td>
</tr>
<tr>
<td>Price Pressure</td>
<td>1060</td>
<td>-930</td>
<td>-100</td>
<td>-100</td>
</tr>
</tbody>
</table>

In the table, power shortage volume refers to energy from any of the following sources:

- energy produced by fast disturbance reserves for balance management purposes,
- energy not served due to disconnecting consumers for balance management purposes, and
- energy produced by units that are part of the strategic reserve.

The assessment was not performed for the New Technology scenario because the utilised methodology does not properly capture adequacy effects of short-term batteries and load shifting, which are key elements in the New Technology scenario.

The SE1-Fi alternative provides the most significant adequacy contribution, being the first project to be implemented. The second investment also provides a positive adequacy contribution, but this is naturally smaller than the contribution from the first project. There are no significant differences between the SE2-Fi HVDC connection and SE3-Fi HVDC connection from adequacy perspective. The SE3-Fi alternative is marginally better in CO₂ focus scenario.

**System perspective**

Currently Finland is connected to the Nordic Synchronous area with two AC overhead lines between SE1 and FI. If one of the AC lines is taken out of operation due to outages or maintenance, only one AC line would remain connecting Finland with Sweden. With the SE1-Fi alternative, a third AC connection would be established and the risk of Finland losing its connection to the Nordic synchronous area would be
greatly reduced. A split of the synchronous system would result in a large reduction in inertia and inaccessible ancillary services in the partial systems. This means that without a third AC connection renewal and maintenance of one of the current lines could prove difficult. It is difficult to put a number on how the SE1-Fi alternative would improve system adequacy from this perspective but it has been regarded as an extra advantage.

Another advantage with the SE1-Fi alternative is that an AC line is a relatively straightforward technical solution, with outage durations much less than for HVDC converters and sea cables. The AC alternative is therefore expected to contribute more to system adequacy than the HVDC alternatives.

As discussed in chapter 4.2, there is an additional risk with the SE3-Fi alternative as its suggested configuration with FS2 would have an inherent risk of a bipole trip. The result would be the loss of 1600 MW transmission capacity which could severely impact system adequacy. The risk could, however, be managed with proper technical design but is regarded as a disadvantage for SE3-Fi alternative.

7.2.6 Environmental impact

The environmental impact analysis was divided into three parts:

- Life cycle assessment (LCA)
- Changed production
- Changed grid losses

In the LCA the environmental impact of building, maintaining and decommissioning the grid alternatives was investigated with the help of a tool developed at Svenska kraftnät. The environmental aspects assessed were climate change (measured in CO₂-equivalents), eutrophication (measured in P-equivalents) and acidification (measured in SO₂-equivalents). The calculation was based on assumptions regarding for example fuel consumption, land use and transportation routes, and should be regarded only as rough estimate to compare the different grid alternatives.

An analysis period of 40 years was used. As mentioned earlier, the AC line has a longer lifetime than the HVDC connections, but to be able to compare the grid alternatives the same analysis period was chosen regardless of the technology used. In the NPV calculations, a 25 year analysis period was assumed for the grid alternatives, partly because the expected revenue and costs becomes more uncertain further into the future as the development of the electricity market becomes

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13 Elinda Andersson (2016): Vidareutveckling av metod för bedömning av miljöpåverkan i samhällsekonomiska analyser vid investeringar i det svenska elstamnätet
harder to predict. It is safe to estimate the environmental impact over a 40 year analysis period as it is not as dependent on electricity market development as other impacts. For example the land use and need for forestry maintenance is more or less independent of the development on the electricity market. As the environmental impact is not monetised and included in the NPV it is acceptable to use different analysis periods. The LCA environmental impacts for the different grid alternatives are presented in Figure 31.

![Graphs showing environmental impacts for different grid alternatives.](image)

**Figure 31** Environmental impact of building, maintaining and decommissioning each of the individual grid alternatives during an approximated 40 year lifetime.

Building, maintaining and decommissioning the SE1-FI alternative impacts the environment the least. The SE3-FI alternative has slightly more environmental impact than the SE2-FI alternative, mainly because of its longer route.

New connection will also impact the **electricity production**. A more integrated electricity market leads to a more efficient use of the production sources. Low-priced electricity, such as solar, wind and hydro power, can reach the consumers to a greater extent in an integrated market. Increased capacity between Finland and Sweden decreases the European carbon emission from electricity production in all scenarios and for all grid alternatives according to Figure 32. The
Figure shows the incremental change in carbon emissions from electricity production for SE2-Fi and SE3-Fi when SE1-Fi alternative is already commissioned.

The decrease mainly arises from reduced fossil fuel-based electricity production in Finland and the Baltic countries, which arises due to increased import from surplus areas in northern Sweden and Norway. Whether the HVDC connection is placed in SE2 or SE3 has no significant impact on carbon emissions.

The change in grid losses will impact carbon emissions as electricity needs to be produced to cover the increasing losses and vice versa. The change in grid losses calculated in chapter 7.2.2 has been multiplied with the average carbon emissions from Nordic production in the reference scenario for 2025 and 2035, and the result is presented in Table 28. It can be seen that the climate impact from grid losses are relatively small, due to the low CO₂ emissions from Nordic electricity production.

Table 28 Annual change CO₂ emission [Mt] from the investments impact on grid losses

<table>
<thead>
<tr>
<th>Scenario</th>
<th>SE1-Fi</th>
<th>SE1-Fi + SE2-Fi</th>
<th>SE1-Fi + SE3-Fi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference 2025</td>
<td>-0.00221</td>
<td>0.00287</td>
<td>-0.00476</td>
</tr>
<tr>
<td>Reference 2035</td>
<td>0.00218</td>
<td>0.00462</td>
<td>0.00031</td>
</tr>
</tbody>
</table>

In summary, each of the grid alternatives would reduce the carbon emissions. The emission from building, maintaining and commissioning the cables was estimated to be 0.2-0.5 Mt during a 40 year period while the grid alternative, in average for all scenarios, during the same period...
would decrease the carbon emissions from electricity production by 16 Mt.

7.2.7 Integration of renewables

According to ENTSO-E’s guidelines for CBA, the impact of a grid investment on renewable integration should be measured by the reduction of renewable curtailment (avoided spillage). As curtailment is often due to local grid limitations not captured in either of the two market models used in the study, qualitative reasoning is presented here, supported by simulation results.

With a large amount of wind and solar power there is always a risk that under certain conditions all generation cannot be handled by the grid due to low consumption and/or congested transmission capacity. From that perspective all new grid investments are beneficial for integrating renewable energy, because they enable spreading local production peaks to a larger group of consumers, thus reducing the need to spill excess production.

How much the power transmission between Sweden and Finland increases in the market model simulations has been compared for the different alternatives. The results are presented in Table 29 as annual increase [TWh/y]. The SE1-FI alternative is compared to a situation where no new lines have yet been built, while the two HVDC alternatives are compared to a situation where the SE1-FI alternative has already been commissioned.

Table 29 Increase in power transmission between Sweden and Finland [TWh/y]. For grid alternatives SE2-FI and SE3-FI the figures show the incremental change.

<table>
<thead>
<tr>
<th>Grid alternative</th>
<th>Ref2025</th>
<th>Ref2035</th>
</tr>
</thead>
<tbody>
<tr>
<td>SE1-FI</td>
<td>3.01</td>
<td>4.04</td>
</tr>
<tr>
<td>SE1-FI + SE2-FI</td>
<td>1.58</td>
<td>2.44</td>
</tr>
<tr>
<td>SE1-FI + SE3-FI</td>
<td>1.53</td>
<td>2.42</td>
</tr>
</tbody>
</table>

It can be seen that the differences between HVDC alternatives are small. Of the two HVDC connections, SE2-FI seems to be marginally better at increasing power transmission compared to SE3-FI.

7.2.8 Multi-criteria analysis

An attempt to summarise the non-monetised aspects, in terms compared to no investments, is presented in Table 30. Note, that for the SE1-FI + SE2-FI and the SE1-FI + SE3-FI grid alternatives, the figures represent the incremental change when adding the HVDC connection to the case already including the SE1-FI AC line.
Table 30 Summary of the impacts from the non-monetised aspects. For grid alternatives SE2-Fi and SE3-Fi the figures show the incremental change.

<table>
<thead>
<tr>
<th>Aspect</th>
<th>SE1-Fi</th>
<th>SE1-Fi + SE2-Fi</th>
<th>SE1-Fi + SE3-Fi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reserves and balancing services SE↔FI / SE2↔SE3a</td>
<td>-15 % / -3%</td>
<td>-15 % / -1 %</td>
<td>-15 % / +1 %</td>
</tr>
<tr>
<td>System adequacy/Power shortage volumeb</td>
<td>-64 %</td>
<td>-8 %</td>
<td>-8 %</td>
</tr>
<tr>
<td>System adequacy/System perspective</td>
<td>Increased connection with the Nordic synchronous area, better availability with AC line</td>
<td>Inherent risk of bipole trip</td>
<td></td>
</tr>
<tr>
<td>Environmental impactc</td>
<td>-20 Mt CO₂</td>
<td>-14 Mt CO₂</td>
<td>-13 Mt CO₂</td>
</tr>
<tr>
<td>Integration of renewablesd</td>
<td>3.53 TWh/y</td>
<td>2.01 TWh/y</td>
<td>1.98 TWh/y</td>
</tr>
</tbody>
</table>

aReduced congestion hours (as percentage of time) for the combined market borders between Finland and Sweden (in SE to FI direction) and on the border between SE2 and SE3 (in SE2 to SE3 direction): Average for all scenarios).
bReduced power shortage volume (average for all evaluated scenarios)
cReduced CO₂ emission during a 40 years period including LCA as well as changed production (average for all scenarios).
dIncrease in power transmission between Sweden and Finland (average for ref 2025 and ref 2035)

It can be seen that investments in increased capacity between Finland and Sweden have a positive impact on all the non-monetised aspects evaluated in this study. The SE1-Fi alternative is advantageous in regard to system adequacy, both due to greatly reduced risk of Finland losing its connection to the Nordic synchronous area and by the in general better availability of AC lines compared to HVDC connections. It can also be seen that the number of congestion hours on the border between SE2 and SE3 increases when adding the SE3-Fi connection compared to the individual SE1-Fi alternative and the SE1-Fi + SE2-Fi alternative. For the aspects power shortage volume, environmental impact and integration of renewables, the SE1-Fi alternative provides the most significant contribution because of being the first project to be implemented.
7.2.9 Sensitivity

In the following chapters the outcome from the sensitivity analysis described in chapter 7.1.3 are presented. The result is compared to the NPVs presented in chapter 7.2.3, Table 24.

**Sensitivity 1: Nuclear closure**
The nuclear closure sensitivity had four reactors less in Sweden and one reactor less in Finland compared to the reference scenario. The decreased energy production, approximately 30 TWh/y in Sweden and approximately 9 TWh/y in Finland had to be replaced by imports from other countries. That replacement power, mainly available from low priced areas located west and south of Sweden, was transferred to Finland via Sweden. As a result, the need for new transmission capacity between Sweden and Finland was further increased and the NPVs improved significantly as can be seen in Table 31.

<table>
<thead>
<tr>
<th>Grid alternative</th>
<th>Ref</th>
<th>Sensitivity</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>SE1-FI</td>
<td>1123</td>
<td>2523</td>
<td>+1400</td>
</tr>
<tr>
<td>SE1-FI + SE2-FI</td>
<td>1318</td>
<td>3162</td>
<td>+1844</td>
</tr>
<tr>
<td>SE1-FI + SE3-FI</td>
<td>1447</td>
<td>3244</td>
<td>+1797</td>
</tr>
</tbody>
</table>

**Sensitivity 2: Transmission capacity between SE2 and SE3**
The transmission capacity between SE2 and SE3 sensitivity had approximately 2500 MW less available transmission capacity on average compared to the reference scenario. As a result, there is a minor increase in the value for the SE1-FI alternative and a minor decrease in values for the HVDC options, as can be seen in Table 32. The placement of an HVDC connection in either SE2 or SE3 proved insignificant in this sensitivity.

<table>
<thead>
<tr>
<th>Grid alternative</th>
<th>Ref</th>
<th>Sensitivity</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>SE1-FI</td>
<td>1123</td>
<td>1130</td>
<td>+7</td>
</tr>
<tr>
<td>SE1-FI + SE2-FI</td>
<td>1318</td>
<td>1308</td>
<td>-10</td>
</tr>
<tr>
<td>SE1-FI + SE3-FI</td>
<td>1447</td>
<td>1441</td>
<td>-6</td>
</tr>
</tbody>
</table>

**Sensitivity 3: Continental capacity**
The Continental capacity sensitivity had less transmission capacity between the Nordic countries and continental Europe and the United Kingdom, especially due to two links not being implemented and assuming the DK1-Germany capacity to be on at its current level. As a
result there were fewer possibilities for Nordic countries to export power to Europe, resulting in lower day-ahead market prices in Sweden. Consequently, the new transmission connections between Sweden and Finland became more beneficial, as can be seen in Table 33.

Table 33 Net present value [MEUR] per grid alternative for the “Continental capacity”-sensitivity.

<table>
<thead>
<tr>
<th>Grid alternative</th>
<th>Ref</th>
<th>Sensitivity</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>SE1-FI</td>
<td>1123</td>
<td>1355</td>
<td>+232</td>
</tr>
<tr>
<td>SE1-FI + SE2-FI</td>
<td>1318</td>
<td>1551</td>
<td>+233</td>
</tr>
<tr>
<td>SE1-FI + SE3-FI</td>
<td>1447</td>
<td>1700</td>
<td>+253</td>
</tr>
</tbody>
</table>

7.2.10 Consistency check and confirmation of the PINT results

As described in chapter 6.3.2 the most beneficial individual grid alternative is the SE1-FI alternative, which has 160 MEUR higher NPV than the HVDC alternatives SE2-FI and SE3-FI. However, the PINT studies did not include all information that was used in the socio-economic evaluation. To confirm the original selection, the first PINT round was further analysed including the impact from following factors:

- the cost of the FS2 return current cable, lowering the investment cost of the SE3-FI alternative,
- the losses for all grid alternatives,
- the longer lifetime of the AC-alternative SE1-FI, considering also the lifetime of the existing FS2,
- the possibility of having a higher available net transfer capacity with the SE1-FI alternative, as described in chapter 3.2
- the possible grid investments in the Stockholm area needed for the full utilisation of the SE3-FI alternative, and
- additional benefits due to improved reliability and resiliency of the grid.

The results of the consistency check are shown in Table 34.
Table 34 NPVs for the individual grid alternatives with various uncertainties. The most profitable grid alternative for each uncertainty is shown in bold.

<table>
<thead>
<tr>
<th>[MEUR]</th>
<th>SE1-FI</th>
<th>SE2-FI</th>
<th>SE3-FI</th>
</tr>
</thead>
<tbody>
<tr>
<td>PINT results</td>
<td>1123</td>
<td>962</td>
<td>956</td>
</tr>
<tr>
<td>incl. FS2 return current cable price reduction of 189 MEUR</td>
<td>1123</td>
<td>962</td>
<td>1087</td>
</tr>
<tr>
<td>incl. FS2 return current cable + estimated losses</td>
<td>1084</td>
<td>924</td>
<td>1129</td>
</tr>
<tr>
<td>incl. FS2 return cable + losses + 30 year SE1-FI &amp; 25 year SE3-FI</td>
<td>1228</td>
<td>924</td>
<td>1129</td>
</tr>
<tr>
<td>incl. FS2 return cable + losses + 50 year SE1-FI &amp; 40 year SE3-FI</td>
<td>1591</td>
<td>924</td>
<td>1526</td>
</tr>
<tr>
<td>incl. FS2 return cable + losses + 900 MW capacity for SE1-FI</td>
<td>1146</td>
<td>924</td>
<td>1129</td>
</tr>
<tr>
<td>incl. FS2 return cable + losses + 1000 MW capacity for SE1-FI</td>
<td>1209</td>
<td>924</td>
<td>1129</td>
</tr>
<tr>
<td>incl. FS2 return cable + losses + 65 MEUR investments in SE3</td>
<td>1084</td>
<td>924</td>
<td>1084</td>
</tr>
</tbody>
</table>

When the PINT results were corrected with the impact from the FS2 return current cable, the NPV for the SE3-FI alternative increased by 131 MEUR, which was clearly more beneficial than the SE2-FI alternative but still less beneficial than the SE1-FI alternative. However, as the SE3-FI alternative lowers the total losses while others increase them, including losses the SE3-FI alternative becomes 45 MEUR more beneficial than the SE1-FI alternative. On the other hand, it is worth mentioning that, as stated in chapter 7.2.2, because the method of combining market model data with the PSS/E data is new and it is based on only one inflow year, the results should be seen as a rough approximation.

The next items to evaluate were the longer lifetime and possibly higher capacity of the SE1-FI alternative. The FS2 connection was commissioned in 2011, and will reach 40 year lifetime around 2050 when these new alternatives reach their 25 year valuation period. At that time the FS1 cable, which is planned to be used as return current cable for the SE3-FI alternative after decommissioning FS1, reaches 60 years and most likely needs to be decommissioned. However, SE1-FI, being an AC-line, will have many more operational years after 2050 without any significant reinvestments. As shown in Table 34, only a few additional years are enough to increase the NPV for the SE1-FI alternative to be the highest. Also, in the case that the SE3-FI alternative can be used for 40 years without additional investments to return
current handling, less than 10 additional years for the SE1-FI alternative makes it beneficial.

Based on grid studies it might be possible to utilise more than 800 MW transfer capacity on the SE1-FI alternative. Each 100 MW increases the NPV for SE1-FI by roughly 60-70 MEUR, so with only a 900 MW transfer capacity the SE1-FI alternative has the highest NPV.

In the grid studies it was also noted that further studies are needed to estimate the need for the possible internal reinforcements in SE3 for establishing the SE3-FI alternative. In Finland that alternative requires reinforcement investments of 60 MEUR. In order to have an equal NPV for the alternatives SE1-FI and SE3-FI, the Swedish reinforcements need to be 65 MEUR, which means that with higher investment costs the SE1-FI alternative is the most beneficial.

In summary, even if the SE3-FI alternative is the most beneficial when adding only the impact of the FS2 return current cable and losses, all the other uncertainties favour the SE1-FI alternative. A longer lifetime, the possibility of a higher capacity, and additional investments in SE3, can each make the SE1-FI alternative the most beneficial alternative. Because a combination of these is likely, it is likely that the SE1-FI alternative is the most beneficial. Additionally the impacts on reliability and resiliency of the grid support the SE1-FI alternative, but they are not monetised here. All in all, it can be confirmed that the PINT selection of the SE1-FI alternative as the most beneficial is still valid.

7.3 Conclusions from the socio-economic evaluation

From the results, new transmission capacity between Sweden and Finland is highly beneficial in socio-economic terms. The most beneficial alternative is to increase AC capacity between SE1-FI. That alternative has the highest NPV which is clearly positive in all analysed scenarios and sensitivities, excluding the Price Pressure -scenario where the NPV is close to neutral.

Additionally the SE1-FI alternative has several other advantages due to it being AC line. Compared to the HVDC alternatives, it has a significantly longer lifespan and it is the most robust alternative when evaluating availability. In case of sustained faults, it can be expected to be reconnected in a much shorter time than the HVDC connections. Otherwise in the multi-criteria analysis no grid alternative was shown to be clearly better than the others. Of the possible locations for the AC line in Sweden the Messeaur option is more beneficial than Svartbyn.

Based on the above studies, it is beneficial to have a new HVDC connection between Sweden and Finland in addition to the AC line. The HVDC alternative has a positive NPV in all cases excluding the Price Pressure scenario where it is slightly negative. Originally the two alternatives, SE2-FI and SE3-FI, were rather close to each other in NPV, with the SE2-FI alternative being slightly more beneficial. However,
during the latter phase of this study it became clear that certain actions need to be taken with the return current of the existing FS2 cable. Fingrid and Svenska kraftnät concluded that any solution most likely requires a new return cable to be installed in parallel to FS2. That means that the SE3-Fi alternative is more favourable from an economic perspective, as it provides the required continuous return current path, as well as additional transfer capacity, using only one HVDC connection. This alternative was found sufficiently beneficial in both NPV calculations as with other aspects. Further studies are needed for the SE3-Fi HVDC alternative because there are several technical options for this complex project.

8 Summary and conclusions

8.1 Comparison of the connection alternatives

In this chapter the main differences between the studied alternatives are presented. The different aspects are covered throughout the report but are presented here in a condensed manner in an attempt to make a comparison easier. An attempt has been made to summarise the significant positive and negative aspects of each alternative and the way in which the alternatives compare to each other.

8.1.1 Alternative SE1-Fi, 400 kV AC overhead line

Advantages
Alternative SE1-Fi is the most socio-economically beneficial of the examined alternatives. As an AC connection, it also has a longer technical life span compared to HVDC connections which further increases the cost advantage over its full life span.

The actual capacity of the AC alternative from SE1 to Finland is flexible with a potential for increase, whereas the capacity for the HVDC alternatives is capped at 800 MW.

The SE1-Fi alternative increases system adequacy by increasing the number of AC connections between Sweden and Finland and thus reducing the probability of splitting the synchronous system which in turn would have negative impacts on inertia and ancillary services.

Compared to the HVDC connection alternatives an AC connection can be considered a relatively simple technical solution making it a lower risk investment. An AC connection also has a higher availability compared to an HVDC connection.

The alternative is also more robust than the HVDC alternatives, as it has a high availability.

Disadvantages
No disadvantages could be identified for alternative SE1-Fi.
8.1.2 Alternative SE2-Fi, 800 MW HVDC connection

**Advantages**
An HVDC connection between SE2 and Finland is relatively easy to implement from a grid perspective as the number of reinforcements needed are limited. From a technical perspective the alternative is also considered easier to implement compared to alternative SE3-Fi since it offers a greenfield solution without interfaces to existing equipment.

Compared to alternative SE3-Fi, an HVDC connection between SE3 and Finland, alternative SE2-Fi reduces the overall strain on the Swedish tie lines between SE2 and SE3, potentially reducing the need to reinforce it.

Due to the geographical separation from the existing HVDC connection FS2, this alternative is better from a system stability and security point of view.

**Disadvantages**
Due to higher loading of the grid on the Finnish side combined with losses in the return current cable, calculations indicate that this alternative yields higher losses compared to alternative SE3-Fi.

8.1.3 Alternative SE3-Fi, 800 MW HVDC connection

**Advantages**
Alternative SE3-Fi provides a higher NPV compared to alternative SE2-Fi as the cost of a new return current cable for FS2 is not included in the capital expenditure for this project. This is due to the fact that a separate return current cable is not needed if alternative SE3-Fi is constructed.

**Disadvantages**
Alternative SE3-Fi is more difficult to implement due to the need for grid reinforcements and other measures in both Sweden and Finland as it increases transmission through already strained parts of the grid.

Compared to the other alternatives, this alternative causes problems from a system stability point of view.

The alternative is more technically challenging than the others since it involves integrating a new HVDC connection with the existing FS2. Measures will have to be taken in order to minimise the risk of bipole failure and simultaneous tripping of both links.

8.2 Summary and conclusion

Different alternatives, connections from SE1, SE2 and SE3 price areas to Finland were evaluated in this study. Four connection alternatives were investigated: an AC line between SE1 and Finland an AC cable between SE2 and Finland, an HVDC connection between SE2 and Finland and an HVDC connection between SE3 and Fi.
Grid studies were performed to investigate the feasibility of integrating the different alternatives into the system. An AC line between SE1 and FI and an HVDC connection between SE2 and FI were considered feasible. The HVDC alternative between SE3 and FI needs further studies to determine the amount of reinforcements needed, and to investigate the technical options for connecting this alternative to FS2 in bipole operation. The alternative involving an AC cable between SE2 and FI was rejected due to poor utilisation of the cable. If, however, a connection between SE2 and Finland is desired, this alternative in combination with a phase shifting transformer could be a viable alternative to an HVDC connection.

In a technical review of the HVDC alternatives the need for a metallic return path for FS2 was identified as a crucial factor. This reduces the additional overall cost of the SE3 to FI HVDC alternative since this HVDC connection can be used in a bipole configuration with FS2 eliminating the need for a new return current cable. This configuration does however risk the tripping of both HVDC connections. The SE2 to FI HVDC alternative was considered to be a more straightforward technical solution.

The routing, environmental aspects and permissions for the three alternatives remaining after the grid study have been investigated. Some risks were identified, but based on current information all alternatives are feasible.

The benefits of the proposed alternatives were evaluated from a socio-economic perspective in the market studies. The results indicate that increased capacity between Sweden and Finland is highly beneficial both in monetary terms and qualitative terms. The alternatives render in general high positive NPVs with a relative short break-even time and were found advantageous regarding: potential trade of ancillary services, system adequacy, environmental emissions and potential of integrating renewable energy sources.

Most beneficial is a new AC line between SE1 and FI. Second is the SE3 to FI HVDC connection, which has a higher NPV when reducing the investment cost with the cost for a new metallic return cable.

Advantages and disadvantages of the remaining alternatives have been compiled and summarised. The new AC line between SE1 and FI is most advantageous. When comparing the two HVDC alternatives the SE2 to FI HVDC connection has more advantages overall.

After considering the factors addressed in this report, it was concluded that a new AC connection between SE1 and FI increases socio-economic welfare as well as improves the technical performance of the system. While a new HVDC connection between SE2 or SE3 and FI also is socio-economically beneficial there are some technical and system related issues, especially with the SE3 to FI alternative, that need to be further assessed.
Appendix

Appendix 1  Routing Finnish side

Essential environmental features within and nearby the Finish corridors for the grid alternatives are presented in the table below.

<table>
<thead>
<tr>
<th>Environmental values</th>
<th>SE1-Fi Finnish part (Pyhänselkä-Kukkolankoski)</th>
<th>SE1-Fi Finnish part (Pyhänselkä-Vuennonkoski)</th>
<th>SE2-Fi Finnish part (Tuovila-Korsnäs-EEZ)</th>
<th>SE3-Fi Finnish part (Lieto-Rauma-Rihtniemi-EEZ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nature is most sensitive along SE1-Fi. Large wilderness areas with forests and mires are characteristic to the route. Especially wetland areas are important for birds and overall biodiversity. Passes through two Natura 2000 areas (Tuuliaapa-Heposuo FI1101402, Nikkilänaapa FI1301605) which are also partly conservation areas. Crosses two waterways included in Natura 2000 network (Kiiminkijoki FI1101202, Tornionjoki-Muoniojoki FI1301191). Bypasses several bird areas included in Natura 2000 network. Possible need for more detailed route planning.</td>
<td>Nature is most sensitive along SE1-Fi. Large wilderness areas with forests and mires are characteristic to the route. Especially wetland areas are important for birds and overall biodiversity. Passes through three Natura 2000 areas (Tuuliaapa-Heposuo FI1101402, Nikkilänaapa FI1301605 and Hurujärvi-Iso-Mustajärvi FI1301909), which are also partly conservation areas. Bypasses several bird areas included in Natura 2000 network. Possible need for more detailed route planning and/or law reform.</td>
<td>Bypasses Natura 2000 area with SPA designation (Kackurmossen FI0800018); possible need for more detailed route planning. Intersects one Finnish Important Bird Area (Finiba), Hälsön matalikot. Submarine cable intersects one Important Bird and Biodiversity Area (IBA), Merenkurkku archipelago. Bypasses several other Natura areas; conflicts are unlikely.</td>
<td>Bypasses several Natura 2000 areas; conflicts are unlikely. Submarine cable intersects with Bothnian Sea National Park, one Important Bird and Biodiversity Area (IBA), Archipelago of Rauma-Luvia and one Finnish Important Bird Areas, Finiba (Coast of Uusikaupunki). Conflict with Bothnian Sea National Park, need for law reform. Agricultural areas common, 29% of onshore transmission lines length.</td>
<td></td>
</tr>
</tbody>
</table>
### Inhabited areas
- Approx. 40 houses near (less than 150 m) transmission line route. Only a few villages near transmission line.
- Approx. 30 houses near (less than 150 m) transmission line route. Only a few villages near transmission line.
- Approx. 20 houses near (less than 150 m) transmission line route. Divides three villages as a new infrastructure corridor without more detailed route planning.
- Approx. 80 houses near (less than 150 m) transmission line route. Plenty of dense inhabitation in the immediate vicinity of the line and surrounding areas.

### Infrastructure and other technical obstacles
- None
- None
- Passes through one wind park reservation area at sea. Conflicts are probably avoidable.
- Crosses one submarine cable and three fairways.

### Landscape values and cultural heritage
- Passes through nationally valuable landscape area of Tornionjoki parallel to existing transmission line corridor.
- Passes through several regional landscape areas.
- The most environmentally sensitive landscapes are major river valleys and related old settlement (4-5 together with classified values).
- Passes through nationally valuable landscape area of Tornionjoki parallel to existing transmission line corridor.
- Passes through several regional landscape areas.
- The most environmentally sensitive landscapes are major river valleys and related old settlement (4-5 together with classified values).
- Passes through two regional landscape areas. Bypasses three regional landscape areas.
- The most environmentally sensitive landscapes are agricultural landscapes related to old settlements.
- Ten archaeological findings near transmission line and one wreck in submarine cable corridor.
- Wide areas of cultural landscape and old settlement are characteristic to the route. Several valuable areas on the influenced area.
- The most environmentally sensitive area is the Aurajoki river valley.
- 14 archaeological findings near transmission line and 2 wrecks in submarine cable corridor.
### Surface and ground waters

- Four archaeological findings near transmission line.
- Intersects 20 rivers. Widest three river crossings 240-420 meters.
- Intersects three important water acquisition areas.
- Intersects one small river.
- Intersects one important water acquisition areas.
- Intersects three small rivers.
- No intersections with important water acquisition areas.
Appendix 2  
Routing Swedish side

Essential environmental features within and nearby the Swedish corridors for the grid alternatives are presented in the table below.

<table>
<thead>
<tr>
<th>SE1-Fi (Messaure-Vuennonkoski)</th>
<th>SE1-Fi Swedish part (Messaure-Kukkolankoski)</th>
<th>SE1-Fi Swedish part (Svartbyn-Kukkolankoski)</th>
<th>SE2-Fi Swedish part (Hjälta combination of alt 2 and 1 from Preliminary feasibility Study)</th>
<th>SE3-Fi Swedish part (Dannebo alt 2)</th>
</tr>
</thead>
</table>
| Environmental values (Within corridor) | • Three intersections with Nature preservation Areas of national interest (Råneälven, Kalixälven and Torneälven).  
• Intersects two Habitat protection areas  
• Natura 2000 (the river systems of Råneälven and Torne-Kalix).  
• Two Extended Shore protection areas (Hästängsholmen and Näset). | • Three intersections with Nature preservation Areas of national interest (Råneälven, Kalixälven and Torneälven).  
• Intersects four Habitat protection areas  
• Natura 2000 (the river systems of Råneälven and Torne-Kalix).  
• Intersection with four Protection plans for mires at several locations. | • Four intersections with Nature preservation Areas of national interest (Persöfjärden, Råneälven, Kalixälven and Torneälven).  
• Natura 2000 (the river systems of Råneälven and Torne-Kalix).  
• Natura 2000, bird directive (Persöfjärden)  
• Wetland convention (RAMSAR) (Persöfjärden)  
• Intersection with one Protection plan for mires. | • Three Nature Preservation Areas of national interest (all rivers)  
• Protected watercourses (river Moälven)  
• Natura 2000 area (Habitats Directive) (river Moälven).  
• An area with Nature Conservation Agreement (natural coniferous forest).  
• Landfall situated | • Intersects a Nature preservation area of national interest (Forsmark-Kalirigafort).  
• Shore protection areas |
CROSS-BORDER CAPACITY STUDY BETWEEN FINLAND AND SWEDEN

- Intersection with two Protection plans for mires at several locations.
- Wetland inventory covers large parts of the corridor.
- Swamp forests cover large parts of the corridor.
- Intersects three areas of Nature protection agreements.
- Swamp forests cover large parts of the corridor.
- Intersects one area of Nature protection agreements.

<table>
<thead>
<tr>
<th>Inhabited areas (within corridor)</th>
<th>Residential buildings: 9</th>
<th>Complementary buildings: 23</th>
<th>Other buildings: 5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Residential buildings: 19</td>
<td>Complementary buildings: 49</td>
<td>Other buildings: 10</td>
</tr>
<tr>
<td></td>
<td>Industry: 5</td>
<td>Communal function: 1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(treatment plant)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residential buildings: 77</td>
<td>Complementary buildings: 253</td>
<td></td>
<td>Industry: 7</td>
</tr>
<tr>
<td>Other buildings: 51</td>
<td>Complementary buildings: 88</td>
<td></td>
<td>Communal function: 3</td>
</tr>
<tr>
<td>Industry: 7</td>
<td></td>
<td></td>
<td>Buisness: 1</td>
</tr>
<tr>
<td>Buisness: 1</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Infrastructure and other technical obstacles (Within corridor)</th>
<th>Residential buildings: 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>One intersection with Railroad of national interest</td>
<td></td>
</tr>
<tr>
<td>Two intersections with Highway of national interest</td>
<td></td>
</tr>
<tr>
<td>One intersection with Railroad of national interest</td>
<td></td>
</tr>
<tr>
<td>Two intersections with Highway of national interest</td>
<td></td>
</tr>
<tr>
<td>Four intersections with Railroad of national interest</td>
<td></td>
</tr>
<tr>
<td>Two intersections with Highway of national interest</td>
<td></td>
</tr>
<tr>
<td>Intersects one Military area of national interest (Luleå)</td>
<td></td>
</tr>
<tr>
<td>The corridor intersects a Fairway of national interest</td>
<td></td>
</tr>
<tr>
<td>Three intersections with</td>
<td></td>
</tr>
<tr>
<td>Crosses Fairways of national interest at 6 places.</td>
<td></td>
</tr>
<tr>
<td>The corridor intersects an area of national interest of</td>
<td></td>
</tr>
</tbody>
</table>
CROSS-BORDER CAPACITY STUDY BETWEEN FINLAND AND SWEDEN

- Intersects a Military area of national interest (Lombens and Orretråks field of fire).
- Military Influential area for air space, military.
- Military Stop area for high objects.

**Nearby corridor:**

- Intersects a Military area of national interest (Lombens and Orretråks field of fire).
- Influential area for air space, military.
- Military Stop area for high objects.

**Railroad of national interest:**

- Two intersections with highway of national interest
- Passes the border of a shooting area

**Nuclear Repository (Område för slutförvar i Östhammars kommun):**

- Area of Commercial fishery (Bottenhavet).
- Crosses an area of Underwater activity prohibited area

**Landscape values and cultural heritage (Within corridor):**

- Two intersections with Recreational Areas of national interest (the rivers of Kalix-Kaitum and Torne-Muonio).
- One intersection with Cultural Historical Area of national interest (Tornedalen).
- Six intersections with Reindeer Husbandry Areas of national interest.
- Intersects with one

- Two intersections with Recreational Areas of national interest (the rivers of Kalix-Kaitum and Torne-Muonio).
- One intersection with Cultural Historical Area of national interest (Tornedalen).
- Seven intersections with Reindeer Husbandry Areas of national interest.

**Recreational Area of national interest:**

- Reindeer Husbandry Area of national interest
- Corridor intersects six ancient monuments.
- Corridor intersects the outer area of a meadow land.

**Crosses an area of Landscape protection at two places (Area by Öregrund and Östhammar):**

- Crosses an area of Underwater activity prohibited area.
area of Program of cultural environment at two places.  
• Intersects with three areas of Preservation of cultivated landscapes  

| Surface and ground waters (Within corridor) | The corridor intersects surface water at 73 places. | The corridor intersects surface water at 79 places. | The corridor intersects surface water at 40 places. | The corridor intersects two water protection areas  

|  |  |  | • The corridor intersects surface water at 43 places.  
|  |  |  | • The corridor intersects one water protection area |
Appendix 3  
Investment cost

The investment costs of alternatives SE1-FI, SE2-FI and SE3-FI used in the net present value calculations are presented in the table below. Different routing options were proposed for the SE1-FI alternative depending on the Swedish connection point in either Svartbyn or Messaure and on the path via either Vuennonkoski or Kukkolankoski in Finland. The investment cost for the return cable, estimated to 189 MEUR, is not deducted from the SE3-FI alternative in the figures presented below.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SE</td>
<td>FIN</td>
<td>SE-FI</td>
<td>FI-&gt;SE</td>
<td>total</td>
<td>SE land</td>
<td>FI land</td>
</tr>
<tr>
<td>SE1-FI</td>
<td>Svartbyn</td>
<td>Keminmaa</td>
<td>800</td>
<td>900</td>
<td>119</td>
<td>110</td>
<td>9</td>
</tr>
<tr>
<td>SE1-FI</td>
<td>Messaure</td>
<td>Keminmaa</td>
<td>800</td>
<td>900</td>
<td>220</td>
<td>185</td>
<td>35</td>
</tr>
<tr>
<td>SE1-FI</td>
<td>Messaure</td>
<td>Keminmaa</td>
<td>800</td>
<td>900</td>
<td>219</td>
<td>210</td>
<td>9</td>
</tr>
<tr>
<td>SE2-FI</td>
<td>Hjällta</td>
<td>Tuovila</td>
<td>800</td>
<td>800</td>
<td>305</td>
<td>120</td>
<td>61</td>
</tr>
<tr>
<td>SE3-FI</td>
<td>Dannebo</td>
<td>Rauma</td>
<td>800</td>
<td>800</td>
<td>233</td>
<td>2</td>
<td>34</td>
</tr>
</tbody>
</table>
Appendix 4  Comparison to TYNDP2016 results

The simulation results in this study show much higher socio-economic welfare compared to the results in ENTSO-E’s Ten-Year Network Development Plan 2016 (TYNDP16). This is true both in the medium term (year 2020 in TYNDP16, year 2025 in this study) and the long term (year 2030 in TYNDP16, year 2035 in this study). The difference is estimated\(^\text{14}\) to be due to several differences in scenarios, modeling specifics and inputs.

The most important differences include:

1. Scenarios are different
   - In general, the Finnish power deficit is lower in TYNDP16 scenarios than in this study’s reference scenario, whereas the Swedish power surplus is lower in TYNDP16 than in this study’s reference scenario. This has an impact on interconnector benefit. The differences in balances relate to differences in scenario storylines, scenario building techniques deployed by ENTSO-E and study years. In addition, the power balance in Baltics and Poland was more negative in this study compared to TYNDP16 scenarios, further increasing the flow from Sweden to Finland to cover the transit flows via Finland to Baltics and sometimes onwards to Poland.

2. Specifics in modeling methodology are different
   - The reference capacity (i.e. capacity if no new investments are done) from Sweden to Finland is 2000 MW in this study. In TYNDP16, reference capacity was 2400 MW for third AC and 2800 MW for Fenno-Skan renewal\(^\text{15}\). Higher reference capacity in TYNDP16 causes the investments to be less profitable, based on the implicit assumption that the operation of present Fenno-Skan 1 could continue also after 2030.
   - Often in the Nordic countries, the interconnectors show highest benefits in wet, dry, or cold weather conditions, rather than in average conditions. TYNDP16 studied only one (median) hydro year, i.e. the benefits in different weather patterns are not included. This study covers 51 historical weather years. This allows

\(^{14}\) No explicit studies were carried out to verify the importance of the mentioned factors to the results, rather the list is based on expert view on the importance of scenarios, modeling methods and input data detail to the results.

\(^{15}\) Different reference capacities were due to the TYNDP methodology of defining mid-term, long-term and future projects and the respective reference capacities.
each weather pattern to contribute to the results according to its historical probability.

3. Input data is of higher quality in this study
   - This study allows use of more detailed input data compared to TYNDP16, related especially to availability and cost of thermal generation in the Nordic countries. This provides better reflection of market dynamics when thermal generation sets the price. The more accurate modeling leads to more accurate welfare assessment.
   - The utilisation rate for wind power were particularly low in TYNDP16 calculations. This study utilised wind availability, which is in line with actual utilisation rate seen in the real system. Higher wind power utilisation rate gives higher energy balance in the Nordic countries (particularly in Sweden) which also drives the need for interconnectors.

A comparison of energy balances in different scenarios is given in Table 35. A comparison of SEW in a single year is given in Table 36. SEW value for TYNDP study corresponds to the median hydro year, whereas SEW value for this study is the average of 51 hydro years.

**Table 35. Annual electricity balances for selected areas.**

<table>
<thead>
<tr>
<th>Country balance</th>
<th>TYNDP2016, vision</th>
<th>Capacity Study, scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>V1</td>
<td>V2</td>
</tr>
<tr>
<td>Denmark</td>
<td>-9</td>
<td>2</td>
</tr>
<tr>
<td>Balics + Poland</td>
<td>19</td>
<td>10</td>
</tr>
<tr>
<td>Finland</td>
<td>-1</td>
<td>-2</td>
</tr>
<tr>
<td>Germany</td>
<td>26</td>
<td>-24</td>
</tr>
<tr>
<td>Norway</td>
<td>12</td>
<td>19</td>
</tr>
<tr>
<td>Sweden</td>
<td>13</td>
<td>20</td>
</tr>
</tbody>
</table>
Table 36. Comparison of socioeconomic welfare in a single simulation year.

<table>
<thead>
<tr>
<th>SEW(^a) in MEUR/y</th>
<th>TYNDP2016, vision</th>
<th>Capacity Study(^b), scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>V1</td>
<td>V2</td>
</tr>
<tr>
<td>SE1-FI</td>
<td>&lt;10</td>
<td>&lt;10</td>
</tr>
<tr>
<td>SE3-FI</td>
<td>&lt;10</td>
<td>&lt;10</td>
</tr>
</tbody>
</table>

\(^a\)TYNDP16: benefit in a single (median) hydro year; Capacity study: average benefit of 51 weather years.

\(^b\)Figures for SE3-FI represent the incremental change in NPV when adding the HVDC connection to the already commissioned SE1-FI alternative.

The scenarios, modeling methodology and input data accuracy used in this study are considered to better capture and represent the drivers for the need of new interconnectors between Sweden and Finland. Therefore, the socioeconomic welfare results presented in this study are considered more representative than those obtained in TYNDP16.
Appendix 5  Percentages of congestion hours

The share of congestion hours for the borders between Sweden and Finland as well as for the internal borders in Sweden are presented for the different grid alternatives are presented in the tables below. The result is extracted from BID simulation for all 51 historical weather years corresponding to 446,760 hours in total.

<table>
<thead>
<tr>
<th>Grid alternative</th>
<th>Border</th>
<th>Ref2025</th>
<th></th>
<th>Ref2035</th>
<th></th>
<th>Price Pressure</th>
<th></th>
<th>CO2-focus</th>
<th></th>
<th>New Tech</th>
<th></th>
<th>Average</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>No new projects</td>
<td>SE1-Fi</td>
<td>64</td>
<td>0.64</td>
<td>68</td>
<td>0.68</td>
<td>35</td>
<td>0.35</td>
<td>78</td>
<td>0.78</td>
<td>70</td>
<td>0.70</td>
<td>63</td>
<td>0.63</td>
</tr>
<tr>
<td></td>
<td>SE3-Fi</td>
<td>68</td>
<td>0.68</td>
<td>75</td>
<td>0.75</td>
<td>24</td>
<td>0.24</td>
<td>26</td>
<td>0.26</td>
<td>84</td>
<td>0.84</td>
<td>77</td>
<td>0.77</td>
</tr>
<tr>
<td></td>
<td>SE-Fi (total)</td>
<td>59</td>
<td>0.59</td>
<td>64</td>
<td>0.64</td>
<td>20</td>
<td>0.20</td>
<td>11</td>
<td>0.11</td>
<td>77</td>
<td>0.77</td>
<td>58</td>
<td>0.58</td>
</tr>
<tr>
<td>SE1-Fi</td>
<td>SE1-Fi</td>
<td>47</td>
<td>0.47</td>
<td>51</td>
<td>0.51</td>
<td>21</td>
<td>0.21</td>
<td>67</td>
<td>0.67</td>
<td>54</td>
<td>0.54</td>
<td>48</td>
<td>0.48</td>
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<tr>
<td></td>
<td>SE3-Fi</td>
<td>60</td>
<td>0.60</td>
<td>68</td>
<td>0.68</td>
<td>18</td>
<td>0.18</td>
<td>27</td>
<td>0.27</td>
<td>82</td>
<td>0.82</td>
<td>71</td>
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</tr>
<tr>
<td></td>
<td>SE-Fi (total)</td>
<td>41</td>
<td>0.41</td>
<td>46</td>
<td>0.46</td>
<td>11</td>
<td>0.11</td>
<td>66</td>
<td>0.66</td>
<td>50</td>
<td>0.50</td>
<td>43</td>
<td>0.43</td>
</tr>
<tr>
<td>SE1-Fi + SE2-Fi</td>
<td>SE1-Fi</td>
<td>33</td>
<td>0.33</td>
<td>36</td>
<td>0.36</td>
<td>13</td>
<td>0.13</td>
<td>55</td>
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<td>39</td>
<td>0.39</td>
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<tr>
<td></td>
<td>SE2-Fi</td>
<td>61</td>
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<td>69</td>
<td>0.69</td>
<td>28</td>
<td>0.28</td>
<td>10</td>
<td>0.10</td>
<td>80</td>
<td>0.80</td>
<td>72</td>
<td>0.72</td>
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<tr>
<td></td>
<td>SE3-Fi</td>
<td>43</td>
<td>0.43</td>
<td>53</td>
<td>0.53</td>
<td>9</td>
<td>0.09</td>
<td>28</td>
<td>0.28</td>
<td>74</td>
<td>0.74</td>
<td>56</td>
<td>0.56</td>
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<tr>
<td></td>
<td>SE-Fi (total)</td>
<td>24</td>
<td>0.24</td>
<td>29</td>
<td>0.29</td>
<td>5</td>
<td>0.05</td>
<td>3</td>
<td>0.03</td>
<td>51</td>
<td>0.51</td>
<td>32</td>
<td>0.32</td>
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<tr>
<td>SE1-Fi + SE3-Fi</td>
<td>SE1-Fi</td>
<td>37</td>
<td>0.37</td>
<td>40</td>
<td>0.40</td>
<td>20</td>
<td>0.20</td>
<td>3</td>
<td>0.03</td>
<td>56</td>
<td>0.56</td>
<td>42</td>
<td>0.42</td>
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<tr>
<td></td>
<td>SE3-Fi</td>
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<td>0.50</td>
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<td>0.17</td>
<td>72</td>
<td>0.72</td>
<td>54</td>
<td>0.54</td>
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<tr>
<td></td>
<td>SE-Fi (total)</td>
<td>24</td>
<td>0.24</td>
<td>29</td>
<td>0.29</td>
<td>4</td>
<td>0.04</td>
<td>3</td>
<td>0.03</td>
<td>52</td>
<td>0.52</td>
<td>32</td>
<td>0.32</td>
</tr>
</tbody>
</table>
### CROSS-BORDER CAPACITY STUDY BETWEEN FINLAND AND SWEDEN

**FD** = Forward direction, **RD** = Reverse direction

<table>
<thead>
<tr>
<th>Grid alternative</th>
<th>Border</th>
<th>Ref2025</th>
<th>Ref2035</th>
<th>Price Pressure</th>
<th>CO2-focus</th>
<th>NewTech</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>FD</td>
<td>RD</td>
<td>FD</td>
<td>RD</td>
<td>FD</td>
<td>RD</td>
</tr>
<tr>
<td>No new projects</td>
<td>SE1-SE2</td>
<td>1.9</td>
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<td>1.9</td>
<td>0.0</td>
<td>2.5</td>
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</tr>
<tr>
<td></td>
<td>SE2-SE3</td>
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<td>7.2</td>
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<tr>
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<td>SE3-SE4</td>
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<td>0.0</td>
<td>0.1</td>
<td>0.2</td>
<td>0.3</td>
<td>0.5</td>
</tr>
<tr>
<td>SE1-Fi</td>
<td>SE1-SE2</td>
<td>0.4</td>
<td>0.0</td>
<td>0.4</td>
<td>0.2</td>
<td>0.4</td>
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</tr>
<tr>
<td></td>
<td>SE2-SE3</td>
<td>2.5</td>
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<td>3.5</td>
<td>0.0</td>
<td>4.4</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>SE3-SE4</td>
<td>0.0</td>
<td>0.0</td>
<td>0.1</td>
<td>0.3</td>
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<td>1.8</td>
</tr>
<tr>
<td>SE1-Fi + SE2-Fi</td>
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<td>0.6</td>
<td>0.1</td>
<td>1.1</td>
<td>0.0</td>
</tr>
<tr>
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<td>SE2-SE3</td>
<td>1.3</td>
<td>0.0</td>
<td>2.2</td>
<td>0.0</td>
<td>1.5</td>
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</tr>
<tr>
<td></td>
<td>SE3-SE4</td>
<td>0.2</td>
<td>0.0</td>
<td>0.1</td>
<td>0.3</td>
<td>0.0</td>
<td>1.8</td>
</tr>
<tr>
<td>SE1-Fi + SE3-Fi</td>
<td>SE1-SE2</td>
<td>0.4</td>
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<td>0.5</td>
<td>0.1</td>
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</tr>
<tr>
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<td>1.6</td>
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<tr>
<td></td>
<td>SE3-SE4</td>
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<td>0.0</td>
<td>0.1</td>
<td>0.3</td>
<td>0.0</td>
<td>1.8</td>
</tr>
</tbody>
</table>