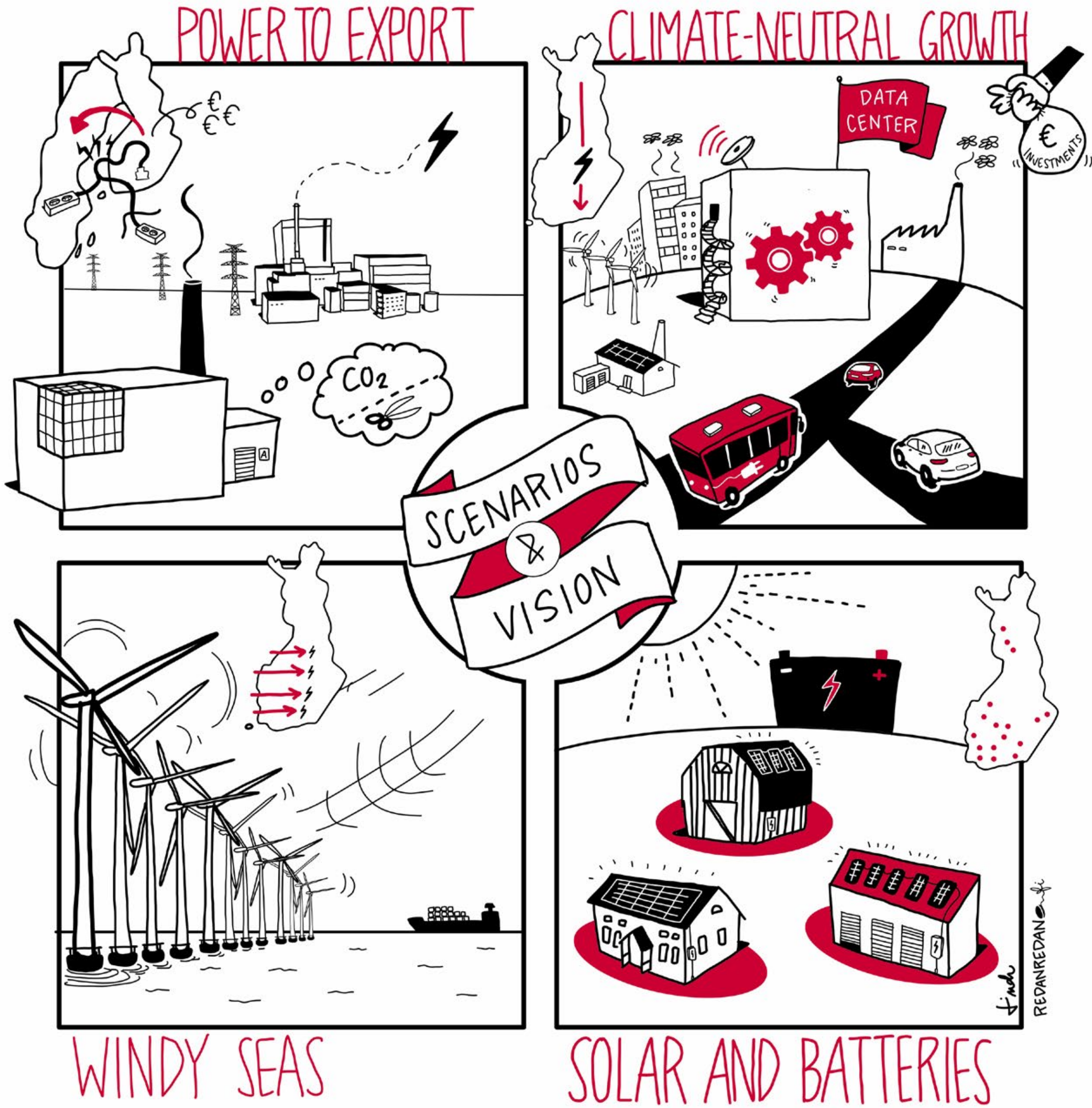

Network vision

FINGRID

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Back to the future

Planning and designing the main grid is a long-term task that requires the ability to forecast long-term needs. The implementation of a 400 kV transmission line takes almost ten years, including the permit processes. Once built, transmission infrastructure will be in place for several decades, even up to 100 years. Therefore, it is important that the infrastructure matches long-term needs as well as possible and also serves future generations.

In order to determine future investment needs, Fingrid creates network visions at regular intervals. The earliest vision I can remember was created in 2007 and it looked forward to 2030. Since then, the vision has been updated every few years and its foresight has been moved accordingly – we are now in Part 5 and looking at 2035 and 2045. Has anything changed in the forming of the visions? Firstly, the vision was initially the best guess for the future, while today it contains a number of different scenarios. Secondly, we could not predict the change in the production structure of electricity accurately enough, and were supposing that electricity consumption will not increase significantly in the future. However, the change in the production and consumption structure has only begun to materialise in recent years as a result of climate objectives. Thirdly, this is the first time our network vision is open for comments from our stakeholders, so for you this is only part one. Anyway, the story is as engaging as the film series referred to in the title, no matter where you jump in.

At the moment, the rapid growth of wind power poses a particular challenge to the planning of the main grid. Why not simply design a network that can accommodate a lot of wind power? The number of pending wind power projects is huge, and it is very difficult to predict which of them will actually reach production and in which locations the main grid needs therefore to be strengthened. On the other hand, the construction of wind power is driven by the market, which means that its growth also requires a significant increase in electricity consumption. Therefore, we should also predict the future structure of consumption and the location of significant consumption facilities. By creating different scenarios, we can identify different alternative futures and the associated grid strengthenings and can therefore make preliminary preparations for them. If we waited first to see what the future actually brings, we would probably be far too late in building the grid.

Since the production and consumption of electricity is market-driven, it is important for Fingrid to communicate with market parties and hear their views on the future. It would be unfortunate to hear that our completed network plans do not match the views of the parties that invest in new electricity production and consumption. That is why we have now opened up our network vision process to our stakeholders. We thank you for the comments we have received and also hope for a lively discussion on these visions we have published. But please remember that our scenarios are not trying to be the best guesses about the future – instead, they highlight the phenomena that will challenge the capacity of the main grid in different ways. Nevertheless we believe that our scenarios will also benefit our stakeholders. After all, the transformation of the energy system is a common challenge that cannot be solved by merely strengthening the grid.

Jussi Jyrinsalo
Senior Vice President, Grid Services and Planning

Executive Summary

Fingrid's network vision is a long-term vision of the development needs and solutions of the main grid based on a range of scenarios on the production and consumption structure of electricity. Europe, and Finland as a part of it, are in the midst of an energy transition that opens up opportunities for many development paths. The network vision examines years 2035 and 2045. This way, the vision extends over a sufficiently long timespan so that it is helpful in planning. The main focus of the analysis of grid development needs is on 2035, which is a particularly interesting year since it is also the target year for Finland's carbon neutrality.

The network vision uses four future scenarios to assess the need to strengthen the main grid. Fingrid requested its customers and stakeholders to provide feedback on the scenarios during their preparation in August–September 2020. The most significant variables in the scenario are electricity consumption in industry, heating and transport, the production and location of onshore and offshore wind power, the amount of distributed solar power, flexibility available in generation and consumption, and the future of nuclear power plants.

The network vision demonstrates that Finland's carbon neutrality target for 2035 is achievable as far as the main grid is concerned. Achieving this objective will require significant investments of around EUR 3 billion in the grid over the next 15 years. On this basis, Fingrid has already updated its investment plan and expects to invest approximately EUR 2 billion in the grid over the next ten years. If a significant amount of new electricity-intensive industry is created in Finland or Finland becomes an exporter of electricity and electricity based fuels, more investments in the grid are likely to be needed than described above. In addition, the figures do not take into account the costs of connecting offshore wind power, which is currently not the responsibility of the TSO.

In all the scenarios examined, the need to transmit electricity from Northern Finland to Southern Finland will increase significantly. The transmission capacity of the grid's main transmission cross-sections, i.e. Cross-section Central Finland and the Kemi-Oulujoki river, must be increased many-fold in order to maintain Finland as a single electricity bidding zone and to enable the same market price for electricity throughout the country.

The envisioning efforts revealed the need for new transmission connections to Sweden and Estonia by 2035. The market benefits of the connections depend on the development of the electricity market in the Baltic Sea region and other transmission connections in the region. Fingrid will continue to analyse the new Swedish and Estonian transmission connections in more detail as part of the international cooperation in grid planning.

Preparations are made for staged investments in the 400 kV transmission lines of the grid. Fingrid will discuss the investments necessary in the next ten years in more detail in the main grid development plan that will be published in the summer. In addition to transmission line investments, Fingrid is preparing to utilise new solutions, such as adjustable reactive power compensators, utilisation of weather-dependent load on transmission lines and location-based flexible markets.

Solutions used for avoiding transmission line intersections in the current main grid were studied as part of the main grid visioning. In some cases, changing these solutions would enable the transmission capacity of the grid to be increased cost-effectively. Fingrid will investigate this in more detail in 2021.

If Finland's electricity production and consumption increases very strongly in the future, for example as a result of energy exports, the technical solutions traditionally used by Fingrid in the main grid may not be sufficient to meet electricity transmission needs. As a result of the visioning effort, Fingrid is launching concept studies on possible future solutions. The solutions to be explored further include the use of a voltage of 750 kilovolts, 400 kV dual circuits, new types of conductors and HVDC transmission links within Finland.

1. Introduction

Fingrid's network vision aims to provide an insight into the long-term development needs of the main transmission grid (≥ 220 kV) and the solutions to these needs. Europe, and Finland as a part of it, are in the midst of an energy transition that opens up opportunities for many development paths. The planning of the main grid shall anticipate the future changes well in advance. This way, the future grid investments and the reliable operation of the electricity system as a platform for a common electricity market can be implemented cost-effectively, even as the operating environment changes. The network vision also increases our understanding of the electricity system of the future and the associated challenges, as well as the things that must be taken into account when planning the grid of the future. In addition, the network strengthening needs identified in the network vision also provide a good starting point for updating the development and investment plan for the main grid.

Fingrid has chosen to examine the period from 2035 to 2045 for its network vision to ensure that the vision extends far enough into the future with respect to the planning of the main grid. The focus of the investigation of network solutions is mainly on 2035, and the visioning effort has identified the network strengthening needs required by that point in time. 2035 is a particularly interesting year, since it is the year by which Finland aims to become carbon neutral. The year 2045 will be examined through potential trends in electricity generation and consumption.

This document presents the visioning process from the building of scenarios to creating the network vision. The introductory chapter discusses the process of the visioning effort and its relationship to Fingrid's network planning. Chapter 2 presents the assumptions underlying the visions of potential changes in the operating environment through four different scenarios. Chapter 3 presents the scenario-specific internal transmission needs in Finland that were discovered as a result of market simulations run for the scenarios. The chapter also discusses the cross-border transmission needs arising from the scenarios and the preliminary profitability assessments of the different cross-border lines. Chapter 4 presents the network strengthening needs identified on the basis of the transmission needs in each scenario and the resulting vision of the network solutions that are most necessary to implement by 2035. Chapter 5 deals with specific issues raised during the visioning effort.

1.1 The network visioning process

The network vision is a part of Fingrid's network planning. The purpose of the network vision is not to present a detailed investment plan because the vision looks at long-term changes that are difficult to predict. Therefore, the visioning effort will result in an opinion on how the main grid should be strengthened after the current investment plan ends. The effort will also result in a number of pre-considered alternative solutions for different paths of future development. The work done with network vision is utilised further in the main grid development plan created every two years.

Figure 1 outlines Fingrid's network design process for internal connections in Finland. Before an investment decision is made, detailed network surveys and route plans will be drawn up for the identified transmission line and network solutions. An environmental impact assessment is carried out next. After the investment decision has been made, the procurement procedure and construction will begin. The network planning process related to cross-border connections differs in part from the above, since the planning is carried out together with neighbouring TSOs and through ENTSO-E, the European Network of Transmission System Operators for Electricity.

Overall, the process from a vision to a completed transmission line takes 10–25 years. Some of the solutions identified in the visioning process might not be implemented if it is later determined that there is no need for them. The method and schedule for the planned network strengthening projects will be specified in connection with the investment decisions. The plans must be kept flexible before that, since the operating environment is constantly changing. The plans are influenced by a number of factors, such as the needs of the existing and new customers as well as changes in the electricity market and regulations.

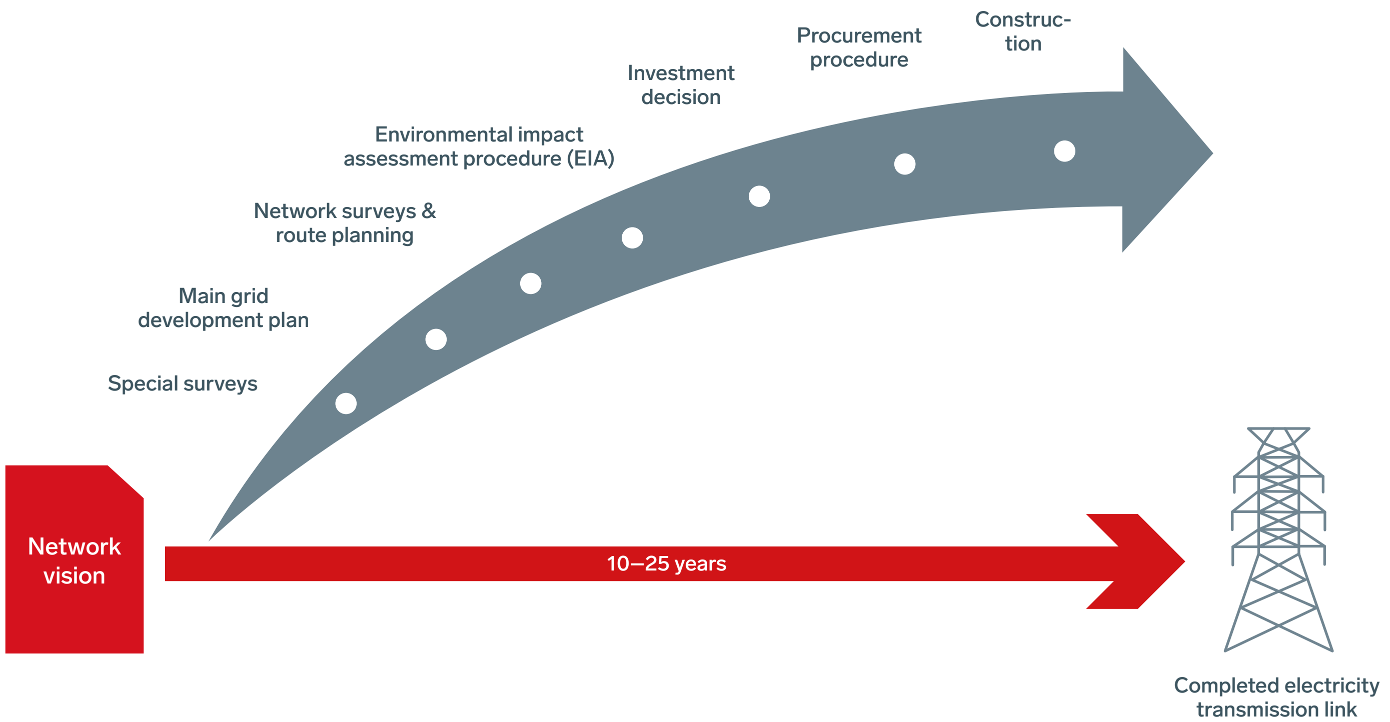


Figure 1 Fingrid's network planning process.

The network visioning process, as well as all other long-term network planning by Fingrid, can be divided into following parts. The first part is the identification of different changes in the operating environment. This serves as the basis for building suitable scenarios in which Finland's electricity production and consumption can be presented in numbers. In the next phase, the scenarios are used as input for electricity market simulations which allow further refinement of the baseline data of the scenarios. For example, the simulation results reveal what kind of production, consumption and transmission situations the grid should allow in different scenarios. The simulations also provide information on the availability of electricity. Finally, network calculation tools are used for examining in detail what kind of network solutions are needed to enable the future grid to meet the simulated transmission needs.

2. Scenarios

2.1 Creating scenarios

The network vision work involves assessing the need to strengthen the main grid under different scenarios. The scenarios represent the potential trends in electricity consumption and generation, for which contingencies must be made in the main grid plan. The most significant variables in the scenarios are the electricity consumption of industry, heating and transport and the regional distribution of this consumption, the production and location of onshore and offshore wind power generators, the amount of decentralised solar power, flexibility available in generation and consumption, and various potential combinations of new nuclear power construction and the continued operation of existing nuclear power plants. Four different scenarios have been created by consistently combining these and other variables, and each scenario is intended to give rise to distinct development needs for the main grid.

The network vision work aims to identify the main grid solutions that will be required in the future. It is particularly important to identify solutions that serve several of the scenarios or even all four. The development pathways have been incorporated into the scenarios in such a way that they do not counteract each other's effects from the perspective of network development. Instead, each scenario contains challenging elements with regard to network development, such as large net imports/exports of electricity or major needs for transmission within the country. The scenarios are not forecasts for the future, nor do they seek to describe how Fingrid would like the future to be. The analysis places equal value on each scenario.

Fingrid has created its scenarios for Finland independently. The low-carbon roadmaps published in the spring of 2020 were a key source of data, especially in terms of electricity consumption trends. In addition to the electrification pathways described in the low-carbon roadmaps, some of the scenarios include other sources of growth in electricity consumption, such as larger amounts of Power-to-X generation located in Finland. In terms of electricity generation, the scenarios are based on varying assumptions of the potential for and profitability of building different forms of electricity generation. These were then used as the basis for preparing a suitable electricity generation structure for each scenario.

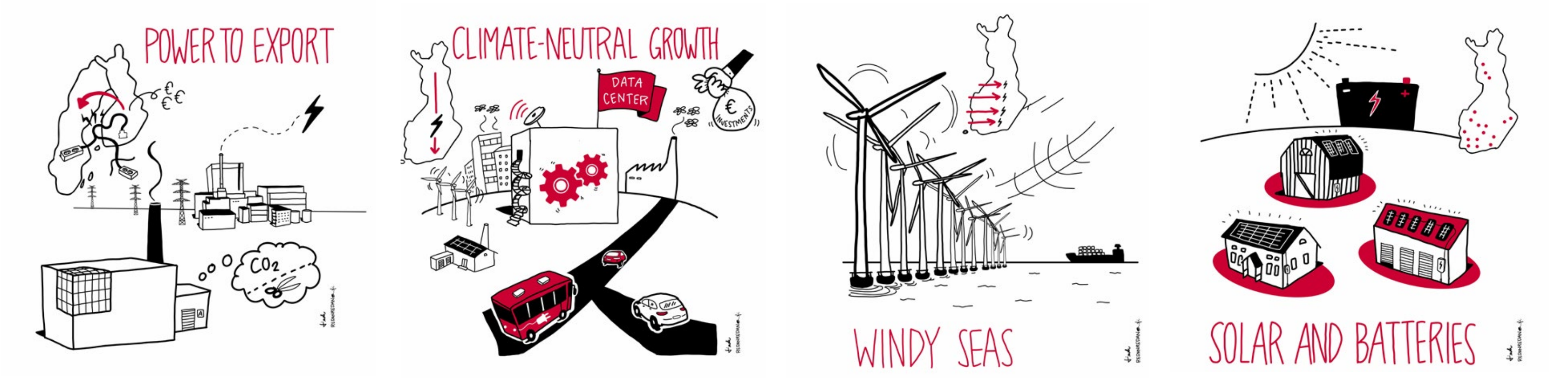
Fingrid has asked stakeholders and customers for feedback on the scenarios. The stakeholders and customers were asked to comment on the draft version of the scenarios in the autumn of 2020. The draft scenarios gathered a lot of feedback, which helped us refine the scenarios that ended up in the network vision. A summary of the feedback on the scenarios here (in Finnish).

The joint European scenarios prepared by ENTSO-E and ENTSOG under the Ten-Year Network Development Plan (TYNDP)[1] were used as information sources for other countries, along with more detailed information obtained from transmission system operators in the Baltic Sea region. This information has been altered in the scenarios to ensure that the assumptions for other European countries are consistent with Fingrid's assumptions for Finland. In particular, the scenarios include specific variations in regional development pathways with the greatest relevance for and impact on Finland, such as nuclear power in Sweden.

The four scenarios examined here are called Power to Export, Climate-Neutral Growth, Windy Seas, and Solar and Batteries. Figure 2 shows a brief description of each scenario. Table 1 compares the most significant variables of the scenarios. Each scenario is presented in more detail in Chapter 2.2–2.5. Chapter 2.6 contains a summary that compares the scenarios to each other.

[1] More information on ENTSO-E and ENTSOG TYNDP process and scenarios

Figure 2 Scenarios of the network vision.



Power to Export

- Scenario is slightly behind the schedule with Finnish carbon neutrality goals
- Fossil-fueled energy is replaced by electricity and e-fuels, but the pace is slower than in other scenarios
- Onshore wind power and nuclear power are the dominant forms of electricity generation, combined heat and power is mainly maintained
- Electricity exports drive growth in electricity generation.

Climate-Neutral Growth

- Finnish carbon neutrality goals are achieved
- Fossil-fueled energy is replaced by electricity and e-fuels
- Significant new electricity-intensive industrial production in Finland
- High onshore wind power and maximum north-south electricity transmission

Windy Seas

- Finnish carbon neutrality goals are achieved
- Fossil-fueled energy is replaced by electricity and e-fuels
- Significant new electricity-intensive industrial production in Finland
- Lots of offshore wind power
- Electricity generation is increasingly focused on the west coast

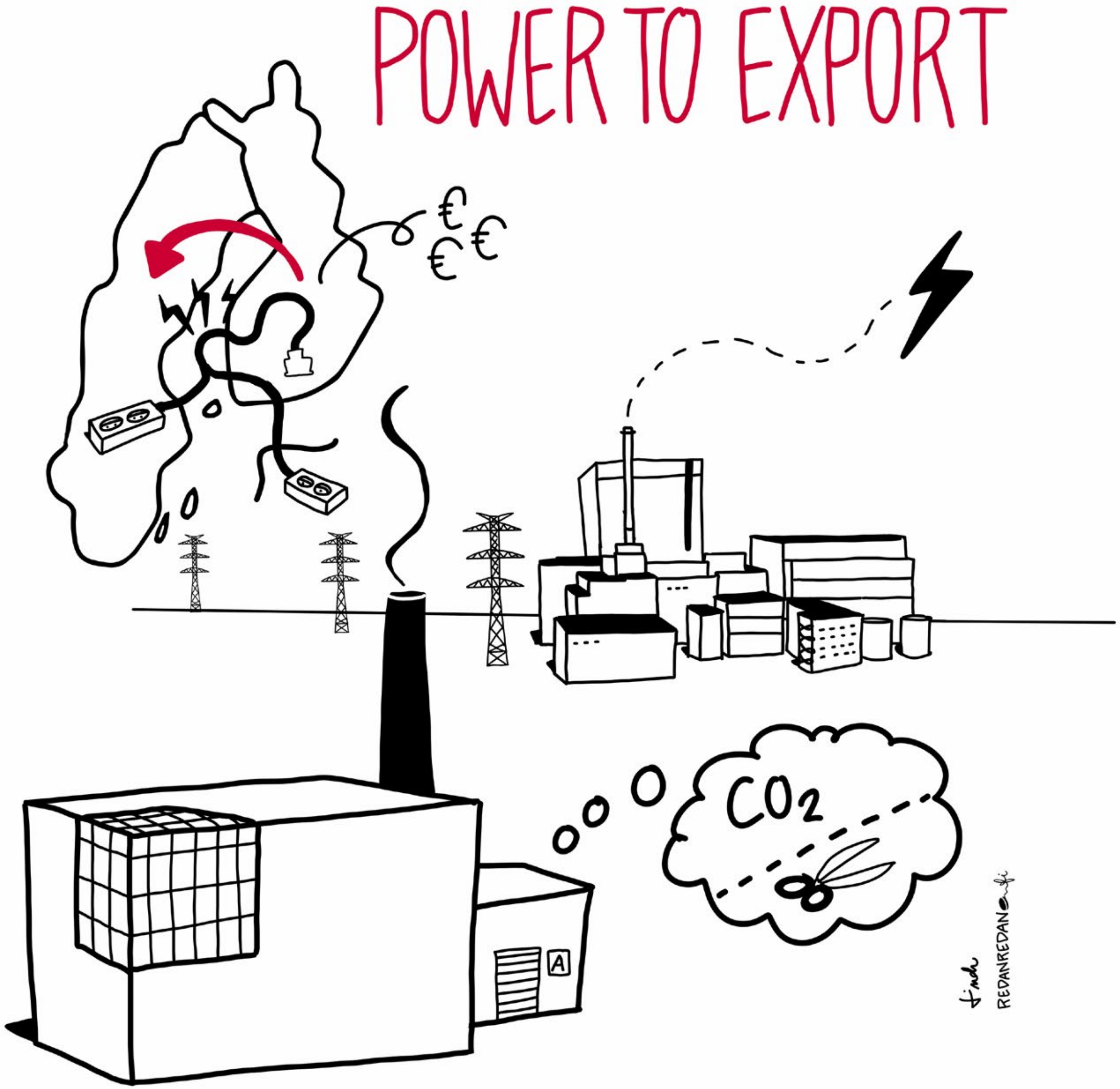
Solar and Batteries

- Finnish carbon neutrality goals are achieved
- Fossil-fueled energy is replaced by electricity and e-fuels
- Lots of decentralized solar power and battery storage connected to distribution networks
- Small amounts of conventional power generation, low inertia
- On an annual basis, Finland will remain a net importer of electricity

Table 1 Scenarios of the most significant variables of scenarios.

Most significant variables in the scenarios	Power to Export	Climate-Neutral Growth	Windy Seas	Solar and Batteries
Hydroelectric power	≈	≈	≈	≈
Onshore wind power	++	+++	+	+
Offshore wind power	+	++	+++	+
Solar power and energy storage	+	+	+	+++
Nuclear power	+	≈	+	-
Other thermal power	-	--	--	-
Electricity consumption	+	+++	+++	+
Available demand-side response	+	+++	+++	++
Annual balance of electricity exports and imports	Exports	Balanced	Balanced	Imports

The table shows how the most significant variables differ between the scenarios. The variables in the table are not comparable with each other. More precise figures on the differences between the variables from one scenario to the next are presented in the section entitled “Summary of the scenarios”. Meanings of the symbols used in the table: ≈ no significant change, + increase, - decrease.



In the Power to Export scenario, the development of the EU's emissions stays in line with the European Green Deal target proposed by the European Commission (at least a 55% reduction in emissions by 2030 compared to 1990 levels and climate neutrality by 2050)[2]. However, Finland might not fully meet the carbon neutrality target set for 2035. Fossil fuels are replaced by electricity and e-fuels in transport, heating and industry, but the pace is more moderate than in other scenarios.

[2] https://ec.europa.eu/clima/policies/eu-climate-action/2030_ctp_en

In terms of the network structure, this scenario describes a future in which Finland is a net exporter of electricity. Power to Export is a scenario in which Finland's consumption grows clearly from current levels, but nevertheless remains below other scenarios. A substantial amount of onshore wind power will be constructed in Finland, not only for covering Finland's own electricity consumption, but also because it will be competitive in the joint European electricity market due to Finland's good wind and construction conditions.

Table 2 Electricity consumption in the Power to Export scenario.

Electricity comsuption under the Power to Export scenario (TWh)	2018	Change 2018–2035	2035	Change 2035–2045	2045
Industry	42	+15	57	+10	67
Heating	17	+3	20	+1	21
Transport	1	+3	4	+3	7
Other consumption and losses	28	-5	24	-3	21
Total	87	+17	105	+11	116

The electricity consumption in the Electricity for Export scenario is described in Table 2. Electricity consumption will increase in industry, transport and heating. Fossil heating of buildings will be replaced primarily by electricity, and other forms of heating will also partially switch to electric solutions. With regard to heating solutions, it is assumed that the energy efficiency of buildings will increase, which will curb the growth in electricity consumption. The use of electricity in passenger transport will grow moderately.

Electricity consumption in manufacturing will increase in connection with the electrification of the existing industry, but the increase of electricity consumption foreseen in the industrial low-carbon roadmaps is slower than in other scenarios[3]. In addition, Finland will not attract significant new investments in electrically intensive industries. Demand-side response will increase, mainly thanks to the flexibility provided by smart charging systems for electric vehicles.

Table 3 Electricity generation capacity in the Power to Export scenarios.

Electricity generation capacity under the Solar and Batteries scenario (GW)	2018	2035	2045
Hydroelectric power	3	3	3
Onshore wind power	2	15	20
Offshore wind power	0	1	2
Solar power	0	3	5
Nuclear power	2.8	5.6	5.6
Other thermal power	8	6	5

Electricity generation under the Power to Export scenario (TWh)	2018	2035	2045
Hydroelectric power	13	14	14
Onshore wind power	6	52	72
Offshore wind power	0	5	11
Solar power	0	2	4
Nuclear power	22	42	41
Other thermal power	27	12	10
Total generation	67	127	152
Total consumption	87	105	116
Finland's power balance	-20	+22	+36

[3] In the Power to Export scenario, the increase in consumption in the metal industry is based on the 'Accelerated technological development' scenario of the technology industry roadmap. In the chemical industry, the increase is based on the 'fast'' scenario of the chemical industry roadmap (scope 1 and scope 2).

The electricity generation capacity and generation in the Power to Export scenario are described in Table 3. Combined heat and power plants will replace fossil fuels with biofuels, so the amount of electricity generated by large combined heat and power plants will decrease more slowly than in the other scenarios. Nuclear power generation will increase with the commissioning of the Olkiluoto 3 and Hanhikivi 1 units. It is also assumed that the service lives of the old units in Loviisa and Olkiluoto will be extended so that they are still in operation in 2045. Hydroelectric power output is assumed to remain at the present level.

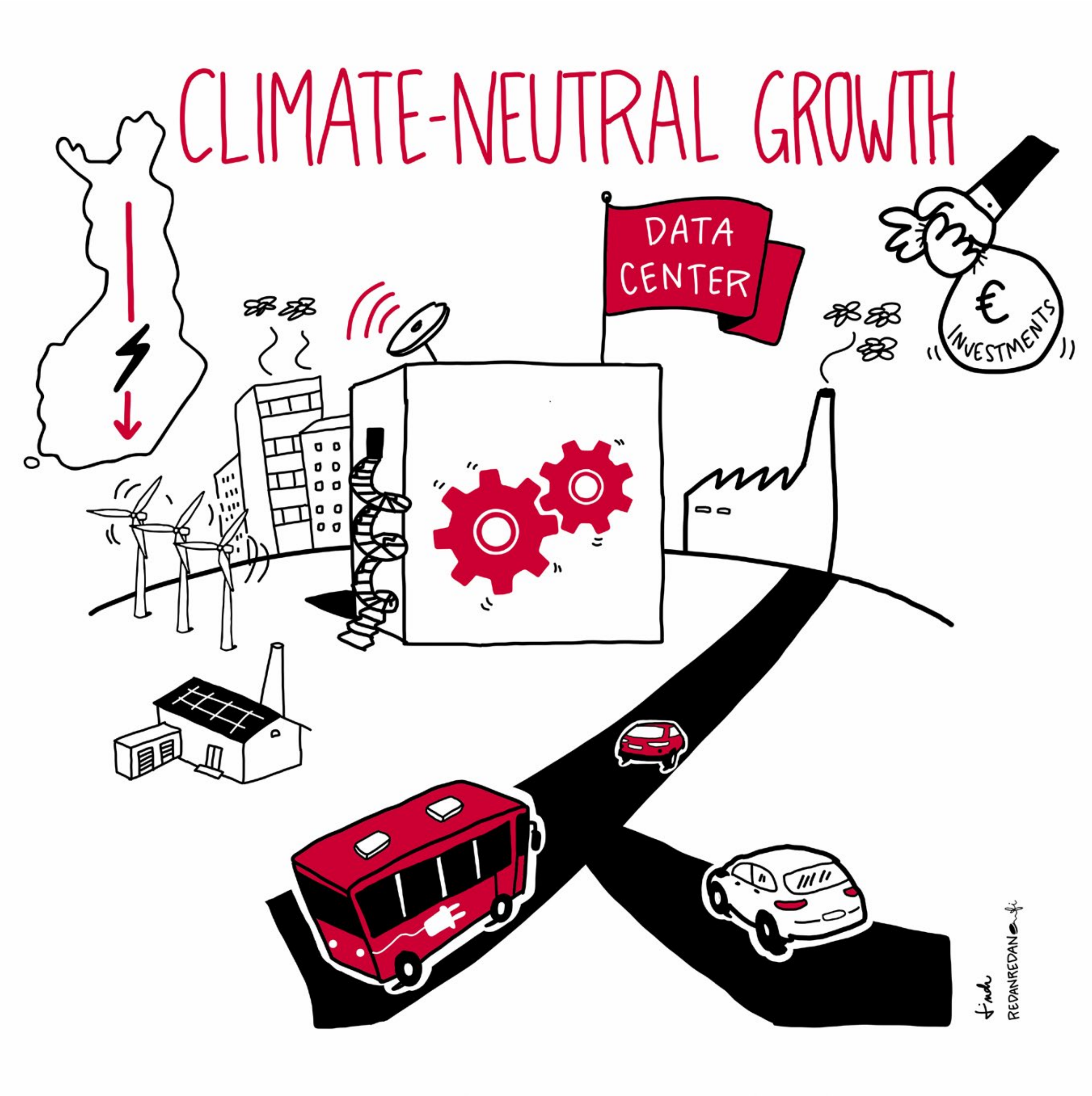
In this scenario, onshore wind power capacity will increase by about 1,000 megawatts per year until 2035, after which growth will slow down. Approximately 1,000 megawatts of offshore wind capacity will be generated in Finland's maritime areas by 2035 and approximately 2,000 megawatts by 2045, but in this scenario, the costs of offshore wind power will not become significantly lower than onshore wind power.

The surrounding world

This scenario assumes that the emission reduction targets in the EU's European Green Deal will be met. Replacing fossil fuels with electricity elsewhere in Europe enables Finland to export clean electricity. Sweden will stop using nuclear power by 2045. The Vyborg HVDC transmission link between Finland and Russia will be refurbished, and a total capacity of 1,300 megawatts will be available for both exports and imports in 2035 and 2045. The applicable sections of the 'Global Ambition' and 'Distributed Energy' scenario in the TYNDP were used as the source data for other countries in this scenario.

Which challenges does this scenario pose for network development?

The scenario foresees Finland becoming an electricity exporter, so this scenario highlights in particular the network investments required to enable exports. Since electricity exports mainly utilise connections originating from Southern Finland, the scenario also challenges Finland's north-south transmission.



Under the Climate-Neutral Growth scenario, Finland will reach its target of becoming carbon-neutral, thanks in large part to the electrification of industrial processes, heating and transport, as well as an increase in clean electricity generation. Finland will be a highly attractive location for new investments in industries that require electricity, and this will lead to greater increases in electricity consumption than in the other scenarios. In addition to Finland's own climate targets, increased energy exports, for example in the form of hydrogen and fuels, will increase Finland's electricity consumption.

From the perspective of the main grid, this scenario envisages more north-to-south transmission than any of the other scenarios. The majority of wind power is north of cross-section Central Finland[4]. Most of the consumption, however, lies south of the cross-section. On the other hand, wind power is also being built in Eastern Finland and to some extent also at sea.

Table 4 Electricity consumption under the Climate-Neutral Growth scenario.

Electricity consumption under the Climate-Neutral Growth scenario (TWh)	2018	Change 2018–2035	2035	Change 2035–2045	2045
Industry	42	+44	86	+72	158
Heating	17	+9	26	-1	25
Transport	1	+4	5	+6	11
Other consumption and losses	28	-1	28	0	28
Total	87	+57	145	+77	222

The electricity consumption under the Climate-Neutral Growth scenario is described in Table 4. In this scenario, electricity consumption will increase substantially due to the electrification of industrial processes, transport and heating, as well as growth in the production of climate-neutral fuels and materials. Most of the targets described in the industrial low-carbon roadmaps for the electrification of processes will be reached. Finland will also be attractive for new investments in electricity-intensive industries, which increases the electricity consumption of data centres and Power-to-X industries. In this scenario, the electricity consumption of Power-to-X production in the EU will be around 1,500 terawatt hours in 2045. This offers significant growth potential for European clean electricity production. The scenario assumes that Finland has a significant amount of hydrogen production in 2045, both for domestic use and for exports. In addition, the low-carbon roadmaps for the chemical industry foresee changes in electricity consumption related to the substitution of fossil raw materials, and this will also provide substantial potential for growth in electricity consumption.

Most of the fossil fuel used for heating will be replaced by technologies based on electricity. Electricity will replace the majority of the combustion processes in district heating, as well as oil- and gas-fired heating in individual buildings. The electricity consumed by transport will increase when passenger transport is almost entirely electrified by 2045, and cargo traffic will also begin using electronic solutions in significant amounts.

The scenario envisages an increase in demand-side management. Assumptions on demand-side management in all scenarios are discussed in more detail in Chapter 5.1. The production of hydrogen and some new industrial processes are assumed to be able to provide demand-side response. As the production of district heating is electrified, heat storage facilities and demand-side management for heating can be utilised to optimise the use of electricity in the district heating system. The charging of electric cars is assumed to be mainly driven by the market prices of electricity. In all demand-side response categories, demand-side response is expected to increase over time. Most of the demand-side response is assumed to be available on an hourly and daily level.

[4] Cross-section Central Finland (also known as Cross-section P1) is the border between the transmission lines of Northern and Southern Finland defined in electrical engineering terms. In the future, the precise location of Cross-section P1 will be affected by matters such as the connection of production and consumption along north-south transmission lines. The main grid must be capable of transmitting the output of these facilities from the north to the south over Cross-section P1. There must be sufficient capacity in the cross-section to prevent Finland from being divided into different electricity trading areas.

Table 5 Electricity generation capacities and generation in the Climate-Neutral Growth scenario.

Electricity generation capacity under the Climate-Neutral Growth scenario (GW)	2018	2035	2045
Hydroelectric power	3	3	3
Onshore wind power	2	22	43
Offshore wind power	0	3	4
Solar power	0	3	5
Nuclear power	2.8	4.6	2.8
Other thermal power	8	4	4

Electricity generation under the Climate-Neutral Growth scenario (TWh)	2018	2035	2045
Hydroelectric power	13	14	14
Onshore wind power	6	79	160
Offshore wind power	0	13	21
Solar power	0	2	4
Nuclear power	22	33	16
Other thermal power	27	9	8
Total generation	67	150	223
Total consumption	87	145	222
Finland's power balance	-20	+5	+1

The electricity generation capacity and generation in the Climate-Neutral Growth scenario are described in Table 5. Significant growth in electricity consumption will create a good investment environment for clean electricity generation. The cost of producing wind power has continued to fall and administrative obstacles have been overcome. As a result, onshore wind capacity will increase at an annual rate of more than 1,000 megawatts, exceeding 20,000 megawatts by 2035 and 40,000 megawatts by 2045.

Most investments in wind power will be made in Western Finland until the end of the 2020s (Ostrobothnia and Sea Lapland). After 2030, more investments will be made in Central and Northern Lapland, and there will also be significant investments in Eastern Finland, where the problems posed to surveillance radars, among other things, have been overcome. Onshore wind will remain more competitive than offshore wind in Finland, but offshore wind projects will also take place in Finland's maritime areas. The amount of decentralised solar power will increase, mainly as a consequence of the interest and activity of households.

As CHP plants age, replacement investments will mainly be made in electricity-based technologies and boilers. No new CHP plants will be built and by 2035 a significant number of district heating CHP plants will have been decommissioned. Industries will continue to use CHP if they are fuelled by side streams that cannot be used for any other purpose. Hydroelectric power output is assumed to remain at the present level.

Regarding nuclear power, the scenario assumes that the nuclear power units currently operating in Loviisa and Olkiluoto will be decommissioned when their existing operating permits expire. Currently, the Loviisa 1 and 2 operating permits are valid until the end of 2027 and 2030[5], respectively, and the licences for both units in Olkiluoto are valid until the end of 2038[6]. Olkiluoto 3 is assumed to be in operation, and the Hanhikivi nuclear power plant is expected to be completed before 2035.

[5] Loviisa 1 and 2 - Website of the Ministry of Economic Affairs and Employment (tem.fi)
[6] Olkiluoto 1 and 2 - Website of the Ministry of Economic Affairs and Employment (tem.fi)

This scenario seeks to challenge the grid's north-south transmission capacity. The need for increased north-south transmission is caused by the location of Hanhikivi in a more northern area of Finland and the removal of the Loviisa plant from the 2035 scenario and Olkiluoto units 1 and 2 from the 2045 scenario.

The surrounding world

In this scenario, the EU will be climate neutral by 2050. Replacing imported fossil fuels with electricity generated in Europe and synthetic fuels made using electricity will increase electricity consumption significantly, thereby improving Europe's energy self-sufficiency. Sweden's nuclear power is assumed to have been decommissioned by 2045. The Vyborg HVDC transmission link between Finland and Russia will be refurbished, and a total capacity of 1,300 megawatts will be available for both exports and imports in 2035 and 2045.

The Climate-Neutral Growth scenario is not a direct consequence of any of the TYNDP scenarios, but the initial information has been integrated where appropriate.

Which challenges does this scenario pose for network development?

In this scenario, most of Finland's rapid increase in electricity consumption is assumed to be concentrated to the south of Cross-section Central Finland, while generation investments — especially wind power — will mainly occur to the north of Cross-section Central Finland. The scenario challenges the transmission capacity between Northern and Southern Finland as the output must be transmitted from the north of the cross-section to the south. This scenario also envisages a dramatic increase in electricity transmission to urban areas as heating and transport are electrified and the combined heat and power capacity decreases.

WINDY SEAS

The key factor in the Windy Seas scenario is a sharp increase in offshore wind power generation. Under this scenario, Finland will reach its target of becoming carbon-neutral, thanks in large part to the electrification of industrial processes, heating and transport, as well as an increase in clean electricity generation. Finland will be an attractive location for new investments in industries that require clean electricity, but the rise in electricity consumption will be slightly less pronounced than in the Climate-Neutral Growth scenario.

Offshore wind power is assumed to be concentrated on the west coast, which will pose challenges for the main grid's transmission capacity. The main grid must be capable of transmitting the substantial wind power output onwards to consumption sites. In this scenario, the amount of electricity transmitted from the main grid to urban areas will increase.

Table 6 Electricity consumption under the Windy Seas scenario.

Electricity consumption under the Windy Seas scenario (TWh)	2018	Change 2018–2035	2035	Change 2035–2045	2045
Industry	42	+36	78	+50	128
Heating	17	+10	26	-1	26
Transport	1	+4	5	+6	11
Other consumption and losses	28	-1	27	0	27
Total	87	+48	136	+55	191

The electricity consumption under the Windy Seas scenario is described in Table 6. Industrial carbon neutrality targets are met thanks to the electrification of processes. In particular, the chemical and steel industries will be able to substitute processes based on fossil energy sources with electricity and with e-fuels. Finland will be a competitive place for industries that require clean electricity, but the competitive advantage and the consequent overall electricity consumption by industries will be slightly smaller than in the Climate-Neutral Growth scenario. However, a significant amount of new electrically intensive industry and Power-to-X production is created in Finland.

Most of the fossil fuel used for heating will be replaced by technologies based on electricity. Electricity will replace the majority of the combustion processes in district heating, as well as oil- and gas-fired heating in individual buildings. Electricity consumption in transport will increase as passenger transport will be almost completely electric by 2045. Freight transport will also use a significant amount of electric solutions.

The scenario envisages an increase in demand-side response. Assumptions on demand-side management in all scenarios are discussed in more detail in Chapter 5.1. The production of hydrogen and some new industrial processes are assumed to be able to provide demand-side response. As the production of district heating is electrified, heat storage facilities and demand-side response for heating can be utilised to optimise the use of electricity in the district heating system. The charging of electric cars is assumed to be mainly driven by the market prices of electricity. In all demand-side response categories, demand-side response is expected to increase over time. Most of the demand-side response is assumed to be available on an hourly and daily level.

Table 7 Generation capacity and generation of electricity in the Windy Seas scenario.

Electricity generation capacity under the Climate-Neutral Growth scenario (GW)	2018	2035	2045
Hydroelectric power	3	3	3
Onshore wind power	2	10	10
Offshore wind power	0	10	20
Solar power	0	3	5
Nuclear power	2.8	4.4	4.6
Other thermal power	8	4	4

Electricity generation under the Windy Seas scenario (TWh)	2018	2035	2045
Hydroelectric power	13	14	14
Onshore wind power	6	33	33
Offshore wind power	0	54	108
Solar power	0	2	4
Nuclear power	22	33	32
Other thermal power	27	9	8
Total generation	67	145	199
Total consumption	87	136	191
Finland's power balance	-20	+9	+8

The electricity generation capacity and generation in the Windy Seas scenario are described in Table 7. Significant growth in electricity consumption will create a good investment environment for clean electricity generation. The capacity of wind power will initially increase at a steady annual rate of over 1,000 megawatts, exceeding 10,000 megawatts in the late 2020s. The growth rate will then accelerate and 20,000 megawatts will be reached by 2035. In the early 2020s, most of the wind power will have been built on land, but the construction of offshore wind will have gradually become more profitable than onshore wind power. In 2035, the capacity of both offshore and onshore wind will be around 10 gigawatts, and by 2045 the capacity of offshore wind power (20 gigawatts) will have doubled compared to onshore wind power (10 gigawatts) and is even higher in terms of energy. The construction of offshore wind power on this scale has required not only a reduction in the cost level of the technology, but also a reduction in the cost of connecting offshore wind or, alternatively, subsidies for the connection.

The amount of decentralised solar power will increase, mainly as a consequence of the interest and activity of households. As CHP plants age, replacement investments will mainly be made for electric heating and boilers. No new CHP plants will be built and by 2035 a significant number of district heating CHP plants will have been decommissioned. Most of the combined heat and power capacity used by industry will remain. Hydroelectric power output is assumed to remain at the present level.

Regarding nuclear power, the operation of the old nuclear power units in Loviisa is assumed to be extended by 10 years until 2037 and 2040 respectively. The commissioning of the Hanhikivi plant is expected to be delayed until around the same time that the Loviisa units are decommissioned. The service lives of the old units in Olkiluoto will be extended until the end of the 2040s.

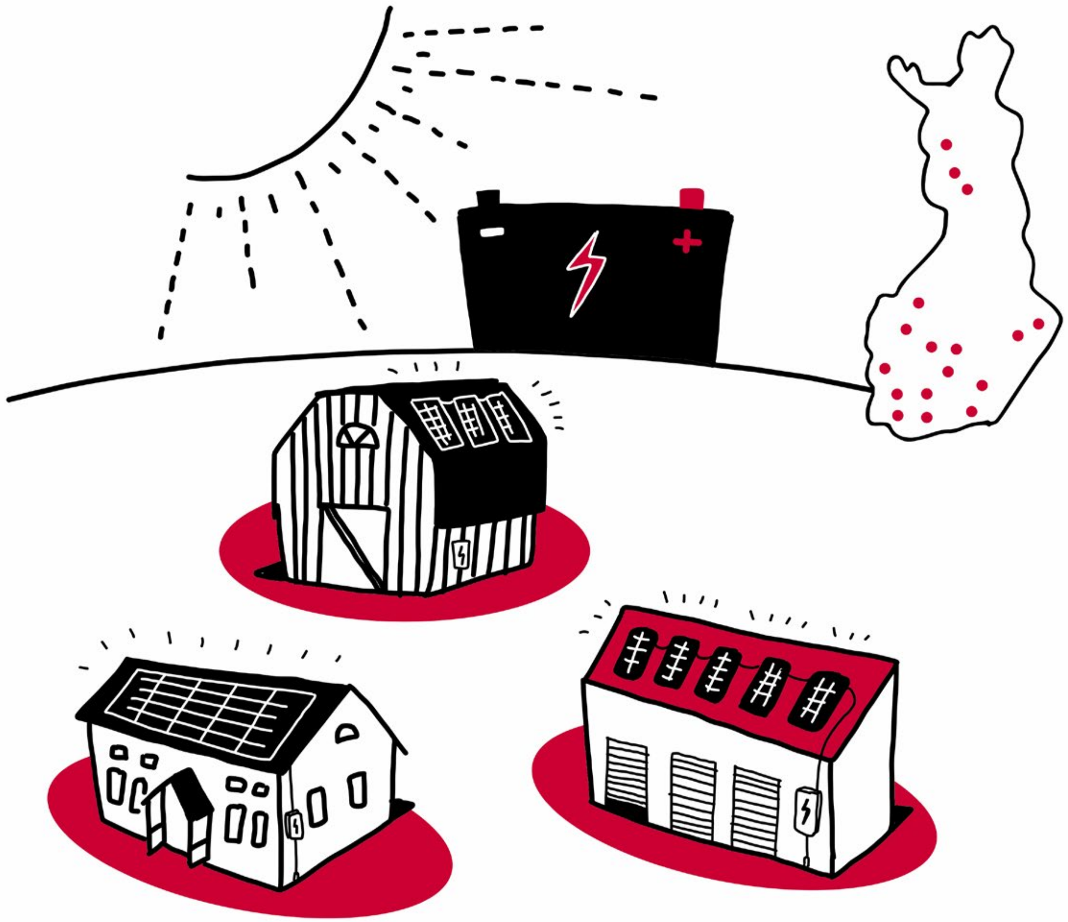
The surrounding world

Offshore wind will become the most competitive form of electricity generation in Europe as a result of lower production costs or subsidies from public funds. At the same time, opposition to onshore wind will limit the use of the largest and most efficient wind farm plants on land. The scenario makes use of the TYNDP "Global Ambition" scenario in the sections that apply to other European countries.

Significant amounts of wind power will be built in the North Sea as well as in the Baltic Sea. In Europe, no new decisions will be made to prematurely decommission nuclear power plants, but the decisions that have already been made will not be reversed. Sweden will still have a substantial amount of nuclear power in operation in 2045. Under this scenario, the Vyborg HVDC transmission link will not be replaced, and it will be decommissioned after 2030.

Which challenges does this scenario pose for network development?

This scenario calls for a large amount of new generation on the west coast of Finland. In this scenario, Finland's electricity consumption will increase, and electricity must be transmitted from the west coast to the points of consumption. This scenario also envisages a dramatic increase in electricity transmission to urban areas as heating and transport are electrified and the combined heat and power capacity decreases.



SOLAR AND BATTERIES

The significant variables in the Solar and Batteries scenario are the growth in the amount of decentralised solar power and the reduction in the amount of nuclear power. Finland will reach its target of becoming carbon-neutral, thanks in large part to the electrification of industrial processes, heating and transport, as well as an increase in clean electricity generation. The electrification of Finnish industry will follow the route laid out in the low-carbon roadmaps, but Finland will not attract any new industrial production.

From the perspective of the main grid, decentralised generation and the transformation of households and other electricity consumers into producer-consumers will give rise to new challenges. The scenario assumes that distribution networks will enable households to dramatically increase their solar power output and that batteries will be connected to the grid in growing numbers. In addition, the reduction in the amount of electricity generated by nuclear power and other conventional methods will pose a challenge for the operation of the power system and especially the efforts to ensure sufficient inertia in the power system.

Table 8 Electricity consumption under the Solar and Batteries scenario.

Electricity consumption under the Solar and Batteries scenario (TWh)	2018	Change 2018–2035	2035	Change 2035–2045	2045
Industry	42	+26	68	+9	76
Heating	17	+1	17	+0	18
Transport	1	+3	4	+1	5
Other consumption and losses	28	-1	28	-2	26
Total	87	+29	117	+9	125

The electricity consumption under the Solar and Batteries scenario is described in Table 8. The targets described in the industrial low-carbon roadmaps are met thanks to the electrification of processes. In particular, it was possible to replace fossil energy with electricity in the processes of the chemical and steel industries. Electricity consumption will increase, but the growth will be more moderate than in the Windy Seas and Climate-Neutral Growth scenarios.

The electrification of heating will become more common, but fossil heating fuels will mainly be replaced by using geothermal energy, harnessing waste heat and using biofuels, so the use of electricity in heating will increase only moderately.

Passenger and cargo transport will move away from fossil fuels. Hydrogen will become a major transport fuel alongside electricity, and this will reduce the direct consumption of electricity by electric cars.

Demand-side response will become more commonplace chiefly due to the growth in decentralised energy storage, smart charging of electric vehicles and the use of Vehicle-to-Grid technology.

Table 9 Generation capacity and generation of electricity in the Solar and Batteries scenario.

Electricity generation capacity under the Solar and Batteries scenario (GW)	2018	2035	2045
Hydroelectric power	3	3	3
Onshore wind power	2	11	13
Offshore wind power	0	1	1
Solar power	0	6	16
Nuclear power	2.8	3.4	1.9
Other thermal power	8	4	5

Electricity generation under the Solar and Batteries scenario (TWh)	2018	2035	2045
Hydroelectric power	13	14	14
Onshore wind power	6	38	46
Offshore wind power	0	3	6
Solar power	0	5	13
Nuclear power	22	26	13
Other thermal power	27	12	12
Total generation	67	98	105
Total consumption	87	117	125
Finland’s power balance	-20	-19	-21

The electricity generation capacity and generation under the Solar and Batteries scenario are described in Table 9. This scenario is characterised by solar power decentralised into small units and batteries used by households and the service sector. The amount of wind power will also increase, but the rate of growth will be slower than in the other scenarios. Local energy generation will be favoured, and investments will be made in wind power projects in rural parts of Southern Finland. Approximately 1,000 megawatts of offshore wind power capacity will also be built. As the costs of solar power fall substantially, solar energy will also be used in large amounts elsewhere in Europe, which will play a part in Finland becoming a net importer of electricity on an annual basis.

In terms of the generation of district heating, large combined heat and power plants will be replaced by the use of waste heat, geothermal energy and micro CHP plants. Hydroelectric power output is assumed to remain at the present level.

As far as nuclear power is concerned, the scenario assumes that no conventional nuclear power plants will be completed in Finland after Olkiluoto 3 and that the old plants will be decommissioned at the end of their current operating licences, currently the Loviisa 1 and 2 operating licences will be valid until the end of 2027 and 2030[7], and the operating permits for both units in Olkiluoto will be valid until the end of 2038[8]. Small, modular nuclear power plants are assumed to arise as an alternative for electricity and heat generation towards the end of the 2030s. By 2045, modular nuclear power plants will generate small amounts of electricity, mainly in large cities.

The surrounding world

Replacing fossil energy with renewable energy will improve Europe's energy self-sufficiency, and replacing imported energy with locally-generated energy will increase electricity consumption significantly. The costs of generating solar power will decrease dramatically, and solar power will become the cheapest way of generating electricity in most of Europe. The costs of energy storage technologies will also decrease substantially, so decentralised energy generation will become significantly more profitable. Sweden's nuclear power plants are assumed to have been closed by 2045. Under this scenario, the Vyborg HVDC transmission link will not be replaced, and it will be decommissioned after 2030. The scenario makes use of the TYNDP "Distributed Energy" scenario in the sections that apply to other countries around the world.

Which challenges does this scenario pose for network development?

This scenario envisages a significant amount of new, decentralised generation and a reduction in the number of conventional power plants connected to the main grid. This will lead to a decrease in system inertia, which will pose challenges in terms of maintaining the frequency on the main grid. The same trend will also be accompanied by other technical challenges, such as the adequacy of fault currents and voltage support on the main grid. The scenario assumes that distribution networks will develop to meet the needs of decentralised generation and electricity storage.

7 Loviisa 1 and 2 - Website of the Ministry of Economic Affairs and Employment (tem.fi)
8 Olkiluoto 1 and 2 - Website of the Ministry of Economic Affairs and Employment (tem.fi)

2.6 Summary of the scenarios

This section presents a summary and comparison of the scenarios. Finland's carbon neutrality target for 2035 will be achieved in three of the scenarios (Climate-Neutral Growth, Windy Seas and Solar and Batteries). In the Power to Export scenario, carbon neutrality targets might not be achieved on schedule. Industrial electricity consumption increases under all scenarios. The growth is most dramatic in the scenarios where Finland's goal of becoming carbon-neutral is reached by increasing the consumption of electricity. Electricity consumption will increase even further if products made using electricity (such as hydrogen) are also refined for export purposes, or cheap, clean electricity attracts new industrial investments to Finland, such as data centres. The consumption of electricity for heating will increase, particularly when the fossil fuels used to generate district heat are replaced by solutions that use electricity. The consumption of electricity for transport will increase under all the scenarios, but the scenarios envisage differing degrees of electrification. Figure 3 below presents the electricity consumption under the scenarios in comparison with the consumption in 2018.

Figure 4 below and tables 10–13 present the amount of electricity generation, Finland's power balance, and the electricity generation capacity under different scenarios in 2035 and 2045. The amount of onshore wind power will increase significantly under all the scenarios, although the growth will be most pronounced in the Climate-Neutral Growth scenario. The amount of offshore wind power will increase, especially under the Windy Seas scenario, while the production of solar power will increase most rapidly under the Solar and Batteries scenario.

Figure 3 Consumption of electricity under the scenarios.

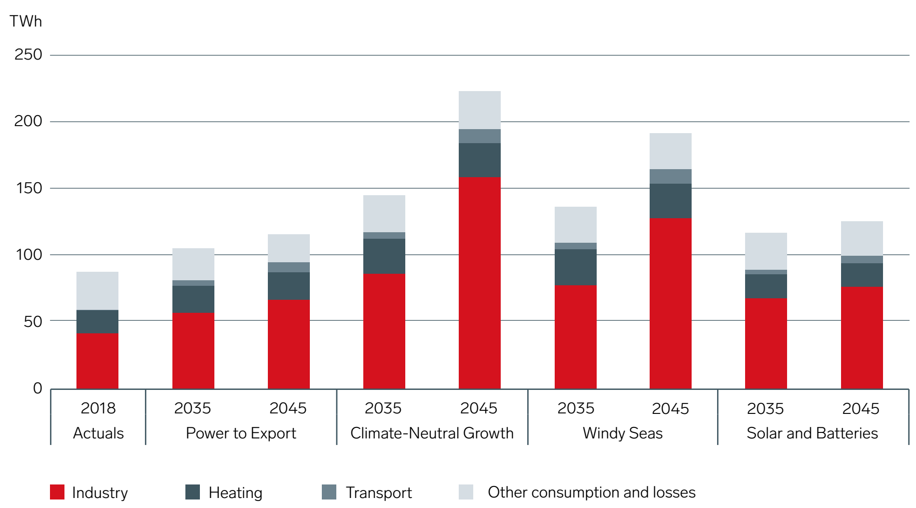


Figure 4 Electricity generation under the difference scenarios.

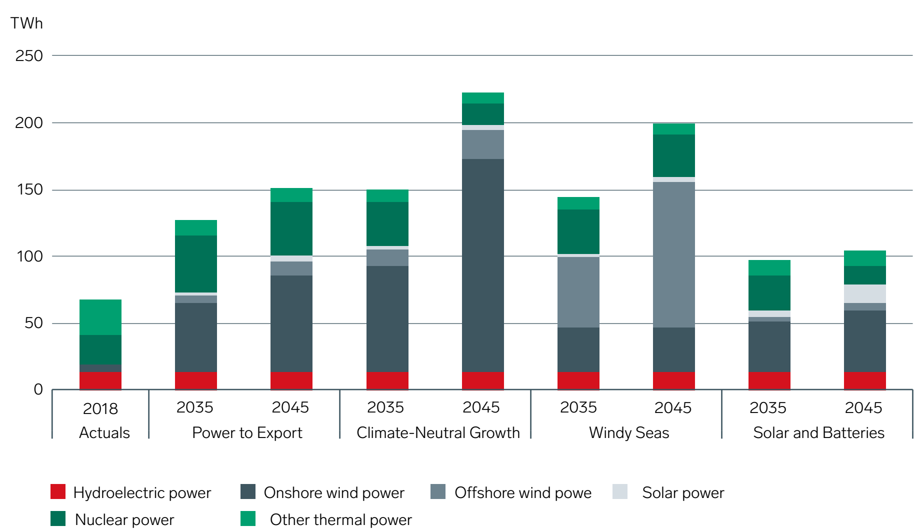


Table 10 Power balance under the different scenarios in 2035.

Power balance 2035 (TWh)	Power to Export	Climate-Neutral Growth	Windy Seas	Solar and Batteries
Hydroelectric power	14	14	14	14
Onshore wind power	52	79	33	38
Offshore wind power	5	13	54	3
Solar power	2	2	2	5
Nuclear power	42	33	33	26
Other thermal power	12	9	9	12
Total generation	127	150	145	98
Total consumption	105	145	136	117
Finland's power balance	+22	+5	+9	-19

Table 11 Power balance under the different scenarios in 2045.

Power balance 2045 (TWh)	Power to Export	Climate-Neutral Growth	Windy Seas	Solar and Batteries
Hydroelectric power	14	14	14	14
Onshore wind power	72	160	33	46
Offshore wind power	11	21	108	6
Solar power	4	4	4	13
Nuclear power	41	16	32	13
Other thermal power	10	8	8	12
Total generation	152	223	199	105
Total consumption	116	222	191	125
Finland's power balance	+36	+1	+8	-21

Table 12 Generation capacity under the different scenarios in 2035.

Capacity 2035 (GW)	Power to Export	Climate-Neutral Growth	Windy Seas	Solar and Batteries
Hydroelectric power	3	3	3	3
Onshore wind power	15	22	10	11
Offshore wind power	1	3	10	1
Solar power	3	3	3	6
Nuclear power	5.6	4.6	4.4	3.4
Other thermal power	6	4	4	4

Table 13 Generation capacity under the different scenarios in 2045.

Capacity 2045 (GW)	Power to Export	Climate-Neutral Growth	Windy Seas	Solar and Batteries
Hydroelectric power	3	3	3	3
Onshore wind power	20	43	10	13
Offshore wind power	2	4	20	1
Solar power	5	5	5	16
Nuclear power	5.6	2.8	4.6	1.9
Other thermal power	5	4	4	5

3. Transmission needs

3.1 Main transmission cross-sections within Finland

The hourly transmission needs in Finland's main transmission cross-sections for 2035 and 2045 are calculated by running market simulations for each scenario. Based on the results, it can be estimated how much transmission capacity is needed in the cross-sections in order to meet electricity transmission needs without dividing Finland into several electricity market bidding zones. The results for Finland's two main cross-sections are presented in Chapters 3.1.1 and 3.1.2

Finland's main transmission cross-sections are shown in Figure 5 below. Finland's southernmost main transmission cross-sections is called the Cross-section Central Finland, also referred to as Cross-section P1. It is the border between the transmission lines of Northern and Southern Finland defined in electrical engineering terms. In the future, the precise location of Cross-section P1 will be affected by matters such as the connection of electricity production and consumption along north-south transmission lines.

The more northern of Finland's main transmission cross-sections is called the Kemi-Oulujoki Cross-section, also referred to as Cross-section P0. It is the border located between rivers Kemijoki and Oulujoki that intersects the transmission lines and is defined in electrical engineering terms. The exact location of this cross-section might also change in the future.

Figure 5 Main transmission cross-sections within Finland. In the future, the locations of the cross-sections might change as a result of, amog other things, the change in the location of electricity production and consumption.

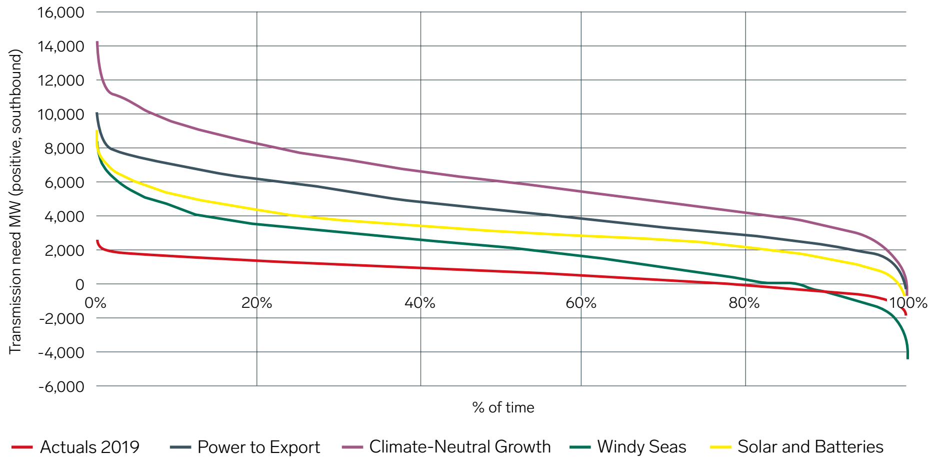
3.1.1 Transmission needs through the Cross-section Central Finland (P1)

Electricity transmission needs through the Cross-section Central Finland will increase significantly in all scenarios. Figure 6 presents the transmission needs in different scenarios in 2035.[9] The maximum transmission requirement varies from 9,000 megawatts to 14,500 megawatts in the scenarios, while the transmission capacity that would cover 99% of the transmission situations varies between 7,000 megawatts and 12,000 megawatts. In 2019, the maximum transmission requirement was 2,500 megawatts and the 99th percentile is 2,100 megawatts. The current maximum capacity of the cross-section is approximately 3,400 megawatts. In all scenarios, the highest 1% of the transmission situations give rise to a significant need for extra strengthening compared to a situation where only 99% of transmission situations could be covered (a difference of around 2,000–2,500 megawatts). One new 400 kilovolt transmission line with compensation investments will increase the capacity by about 1,000–1,500 megawatts, so two new transmission lines would be needed for the highest transmission peaks, the total duration of which is approximately 100 hours a year. From national economy and land use perspectives, it may be justified to try to resolve the highest 1% of transmission situations in ways other than by building additional transmission lines, for example by utilizing Dynamic Line Rating (DLR)[10] technology that measures the load capacity of the lines in real time, or by taking advantage of flexibility in production and consumption.

[9] The transmission needs simulated for 2035 have been calculated using a weather scenario corresponding to the historic year 1999. Transmission needs vary slightly in different weather scenarios.

[10] Dynamic Line Rating (DLR) refers to the dynamic load capacity of transmission lines depending on the prevailing weather conditions, such as temperature and wind. The DLR device measures the loads handled by the line in real time in different weather conditions. More information about the DLR technology.

Figure 6 Transmission needs through Cross-section Central Finland (P1) in the different scenarios in 2035 compared to the actual level in 2019.



In the Power to Export scenario, the peak power of electricity transmission needs from north to south will approximately quadruple and net energy transmission will increase approximately sevenfold compared to the 2019 level. In this scenario, approximately 70% (approx. 11 gigawatts) of the wind power capacity is located north of the Cross-section Central Finland. In the scenario, nearly 80% of the electricity consumption is located south of the cross-section, in addition to which almost all electricity exports take place from southern Finland to Estonia, Russia and central Sweden. In addition, the Hanhikivi nuclear power plant contributes to the electricity surplus in Northern Finland.

In the Solar and Batteries scenario, the peak power of electricity transmission needs from north to south more than triples and the annual amount of net energy transmitted increases fivefold compared to the 2019 level. The increase in transmission needs is caused especially by the increase in onshore wind power and the increased import of electricity from northern Sweden to Finland. In this scenario, approximately 60% (approx. 7 gigawatts) of the wind power capacity is located north of the Cross-section Central Finland. Under this scenario, the expected increase in industrial electricity consumption in Northern Finland has a particularly strong effect in curbing the growth in transmission needs, although 75% of Finland's total electricity consumption takes place south of the Cross-section Central Finland.

In the Windy Seas scenario, the north-south transmission needs are the lowest of the scenarios, but even then the need for electricity transmission from north to south will more than triple from the 2019 levels. More than 6 gigawatts of onshore wind power, which accounts for more than 60% of Finland's onshore wind power, and 3.5 gigawatts of offshore wind power, which comprises 35% of Finland's offshore wind power, are located north of the Cross-section Central Finland. The construction of offshore wind power south of the Cross-section Central Finland significantly reduces the need for north-to-south transmission compared to a situation in which offshore wind power would be constructed in northern Finland. The growth in industrial electricity consumption in Northern Finland contributes to curbing the need for transmission, even though more than 75% of Finland's electricity consumption takes place south of the Cross-section Central Finland.

In the 2045 scenarios, the transmission needs have grown significantly from those of 2035. There is also a lot of variation between the scenarios. In 2045, a transmission capacity that covers 99% of the situations would be 8 gigawatts in the Sun and batteries scenario, 11 gigawatts in the Power to Export and Windy Seas scenario and as much as 25 gigawatts in the Climate-neutral growth scenario. In the scenarios, the transmission capacity that can cover the maximum transmission needs is 2 to 5 gigawatts greater than the transmission capacity that can cover 99% of the transmission situations.

In summary

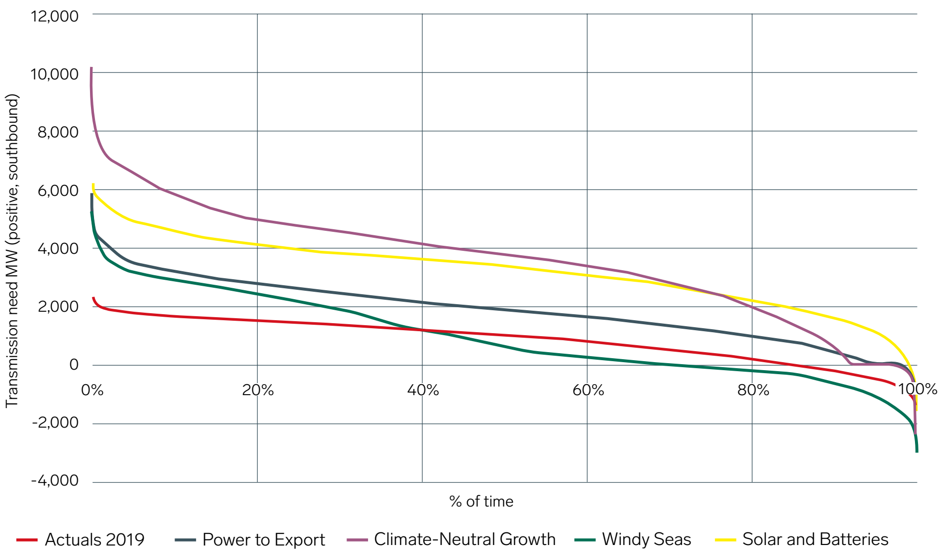
1. In all scenarios, the need for transmission over the Cross-section Central Finland will increase significantly and the capacity of the cross-section must be increased many-fold in order to keep mainland Finland as a single electricity market bidding zone.
2. The capacity needed for 2035 in the Climate-Neutral Growth scenario will be sufficient even in 2045 in the rest of the scenarios.
3. The electricity transmission capacity required in the Climate-Neutral Growth scenario in 2045 is unlikely to be achievable by utilising traditional 400 kV single circuit lines, which means that a significant amount of new solutions are needed. A transmission capacity of 25–30 gigawatts would require approximately 20 traditional 400 kV wires for the Cross-section Central Finland (in 2020, there were 4 such lines), which is not possible from the perspective of construction and land use, and is very likely economically unfeasible as well. In this scenario, Finnish conditions need new technical solutions, which are discussed in more detail in Chapter 4.8.
4. The increase in transmission needs depends very heavily on the location of electricity production and consumption within Finland. The assumptions made about this have a strong impact on the outcome of the analysis.

The necessary network solutions are discussed in more detail in Chapter 4.

3.1.2 Transmission needs of the Cross-section Kemi-Oulujoki (P0)

Transmission needs in the main grid through the Cross-section Kemi-Oulujoki will increase significantly in all scenarios. Figure 7 shows the transmission needs in 2035. The maximum transmission requirement varies from 5,500 megawatts to 10,000 megawatts in the scenarios, while the transmission capacity that would cover 99% of the transmission situations varies between 4000 megawatts and 7500 megawatts, depending on the scenario. In 2019, the maximum transmission need was 2 300 megawatts and the 99th percentile was 2000 megawatts. The current maximum capacity of the cross-section is approximately 2 400 megawatts. In all scenarios, the highest 1% of the transmission situations give rise to a significant need for extra strengthening compared to a situation where only 99% of transmission situations could be covered (a difference of around 1,000–2,500 megawatts). One new 400 kilovolt transmission line with compensation investments will increase the capacity by about 1,000–1,500 megawatts, so 1 or 2 new transmission lines would be needed for the highest transmission peaks, the total duration of which is approximately 100 hours a year. From national economy and land use perspectives, it may be justified to try to resolve the highest 1% of transmission situations in other ways than by building additional transmission lines, for example by utilizing Dynamic Line Rating (DLR) technology that measures the load capacity of the lines in real time, or by taking advantage of flexibility in production and consumption.

Figure 7 Transmission needs through the Cross-section Kemi-Oulujoki in the different scenarios in 2035 compared to the actual lecel in 2019.



The transmission need through the cross-section is greatest in the Climate-Neutral Growth scenario. This is the result of a high amount of onshore wind power (about 9 gigawatts) north of the cross-section and the increasing transmission capacity between northern Sweden (SE1) and Finland (totalling 2800 megawatts in this scenario). In other scenarios, the peak transmission requirement is clearly lower due to lower wind power production north of the cross-section (approximately 3–5 gigawatts). In the Solar and Batteries scenario, the average transmission requirement is clearly higher than in the Windy Seas and Power to Export scenarios. This is partly due to the high electricity imports of the Solar and Batteries scenario, a significant part of which comes from Sweden's northern AC connections. In the Power to Export scenario, the amount of onshore wind power north of the Cross-section Kemi-Oulujoki increases transmission needs, but this is partly offset by the high volume of electricity export (including exports to northern Sweden). The lowest amount of north-south transmission through Cross-section Kemi-Oulujoki takes place in the Windy Seas scenario. Some transmission also takes place in the south-north direction, as the majority (about 90%) of offshore wind is located south of the cross-section.

In 2045, the highest transmission need through the Cross-section Kemi-Oulujoki occurs in the Climate-Neutral Growth scenario. In the scenario, 99% of transmission situations can be covered by a transmission capacity of approximately 16,500 MW, whereas in other scenarios 99% of transmission situations can be covered by a transmission capacity of 5,500–6,000 MW. This is due in particular to the high amount of wind power north of the cross-section, which in the Climate-Neutral Growth scenario is 18 gigawatts in 2045 and corresponds to about 40% of Finland's total wind power capacity. In other scenarios, the amount of wind power north of the cross-section is about 3–8 gigawatts.

In summary

1. In all scenarios, the need for transmission over the Cross-section Kemi-Oulujoki will increase significantly and the capacity of the cross-section must be increased many-fold in order to keep mainland Finland as a single electricity market bidding zone.
2. The need for transmission depends heavily on the magnitude of production north of the cross-section, where the potential consists largely of onshore wind power. As a result, the transmission need is substantially higher in the Climate-neutral growth scenario, in which the potential of Lapland's onshore wind power is utilised widely. The prerequisite for an increased electricity production is an increase in electricity consumption, which is assumed in the scenarios to take place in Southern Finland. If a higher share of consumption were close to production, the need for transmission over the cross-section would be lower.
3. The electricity transmission capacity required in the Climate-Neutral Growth scenario in 2045 is unlikely to be achieved by utilising traditional 400 kV single circuit lines. In this scenario, new technical solutions are needed and they are discussed in more detail in Chapter 4.8.

3.2 Cross-border connections

This chapter presents the assumptions concerning cross-border connections in the network vision and presents a preliminary utility benefit analysis of the cross-border connection options. The results for cross-border connections are indicative. If necessary, more detailed analyses will be carried out in cooperation with the neighbouring TSOs or as part of regional cooperation. Economic analyses are also carried out at the European level every two years in ENTSO-E's Ten-Year Network Development Plan (TYNDP). The benefits of cross-border connections have been examined by simulating the economic benefits of the Baltic Sea region and Western Europe. Thus, the analysis is not based solely on an assessment of the economic benefits for Finland.

3.2.1 Sweden

All scenarios of the network vision assume that the third AC connection between Finland and Sweden, RAC3, scheduled to be completed in 2025, is operational. The 2035 scenarios assume that the Fenno-Skan 1 connection will be decommissioned.[11] The network vision evaluates three new cross-border transmission options (+800 megawatts) between Finland and Sweden:

- A fourth AC connection between bidding zones SE1 and FI (RAC4).
- A HVDC transmission link in Kvarken between bidding zones SE2 and FI.
- Fenno-Skan 3 HVDC transmission link between bidding zones SE3 and FI.

The purpose of the analysis was to perform an initial survey of the potential of new connections, which means that the results are only indicative. Any further, more detailed studies on cross-border transmission connections will be made in conjunction with Svenska Kraftnät.

The results indicate that in all scenarios of the network vision, increasing cross-border transmission capacity to Sweden by 2035 in addition to RAC3, seems useful. This also applies if the lifespan of the Fenno-Skan 1 connection can be extended to 2040.

All of the three projects are profitable in the scenarios, but there are differences in the profitability. If the transmission direction were to be primarily electricity imports, the most appropriate endpoint on the Swedish side would be the SE1 or SE2 bidding zone (RAC4 or Kvarken). If, on the other hand, the connection were primarily for export purposes, Fenno-Skan 3 would be a more profitable option. From the perspective of balancing production and consumption, all connections work well. The cost of RAC4 is likely to be lower than either of the DC connections. The market effects of RAC4 and Kvarken are similar, with the assumed difference in investment costs tipping the comparison to RAC4's favour. In the market calculations and network calculations performed for the 2035 scenarios, RAC4 was assumed to be operational in the Climate-Neutral Growth and Solar and Batteries scenarios. Similarly, Fenno-Skan 3 was assumed to be operational in the Power to Export and Windy Seas scenarios.

In the long term, it might become possible to connect offshore wind along the Kvarken and Fenno-Skan transmission links. The solution is called a hybrid HVDC transmission link. An intermediate station located in Åland would be a cheaper potential option than substations built at sea, especially for Fenno-Skan. However, these solutions mainly represent long-term potential. The ability to implement them by 2035 would require the rapid development of a technology for a network that consists of several interconnected HVDC transmission links or alternatively several separate conventional connections, assuming that a significant amount of wind power will be connected (the maximum power of one conventional connection is approximately 1,000 megawatts). This option has therefore not been considered as part of the network vision.

[11] Fingrid and Svenska kraftnät are currently exploring the possibility to extend the service life of the connection until 2040

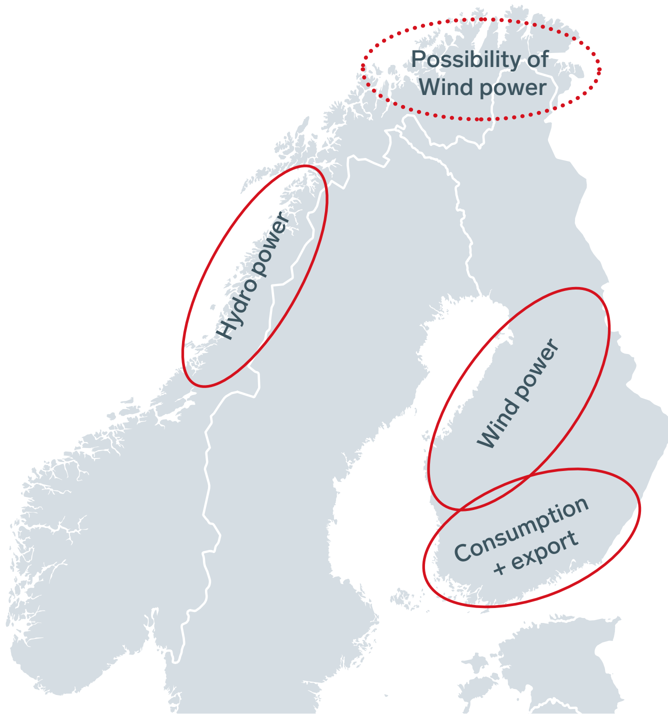
3.2.2 Norway

In all of the network vision scenarios for 2035 and 2045, the assumption has been made that the transmission link between Finland and Northern Norway (Finnmark) has been strengthened by a back-to-back DC station built by the Norwegian TSO and that there is a market limit of 150 megawatts in both directions between Finland and the NO4 bidding zone. This solution has previously been explored as part of the Nordic Grid Development Plan 2019[12]. The profitability of the solution has not been assessed separately in the network vision.

Increasing capacity to more than 150 megawatts would require the construction of a new transmission link from Finnmark to Finland and other technical solutions. On the other hand, based on the analyses carried out in the Nordic network plan, a 400 kV AC connection alone would not be feasible from a technical or market point of view. For reasons of voltage and stability, the capacity of the connection would remain low, the amount of electricity transmitted would be difficult to bring in line with the solution offered by the power exchange, and the risk of internal bottlenecks in Northern Norway would increase.[13]

If a reasonably-priced solution were found that would allow the market-based transmission of electricity from the hydropower-intensive southern areas of price area NO4 to Southern Finland, its economic benefits should be investigated further. Such a link would enable electricity to be traded between Norway's hydropower-intensive and Finland's (future) wind-power-intensive systems and provide connection opportunities for wind power in the Finnmark region of Norway (if any will be constructed). In Fingrid's understanding, making this possible would require a significant strengthening of the network in Norway and also in Finland, where the network would need to be strengthened all the way from Northern Lapland to Southern Finland. In addition to network strengthening, network solutions that direct the flow of power as desired between Northern Norway and Finland would also be needed. These could include, for example, a larger back-to-back link between Finland and Norway, a longer HVDC transmission link between Finland and Norway, one or more phase shifting transformers or controllable series compensators.

Figure 8 Illustration of the distance between the production hubs of bidding zone NO4 and Finland.



Due to the long distances, such a solution would probably be very costly. Understanding the costs and the operation of the link would require a highly detailed understanding of the electricity system in Northern Norway and the possibilities for strengthening the network in northern Norway. Therefore, the overall economic profitability of such a heavy-duty transmission link cannot be meaningfully examined in a report prepare solely by Fingrid.

[12] Nordic Grid Development Plan 2019 (NGDP 2019).
[13] NGDP 2019, s. 37

3.2.3 Estonia

Increasing transmission capacity between Finland and Estonia seems economically beneficial in 2035 in all scenarios and when the following assumptions are made:

1. Electricity consumption in the Baltic countries is expected to increase while electricity production based on fossil fuels will decrease.
2. The trade of electricity between the Baltic countries and Russia is assumed to end as the Baltic states synchronise with the Central European electricity system.
3. Although the production of renewable electricity in the Baltics is increasing, on an annual level the Baltic states are mostly net importers of electricity in the scenarios.
4. At the same time, the transmission capacity between Estonia and Latvia, Latvia and Lithuania and Lithuania and Poland, can also be strengthened at a reasonable cost.

The EstLink 3 connection and the confirmed transmission route through the Baltics have been taken into account in the market simulation and network calculations for all 2035 scenarios in the network vision.

At first, the connection would primarily be an export link from Finland to Estonia. This would allow a greater amount of wind power construction in Finland, which in turn would require strengthening of the network in Finland between wind power production areas and the starting point of the EstLink 3 on the south coast. In particular, the further construction of offshore wind power in the Baltics causes uncertainty in the assumptions, as even a single large 1,000 megawatt offshore wind farm would meet about half of Estonia's current electricity consumption and about one-sixth of the total electricity used by the Baltics. Consequently, even a single investment could have a significant impact on the market benefits of the link. In addition, the implementation of the Baltic Sea Offshore Grid would have a significant impact on the profitability of cross-border connections in the region. If the offshore grid were to become a reality, EstLink 3 could potentially be a part of it.

If EstLink 3 were to be implemented, the possibilities for a joint project that would at the same time strengthen the transmission capability through Finland, Estonia, Latvia, Lithuania and Poland should be investigated. Such a project would, of course, require that all TSOs in the region be interested in it. In practice, such a project could not be initiated until the Baltic synchronisation has taken place. By then, the factors affecting the profitability of EstLink 3 are likely to be known.

3.2.4 Russia

The Vyborg HVDC substation was commissioned for the most part in the 1980s and its modernisation will probably become topical during the period investigated in this document. Modernisation of the substation would improve the technical requirements for the transmission of electricity between Russia and Finland and would also provide the opportunity to increase transmission capacity from Finland to Russia (the present capacity is highly asymmetric). Since the HVDC substation to be modernised is located in Russia, Fingrid does not play a role in the decision, but builds and maintains the main grid on the Finnish side so that cross-border trade is possible. In addition to renewing grid property, more flexible rules would promote trade and be economically beneficial to Finland and Russia.

In the Power to Export and Climate-Neutral Growth scenarios, the transmission capacity between Finland and Russia was assumed to be confirmed as a two-way 1,300-megawatt HVDC transmission link by 2035. The Climate-Neutral Growth scenario also assumed that the current, very significant impact of the capacity payments on the Russian side on cross-border trade would be eliminated. Similarly, in the Windy Seas and Solar and Batteries scenarios, it was assumed that no electricity would be transmitted between Finland and Russia, as described in Chapter 2.

In the Power to Export scenario, electricity is also exported significantly from Finland to Russia. This contributes to an increase in the need for transmission and investment within Finland in the north-south direction, as Finland's production surplus is north of the Cross-section Central Finland. In the Climate-Neutral Growth scenario, electricity transmission varies greatly as capacity payments do not restrict trade. On the other hand, Russia is assumed to construct some wind power as well. There is no electricity trade between Russia and the Baltic states in the scenarios.

3.2.5 Summary of the cross-border connections

Figure 9 presents cross-border transmission capacities and Figure 10 transmissions through the Finnish cross-border connections in the different scenarios in 2035. The capacities are presented in megawatts. Transmissions are presented as annual energy (terawatt hours/year) in conditions corresponding to average inflow, wind and temperature. The weather conditions cause great hourly and annual variation on the cross-border transmissions.

Figure 9 Cross-border transmission capacities in the scenarios in 2035.

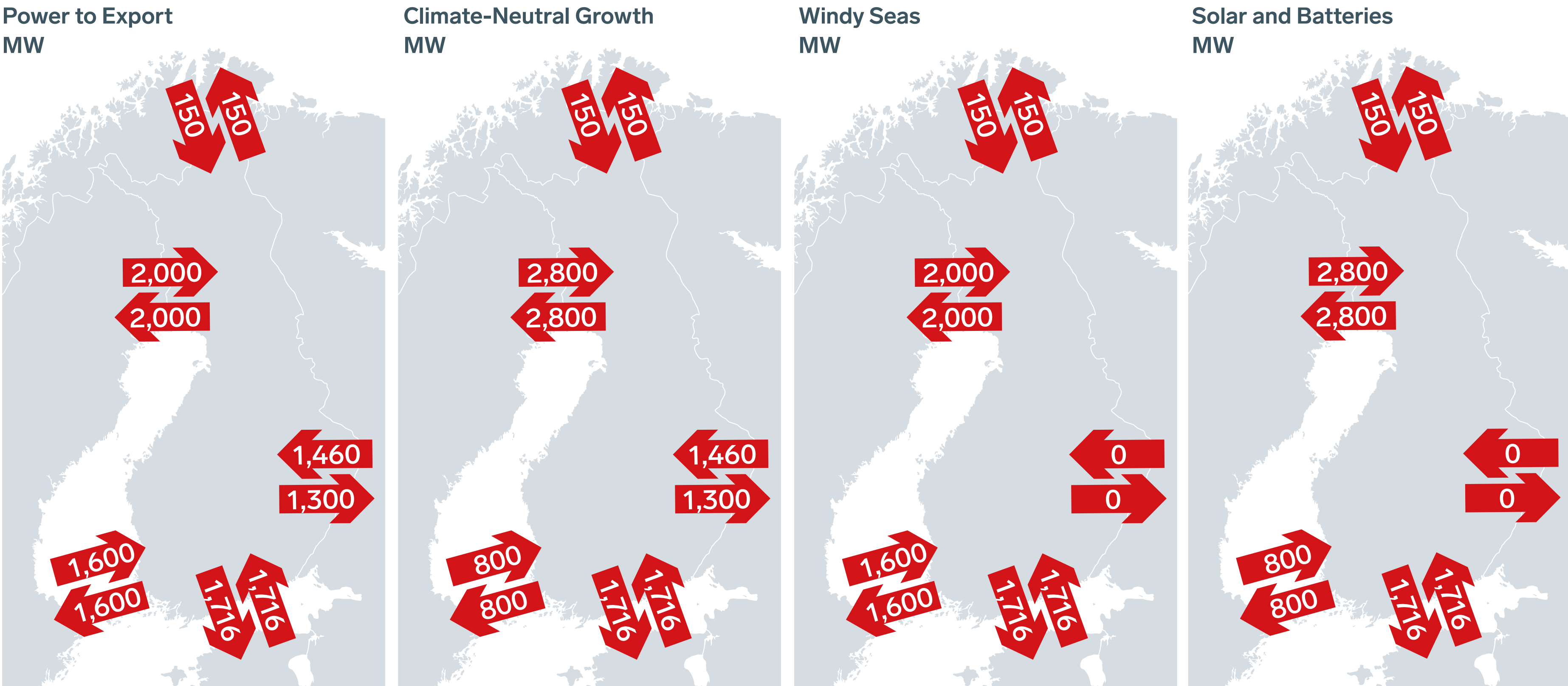
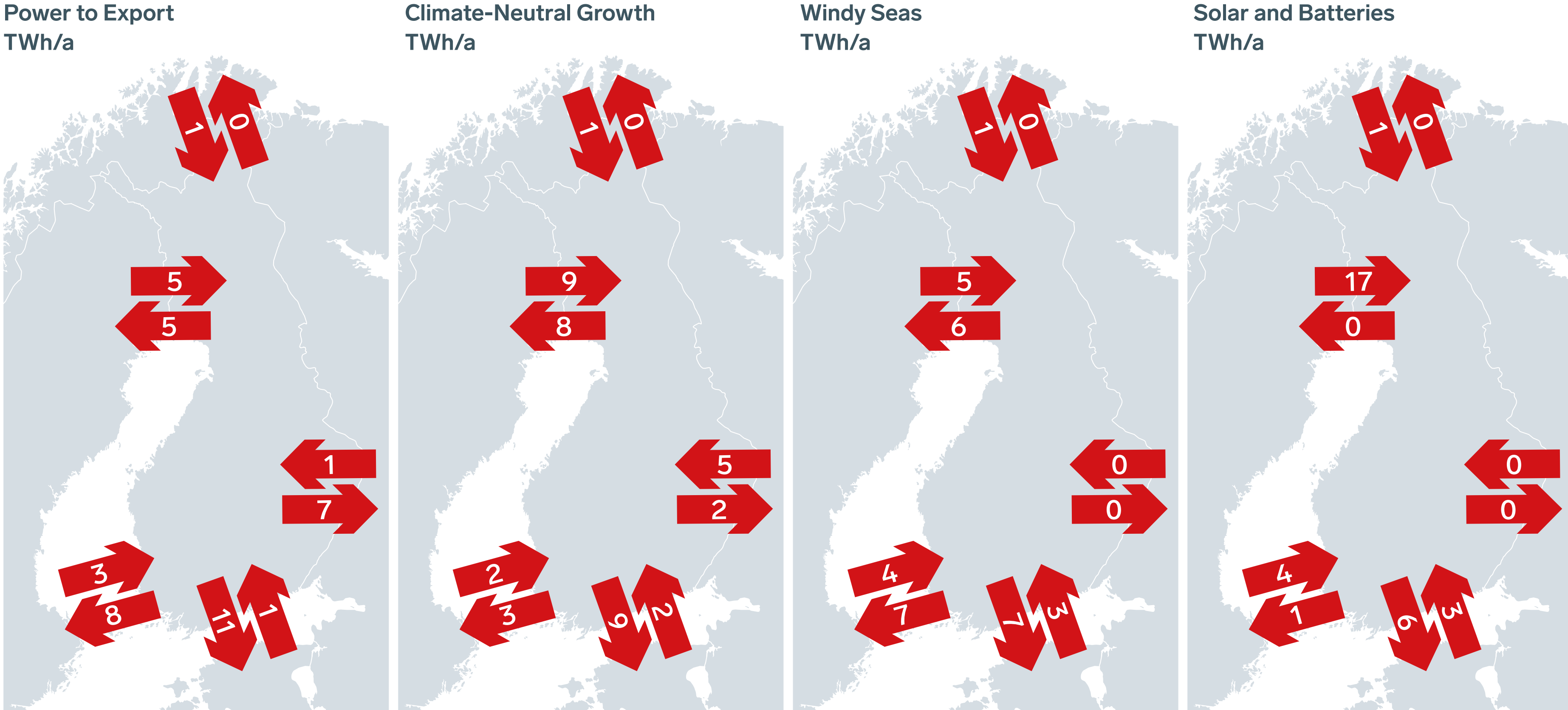


Figure 10 Cross-border transmissions in a accordance to average weather conditions in the scenarios in 2035.



Finland's electricity transmission with Northern Sweden (SE1) consists of high-volume imports in the Solar and Batteries scenario and is balanced in other scenarios. Transmission to central Sweden is export-oriented in the Power to Export and Windy Seas scenarios, balanced in the Climate-Neutral Growth scenario and import-intensive in the Solar and Batteries scenario. A more balanced net transmission than the present situation will allow for better use of links to balance production and consumption, which is important when there is a high level of variable production on both sides of the border.

Electricity transmission to Estonia is export-intensive in all scenarios. The export is highest in the Power to Export scenario and lowest in the Solar and Batteries scenario. The volume of exports to Estonia is affected by Finland's own surplus or deficit and the Baltic power balance.

Electricity transmission with Russia is export-intensive in the Power to Export scenario and import-oriented in the Climate-Neutral Growth scenario. In other scenarios, it was assumed that the possibility of electricity trade with Russia is eliminated if the Vyborg link is not modernised. In the Climate-Neutral Growth scenario, the net import is based on an assumption that Russia constructs wind power as well and capacity payments are eliminated from cross-border trade, bringing more variation into the cross-border transmissions.

4. Grid strengthening needs

4.1 The network calculation process

Market modelling assumes that there are no restrictions on transmission capability within Finland's bidding zone. In reality, however, the transmission capability of the physical transmission network is limited, which means that the results of the market simulation must be transmitted into a network calculation software for deeper analysis. For that purpose, a baseline model describing the situation in 2035 was created in the network calculation software, describing the current main grid, the 110 kV grid of the DSOs and the grid strengthenings in accordance with the 10-year development plan of the main grid. The baseline model also contains a rough description of wind power connections to the network by adding, among other things, the necessary 400/110 kV transformers. However, the wind power connections were not modelled in detail, nor are they presented in more detail in the network vision.

The common baseline model is used for creating simulated network operating situations for each hour of the year in each scenario, utilising the results of the market simulation. When the situation is analysed throughout the year, the challenges of each scenario can be discovered and solved by adding strengthenings on top of the baseline model. After a sufficient number of iteration rounds, a preliminary list is made of the grid strengthenings needed in each scenario in order to achieve sufficient system security and transmission capability.

4.2 Technologies and limitations used

The starting point for resolving the additional transmission needs identified in the scenarios was the addition of series-compensated 400 kV transmission lines across the main transmission cross-sections. All of these transmission line strengthenings are presented in the subchapters below. The need for parallel compensation has not been explored in detail in the network vision due to the local and scenario-dependent nature of the parallel compensation.

The assumption concerning the investigated network solutions was that the required amount of parallel compensation will be significantly higher than at present, but its exact amount or location was not specified. Another reason for excluding parallel compensation from this network vision is that its implementation is substantially faster than the construction of a transmission line. Now that the network vision has been created, Fingrid will start investigating the need for parallel compensation in more detail in 2021.

The aim was to design a cost-effective N–1 secure[14] power transmission grid in different scenarios. The modelling of the 2035 Windy Seas, Power to Export and Solar and Batteries scenarios achieved N–1 security in the main power transmission grid, but due to the enormous construction needs in the Climate-Neutral Growth scenario, the analysis focuses on finding the most essential strengthening needs instead of trying to make the grid completely N–1 secure. The most cost-effective way of increasing transmission capacity in order to achieve N–1 security might be demand-side management, which is particularly necessary in the Climate-Neutral Growth scenario. When analysing the network strengthenings presented in the network vision, please keep in mind that the assumptions made in the scenarios regarding the location of consumption and production have a strong impact on the strengthening proposals presented in the paragraphs below.

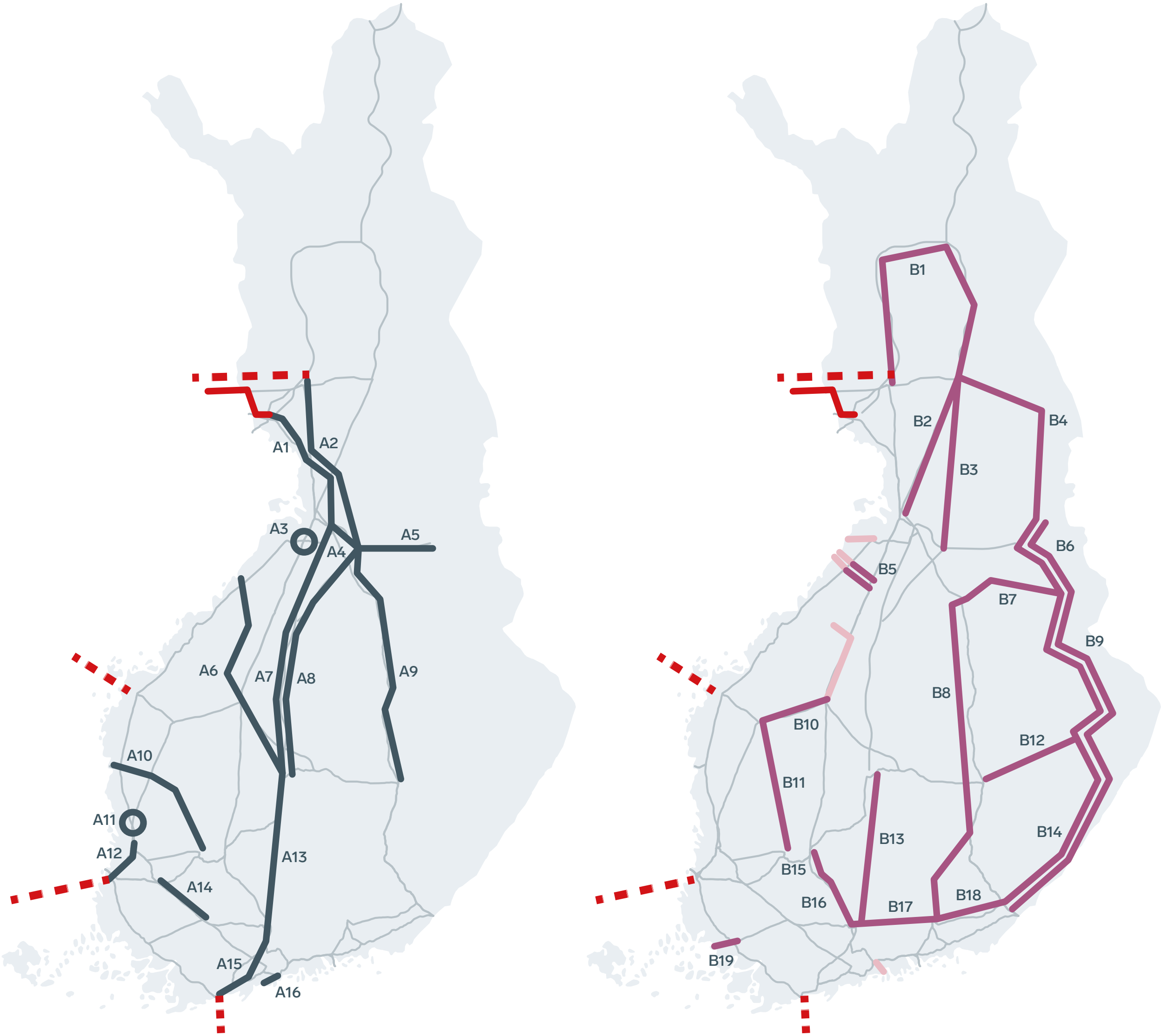
[14] N–1 security means that the system can withstand the usual individual defects and the disconnection of the failed component. N–0 security, on the other hand, describes that the system is durable in an intact state, i.e. before a failure.

4.3 Strengthenings of the main transmission network required by 2035

Network strengthenings were studied separately in each scenario, and the scenario-specific strengthenings are presented in Chapters 4.4 to 4.7. However, the different scenarios describe different development paths whose realisation cannot be fully predicted. This summary seeks to identify the strengthenings that serve as many different scenarios as possible.

Figure 11 shows an overview of the 2035 network strengthenings. The left figure shows the likely needed strengthenings. The right figure shows the strengthenings that are partially alternatives to each other and whose need depends on a specific development path. It should also be noted that the likely-to-be-needed lines shown in the left figure are not enough by themselves in any of the scenarios – all scenarios also require some of the line strengthenings shown in the right figure. The figures also show in red the cross-border connections included in the scenarios. The new lines shown in Figure 11 have not been examined from the perspective of route planning and land use. The lines shown on the map represent the need for lines between stations and might not correspond to actual line routes. The route planning of the new lines and more detailed network surveys will be carried out as the line projects progress.

Figure 11 An overview of the identified network strengthening needs for 2035. The line routes shown on the map representthe need for electricity transmission between stations and might not correspond to actual line routes.



Number	Line
A1	Pyhänselkä–Herva–Viitajärvi–RAC3
A2	Nuojuankangas–Herva–Petäjäskoski
A3	Implementation of line crossings in Northern Ostrobothnia
A4	Pyhänselkä–Nuojuankangas
A5	Nuojuankangas–Seitenoikea
A6	Jylkkä–Petäjävesi
A7	Forest Line 1 (under construction)
A8	Forest Line 2
A9	Lake Line 2
A10	Kristinestad–Melo
A11	Implementation of line crossings in Southern Ostrobothnia
A12	Rauma–Ulvila
A13	Petäjävesi–Hikiä
A14	Huittinen–Forssa 2
A15	Inkoo–Hikiä
A16	Helsinki 400 kV cable
B1	Ring connection in Lapland
B2	Pirttikoski–Pikkarala
B3	Pirttikoski–Nuojuankangas
B4	Pirttikoski–Kuusamo–Suomussalmi
B5	Hanhela–Lumijärvi (douple line)
B6	Suomussalmi–Seitenoikea–Kuhmo (douple line)
B7	Vuolijoki–Kajaani–Kuhmo
B8	Vuolijoki–Pieksämäki–Koria
B9	Kuhmo–Kontiolahti (douple line)
B10	Alajärvi–Seinäjoki
B11	Seinäjoki–Melo
B12	Huutokoski–Kontiolahti
B13	Petäjävesi–Hikiä 2
B14	Kontiolahti–Yllikkälä (douple line)
B15	Kangasala–Lavianvuori
B16	Lavianvuori–Hikiä
B17	Hikiä–Koria
B18	Koria–Yllikkälä
B19	Lieto–Naantalinsalmi

- Likely to be needed
- The need depends on a specific development/ The solutions are alternatives to each other
- Customer project
- Third 400 kV AC connection to Sweden
- A new connection is assumed in the scenario

In several scenarios, the necessary strengthenings can be divided into two groups: Those already present in the grid development plan 2019[15] and those that emerged as new needs in the network vision. The following internal line investment needs already presented in the development plan and described in the baseline model were discovered to be necessary also in the scenarios:

- Forest Line
- Lake Line 2
- Petäjävesi–Hikiä
- Second Huittinen–Forssa line
- Sweden–Viitajärvi–Herva–Pyhänselkä (RAC3)
- Petäjäskoski–Herva–Nuojuankangas
- Nuojuankangas–Seitenoikea
- Pyhänselkä–Nuojuankangas
- Helsinki Cable (Länsisalmi–Viikinmäki)

In addition to the above, the analysis revealed new investment needs in different parts of Finland. In the category of likely-to-be-needed connections, Forest Line 2 is needed to strengthen the north-south transmission. The line is intended to run from Nuojuankangas via Kinnula to Petäjävesi. The grid in Southern Finland should be strengthened with Rauma–Ulvila and Inkoo–Hikiä lines, especially if the new cross-border connections EstLink 3 and Fenno-Skan 3 included in the network calculations are implemented with the expected terminals. The implementation of the crossings with the existing Pikkarala and Ulvila lines is an inexpensive way to increase transmission capacity on the Coastal Line.

Transmitting electricity from the wind power farms that will be constructed on the west coast to the southern parts of the country creates a need for a Jylkkä–Toholampi–Petäjävesi connection. This connection is very likely to be needed already in the 2020s due to wind power farms that will be constructed on the west coast in the next few years. Further south in Ostrobothnia, transmitting the production surplus out of the area is likely to require a new line connection between Kristiinankaupunki and Nokia (Melo). The need for this connection is also likely to be realised already in the 2020s if the wind power capacity in the area grows as expected. In Southern Finland, it is likely that the Kangasala-Lavianvuori connection needs to be strengthened.

A large number of other important scenario-specific investment targets were also discovered and they are shown on the map in violet. The scenario-specific investment needs are discussed in subchapters 4.4.–4.7. Due to their scenario dependency, the line investments shown in violet will be investigated if certain scenario-specific triggers are met.

For example, the Pirttikoski–Pikkarala modernisation, Pirttikoski–Nuojuankangas, Vuolijoki–Pieksämäki, the second Petäjävesi–Hikiä line and Pieksämäki–Koria lines will become necessary if the north-south transmission increases even further.

If the continuous growth of wind power in Ostrobothnia and the offshore wind generated on the west coast are realised, the lines Seinäjoki–Melo, Seinäjoki–Alajärvi and Kangasala–Hikiä will become necessary.

If the radar challenges in Eastern Finland can be solved and a significant amount of wind power could thus be built in the area, the following projects will become necessary: Seitenoikea–Kuhmo–Kajaani–Vuolijoki, Pirttikoski–Kuusamo–Suomussalmi–Seitenoikea,

Kuhmo–Kontiolahti–Yllikkälä–Koria and Kontiolahti–Huutokoski. Some of these transmission corridors might require two 400 kV wires depending, for example, on the amount of production to be connected. If a significant amount of wind power is built in Lapland, a 400 kV ring connection will probably have to be built in Lapland.

In addition to the proposed line investment needs, dozens of new 400 kV transformers will be needed and parallel compensation capacity must be significantly increased from the present level. These needs have not been specifically examined in the network calculations, but an estimate of the scale of the corresponding investments has been included in the investment costs presented in Chapter 4.9.

[15] https://www.fingrid.fi/globalassets/dokumentit/fi/kantaverkko/kantaverkon-kehittaminen/kantaverkon_kehittamissuunnitelma-2019-2030.pdf

The new cross-border connections shown in the figure are the choices made in the different scenarios. The network calculations take into account the EstLink 3 connection in all scenarios, the Fenno-Skan 3 link in two scenarios and the RAC4 connection in two scenarios. The cross-border connections are discussed in more detail in Chapter 3.2.

4.4 Scenario-specific review: Windy Seas

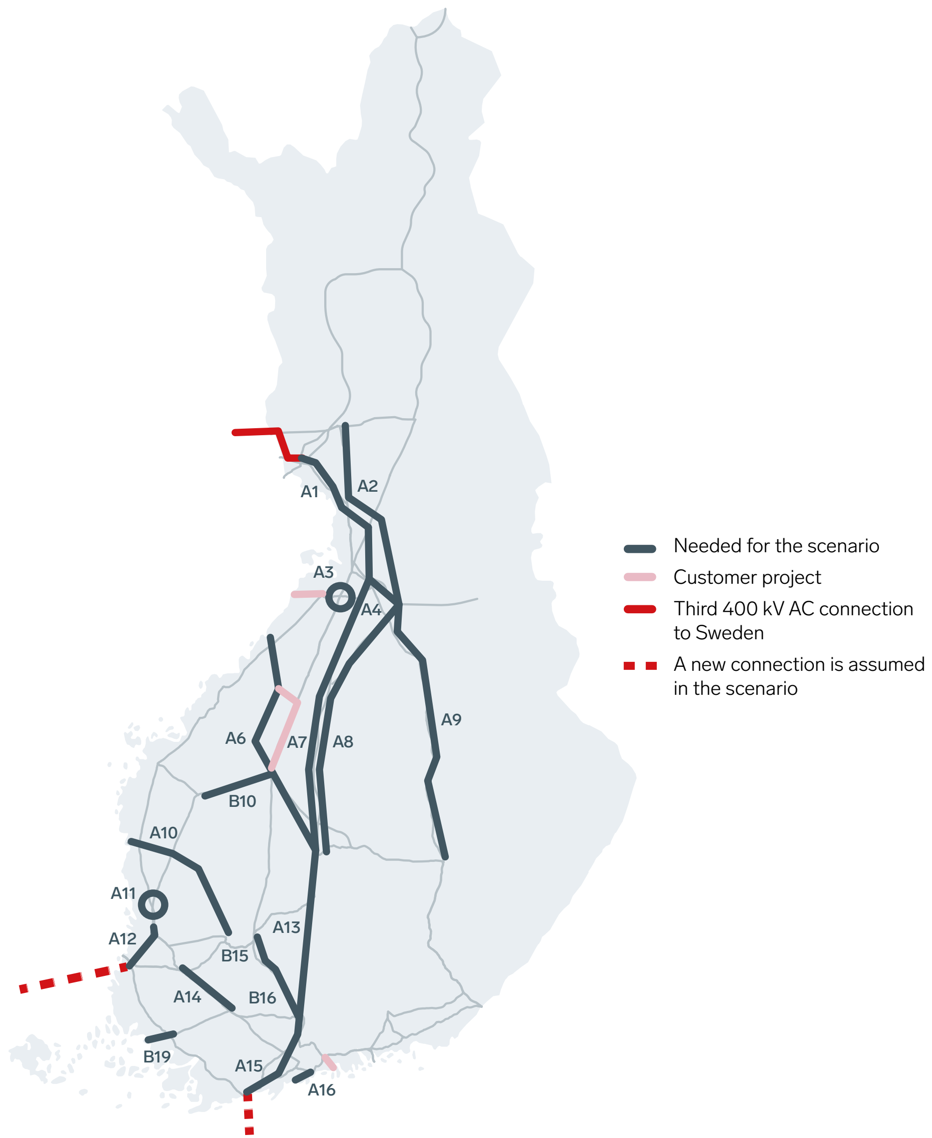
A special characteristic in the Windy Seas scenario – in addition to offshore wind power – is a large transmission volume from the west coast to the rest of Finland. The scenario also requires network strengthenings to enable the increasing north-south power transmission. Figure 12 below shows the proposed network solution for the scenario.

The network solution requires five 400 kV transmission lines for the Cross-section Kemi-Oulujoki (there were three lines in 2020). Eight 400 kV transmission lines are needed for the Cross-section Central Finland (there were four lines in 2020). These lines would allow for increased power transmission from north to south. Of the lines in the Cross-section Central Finland, especially the Jylkkä–Toholampi–Petäjävesi line would help in the west-east transmission necessitated by onshore and offshore wind power.

Ostrobothnia has a large surplus that needs to be transmitted out of the area. High-volume power transmission out of the area would become possible by the implementation of, and the Kristinestad–Melo and Seinäjoki–Alajärvi 400 kV line strengthenings as well as line crossings at the southern and northern borders of the area, which would increase the capacity of the Coastal Line. In addition, the Jylkkä–Toholampi–Petäjävesi line mentioned above would relieve pressure in the Northern Ostrobothnia region.

In the south, Rauma–Ulvila, Huittinen–Forssa and Kangasala–Lavianvuori–Hikiä 400 kV lines, among other things, enable an increase in west-east and north-south power transmission. The Petäjävesi–Hikiä and Hikiä–Inkoo 400 kV lines enable north-south transmission from the Oulujoki level to Southern Finland and further to the Baltic states via the Estlink 3 connection.

Figure 12 The investment need of the Windy Seas scenario in 2035.



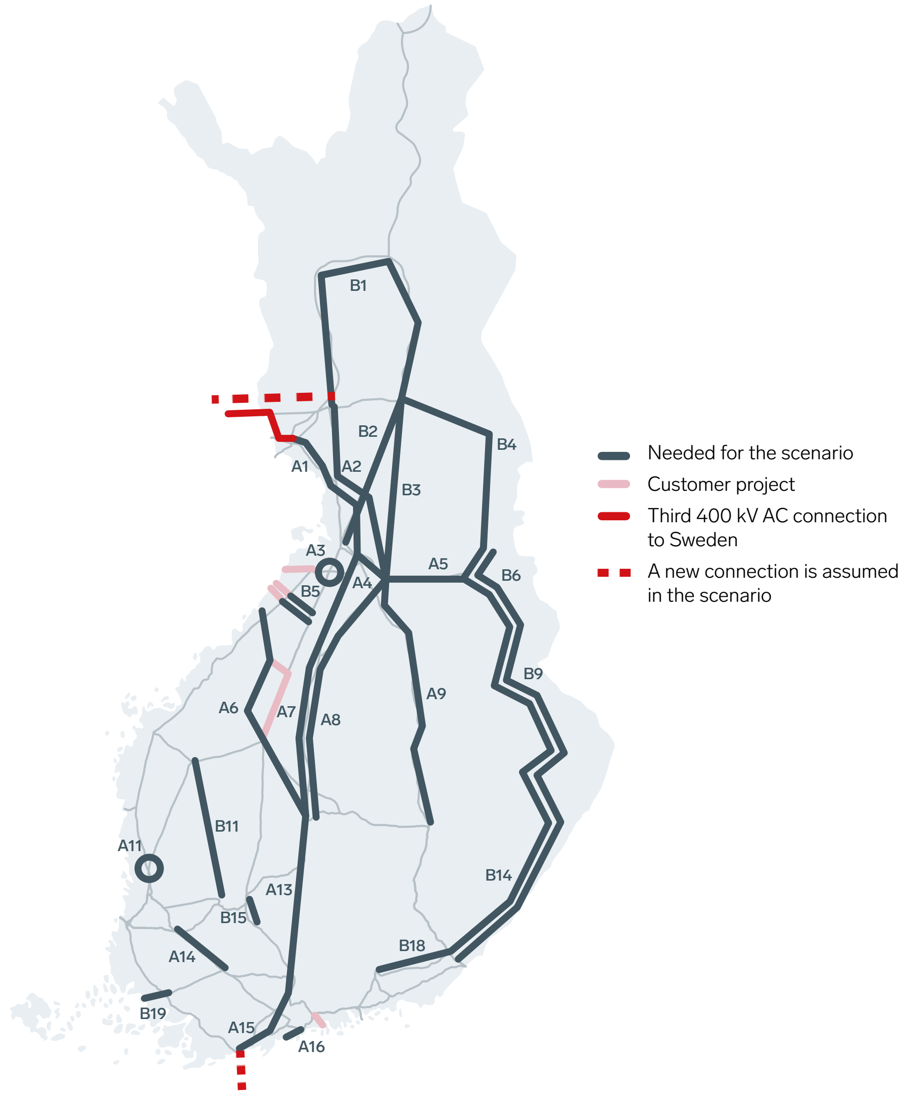
4.5 Scenario-specific review: Climate-Neutral Growth

The Climate-Neutral Growth scenario has a very large amount of new wind power and new consumption. Since these large investments in production and consumption are not located in the same area, they create a great pressure to increase transmission capacity. This represents a major challenge for additional construction of the grid so that the production and consumption structure presented in the scenario can be realised. The current operating models and technologies might not be enough for building a sufficient grid in all respects at this pace. Therefore, the solutions presented in this document focus on proposing a minimum technical solution that would achieve a maximum increase in transmission capacity while taking practical limits into account. The network solution thus contains the assumption that in the most difficult transmission situations the gird can be supported, for example, by utilizing Dynamic Line Rating technology that measures the loadability of lines in real time or by utilising production- or demand-side flexibility.

The investments needed in the Climate-Neutral Growth scenario are shown in Figure 13 below. To meet the needs of increased north-south transmission and wind power in Eastern Finland, new connections Pirttikoski–Nuojuankangas and Pirttikoski–Kuusamo-Suomussalmi were added as well as a Suomussalmi–Seitenoikea–Kuhmo–Kontiolahti–Yllikkälä dual line. In this scenario, it was better for the grid not to connect Kajaani and Kuhmo, as the dual circuit in the east is sufficient for the needs of the grid. In order to increase wind power in Lapland, a 400 kilovolt ring connection was built in Lapland, running along the existing 220 kV line route.

The Jylkkä–Toholampi–Petäjävesi and Seinäjoki–Melo connections were highlighted as other internal strengthenings necessary for the wind power on the west coast. In addition, a third Pysäysperä–Petäjävesi line also appeared useful in the scenario, but three parallel 400 kV lines would be very challenging in terms of land use, so that line was excluded in the solutions of this scenario. The scenario assumes that the new RAC AC connections RAC3 and RAC4 are built between northern Sweden and Finland, as well as a third HVDC transmission link from Inkoo between Estonia and Finland.

Figure 13 Investment needs for 2035 required by the Climate-Neutral Growth scenario.



4.6 Scenario-specific review: Solar and Batteries

Based on the market simulation of the Solar and Batteries scenario, Finland's balance is clearly in deficit and the biggest network strengthening need is in the north-south capacity of the grid, all the way from the Swedish land border to Inkoo. Figure 14 below shows the grid solution for the scenario. The scenario assumes that the new RAC AC connections RAC3 and RAC4 are built between northern Sweden and Finland, and a third HVDC transmission link is built from Inkoo between Estonia and Finland.

The challenges of the scenario are similar to the current situation, so the already planned grid strengthenings were included in the baseline model as they are well-suited to the scenario and increase the transmission capacity efficiently. More capacity is nevertheless needed, and network simulations indicate that at least the following strengthenings are necessary: Forest Line 2, Petäjävesi–Hikiä's second circuit and Inkoo–Hikiä connections. Other detected strengthening needs are for the Rauma–Ulvila connection and the modernisation of the Hirvisuo series capacitor. A particular characteristic of this scenario is that ensuring enough inertia might pose challenges for operational performance. Inertia is discussed in Chapter 5.3.

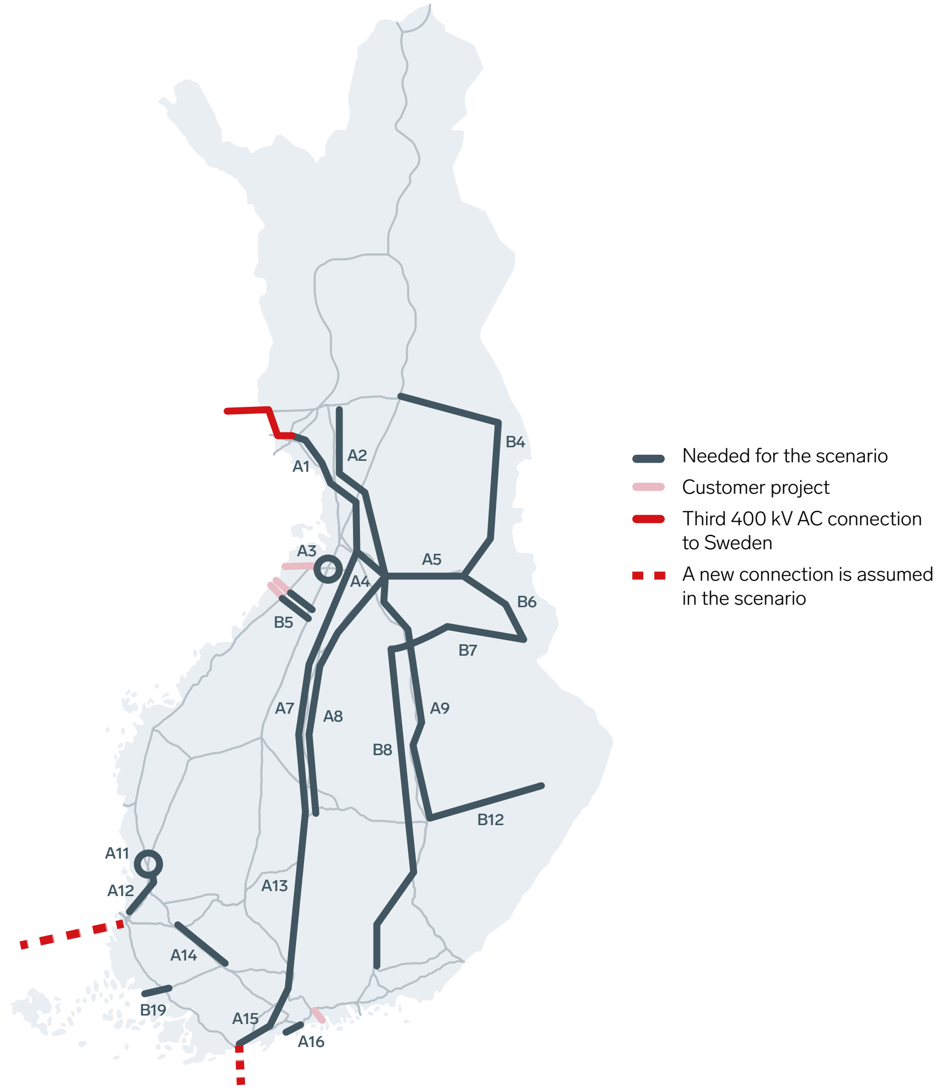
Figure 14 Investment need in the Solar and Batteries scenario.

4.7 Scenario-specific review: Power to Export

The Power to Export scenario highlights the need for network strengthenings necessitated by a significant increase in wind power production in Eastern and Northern Finland: The surplus production in the area is collected and transmitted to other areas by the Pirttikoski–Kemijärvi, Pirttikoski–Maaninkavaara–Kuusamo–Suomussalmi–Seitenoikea, Seitenoikea–Kuhmo–Kajaani–Vuolijoki and Kontiolahti–Huutokoski lines. The need to increase the north-south transmission capacity is present in all scenarios. In the Power to Export scenario, this manifests itself as the construction of the Forest Line 2 and Vuolijoki-Pieksämäki-Koria connections. The investment needs in the Power to Export scenario are shown below in Figure 15.

To ensure the transmission capacity of the new cross-border connections Fenno-Skan 3 and Estlink 3, constriction of Rauma–Ulvila and Inkoo–Hikiä connections is needed. To utilise the full capacity of the Coastal Line, crossings are needed at its southern and northern ends. In addition, the nominal current of the Hirvisuo series capacitor must be increased.

Figure 15 Investment needs in the Power to Export scenario.



4.8 Strengthening the main grid after 2035

Due to the uncertainty of future network solutions, the solutions for 2045 were examined on the basis of the 2035 solutions and simulated transmission needs across the main transmission cross-sections. Figures 16 and 17 show the duration of the transmission needs across Finland's main cross-sections in different scenarios. The 2035 transmission needs of the Climate-Neutral Growth scenario are mostly greater or equal to the transmission needs of other scenarios in 2045. This suggests that the network solution presented for the Climate-Neutral Growth scenario for 2035 indicates the solutions needed in other scenarios in 2045.

However, if the future develops in the direction of the Climate-Neutral Growth scenario, it is critical that the main grid in 2045 be significantly broader and stronger than it is now. A significant challenge might also arise in the world of the Windy Seas scenario, for example if 20 gigawatts of offshore wind power is built in Finland. The transmission need of this scenario cannot be seen directly from the curves above depicting the transmission need through the Cross-section Central Finland and Cross-section Kemi-Oulujoki.

Alternatively, energy transmission would be not carried out solely as electricity. Instead, a significant portion of energy transmission in Finland would take place in gas pipelines, for example. This way, electrolysers could be placed close to electricity generation and the produced hydrogen could be transferred to the end users in the pipeline. The third option is to manage bottlenecks in the power grid by taking advantage of local flexibilities available on the market, such as heat storages for heating that is becoming increasingly electric, storing electricity in battery storage power plants and electric cars, or carbon-neutral peak power.

Since the current standard solutions will not be enough in all of the scenarios even in 2035, the most ambitious scenarios for energy exports require that new solutions must be widely in place shortly after 2035. That

Figure 16 Transmission need in the Cross-section Central Finland in different scenarios in 2035 and 2045.

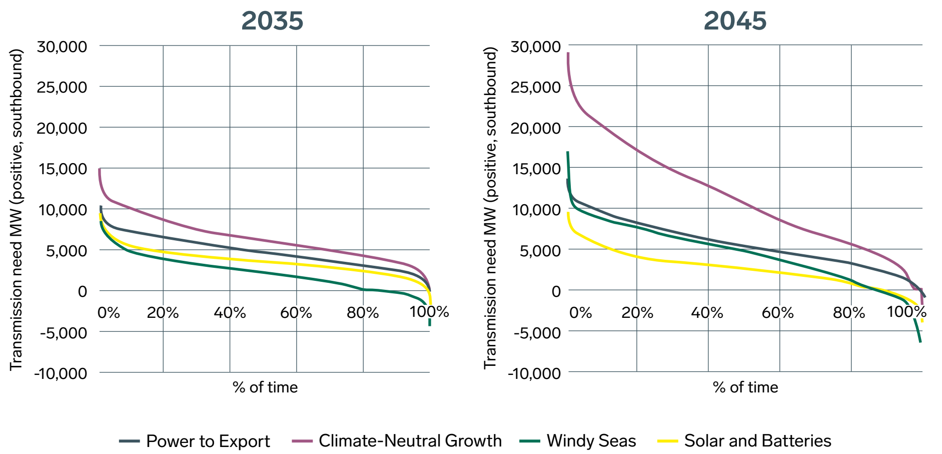
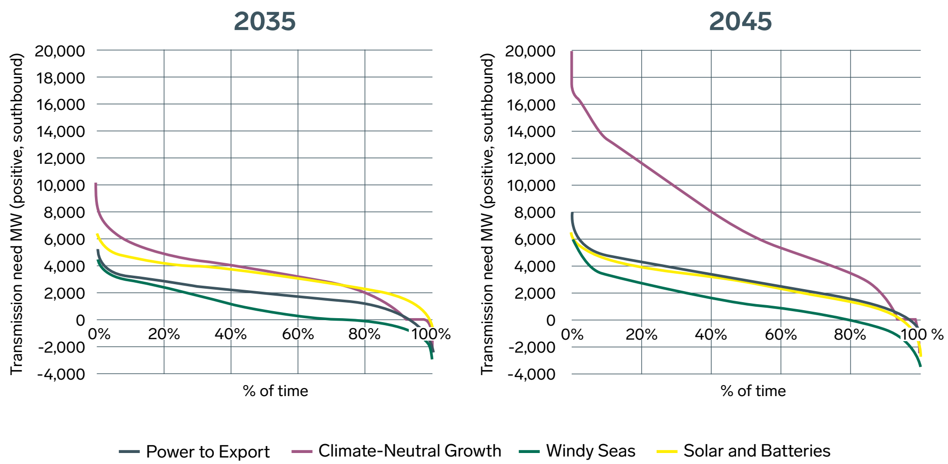


Figure 17 Transmission need in the Cross-section Kemi-Oulujoki in different scenarios in 2035 and 2045.

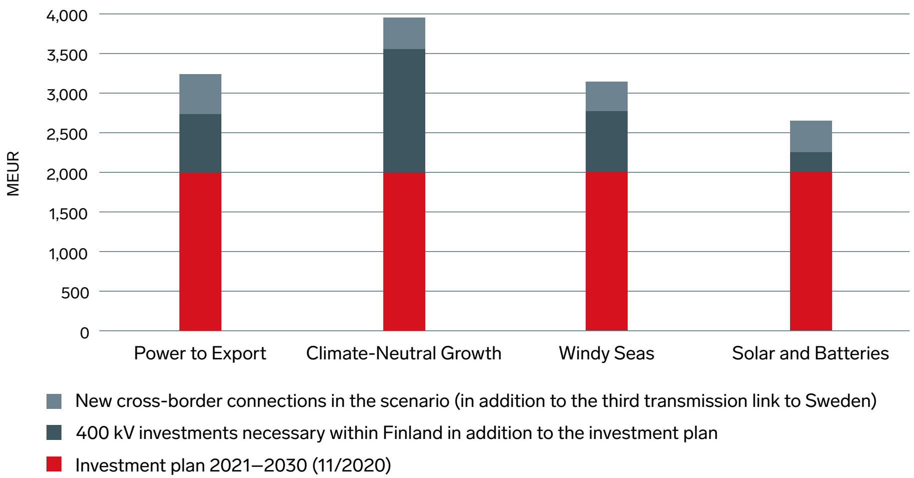


is why, in the near future, we will have to investigate not only traditional transmission line investments, but also entirely new technical solutions. The identified potential solutions that require further investigation include the benefits of DLR technology, the implementation of transmission line crossings in the main power transmission grid, using a voltage of 750 kV, dual 400 kV circuits and new conductors such as 4-Finch conductors. Unifying parallel and series compensation solutions would speed up their implementation. The possible use of HVDC transmission links within Finland would require broader investigation.

4.9 Investment costs

Figure 18 presents an estimate of the magnitude of the investment costs required by the network strengthenings in each scenario by 2035. The 110 kV network is not included in the figures, except for the solutions described in the investment plan for 2021–2030[16] published on 26 November 2020. Likewise for the 400 kV network, the estimate is indicative and contains uncertainties,

Figure 18 Estimate of the magnitude[17] of grid investment needs in different scenarios in 2021–2035.

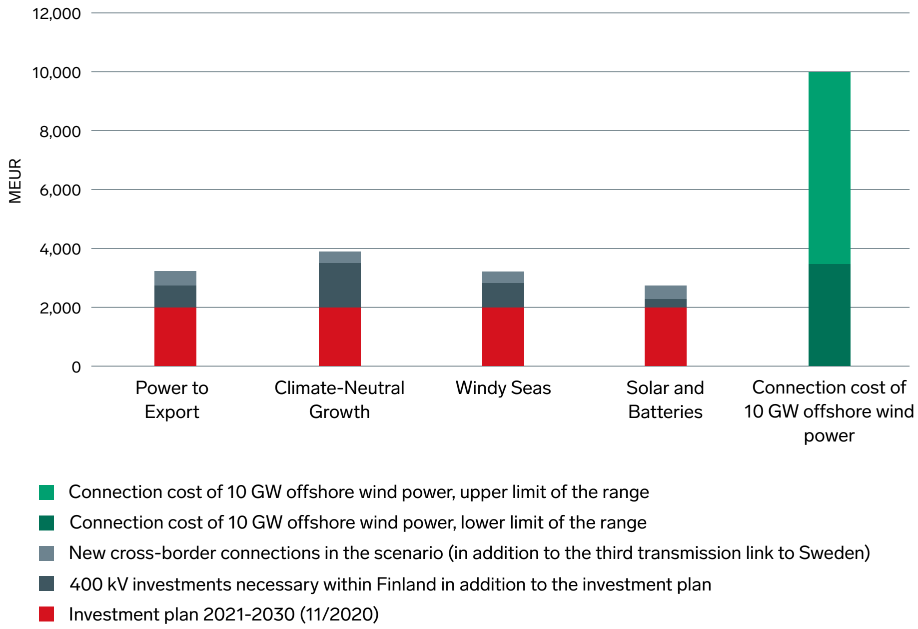


for example with regard to the development of unit costs and, in particular, the magnitude of investments in compensation and transformation capacity.

The amount of investments needed, in addition to the approximately EUR 2 billion investment plan for 2021–2030 that was updated in November 2020, ranges from the approximately EUR 600 million in the Solar and Batteries scenario to approximately EUR 2 billion in the Climate-Neutral Growth scenario. The share of the cross-border connection potentially implemented in the 2030s would be EUR 400–500 million if the EstLink 3 and either the fourth AC connection or Fenno-Skan 3 were implemented and their investment costs were divided equally among the TSOs. The impact of the investments on the unit price of the main grid tariff is mitigated by the significant increase in electricity consumption expected in the scenarios.

If offshore wind requires extending the grid to the sea[18], the investment costs would increase substantially. This impact has been investigated in the Windy Seas scenario in which the amount of offshore wind in Finland was 10 gigawatts in 2035. Connecting such an amount requires sea connections from the sea to shore. The connecting costs of offshore wind depend heavily on the distance between the wind farm and the mainland as well as on the technology used. If the costs of the transmission infrastructure totalled between EUR 350 and EUR 1000/kW, the investments required for 10 gigawatts would be between EUR 3.5 billion and EUR 10 billion, i.e. the development costs of the main grid would at least double, if not increase by greater multiples (Figure 19). The cost range has been calculated on the basis of reports from the North Sea Wind Power Hub consortium[19], the Danish Energy Agency[20] and DNVGL[21], and with an assumption that the wind farms are located about 30–100 kilometres off the coast. Such additional investments would have a significant impact on both the main grid tariff and Fingrid's ability to carry out other development projects in the main grid.

Figure 19 The investment needs of the main grid in different scenarios in 2021–2035 compared to the connection cost of 10 GW of offshore wind power.



[16] https://www.fingrid.fi/sivut/ajankohtaista/tiedotteet/2020/fingrid-investoi-kantaverkkoon-ennatykselliset-kaksi-miljardia-euroa/

[17] The estimate includes the investment plan 2021–2030, the necessary replacement investments by 2035 and the investments in the 400 kV network needed from the perspective of the main transmission grid. The costs presented do not include those costs of the 110 kV investments and the potential 400 kV investments arising out of regional needs that are in excess of the costs presented in the 2021–2030 investment plan.

[18] Expansion of the main grid to the sea refers to a situation in which Fingrid were made responsible for developing and building the offshore connection and transmission cables, substations and possible HVDC systems.

[19] https://northseawindpowerhub.eu/wp-content/uploads/2019/07/Cost-Evaluation-of-North-Sea-Offshore-Wind-1.pdf

[20] Danish Energy Agency & Energinet.dk. Technology Data generation of electricity and district heating p. 241–245.

[21] https://www.tennet.eu/fileadmin/user_upload/Company/News/Dutch/2019/20190624_DNV_GL_Comparison_Offshore_Transmission_update_French_projects.pdf

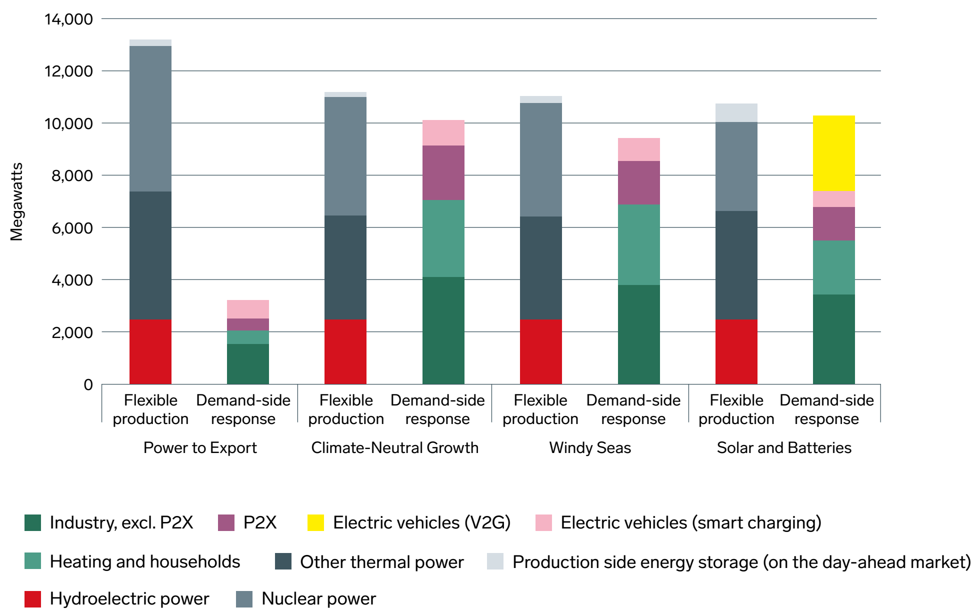
5. Separate questions

5.1 Flexibility

The traditional way of thinking about the electricity system is that flexible generation of electricity smooths out the variation in electricity consumption. In the past, necessary flexibility has been afforded by hydroelectric power or power generated by burning biomass or fossil fuels. As the energy revolution progresses, new production corresponding to the growth in electricity consumption will be mainly weather-dependent wind and solar power, which will increase variability in the electricity system. In addition, as electricity production based on fossil fuels exits, a significant part of traditional flexible production will no longer be available. As a result of these changes, production of electricity alone will no longer smooth out variations in consumption. Instead, flexible resources consisting of both the production and consumption side will smooth out the variation in production and consumption. This market-driven approach ensures that flexibility comes from sources that can produce it the cheapest.

In the network vision scenarios, the flexible resources of the Finnish system consist of both flexible production (hydro power, batteries and a part of bio-based electricity generation) as well as consumption (Power-to-X, flexible industrial processes, data centres, electric cars and heating of buildings). Demand-side response in particular is expected to increase, as economic conditions for it improve thanks to increasingly affordable technology and increase in the variable generation of electricity. Figure 20 presents the amount of controllable electricity generation and flexible consumption available during peak consumption in different scenarios. The figure presents demand-side response compared to a situation in which consumption does not react to the market price. Available flexibility reflects the maximum potential and does not take into account, for example, power plant failures or energy constraints in flexible consumption that acts as an electricity storage facility. For example, intelligent charging of electric cars depends on the car owners' mobility needs and the flexibility of Power-to-X processes depends on the existence, volume and fill level of a hydrogen storage. Flexibility available from electric heating requires, especially in long-term use, an alternative heat source, which, on the other hand, is not available on a large scale in summer when the heating needs are lower. Utilising flexibility requires a functioning flexibility market that allows for the most cost-effective and, when necessary, geographically targeted management of flexibility for each situation.

Figure 20 Weather independent production capacity available during a consumption peak and the demand-side response capacity in the different scenarios. The calculation of flexibility in consumption has been compared to a situation where consumption is not flexible at all.



As district heating becomes increasingly electrified, flexibility gained from the integration of electricity and heat has been estimated to increase significantly. The demand-side management of households is expected to increase somewhat. Intelligent charging of electric cars is expected to provide significant flexibility, in particular by concentrating the charging of cars on low-price hours. As for electric cars, the assumption is that, on average, approximately 30 kWh of the battery capacity of a passenger car is covered by smart charging at an average charging power of 6 kilowatts. In the Climate-Neutral Growth and Windy Seas scenarios, this means a concurrent charging power potential of more than 7 gigawatts in 2035 and approximately 35—40 gigawatt-hours of grid energy storage potential. The utilization of Vehicle-to-Grid technology assumed in the Solar and Batteries scenario adds nearly three gigawatts of power supply towards the grid, when the assumption is that half of smart-charged cars have a Vehicle-to-Grid option.

According to Finnish Energy's low-carbon roadmap[22], 100% of data centre consumption and 25% of the consumption of electrified industrial processes is estimated to be flexible. The flexibility of traditional industry is estimated to remain at the present level or increase a little in the scenarios. Power-to-X production has been estimated to be flexible, taking into account the constraints of hydrogen storage. Processes that are end users of hydrogen are assumed to be inflexible, so the prerequisite for flexibility is that there is a sufficient amount of hydrogen in stock. Electrolysers are assumed to be rated to an average utilisation rate of 50% in order to allocate hydrogen production (as far as allowed by storage) to hours of low-cost electricity.

Due to uncertainties about the flexibility of Power-to-X and future charging practices for electric cars, the Climate-Neutral Growth scenario was subjected to a sensitivity analysis in which both of these consumption categories were assumed to be completely inflexible. Such a scenario requires significantly more electricity storage and transmission or peak power capacity in order to avoid, for example, power deficit situations and to make the scenario viable as a whole. On the other hand, the change had only a minor impact on the transmission needs within Finland. Wind power in Northern Finland plays a significant role in the transmission situations that determine the magnitude of north-south transmissions in Finland. On the other hand, electricity consumption in Southern Finland, export of electricity and the charging of grid electricity storages are also high — regardless of whether the storages are electric cars, batteries/other storages or Power-to-X. In this case, the need for transmission might be even higher if there is a lot of flexibility from consumption and storage in the electricity system, which means that the production peaks of wind power can be fully utilised. If the consumption is not flexible, some wind turbines will have to be stopped in peak situations as electricity prices fall to zero. In this case, transmissions in the main grid will be reduced if production and consumption are geographically far apart.

Therefore, from the perspective of network strengthening it does not matter very much which proportion of flexibility comes from production, consumption or storages. However, there must be a sufficient amount of flexibility: it makes no sense to plan the network according to a situation in which society has a significant risk of lack of capacity in the long term. Such a scenario is not realistic, since price controls investments and the technologies that produce flexibility in the most affordable way will take advantage of the resulting business opportunity. For more information on the sufficiency of power, see Chapter 5.2.

[22] https://energia.fi/files/5064/Taustaraportti_-_Finnish_Energy_Low_carbon_roadmap.pdf

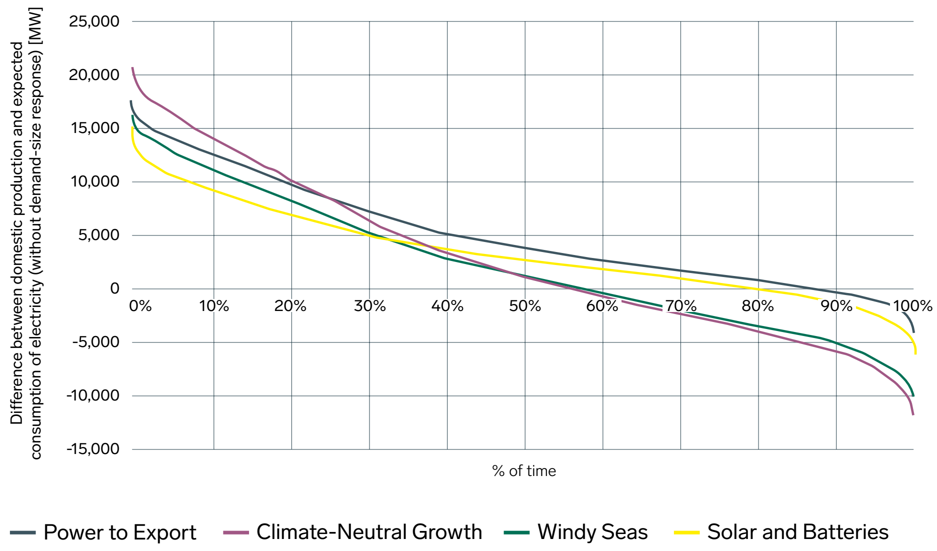
5.2 Power adequacy analyses

The method used for analysing power sufficiency in the network vision is based on a Monte Carlo simulation performed on an electricity market modelling tool. In the Monte Carlo simulation, the random variables are weather-dependent forms of electricity generation, electricity consumption, demand-side response and occasional failures of power plants and transmission connections in each hour of the year investigated. Weather-dependent electricity production refers to solar and wind power, electricity production associated with the production of district heating as well as hydroelectric power, which is dependent on longer-term weather phenomena.

Power sufficiency simulations were performed for each hour of each year reviewed in each scenario. The simulations did not reveal any power shortages in any scenario in either review year. The assumptions of the scenarios, i.e. the flexibility of new consumption of electricity and the free formation of the price of electricity, are key to power sufficiency. The flexibility capacities in the simulations were sufficient in terms of power, and the energy restrictions of the flexibilities were not encountered. It is assumed that signals from electricity prices will guide flexibility on market terms even in the longer term. The assumptions on demand-side management in the scenarios are discussed in more detail in Chapter 5.1. The amount of demand-side management required by power sufficiency can be estimated in more detail by examining Finland's electricity balance in terms of available production and expected consumption in each hour of the year.

The safety margins for power sufficiency were studied by examining a situation similar to a cold year, where temperature-dependent electricity consumption is high in winter. The following looks at what a situation similar to 1987, the coldest year in recent history, would look like in the scenarios of this network vision in the future. The analysis calculated Finland's power balance without demand-side management for each hour of the year. This refers to available domestic production when domestic consumption has been subtracted from it, assuming that consumption is not flexible at all. Figure 21 presents the duration curve of the power balance in the different scenarios in 2035. The availability of wind and solar power, which vary according to weather, has been calculated in accordance with the prevailing weather conditions for each hour.

Figure 21 Duration curves for Finland's internal power balance without demand-side response in 2035. When the power balance is negative, Finland needs electricity imports and flexibility/peak power; when the balance is positive, electricity can be exported and flexible storages replenished. The figure shows simulation results for a year with a very cold winter.

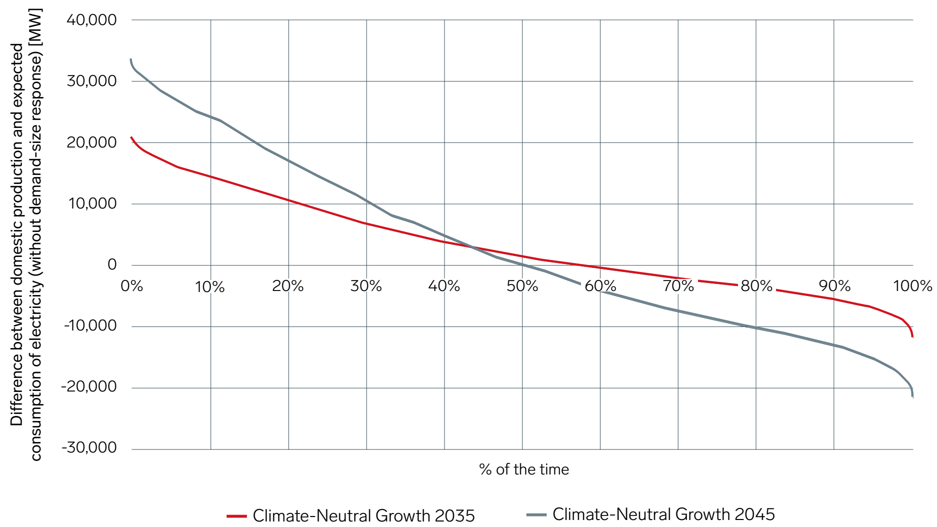


By looking at the duration curves of the power balance, we can see how much and what proportion of the time the electricity generation in the scenarios cannot meet consumption if consumption is not flexible at all. Some 5000–7000 megawatts of the power deficit can theoretically be covered by cross-border connections, assuming that all transmission capacity is available and electricity is available from neighbouring countries. Taking the border transmission capacity into account when looking at a cold year 2035 from the perspective of power sufficiency, demand-side management would not be needed at all in the Power to Export scenario, and very little of it would be needed in the Solar and Batteries scenario. In the Climate-Neutral Growth and Windy Seas scenarios, the required flexibility capacity of electricity consumption would be approximately 5,000–6,000 megawatts to avoid power shortages in 2035.

The differences between scenarios are mainly caused by total electricity consumption and, in particular, the assumptions about the electrification of heating. In the Climate-Neutral Growth and Windy Seas scenarios, the heating of buildings is electrified strongly, which causes consumption spikes to increase. The strongly growing consumption of electricity needs a considerable amount of flexible resources when there is an abundance of weather-dependent electricity generation in the system. The need for flexible resources will increase over time as electricity consumption increases and traditional fossil-based production capacity is removed from the system, resulting in greater demand for flexibility in 2045 than in 2035. Figure 22 illustrates this development in the Climate-Neutral Growth scenario.

Flexibility of new electricity consumption is essential for power sufficiency, especially in the Climate-Neutral Growth scenario in 2045. Moving further into the future in the scenario, there will be a decreasing trend in traditional fossil-based production and an increasing trend in weather-dependent renewable energy production and more flexible consumption in the system. This will significantly increase the magnitude of the required flexible capacity and the number of hours that need flexibility during a year.

Figure 22 Duration curves for Finland's internal power balance without demand-side response in 2035 and 2045 in the Climate-Neutral Growth scenario. When the power balance is negative, Finland needs electricity imports and potential flexibility; when the balance is positive, electricity can be exported and flexible storages replenished. The figure shows simulation results for a year with a very cold winter.



5.3 Operational performance aspects

The future described in the different scenarios of the network vision might bring challenges not only to the transmission capability of the electricity system, but also to its operational performance. While detailed operational performance investigations were excluded from this vision, we wish to point out that when preparing line investments, provisions should also be made for an increase in the need to compensate reactive power, a reduction in inertia and possible increases in fault current, and, on the other hand, greater variability, as the decrease of synchronous machines and the increase in power-park module production will reduce future minimum fault currents.

The transmission capacity of the main grid has been increased by series compensation of the Swedish cross-border connection and long north-south connections, which has successfully increased the natural power of the lines and thus cost-effectively increased the transmission capacity. In the future, as the scenarios are realised, also the southern lines will be running on considerably higher power levels than natural from time to time (consuming more reactive power than they produce), thus increasing the need for reactive power production. However, series compensation is not suitable for the southern parts of the main grid, which is strongly meshed and where transmission lines are shorter. Therefore, the reactive power must be produced by parallel compensation. Parallel compensation is also a cost-effective way of increasing transmission capacity when voltage stability limits transmission capacity. Parallel compensation equipment are needed on several substations south of the Cross-section Central Finland. Parallel compensation can be implemented by switchable installations when they are used for controlling the so-called steady-state voltage and by dynamic compensators (SVC, STATCOM, synchronous compensators) when they are needed to control the voltage in changes of state. Fingrid is planning the compensation of reactive power in more detail as follow-up work to the network vision.

Inertia refers to the ability of the system to resist changes in frequency thanks to energy stored in the rotating masses of the electrical system, such as the rotating machines of synchronous machine power plants. The transition of electricity generation from conventional synchronous machine power plants to power park modules like wind and solar power plants, will lead to a reduction in the inertia of the power system, despite an increase in electricity production and consumption in the scenarios. It is evident that in order to safeguard the stability of the power system in the future, the system needs to develop and utilise characteristics and capabilities of power park modules and the rapid flexibility of loads.

In order to identify the additional resources needed, it is particularly useful to look at the minimum inertia level of the entire Nordic synchronous system. The results of this visioning work do not produce a direct estimate of this, since only the Finnish network was described in the power system simulations. Fingrid is investigating the inertia-related questions in cooperation with the other Nordic TSOs.

As for fault currents, a significant strengthening of the transmission system with new substations and transformers will increase fault currents in the main grid. The management of short circuits and hazard voltage levels in the existing network might require changes in the scope and network topology of switchgears. On the other hand, in some situations there may be very few synchronous machines in the network, which means that short circuit power levels might decrease significantly from the present levels. For example, power electronic devices, such as HVDC transmission links, require the network to have a sufficient short circuit power level. This can be achieved by synchronous machines or synchronous compensators intended for compensation use.

5.4 Long-term potential of power exports

The consumption of energy produced in a climate-neutral way will increase significantly in Europe over the next 30 years. Compared to many other European countries, Finland has excellent potential to produce large quantities of clean and affordable electricity, especially wind power. The utilisation rate of Finland's wind resources has a significant impact on the development needs of the main grid. The export potential has been examined on three levels in the network vision: power exports, exports of e-fuels and exports of electricity-intensive industrial products.

1. **Finland as an exporter of electricity.** This development path would require significant additional construction of electricity transmission connections from Finland to Central Europe. The potential options are either building connections to neighbouring countries (Sweden and Estonia) or direct submarine cable connections from Finland to Poland/Germany. The former option would require that other TSOs strengthen their networks (SE3—SE4—Germany, Estonia—Latvia—Lithuania—Poland). It is unclear whether the neighbouring countries would be in a position to carry out these strengthenings quickly enough and, in any case, export of electricity would depend on the completion and timetable of the strengthenings carried out by the other TSOs. Direct submarine cable connections to Central Europe, on the other hand, would be very expensive (a conservative estimate is several billion euros per connection), which would significantly increase the cost of the transmission and reduce the competitive advantage of Finnish power production. In addition, the end points of the connections would be on the southern coast of the Baltic Sea, which has a surplus of electricity, necessitating the transmission of the electricity significantly further southward to consumption concentrations that experience deficits. As a result, bottlenecks inside the Central European countries would create a significant risk for the economic benefits of the transmission connections.

   Cross-border connections with neighbouring countries also of interest for reasons other than export (such as flexibility and sufficiency of electric power), so they should be promoted in any case. Direct transmission links with Central Europe cannot be categorically excluded at this stage, but the associated high investment costs and risks do not make them attractive when other alternatives exist.

2. **Finland as an exporter of e-fuels.** This refers to a development path in which large quantities of climate-neutral fuels are produced in Finland. The fuels might be gaseous (hydrogen, synthetic methane) or liquid (synthetic petrol, diesel, kerosene, methanol, etc.). A common feature of products is that they are used specifically as fuel in the destination country (e.g. in transport, industrial processes or heating), but their production manifests itself in Finland as electricity consumption. A part of the process is producing hydrogen in electrolysers. If hydrogen is not the final product, a carbon dioxide source is needed, such as flue gas emissions from a pulp mill, in which case carbon dioxide is utilised in the synthesis of synthetic fuel.

   From the perspective of the electricity system, the key questions are 1) what is produced and in which part of Finland and 2) in what form is the product transferred to the end consumer. If the fuel produced is gaseous and its end consumers also consume it as a gas (e.g. hydrogen), the transfer of energy in a gaseous form is, in principle, also efficient. In terms of hydrogen exports, this would require the construction of a hydrogen pipeline from Finland to Central Europe. In methane exports, the existing gas network and the BalticConnector pipeline could potentially be utilised and strengthened. In exports of gaseous energy, the quantities of energy transmitted would be very significant compared to the Finnish electricity system as a whole. For example, the BalticConnector has a transmission capacity[24] of approximately 7.2 Mm3/d, i.e. approximately 3000 MWh/h, which is approximately three times higher than the combined capacity of the EstLink 1 and 2 electricity transmission connections.

   If the export of energy were to take place in a gaseous form, it would probably make sense from the perspective of the electricity network to place the electrolysers as close as possible to electricity production and also to transmit the energy to be exported as gas within Finland. Since a

[24] http://balticconnector.fi/fi/projekti/

hydrogen network does not exist and the existing natural gas network does not extend to the key areas of wind power production, this would require an extension of the gas network. The network vision has not made any more detailed calculations on the necessary investments or which one is more costly in terms of total costs: the transfer of energy as hydrogen or as methane. The possibility of exporting energy as a gas should be explored further. Figure 23 illustrates this point. If the final product is liquid fuel, the situation is more similar to traditional industrial production from the perspective of the grid. Even then, the transfer of energy in a gaseous form

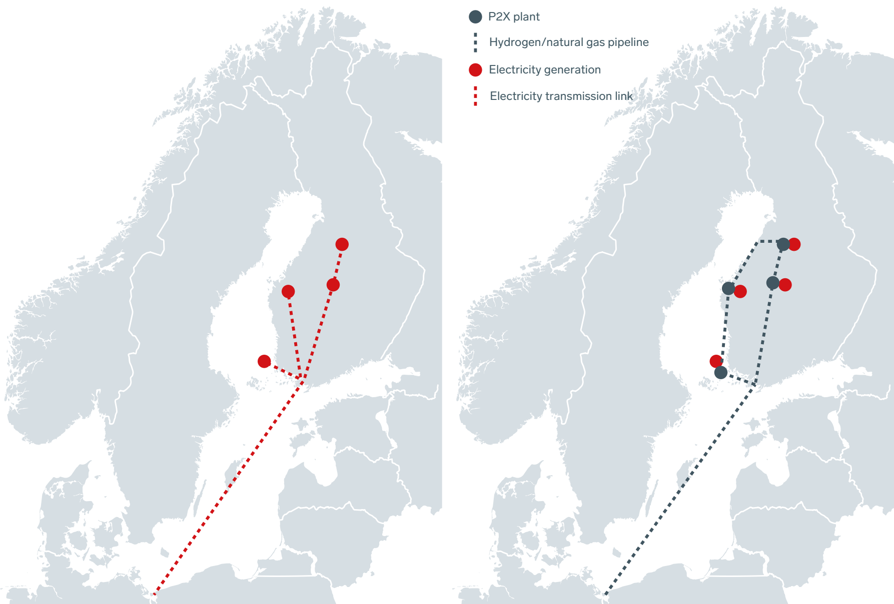


Figure 23 Illustration of the export of electricity and hydrogen/synthetic gas from Finland to Central Europe. If the export product is gas, the transmission of energy as gas within Finland is efficient. In this case, it makes sense to place electrolysers in the wind power production areas. The map is illustrative and does not represent the actual location of production facilities or transmission connections.

might be justified, especially if fuel production were to occur heavily in the south of the country and electricity production in the north.

3. **Finland as an exporter of electricity-intensive products and services.** This refers to a development path in which electricity-intensive industrial products (such as chemical or steel industry products) or services (such as data centres) are produced in Finland with clean electricity. This is already happening today, but in the future it may happen on a much larger scale. In this case, electricity will not be transferred out of Finland as electricity or fuel. This will also have an impact on the efficiency of energy transmission technologies within the country.

The different options have different requirements for the main grid. For example, direct electricity and hydrogen/methane export links to Central Europe are to some extent mutually exclusive solutions. Given the very large scale and impact of the projects, it is necessary to reach a broad consensus at the national level on whether they are needed and to forecast the investment environment before their concrete promotion is started.

5.5 How can Finland be maintained as a single bidding zone for electricity trade?

In accordance with section 40 of the Electricity Market Act, Fingrid plans the main grid in such a way that the transmission capacity of the network is sufficient to ensure that Finland (excluding Åland, which is the responsibility of Kraftnät Åland) stays as a single bidding zone for electricity trade. The network strengthenings presented in Chapter 4 are designed with this in mind.

The network vision indicates that achieving climate objectives while keeping Finland as a unified bidding zone requires significant investments in new line connections and compensation equipment in order to enable sufficient transmission capacity required in the single bidding zone. The north-south transmission capacity must be multiplied step by step in the long term. Due to the peaks in intra-country transmission, maintaining a single bidding zone cost-effectively requires a functioning flexible market and real-time monitoring of network transmission capacity, for example with DLR technology.

If the transmission capacity required by the single bidding zone cannot not be achieved, for example due to challenges associated with the permit process for new transmission lines, Finland might have to be divided into several bidding zones in order to ensure system security. From this point of view, too, it is important that the capability for investing in the grid remains at a good level. The division into bidding zones could also be implemented if it were widely considered to be a better option for the overall interests of society. This reduces the need for grid strengthenings.

If the production of electricity takes place increasingly in the north and consumption moves increasingly to the south while Finland becomes a net exporter of electricity and electricity based fules at the same time, maintaining Finland as a single bidding zone requires the introduction of new technologies and solutions. The amount of electricity production sufficient for net exports depends on the assumptions made. Based on the background assumptions of the network vision, Finland would be able to export electricity when Finland's annual electricity production clearly exceeds 150 terawatt hours.[25] Possible solutions from the TSO's perspective are internal HVDC transmission links, raising the highest voltage level to, e.g. 750 kilovolts, dual circuit lines or high-temperature-resistant conductors(such as 4-Finch). All of these technologies have their own challenges and special characteristics, and their impacts and usability in Finnish conditions must be investigated.

If electricity generation and consumption are close together, the need for transmission capacity decreases. This could mean placing electrolysers next to wind farms and transferring the produced hydrogen in gas pipelines, or alternatively building electricity generation close to industrial plants (e.g. building offshore wind in the vicinity of an industrial plant on the coast). However, there are always a number of factors involved in investing in electricity generation and consumption, and no financial incentives currently exist for co-location. It is worth considering whether co-location of production and consumption could be promoted in some other way than by increasing price areas.

In addition to increasing transmission capacity, one of the alternatives is to manage transmission peaks by utilising flexibility resources available on the electricity market. In practice, electricity production in surplus regions of the country would be reduced or consumption would be increased on market terms and correspondingly in the deficit regions production would be increased or consumption reduced on market terms. The use of flexibility in transmission management could focus, for example, on managing peak transmission situations that occur 1–5% of the time, or on network outages that significantly limit capacity. The challenge in this option is the very strong peaks of the transmission, which challenges the sufficiency of resources in extreme situations. The maximum transmission needs in the Cross-section Central Finland are thousands of megawatts larger than the 99th percentile of the transmission need, which would require a corresponding amount of flexibility resources.

[25] The background assumptions: industrial low-carbon roadmaps (excluding scope 3 of the chemical industry), electrification of passenger transport and partly heavy transport, electrification of heating and data centres will increase annual consumption to 140–150 terawatt-hours by 2050. In addition, if other transport were to increasingly switch to using domestically produced hydrogen, electricity consumption might increase by an additional ~15–20 TWh. In excess of this, the use of electricity would be either exports of electricity itself or exports of products made using electricity

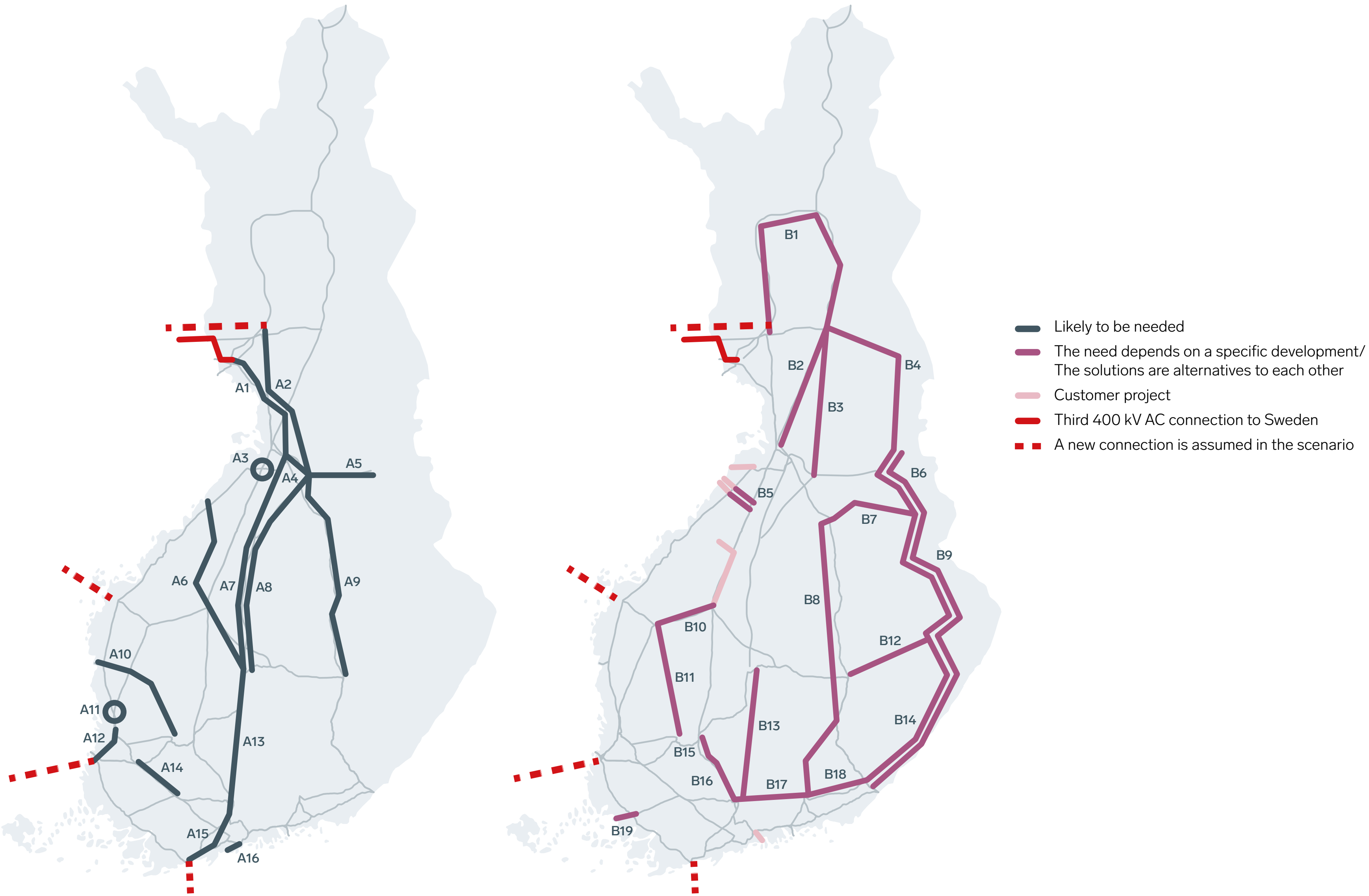
6. Conclusions

The network vision investigated the development needs and solutions of the main grid by four different scenarios. The network vision demonstrates that Finland's carbon neutrality target for 2035 is achievable as far as the main grid is concerned. Achieving this objective will require significant investments in the main grid over the next 15 years.

In all scenarios, the need to transmit energy from Northern Finland to Southern Finland increases significantly in 2035 and the transmission capacity of the grid's main transmission cross-sections, i.e. Cross-section Central Finland and Kemi-Oulujoki, must increase many-fold in order to maintain Finland as a single electricity bidding zone and to enable the same market price for electricity in the whole country.

The grid strengthenings that meet the needs of 2035 are shown in Figure 24. The left map shows the most likely needed strengthenings. The map on the right shows the strengthenings that are partially alternatives to each other and whose need depends on a specific development path. The categorization might not correspond to the order in which the projects are carried out, because if one of the scenarios investigated were to become a reality, all of the strengthenings required in that scenario would become important. In addition to transmission line investments, significant compensation and transformer capacity is also needed.

Figure 24 An overview of the identified networks strengthening needs for 2035. The line routes shown on the map represent the need for electricity transmission between stations and might not correspond to actual line routes.



The figure 23 also shows the need for new transmission links to Sweden and Estonia by 2035, which was identified by a utility benefit analysis run during the creation of the network vision. The new cross-border connections seem economically viable. However, what should be taken into account when considering the strengthening of cross-border connections is that the market benefits of the connections depend on the development of the electricity market in the Baltic Sea region and other cross-border connections in the region as the energy revolution progresses. Fingrid will continue to analyse the new Swedish and Estonian transmission connections in more detail as part of the international cooperation in grid planning.

The network strengthening solutions required for the carbon neutral future translate to investments of approximately EUR 3 billion in the grid over the next 15 years. If a significant amount of new electricity-intensive industry is created in Finland or Finland becomes an exporter of electricity and electricity based fuels, more investments in the grid are likely to be needed than described above. Furthermore, the figures do not take into account the costs of connecting offshore wind power, since they are currently not the responsibility of the TSO.

Preparations are made for staged investments in the 400 kV transmission lines of the grid. Fingrid will discuss the investments necessary in the next ten years in more detail in the main grid development plan that will be published in summer 2021. In addition to transmission line investments, Fingrid is preparing to utilise new solutions, such as adjustable reactive power compensators, utilisation of weather-dependent load on transmission lines and location-based flexible markets.

In addition to grid investments, the electricity system of the future will require a lot of new flexibility in order to function. As the energy revolution progresses, new production corresponding to the growth in electricity consumption will be mainly weather-dependent wind and solar power, which will increase variability in the electricity system. From the perspective of network strengthening it does not matter very much which proportion of flexibility comes from production, consumption or storages. However, there must be a sufficient amount of flexibility: it makes no sense to plan the network according to a situation in which society has a significant risk of lack of capacity in the long term. Such a scenario is not realistic, since price controls investments and the technologies that produce flexibility in the most affordable way will take advantage of the resulting business opportunity.

6.1 Further investigation needs

The process for creating the network vision also identified further investigation needs. If Finland's electricity production and consumption increases very strongly in the future, for example as a result of energy exports, the technical solutions traditionally used by Fingrid in the main grid may not be sufficient to meet electricity transmission needs. Since the current standard solutions will not be enough in all of the investigated scenarios even in 2035, the scenarios with significant energy exports require that new solutions must be widely in place shortly after 2035.

As a result of the visioning effort, Fingrid is launching concept studies on possible future solutions. The identified concepts that require further investigation include the utilisation of DLR technology, the implementation of transmission line crossings in the main power transmission grid, using a higher voltage, dual 400 kV circuits and new conductors such as 4-Finch conductors and the possible use of HVDC transmission links within Finland. In addition, Fingrid will complement the network vision with other technological studies, such as determining the short circuit current levels of the future, analysing the amount of inertia and harmonising the principles of parallel and series compensation.

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