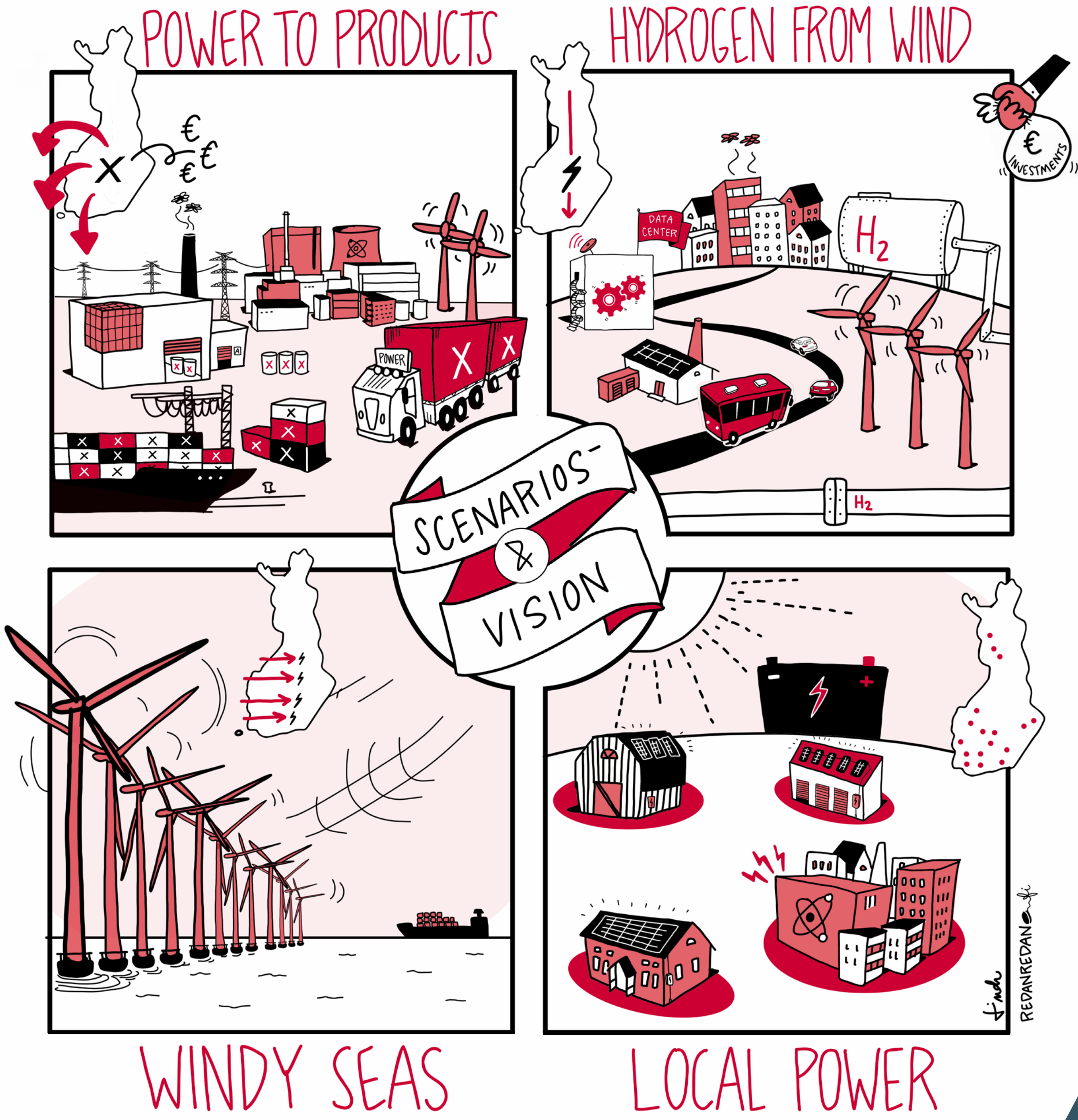

Fingrid's electricity system vision 2023

FINGRID

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Europe's hottest clean energy market

Over the last year, the European energy market has faced the greatest turmoil in its history. Russia has wielded energy as a weapon, and pointed that weapon towards the European Union. Although the situation has appeared difficult at times, and the energy price has hit record highs along the way, the worst is already behind us. A united EU is overcoming the energy crisis. Russia's attempt to weaponise energy failed and will forever more be a damp squib.

The crisis has stirred Europe in many ways. In the coming years, energy prices and energy self-sufficiency will be on the energy policy agenda in a whole new way. Finnish renewable energy combines competitive prices, improved self-sufficiency, and zero emissions. Never before has clean Finnish energy been in such high demand.

Fingrid witnesses this enormous demand every day. The number of enquiries related to connecting renewable electricity production facilities to the main grid has surpassed all previous records, and the total production volume now is almost 250 GW! Most of the enquiries concern wind power, but interest in solar power construction is increasing substantially: the number of connection enquiries has more than trebled compared with a year ago, and the first agreements have already been made to connect solar power to the main grid. At the same time, plans for industrial projects hit the news in Finland almost weekly for their endeavour to use clean electricity: hydrogen production, electric fuels, steel plants, data centres – the list goes on and on. Finland is perhaps the hottest clean energy market in Europe right now!

Fingrid's electricity system vision presents scenarios of the opportunities ahead of an electrifying Finland in the coming decades. At the same time, the work examines the need to strengthen the main grid and changes occurring in the electricity system. In the highest-growth scenarios, the main grid requires significant strengthening. The main new strengthening needs identified in the vision work will be added to Fingrid's investment programme when it is updated in summer 2023. Implementation of new lines however takes time and efforts should be made to speed up the permission processes.

At the same time, efforts must be made to maximise the transmission capacity and increase the utilisation rate of the existing grid and newly built sections. This means adopting new technologies and giving serious consideration to incentives for grid users based on their locations. If the relevant parties can be encouraged to build new production and consumption facilities in favourable locations in terms of the main grid's structure, it will be possible to connect more customers more quickly, thereby accelerating Finland's transition to becoming a carbon-neutral society. As the proportion of renewable energy grows, the established dimensioning practices for the main grid must be scrutinised: it is not appropriate to design the network so that the main grid can receive all the weather-dependent production in the form of infrequent, recurring production peaks. At the same time there is need to control the consumption and production in those rare situations, for which the network has not been dimensioned.

There is currently heated debate in Europe concerning the electricity market model. The analysis of the system vision work demonstrates the importance of flexibility in a modern electricity system. The scenarios identify the price elasticity of electricity consumption – especially hydrogen production – as the key to balancing the clean electricity system of the future. Hydrogen, hydrogen-derived products and heat storage are prerequisites for large-scale demand-side response. The electricity market model should strongly incentivise the balance between electricity consumption and production at all times. This will enable the system to be balanced with the most efficient resources. The economic analysis of the vision work indicates that investments in new, weatherproof electricity production will not be profitable on a wide scale. If electricity consumption and energy storage do not provide the necessary flexibility in the future, new flexibility will be needed in production. Special incentives for new capacity may be required to create this.

The European energy revolution is just getting started and will accelerate in the coming years. Finland has an excellent opportunity to succeed in this transition. We aim to understand the needs of existing and future main grid customers in a rapidly evolving operating environment while enabling as many green economy investments as possible in Finland.

Mikko Heikkilä
Head of Strategic Grid Planning

1 Introduction

Fingrid's electricity system vision aims to showcase Finland's opportunities to compete for electricity production and consumption projects and create a vision of the developments required in the main grid transmission network over the long term. A further goal is to identify and inspire discussion of the challenges and opportunities on the journey through the energy revolution towards becoming an electricity-intensive, carbon-neutral society.

In our vision work, we have permitted ourselves to think big. A strong and reliable main grid enables investments in both electricity-intensive industries and electricity production. Therefore, long-term plans should also prepare for high electricity consumption and production potentials. The aim is not to try to find a single likely scenario, but to highlight different phenomena in different scenarios that challenge the main grid, the electricity market and the electricity system. Assessing the need for change through challenging scenarios helps to ensure that the means to enable electrification development and achieve climate targets can be assessed comprehensively and in a timely manner. At worst, an understatement of the need for change could lead to a situation where a lack of preparedness would limit the progress of electrification, the realisation of industrial investments and the achievement of climate targets, or lead to a deterioration in the system security of the main grid.

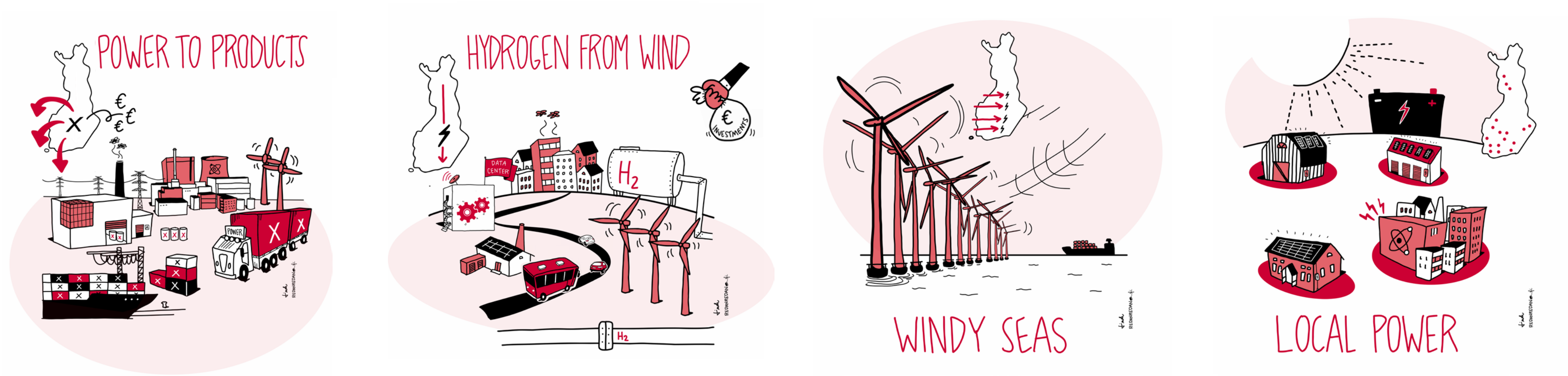
The vision work examines long-term changes that are difficult to predict. The outcomes of the vision work should not be construed as an investment plan or list of intended actions. Instead, the vision work provides insight into the transmission needs, emerging in several scenarios, to be examined after Fingrid's current investment plan. The vision work also indicates the reinforcements needed by the network under certain scenarios and development paths. This information helps to prepare for various eventualities. The main grid development plan, which is published every two years, describes the main grid investments needed over the next ten years.[1]

This document presents Fingrid's four scenarios for trends in production and consumption up to 2035 and 2045. It also presents the developments required in the main grid based on the scenarios and the implications for the electricity system overall as a consequence of the energy revolution described in the scenarios. The reports and scenarios in the electricity system vision were published in draft in August 2022 to allow stakeholders to comment. We then published a summary of the feedback we received in December 2022[2]. The feedback was used to fine-tune the scenarios and report.

The four scenarios in the electricity system vision are called Power to Products, Hydrogen from Wind, Windy Seas, and Local Power. Figure 1 presents brief descriptions of the scenarios. Table 1 presents a comparison of the scenarios based on their most significant variables. Section 2 presents the assumptions behind the scenarios, a summary, and a more detailed description of each scenario. Section 3 describes the cross-cutting themes of the scenarios, electricity consumption trends, electricity generation potential, Finland's competitiveness, and the system flexibility assumed in the scenarios. Section 4 covers the transmission requirements and corresponding grid solutions under each scenario. Section 5 covers the key factors necessary for the scenarios to come to fruition.

[1] The main grid development plan was last updated in autumn 2021. The next update will take place in 2023.
[2] https://www.fingrid.fi/ajankohtaista/tiedotteet/2020/kiitos-arvokkaasta-palautteesta-verkkovision-skenaarioluonnoksiin/ (available only in Finnish).

Figure 1 Scenarios in the electricity system vision.



In all scenarios, transport, heating and industry will become electrified, and carbon neutrality targets will be met

Power to products

- Finland becomes significant exporter of P2X products.
- Wind and solar power grow significantly.
- The hydrogen needed for P2X processes is produced close to demand facilities, and there is no centralised hydrogen storage or network. This increases the strengthening needs of the electricity network and the need for flexibility in the electricity system.

Hydrogen from wind

- Hydrogen production grows in Finland and Finland becomes exporter of hydrogen.
- The hydrogen system acts as an energy storage facility, enabling very large-scale onshore wind power production. At the same time, the volume of conventional electricity production shrinks sharply.
- The change in production and consumption structure challenges technical functioning of electricity system and is reflected as a very high north-south energy transmission need.

Windy seas

- Electricity consumption grows when fossil-fueled energy is replaced by electricity and e-fuels.
- Offshore becomes the dominant form of production.
- The production of electricity is increasingly focused on the west coast, which challenges the transmission of electricity from the west coast to consumption concentrations.

Local power

- Electricity consumption increases, but more moderately than in the other scenarios.
- The growth in electricity production consists of several different technologies, including wind and solar and SMR nuclear power.
- The relatively higher share of production is located in southern Finland, close to consumption concentrations.

Table 1 The most significant variables in the electricity system vision.

The most significant variables in the scenarios	Power to products	Hydrogen from wind	Windy seas	Local power
Hydro power	≈	-	≈	≈
Onshore wind power	+++	+++	+	+
Offshore wind power	++	++	+++	+
Solar power	+++	+++	+	++
Conventional nuclear power	≈	--	≈	≈
SMR nuclear power	≈	≈	≈	+++
Other thermal power	--	---	--	--
Engine power plants and batteries	+++	+++	+	++
Proportion of converter-connected capacity	+++	+++	+++	+
Final electricity consumption*	+++	+++	+++	+
Electric use of electrolysis	+++	+++	++	+
Demand side response of electricity*	+++	++	++	+
Flexibility of the hydrogen system	+	+++	++	≈
Annual balance of electricity exports and imports	Exports	Balanced	Exports	Exports
Annual balance of hydrogen exports and imports	No hydrogen cross-border connections	Exports	Exports	No hydrogen cross-border connections

*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 section 2.2, "Summary of the scenarios". Meanings of the symbols used in the table: ≈ no significant change, + increase, - decrease. *Final electricity consumption and demand side response do not include electrolysis, for which parameters are indicated in their own row.*

In parallel with this vision work, Fingrid and Gasgrid Finland are working together on a separate joint project to explore the potential of the hydrogen economy and the role of energy transmission systems in enabling the hydrogen economy in Finland. Fingrid's electricity system vision scenarios have been prepared from the perspective of the electricity system, and the purpose of the work is to study the development of the electricity system, which requires general assumptions about the hydrogen system. The joint project between Fingrid and Gasgrid examines the hydrogen economy in detail and looks more closely at the potential development pathways for the hydrogen economy and the role of energy transmission systems in enabling the hydrogen economy[3].

[3] https://www.epressi.com/media/userfiles/151043/1655441995/gasgrid-fingrid-vetytaloushankkeen-skenaarioluonnokset.pdf

2 Scenarios

2.1 Starting point for the scenarios

At the centre of the electricity system vision are four different scenarios that represent possible trends in electricity consumption, production and storage. Fingrid has updated the scenarios previously published in the network vision at the beginning of 2021, taking into account the recent signals on the outlook for the long-term development of the energy sector and climate targets. To enable long-term vision work, the scenarios have been prepared for 2035 and 2045. The first of these is of special interest because 2035 is the deadline that Finland has set for becoming carbon-neutral.

The biggest changes compared to the scenarios of Fingrid's network vision completed at the beginning of 2021 are related to greater growth opportunities in new electricity-intensive industries, which also require increased electricity production. In addition, one of the scenarios assumes the commercialisation of small modular nuclear power plants by 2035. The scenarios have also been updated to take into account the key changes in energy trade between Europe and Russia following Russia's invasion of Ukraine.

The most relevant variables in the scenarios in terms of electricity consumption are the consumption due to industry, hydrogen and electricity products, heating, and transport, and the regional distributions of consumption. On the electricity production side, on the other hand, the significant variables are the amount and location of onshore and offshore wind power and solar power. The amount of nuclear power varies in the scenarios depending on the extensions of the service life of existing plants and the construction of new modular nuclear power plants. In addition, the amount of flexibility available in production and consumption, the amount of cross-border electricity transmission capacity, other energy infrastructure, and the import and export needs of neighbouring countries vary in different scenarios. The assumptions made for the rest of Europe are described in more detail in section 3.5.

The modelling of the scenarios has been carried out by simulating the electricity market. The aim of the modelling is to predict how the wholesale electricity market would function and what kinds of investments would be made on market terms in the production of electricity and hydrogen if the operating environment developed as described in the scenario. The key modelling principles are described in Appendix 1.

In all scenarios, Finland's emission-reduction targets will be achieved by 2035. This requires a significant increase in electricity consumption for the electricity system when fossil fuels are replaced by electricity or fuels produced from electricity. In addition, three of the four scenarios take into account Finland's good prerequisites for succeeding in the competition for investments in new electricity-intensive industries, which is reflected in the very strong growth in electricity consumption. In all 2045 scenarios, Finland is carbon negative, and the amount of electricity-intensive industry has increased even further.

The scenarios are not forecasts, but descriptions of the consequences of different, possible developments in the operating environment. It would also be possible to assume negative developments that would hamper the operating environment and the realisation of the energy transition or have a negative impact on Finland's competitiveness. However, a scenario created from such a basis would not challenge Fingrid to prepare for the energy transition, but could only guide it to resolve short-term challenges. The scenarios were created mainly from the perspective of the main grid in order to challenge main grid planning, the structure of the electricity market, and the operation of the electricity system as a whole. In other words, we have not evaluated any factors that would not affect the main grid or that would materially facilitate phenomena related to main grid operations. The scenarios are based on the assumption of a number of positive developments that will allow the scenarios to materialise. Below are the main assumptions about the prerequisites for these developments:

- Finland aims for carbon neutrality in 2035 and the EU for climate neutrality in 2050. Political measures, business and consumer choices, and access to finance enable these targets to be achieved. The scenarios assume that potential geopolitical or economic risks will not slow down the progress of the energy transition or jeopardise Finland's position as an investment target.
- The consequences of climate change, such as possible effects on precipitation volumes, windiness, and sea level, do not substantially change the profitability of electricity production in Finland or neighbouring regions.
- Finland's electricity system operates as part of the Nordic shared operation system. Finland is a unified electricity trade bidding zone as part of a large and functional European electricity market. The internal networks of neighbouring countries do not impose restrictions on cross-border electricity trading and, for example, the current export restriction on Fenno-Skan will be lifted.
- The majority of electricity generation and consumption has been linked to electricity networks; large-scale separate (off-grid) systems are not in use.
- Distribution networks enable new types of electricity production and consumption, such as electric cars, electric heating and distributed solar power, and do not impose significant restrictions on their use.
- The resources required by the energy transition, such as materials and labour for the production and construction of transmission links, wind and solar power plants, and electric vehicles, are available in sufficient quantities.
- There are no breakthroughs in energy technology development or the availability of fuels that would displace wind power in the production of clean energy at a global level or otherwise weaken Finland's relative competitiveness. For example, a significant fall in carbon capture or fossil fuel prices could affect the competitiveness of wind power and clean hydrogen, and thus the exploitability of Finland's wind power potential. Similarly, removing restrictions on the permitting and acceptability of wind power elsewhere in Europe could weaken the competitiveness of Finnish energy.
- Land use and permitting processes do not prevent or significantly slow down the construction of the main grid.

2.2 Summary of the scenarios

This section presents a summary and comparison of the scenarios. Electricity consumption increases in all scenarios as use increases in transport, heating and current industry. All scenarios have the electrification of existing industrial processes and related heat production in common, at least along the path shown by low-carbon roadmaps[4]. In industry, the growth in electricity consumption is particularly strong in the Power to Products, Hydrogen from Wind, and Windy Seas scenarios, in which new electricity-intensive industries emerge in Finland, such as the hydrogen and electric fuel industry, the battery industry, and data centres, or electrolysis for the export of hydrogen. In the Local Power scenario, the growth of electricity consumption in industry is more moderate.

In all scenarios, heating also becomes electrified as solutions based on electricity and the utilisation of waste heat become more common in district heat production. In addition, electricity and heat pumps replace fossil fuels in separate heating. Unlike the other scenarios, however, the Local Power scenario envisages the electricity consumption related to heating increasing only slightly, as the scenario assumes that solutions based on the use of waste heat in particular will reduce district heating emissions. Electric transport increases significantly, and approximately half of Finland's passenger car fleet will be fully electric cars or plug-in hybrids in 2035, but this will have a limited impact on total electricity consumption. Figure 2 below presents electricity consumption in the scenarios in comparison with the consumption in 2021.

Figure 3 and Tables 2–5 present electricity generation, Finland's power balance, and electricity production capacity in the different scenarios in 2035 and 2045. The amount of onshore wind power increases significantly in all scenarios, with particularly strong growth in the Hydrogen from Wind and Power to Products scenarios. Offshore wind power increases, especially in the Windy Seas scenario. Solar power production grows most strongly in the Power to Products scenario. Hydro power remains at its current level in the Power to Products, Windy Seas, and Local Power scenarios. The Hydrogen from Wind scenario envisages a decrease in the amount of hydro power and balancing capacity. The use of fossil fuels for energy generation is negligible in all the scenarios in 2035.

[4] In line with Finland's government programme, in 2020, actors in different sectors drew up sector-specific low-carbon roadmaps that are compatible with climate action. More information: https://tem.fi/tiekartat

Figure 2 **Electricity consumption under different scenarios.**

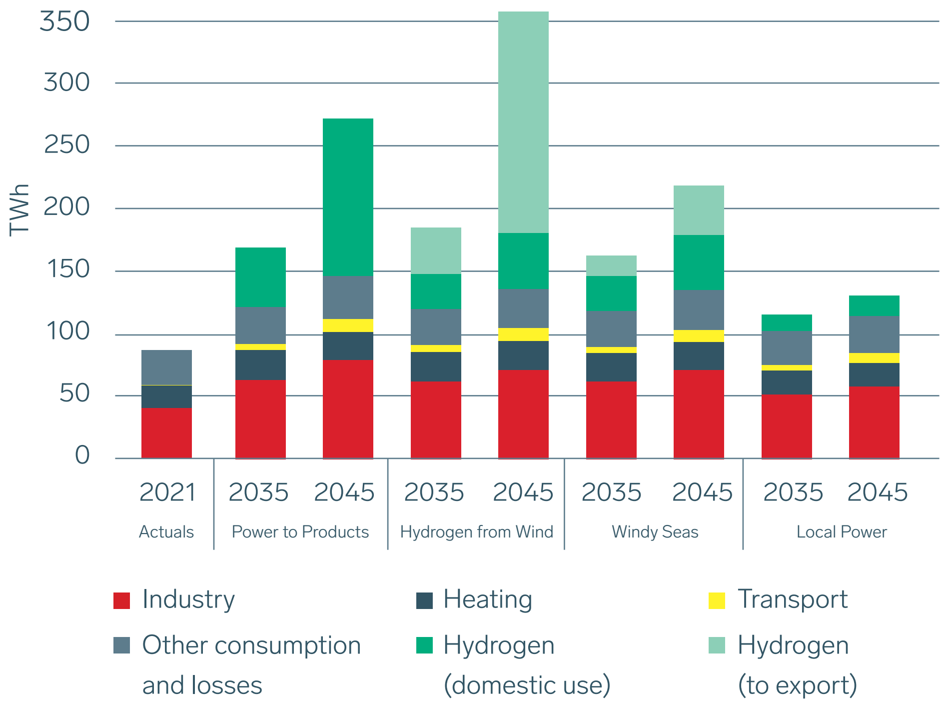


Figure 3 **Electricity generation in different scenarios.**

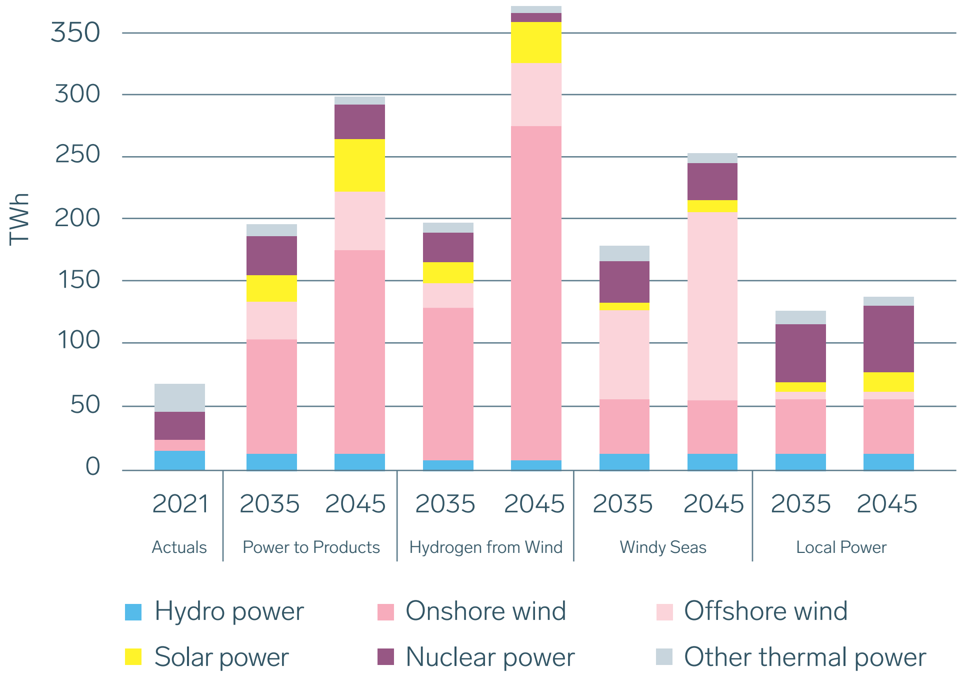


Table 2 Power balance in the different scenarios in 2035.

Power balance 2035 (TWh)	Power to Products	Hydrogen from Wind	Windy Seas	Local Power
Hydro power	14	9	14	14
Onshore wind power	90	121	43	43
Offshore wind power	30	20	71	6
Solar power	20	16	6	7
Nuclear power	31	24	33	46
Other thermal power	9	8	12	11
Total production	196	197	179	127
Total consumption	169	185	163	115
Finland's power balance (net exports)		12	16	12
Share of carbon-neutral electricity generation[5]	100%	100%	100%	100%

Table 3 Power balance in the different scenarios in 2045.

Power balance 2045 (TWh)	Power to Products	Hydrogen from Wind	Windy Seas	Local Power
Hydro power	14	8	14	14
Onshore wind power	162	265	43	43
Offshore wind power	47	50	150	6
Solar power	41	33	9	15
Nuclear power	28	7	30	53
Other thermal power	7	5	8	7
Total production	299	369	252	138
Total consumption	273	359	219	131
Finland's power balance (net exports)	26	10	33	7
Share of carbon-neutral electricity generation	100%	100%	100%	100%

[5] Carbon-neutral electricity generation includes electricity production based on wind, solar and nuclear power, as well as bio, waste and electric fuels.

Table 4 Production capacity in the different scenarios in 2035.

Capacity 2035 (MW)	Power to Products	Hydrogen from Wind	Windy Seas	Local Power
Hydro power	3	2	3	3
Onshore wind power	30	39	13	13
Offshore wind power	7	5	15	1
Solar power	20	15	6	7
Nuclear power	4	3	4	6
Other thermal power	4	4	3	3
Electricity storage (on the day-ahead and intraday market)	4	4	1	3

Table 5 Production capacity in the different scenarios in 2045.

Capacity 2045 (MW)	Power to Products	Hydrogen from Wind	Windy Seas	Local Power
Hydro power	3	2	3	3
Onshore wind power	50	79	13	13
Offshore wind power	10	11	32	1
Solar power	39	30	9	14
Nuclear power	4	2	4	8
Other thermal power	4	5	4	3
Electricity storage (on the dayahead and intraday market)	6	4	1	4

In the scenarios created for the system vision, electricity production and consumption increase considerably faster than in the background scenario for the Climate and Energy Strategy published in 2022[6]. Figures 4 and 5 illustrate the differences. In the scenarios created for the Climate and Energy Strategy, electricity consumption increases to 95–104 TWh by 2035, which is a much slower increase than in the scenarios used for the system vision. Most of the difference is due to industrial electricity consumption: three of the four system vision scenarios assume that Finland will be a very attractive place to invest in energy-intensive industries. Electricity consumption for heating – mainly in the form of electric district heating – is also slightly higher in the system vision scenarios. There is no major difference in the electricity consumed for transportation.

The greatest differences between the scenarios in terms of electricity production are related to wind power production. In the background scenarios created for the Climate and Energy Strategy, the amount of wind power varied between 19 and 30 TWh in 2035. At the current pace of construction, this level will be reached by 2024–2026, so the scenarios created for the system vision foresee a much higher level. The system vision scenarios also include a larger volume of solar power production. There are no differences between the scenarios in terms of hydro power volumes, except under the Hydrogen from Wind scenario. The background scenarios for the Climate and Energy Strategy envisaged a larger volume of nuclear power, as the Hanhikivi 1 nuclear power plant was not included in the system vision scenarios. Furthermore, the background scenarios for the Climate and Energy Strategy included higher biopower volumes than the system vision scenarios.

[6] https://julkaisut.valtioneuvosto.fi/bitstream/handle/10024/164321/TEM_2022_53.pdf?sequence=1&isAllowed=y

Figure 4 Electricity consumption under the background scenarios for the Climate and Energy Strategy and Fingrid's scenarios.

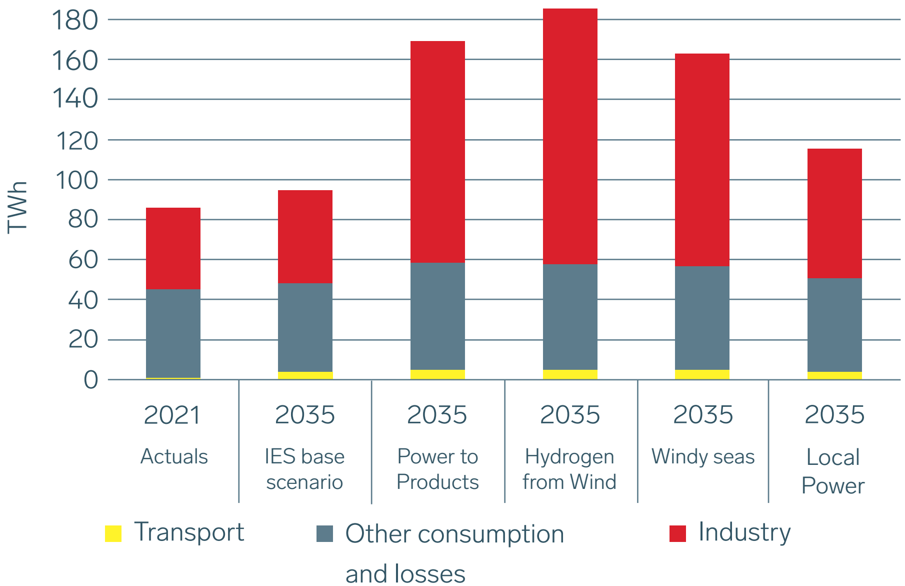
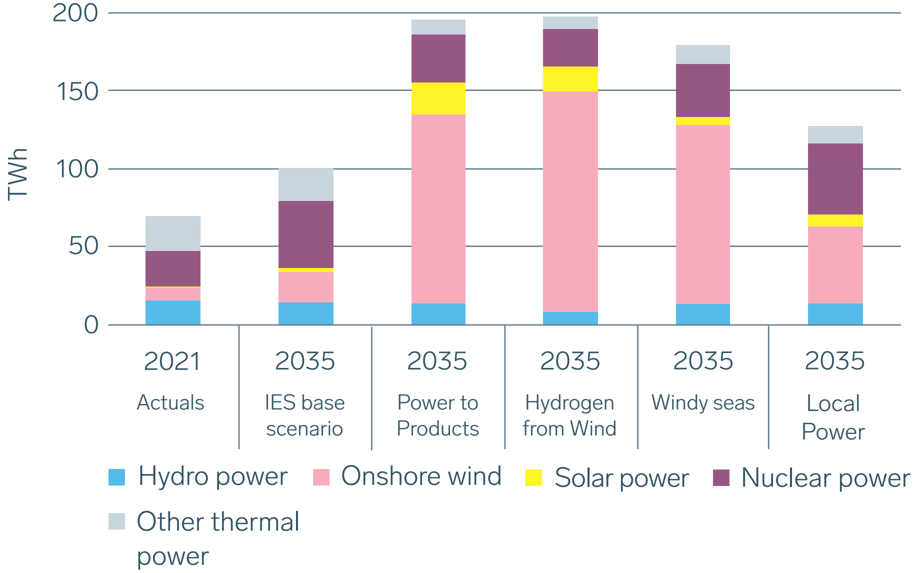
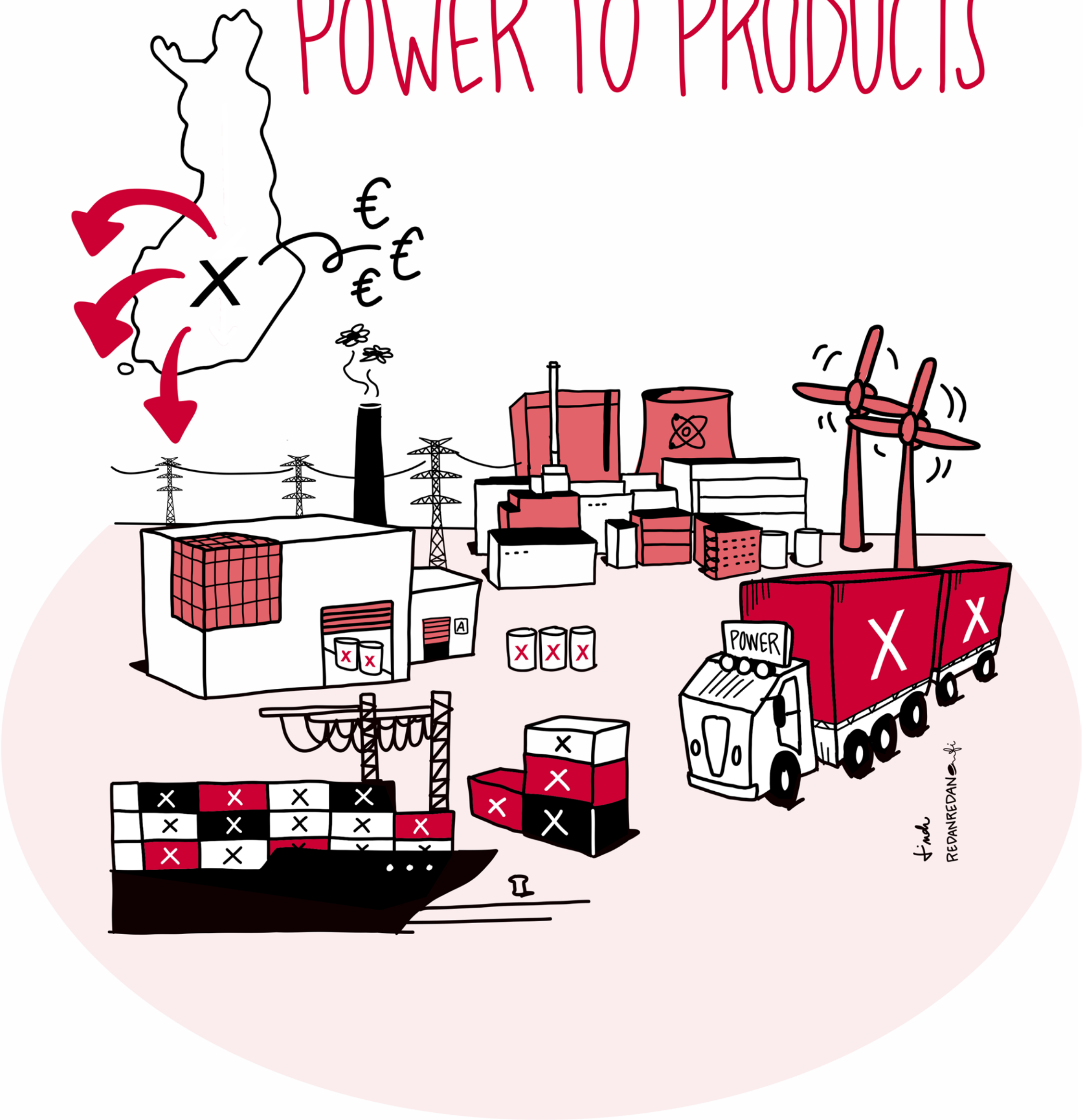


Figure 5 Electricity production under the background scenarios for the Climate and Energy Strategy and Fingrid's scenarios.



2.3

POWER TO PRODUCTS



In the Power to Products scenario, Finland becomes a major exporting country of products made using electricity (P2X products)[7]. The scenario assumes that this is based on hydrogen production located close to hydrogen consumption, which requires the transmission of the electricity needed by the P2X industry to industrial consumption points. In addition, the scenario assumes low P2X demand side response, which increases the need for other flexibility in the electricity system.

In addition to the P2X industry, electricity consumption in other industries grows clearly. In addition, the use of electricity in both district and separate heating and transport increases. The majority of electric cars are charged smartly, and in contrast to the other scenarios, Vehicle-to-Grid technology (V2G) is widely used for two-way charging. In this scenario, P2X products are exported from Finland, not unprocessed hydrogen; thus, export links for hydrogen will not be built.

Electricity production in Finland grows strongly along with consumption. In particular, onshore wind power grows significantly, reaching 30 GW of capacity in 2035 and 50 GW in 2045. Onshore wind power is also increasingly built in eastern Finland, which means that more geographically dispersed wind power produces electricity more evenly than regionally focused wind power. Less wind power is generated in southern Finland, as

[7] In this context, P2X products refer to products produced from electricity and other raw materials (such as nitrogen or bio-based CO2), such as fuels, materials and chemicals. The use of electricity in heating and transport is not classified as P2X products, but has been addressed separately.

the number of suitable project areas is smaller than in the rest of Finland. In addition to onshore wind power, approximately 7 GW of offshore wind power is added to the system, 2 GW of which is expected to be built in the Gulf of Finland, further decentralising the regional location of wind power. In addition, this scenario envisages more solar power than the other scenarios, and the production profile of solar power differs from that of onshore wind power.

The amount of hydro power remains at its current level. The nuclear power plant units in Loviisa and Olkiluoto continue to be operated until 2050. After Olkiluoto 3, however, no new nuclear power is built in Finland, as SMR technology[8] does not break through commercially in this scenario. The amount of biopower decreases moderately.

Table 6 describes electricity consumption in the Power to Products scenario. Table 7 describes the electricity production capacity and annual production.

[8] In this scenario, SMR technology refers to a serially manufactured nuclear power plant with a modular structure and a capacity ranging from the tens to hundreds of megawatts. Such power plants produce both electricity and heat in cities.

Table 6 Electricity consumption in the Power to Products scenario.

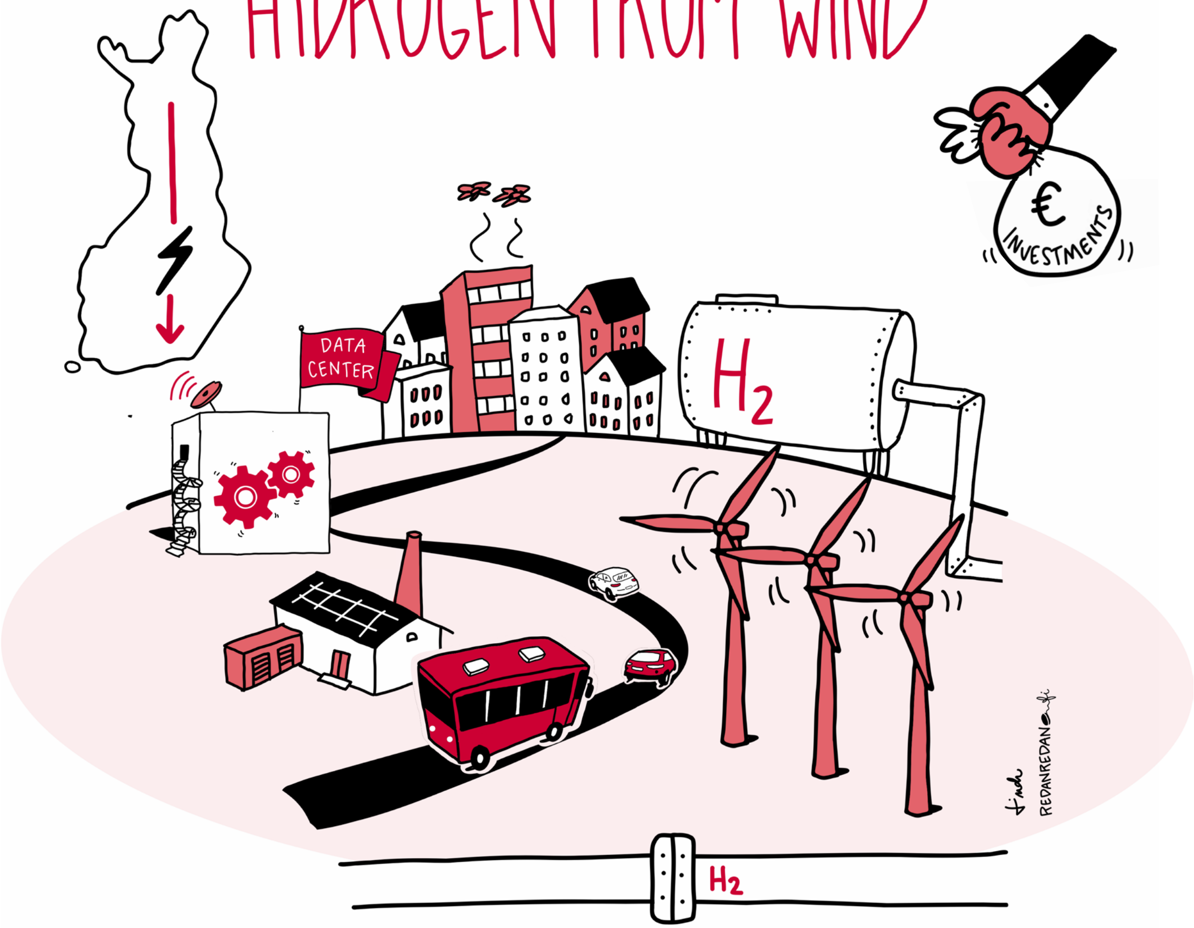
Electricity consumption in the Power to Products scenario (TWh)	2021	2035	2045
Industry excl. electrolysis	40	64	79
Electrolysis	0	47	126
Heating	18	24	23
Transport	1	5	10
Other consumption and losses	28	30	35
Total	87	169	273

Table 7 Production capacity and production of electricity in the Power to Products scenario.

Electricity production capacities in the Power to Products scenario (GW)	2021	2035	2045
Hydro power	3	3	3
Onshore wind power	3	30	50
Offshore wind power	0	7	10
Solar power	0	20	39
Nuclear power	3	4	4
Other thermal power	7	4	4
Total	16	69	111

Electricity production in the Power to Products scenario (TWh)	2021	2035	2045
Hydro power	16	14	14
Onshore wind power	8	90	162
Offshore wind power	0	30	47
Solar power	0	20	41
Nuclear power	23	31	28
Other thermal power	23	9	7
Total production	69	196	299
Consumption	87	169	273
Finland's power balance	-18	27	26

2.4 HYDROGEN FROM WIND



In the Hydrogen from Wind scenario, Finland achieves its carbon-neutrality targets and becomes a significant exporting country of hydrogen. The storage of electricity as hydrogen enables a very high share of variable wind power in the electricity system, resulting in a high share of converter-connected production, low inertia, and maximum north-south energy transmission needs. In the scenario, a significant part of hydrogen is exported via pipeline connections to the rest of Europe.

In addition to the production of green hydrogen, electricity consumption in other industries grows clearly. In addition, the use of electricity in district heating, separate heating and transport increases. The majority of electric cars are charged smartly, but V2G technology is not widely used.

In addition to cross-border hydrogen connections, an extensive hydrogen transmission infrastructure develops within Finland, which contributes to the transmission of energy in the most appropriate way for each situation, either as electricity or as hydrogen. The hydrogen network enables the creation of a multilateral hydrogen market and centralised production and storage of hydrogen, and acts as a hydrogen storage facility in itself. In addition to domestic storage facilities, pipeline connections to hydrogen networks in Sweden and Central Europe allow the system to be balanced using wider geographical electricity production and cost-effective hydrogen salt stone cavern storage in Central Europe.

The massive increase in electricity consumption is met in Finland, especially by onshore wind power. Onshore wind power production increases strongly (2035: 39 GW;

2025–2035 average +2.9 GW per year), and the geographical decentralisation of production clearly expands from the current situation. The radar issue restricting the construction of wind power in eastern Finland is resolved, which enables a significant increase in capacity. In addition, wind power capacity in southern and central Lapland grows strongly. The geographical dispersion of wind power evens out fluctuations in production. Also offshore wind power and solar power grow strongly. This scenario foresees a drop in the volume of hydro power based on Pohjolan Voima's "European Hydrogen Integration" scenario.[9] The hydro power production capacity falls by approximately 1 GW, electricity production decreases by approximately 5 TWh, and balancing capacity and energy storage capacity weaken. Consequently, the system loses a considerable amount of renewable electricity, controllable production capacity, energy storage capacity, and balancing resources at the same time. The lost hydro power in this scenario is offset by hydrogen-fuelled electricity production capacity (controllable production capacity), hydrogen storage (long-term energy storage capacity), batteries (short-term energy storage capacity), and wind power (electrical energy). The volumes of nuclear and biopower also decline under this scenario, increasing the need for hydrogen-fuelled production capacity.

Table 8 describes electricity consumption in the Hydrogen from Wind scenario. Table 9 describes the electricity production capacity and annual production.

Table 8 Electricity consumption in the Hydrogen from Wind scenario.

Electricity consumption in the Hydrogen from Wind scenario (TWh)	2021	2035	2045
Industry excl. electrolysis	40	63	71
Electrolysis	0	65	222
Heating	18	24	24
Transport	1	5	10
Other consumption and losses	28	29	32
Total	87	185	359

Table 9 Production capacity and production of electricity in the Hydrogen from Wind scenario.

Electricity production capacities in the Hydrogen from Wind scenario (GW)	2021	2035	2045
Hydro power	3	2	2
Onshore wind power	3	39	79
Offshore wind power	0	5	11
Solar power	0	15	30
Nuclear power	3	3	2
Other thermal power	7	4	5
Total	16	68	129

Electricity production in the Hydrogen from Wind scenario (TWh)	2021	2035	2045
Hydro power	16	9	8
Onshore wind power	8	121	265
Offshore wind power	0	20	50
Solar power	0	16	33
Nuclear power	23	24	7
Other thermal power	23	8	5
Total production	69	197	369
Consumption	87	185	359
Finland's power balance (net exports)	-18	12	10

[9] https://www.pohjolanvoima.fi/wp-content/uploads/2022/02/Pohjolan-Voiman-toimintaympariston-skenaariot-2035.pdf

2.5

WINDY SEAS

The key factor in the Windy Seas scenario is a sharp increase in offshore wind power. In this scenario, Finland's electricity production focuses heavily on western Finland; a large part of onshore wind power is built there, all offshore wind power and three Olkiluoto nuclear power units are also located on the west coast. A key challenge for the development of the main grid is the transmission of this electricity surplus to consumption concentrations. If offshore wind power could also be built in the Gulf of Finland, it would reduce the need for electricity transmission and balance the offshore wind power production. However, this scenario does not envisage any offshore wind power in the Gulf of Finland in order to highlight the maximum transmission capacity required from the west to consumption centres.

Finland is an attractive location for new investments in industrial sectors that need clean electricity, and electricity demand is expected to grow strongly in industry, heating and transport, but the growth in industry and hydrogen production is assumed to be lower than in the Power to Products and Hydrogen from Wind scenarios. The majority of electric cars are charged smartly, but V2G technology is not widely used.

The Windy Seas scenario assumes the existence of hydrogen transmission infrastructure within Finland, which in part allows energy to be transmitted in the most appropriate way for each situation, either as electricity or hydrogen, but on a smaller scale than in the Hydrogen from Wind scenario. In addition to the domestic hydrogen network, a hydrogen pipeline connection from northern

Finland to northern Sweden has been assumed. However, an export pipeline from Finland to Central Europe is not built in the scenario.

In this scenario, offshore wind power becomes Finland's most significant form of electricity generation by 2035, with an installed offshore capacity of 15 GW and annual electricity production of 71 TWh. The growth of offshore wind power is affected by a more aggressive assumption of falling production costs than in the other scenarios and, at the same time, by the difficulty of building more onshore wind power. Offshore wind farms are assumed to be 10–30 kilometres from the coast, enabling AC grid connections. This makes offshore wind investment costs lower than a wind farm farther offshore using a DC connection. The amount of onshore wind power in Finland remains at about 13 GW. The amount of solar power grows steadily, and the amount of hydro power remains at its current level. The amount of nuclear power remains at the level following the commissioning of Olkiluoto 3 in 2035 and 2045. The amount of biopower decreases moderately.

Table 10 describes electricity consumption in the Windy Seas scenario. Table 11 describes the electricity production capacity and annual production.

Table 10 Electricity consumption in the Windy Seas scenario.

Electricity consumption in the Windy Seas scenario (TWh)	2021	2035	2045
Industry excl. electrolysis	40	63	71
Electrolysis	0	44	83
Heating	18	22	23
Transport	1	5	10
Other consumption and losses	28	29	32
Total	87	163	219

Table 11 Production capacity and production of electricity in the Windy Seas scenario.

Electricity production capacities in the Windy Seas scenario (GW)	2021	2035	2045
Hydro power	3	3	3
Onshore wind power	3	13	13
Offshore wind power	0	15	32
Solar power	0	6	9
Nuclear power	3	4	4
Other thermal power	7	3	4
Total	16	45	67

Electricity production in the Windy Seas scenario (TWh)	2021	2035	2045
Hydro power	16	14	14
Onshore wind power	8	43	43
Offshore wind power	0	71	150
Solar power	0	6	9
Nuclear power	23	33	30
Other thermal power	23	12	8
Total production	69	179	252
Consumption	87	163	219
Finland's power balance (net exports)	-18	16	33

2.6

In the Local Power scenario, Finland's total electricity consumption is modelled on low-carbon roadmap work, so consumption increases strongly, but less than in the other scenarios. Electricity is produced from a variety of sources, the most important of which are onshore wind power, conventional nuclear power, SMR nuclear power and solar power. In the scenario, a higher proportion of electricity production is located in the south and is based on adjustable and synchronously connected units. The amount of flexibility in electricity consumption through sector integration from hydrogen, heating and transport systems is lower than in the other scenarios. The scenario helps to identify the minimum investments in the electricity network and the development measures in the electricity system and market that are necessary for a carbon-neutral Finland.

The growth in electricity consumption is more moderate than in the other scenarios, especially in the production of green hydrogen and in new electricity-intensive industries (such as the battery industry, data centres and the P2X industry). The hydrogen network is not built, and hydrogen storage is marginal, which increases the need for flexible electricity production and electricity storage facilities.

In this scenario, the costs of SMR nuclear power plants decrease rapidly and sharply. Competitively priced small-scale nuclear power plants are already available in the early 2030s, with electrical power in Finland of 2 GW in 2035 and 4 GW in 2045. The power plants are used for combined heat and power production and are located in existing district heating systems. The Loviisa nuclear power plant is used for an extra 20 years, and all the current units at Olkiluoto are still in use in 2045. The costs of solar power decrease more quickly than in the other scenarios, and even Finland's solar power capacity soars. However, the capacity consists mainly of separate systems on individual properties, rather than large solar farms. The growth of wind power fades in the 2030s due to a more moderate increase in electricity consumption and tougher competition from nuclear and solar power. The amount of hydro power remains unchanged, and the amount of biopower decreases moderately.

Table 12 describes electricity consumption in the Local Power scenario. Table 13 describes the electricity production capacity and annual production.

Table 12 Electricity consumption in the Local Power scenario.

Electricity consumption in the Local Power scenario (TWh)	2021	2035	2045
Industry excl. electrolysis	40	52	59
Electrolysis	0	13	16
Heating	18	19	18
Transport	1	4	8
Other consumption and losses	28	27	29
Total	87	115	131

Table 13 Production capacity and production of electricity in the Local Power scenario.

Electricity production capacities in the Local Power scenario (GW)	2021	2035	2045
Hydro power	3	3	3
Onshore wind power	3	13	13
Offshore wind power	0	1	1
Solar power	0	7	14
Nuclear power	3	6	8
Other thermal power	7	3	3
Total	16	34	44

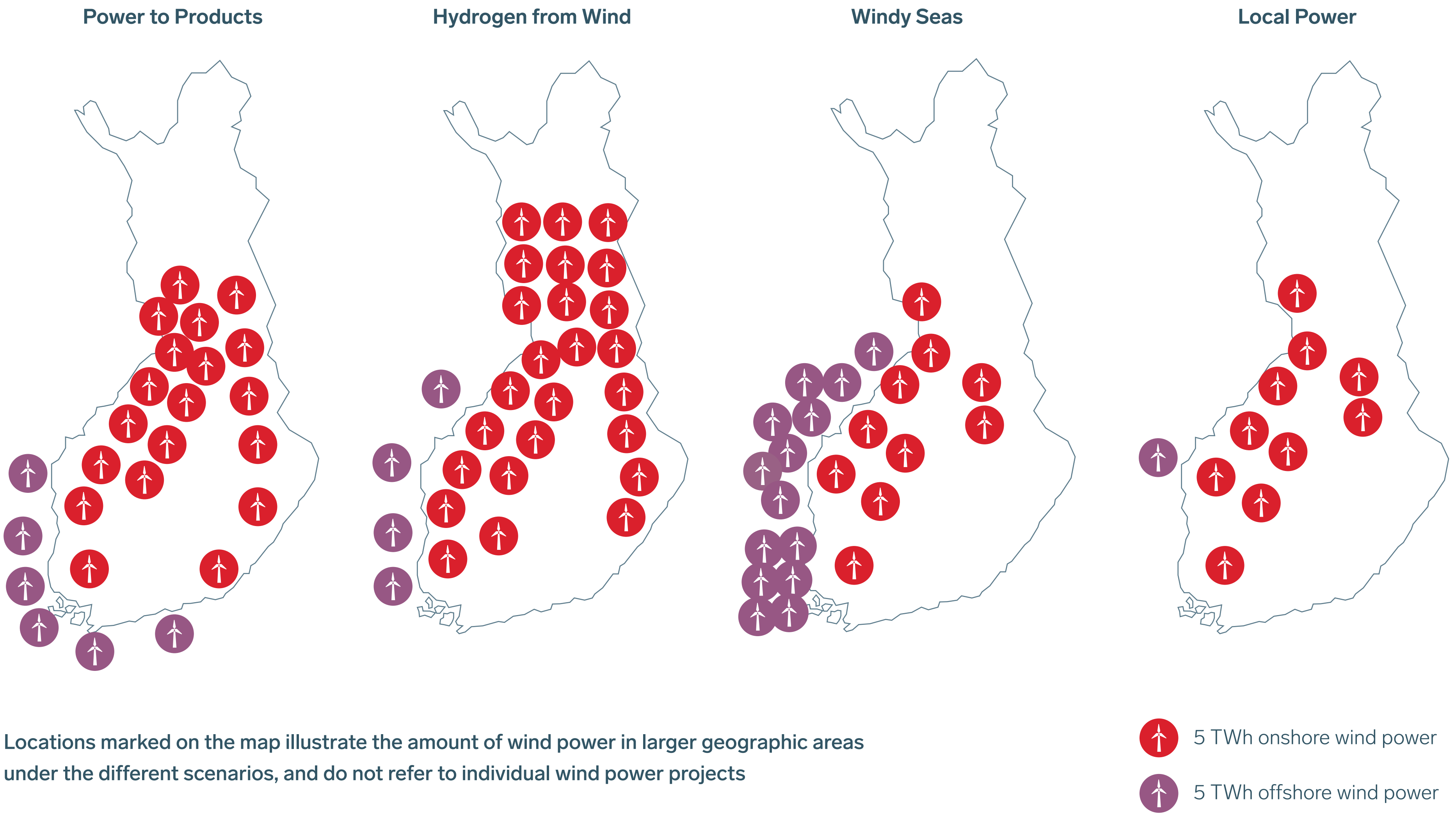
Electricity production in the Local Power scenario (TWh)	2021	2035	2045
Hydro power	16	14	14
Onshore wind power	8	43	43
Offshore wind power	0	6	6
Solar power	0	7	15
Nuclear power	23	46	53
Other thermal power	23	11	7
Total production	69	127	138
Consumption	87	115	131
Finland's power balance (net exports)	-18	12	7

2.7 Assumptions about the geographical distribution of production in the scenarios

Figures 6 and 7 illustrate assumptions about the geographical focus areas of electricity production. The Hydrogen from Wind scenario foresees the greatest geographical dispersion of onshore wind power around Finland, with significant amounts of capacity built in Ostrobothnia, Kainuu, eastern Finland and Lapland. In the Power to Products scenario, onshore wind power is more strongly concentrated in Ostrobothnia, although there are also significant volumes of wind power in eastern Finland. In addition, offshore wind power has the greatest geographical dispersion under the Power to Products scenario, with some of the capacity in the Gulf of Finland. In the Windy Seas scenario, wind power is packed into western Finland when offshore wind power is built on the west coast, and onshore wind power is concentrated in western Finland.

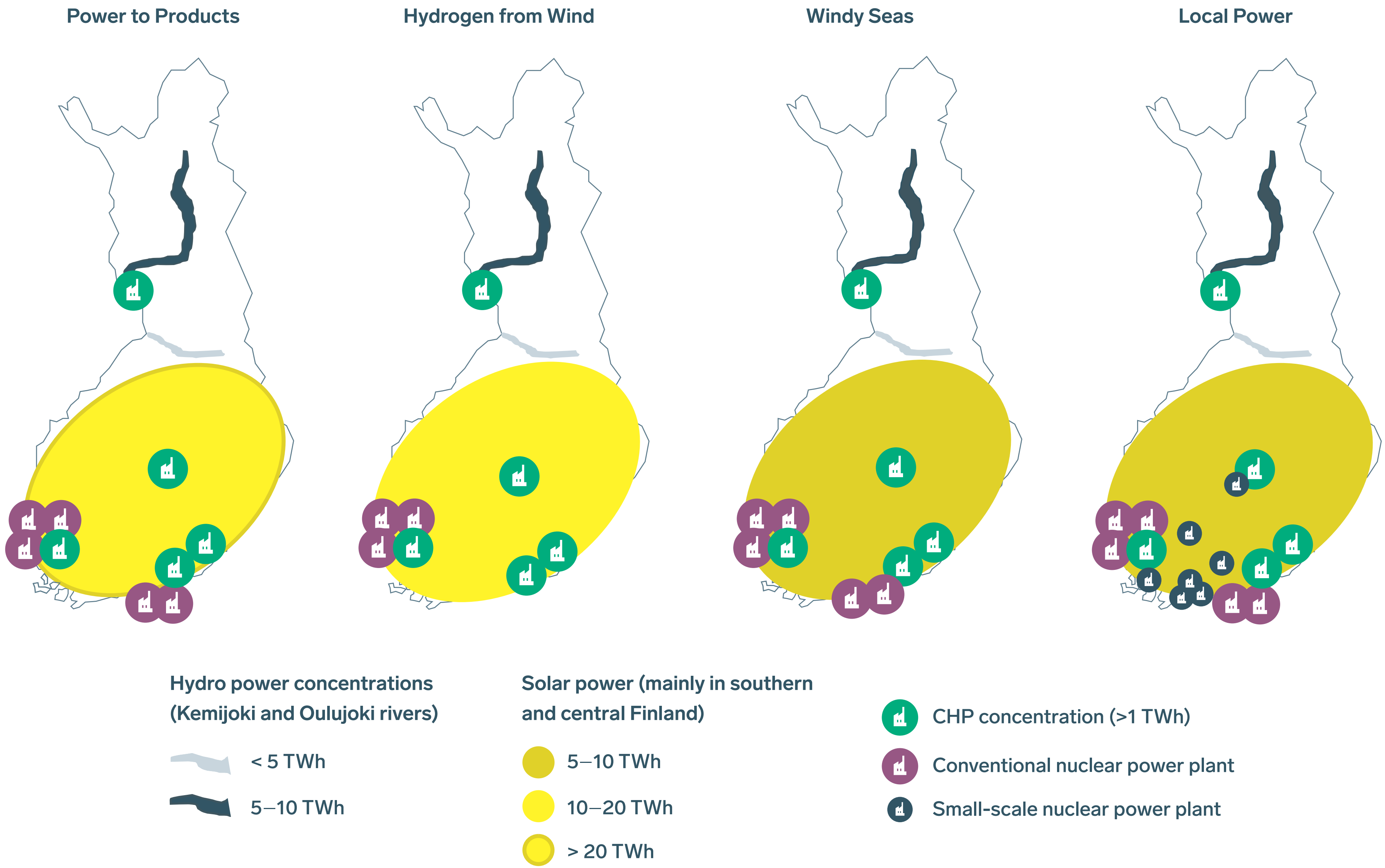
Solar power is mainly located in southern and central Finland, where both roof-mounted capacity and most of the large solar parks are concentrated. In the Local Power scenario, small-scale nuclear power plants are built in the large cities of southern Finland. In 2035, the remaining combined heat and power is based on forest industry side streams and other biomass, and the most significant production concentrations are around the existing bioproduct clusters.

Figure 6 Assumptions about the geographical focus areas of wind power in 2035.



Locations marked on the map illustrate the amount of wind power in larger geographic areas under the different scenarios, and do not refer to individual wind power projects

Figure 7 Assumptions about the geographical focus areas of solar, hydro, nuclear and thermal power in 2035.



2.8 Cross-border connections in the scenarios

2.8.1 Sweden

Today, two 400-kilovolt AC transmission links connect northern Finland to the SE1 bidding zone in Sweden, and two DC transmission links connect southern Finland to the SE3 bidding zone in central Sweden. In addition to the existing transmission links between Finland and Sweden, all the scenarios include the Aurora Line 1 and Aurora Line 2 links between northern Finland and northern Sweden. Aurora Line 1 will increase the SE1—FI transmission capacity to 2,000 megawatts in both directions, adding 800 megawatts of transmission capacity from Sweden to Finland and 900 megawatts from Finland to Sweden. Aurora Line 2 is expected to increase the transmission capacity by another 800 megawatts in the Hydrogen from Wind, Windy Seas, and Local Power scenarios, raising the capacity at the SE1—FI border to 2,800 megawatts. The Power to Products scenario foresees the link being built as a 2 x 400-kilovolt connection, so the additional transmission capacity used in the calculations is 1,600 megawatts, for a total capacity at the SE1—FI border of 3,600 megawatts. The service life of the Fenno-Skan 1 transmission link extends until 2040, so the link is still used in 2035 in all the scenarios. Furthermore, the scenarios assume an end to the internal transmission restrictions in Sweden that currently limit electricity exports from Finland to the SE3 zone. Consequently, the transmission capacity between Finland and SE3 is 1,200 megawatts in both directions in 2035. The Hydrogen from Wind and Windy Seas scenarios assume the construction of the planned Nordic Hydrogen Route, a hydrogen pipeline connection, so northern Finland and northern Sweden will have cross-border electricity and hydrogen transmission capacity. The scenarios do not consider any changes to the geographical distribution of Sweden's bidding zones.

The profitability of new cross-border connections to Sweden is highest under the Power to Products scenario, as the value of cross-border connections as a source of system flexibility is emphasised when there is less flexibility available from hydrogen production. The profitability of a cross-border connection refers to the net economic benefits accruing to market parties, consisting of the change in consumer benefits, producer benefits, and congestion income minus the costs of building and maintaining the connection. The profitability is weakest under the Local Power scenario due to lower electricity consumption and a more even production structure, which reduces price differences between countries in comparison with the other scenarios. In the Hydrogen from Wind and Windy Seas scenarios, the profitability is good, despite the fact that hydrogen production in these scenarios is flexible and cross-border capacity for electricity and hydrogen is available between Finland and Sweden. Cross-border hydrogen transmission capacity enables the electricity consumption of flexible electrolysers to be optimised. However, as electricity consumption increases, the need for new cross-border electricity transmission connections in other sectors will not go away, although the need will naturally be smaller.

As in previous studies, the need for the Fenno-Skan 3 connection appears to increase according to the amount of electricity available for export. Conversely, the need for the Aurora Line 2 connection is greater if there is a shortage of balancing resources. In addition to the market benefits, Aurora Line 2 will enable new electricity production and consumption facilities to be integrated into the electricity networks in northern Finland and northern Sweden more quickly and strengthens the synchronous connection between Finland and Sweden. Fingrid will assess the benefits of the Aurora Line 2 connection in more detail in a joint study with the Swedish transmission system operator, Svenska kraftnät.

2.8.2 Norway

Today, there is a 220-kilovolt AC connection between Finland and Norway, primarily used to balance the power system in the Finnmark region of northern Norway. The system vision scenarios assume that between the countries there is a bidding zone border line and capacity of this connection is increased to 150 megawatts, either through investments in a back-to-back link or as a consequence of other measures to strengthen the power grid in northern Norway.

The scenarios did not assume any new transmission links between Norway and Finland. Fingrid and Statnett have previously studied the prerequisites for building such a connection. The study indicated that for stability reasons, the capacity of the connection would remain low, the amount of electricity transmitted would be difficult to bring into line with the solution offered by the power exchange, and the risk of internal bottlenecks in northern Norway would increase. As Fingrid sees it, resolving these problems 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 would also be needed to direct the flow of power as desired between Northern Norway and Finland. 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-inverting transformers, or adjustable series compensation installations.

If a reasonably-priced solution were found that would allow the market-based transmission of electricity from the hydropower-intensive southern areas of bidding zone NO4 to southern Finland, its economic benefits should be investigated further. Such a connection would enable electricity to be traded between the Norwegian system, which is dominated by hydro power, and the Finnish system, dominated by wind power. The link could also offer connection opportunities for wind power in the Finnmark region. Statnett's ten-year network plan[10] sets out the long-term goal of a network in which the present NO4 bidding zone is bisected by two 400-kilovolt transmission lines to Skaidi. However, by 2030, the 2 x 400-kilovolt link would only be built between Ofoten and Skaidi. Taking into account the increase in electricity production and consumption in Norway, two 400-kilovolt transmission lines are likely necessary to facilitate the energy revolution in Norway alone; they would probably not create any surplus capacity that could boost the cross-border capacity without any new investments targeting the cross-border capacity on the Norwegian side. If a new transmission link were built between Finland and Norway which only boosted the capacity between Finland and Finnmark, the benefits of the link would be substantially smaller, as the link would, in practice, only serve to connect Norwegian wind power to the electricity system of Finland.

[10] https://www.statnett.no/globalassets/for-aktorer-i-kraftsystemet/planer-og-analyser/nup-2021/nettutviklingsplan-2021.pdf

2.8.3 Estonia

Today, there are two HVDC transmission links between Finland and Estonia – EstLink 1 and EstLink 2 – with a combined capacity of 1,016 megawatts. All the scenarios envisage the completion of the EstLink 3 transmission link between the countries by 2035. The assumed capacity of EstLink 3 is 700 megawatts. The EstLink 3 connection is most beneficial under the Windy Seas scenario. The weakest benefit is obtained in the Hydrogen from Wind scenario, due to the existence of a large, parallel hydrogen transmission connection.

In recent years, the main direction of transmission in the EstLink connections has been exports from Finland to Estonia. In the scenarios, the volumes of variable renewable production capacity in the Baltic region have significantly increased, diversifying the transmissions in the connections as the number of intermittent overproduction situations in the Baltics increases. Development is dependent on the attractiveness of the Baltic countries for wind and solar power investments, as all the scenarios assume less electricity production capacity based on fossil fuels in the Baltic countries. A further factor affecting the benefit of the EstLink 3 connection is whether the connection would only be between Finland and Estonia or whether the transmission capacity from Estonia via Latvia and Lithuania to Poland would be developed at the same time. Fingrid will assess the benefits of the EstLink 3 connection in more detail in a joint study with the Estonian transmission system operator, Elering.

2.8.4 Other cross-border connections

The Windy Seas scenario assumes a new electricity transmission connection from Finland to Germany, a connection that is also examined separately in the other scenarios. The market benefit of such a connection would be substantial due to the significant electricity price difference between Finland and Germany, assuming that the connection's capacity did not suffer from electricity transmission bottlenecks within Germany. On the other hand, the cost of building the connection would likely be very high – as much as several billion euros. Fingrid is not actively planning to build an electricity transmission connection to Germany, but the case was wanted to be examined in the scenario with electricity surplus.

In terms of hydrogen transmission connections, the Hydrogen from Wind scenario assumes a pipeline connection from Finland to Central Europe[11] (13 GW) and from northern Finland to northern Sweden[12] (7.2 GW). The Windy Seas scenario only assumes a pipeline connection between northern Finland and northern Sweden. The Hydrogen from Wind and Windy Seas scenarios assume a north-south pipeline connection inside Finland, linking production and demand facilities and cross-border connections for hydrogen. In the Power to Products and Local Power scenarios, no cross-border connections for hydrogen or intra-Finnish pipeline connections have been assumed.

2.8.5 Summary of the cross-border connections

Figure 8 summarises the cross-border transmission capacities in the 2035 scenarios. Figure 9 summarises cross-border transmissions in the 2035 scenarios (average weather over 35 years).

On average, the cross-border connections have net exports under all the scenarios, except for the transmission link between Finland and Norway (Finnmark), which is balanced. The largest exports occur in the Power to Products scenario, with a significant share of the exports heading to the SE1 zone to address growing consumption in the region. In the Hydrogen from Wind and Windy Seas scenarios, hydrogen accounts for some of the exported energy. In this case, the hydrogen is produced in Finland and exported as gas, leading to a low volume of electricity.

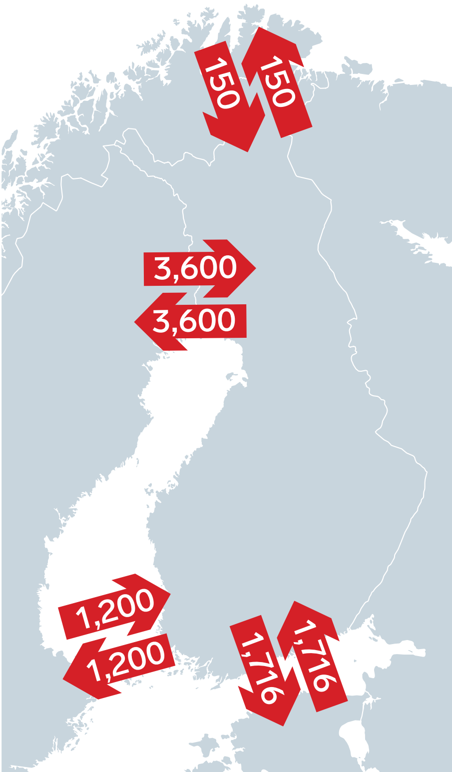
Although the transmission links are, on average, export connections, significant quantities of electricity are transmitted in both directions in all the transmission links. In this respect, the transmission profile of the connections deviates from the situation in recent years, where electricity is mainly imported from Sweden and exported to Estonia and trading rarely occurs in the opposite direction. In the system of the future, using the transmission links to manage fluctuations and keep the system balanced will be important. At the same time, transmissions will become more "two-way", so none of the transmission links will be used solely for imports or exports.

[11] Based on the European Hydrogen Backbone study, the size of the Central European pipeline is assumed to be 13 GW H2. The report is available at: https://gasforclimate2050.eu/wp-content/uploads/2021/06/European-Hydrogen-Backbone_April-2021_V3.pdf

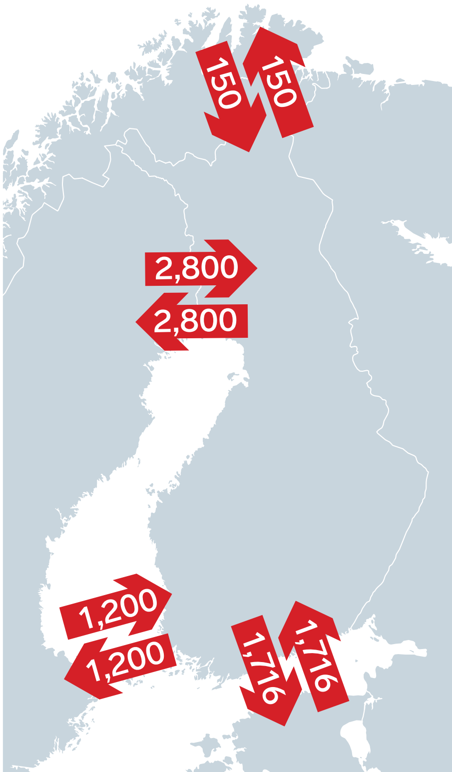
[12] Based on the Bothnian Bay Hydrogen Valley study, the size of the Swedish pipeline connection is assumed to be 7.2 GW H2. The report is available at: https://lutpub.lut.fi/bitstream/handle/10024/163667/Bothnian_Bay_Hydrogen_Valley_Research_Report_Final.pdf?sequence=1&isAllowed=y

Figure 8 **Cross-border electricity transmission capacity in the scenarios for 2035 (MW).**

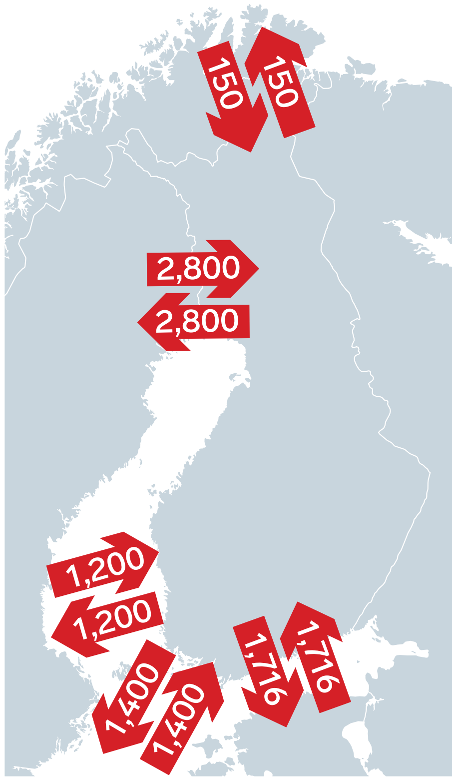
Power to Products
MW



Hydrogen from Wind
MW



Windy Seas
MW



Local Power
MW

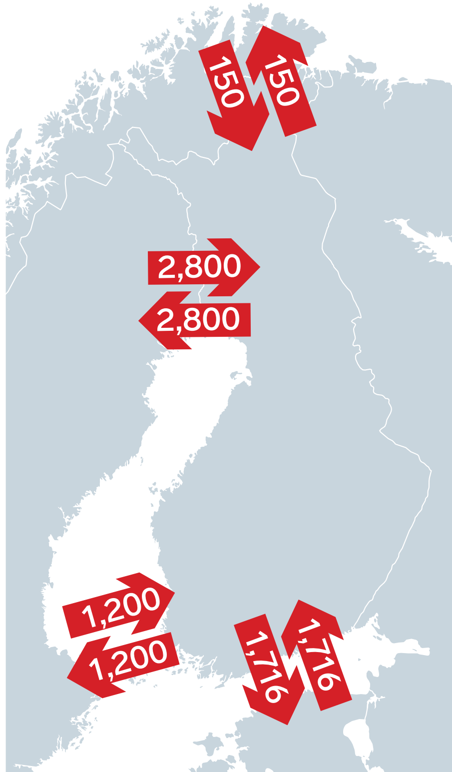
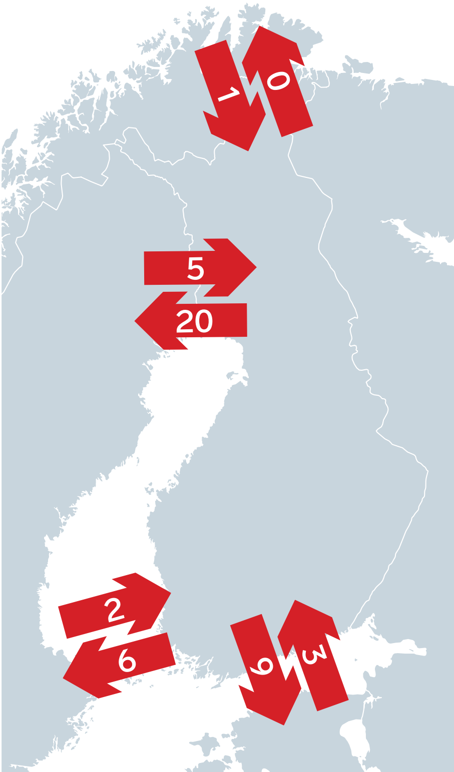


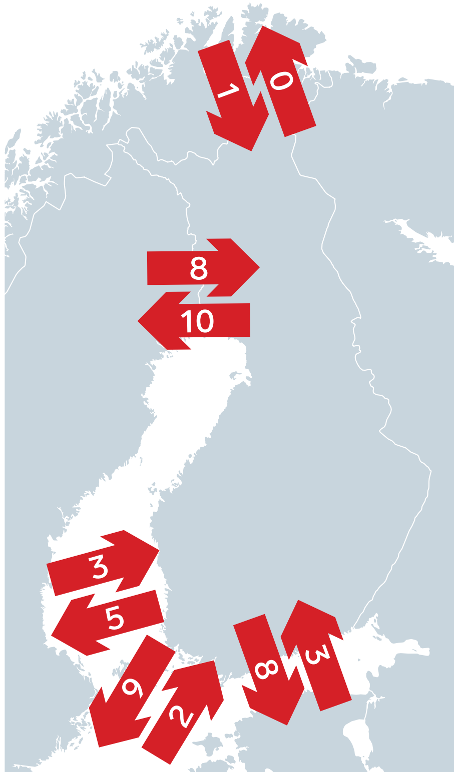
Figure 9 Cross-border transmissions of electricity in the scenarios for 2035 (TWh/a).

Power to Products
TWh/a



Hydrogen from Wind
TWh/a

Windy Seas
TWh/a



Local Power
TWh/a

3 Scenario themes

3.1 Development of electricity demand

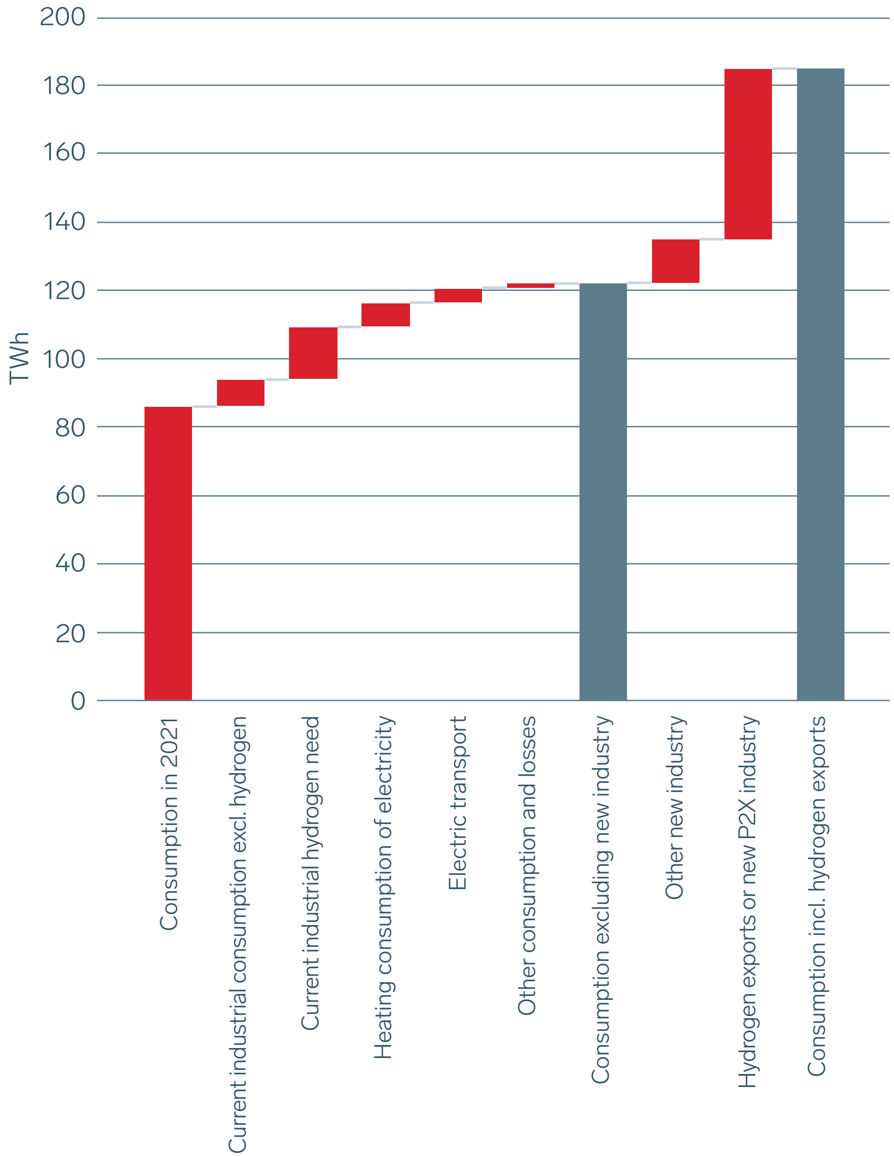
The scenarios anticipate a very strong increase in electricity consumption. Electricity consumption may even double from the current level by 2035, but consumption may also remain lower if one or more growth drivers do not progress. Figure 10 illustrates which components may constitute the growth required for doubling. The figure presents the development of consumption in the Hydrogen from Wind scenario, but the structure is similar in the Power to Products and Windy Seas scenarios, although the amount and purpose of P2X production differs between the scenarios.

The growth in current industrial consumption (+8 TWh, excluding hydrogen) has been estimated on the basis of low-carbon industry roadmaps, and in 2020–2035, it is driven especially by changes in energy sources in chemical and metal industry processes. In addition, the replacement of existing steam-reformed grey hydrogen from natural gas (140 KT/a, +7 TWh of electricity) and the estimated increase in demand for hydrogen in current industries (+180 KT/a, +9 TWh of electricity) would increase electricity consumption on the assumption that the replacement hydrogen is produced using electricity.[13]

Replacing fossil fuels in district heating and separate heating in buildings will increase electricity consumption. The growth depends on how much of the energy is obtained from waste heat and how much the heating needs of buildings decrease as a consequence of climate change and energy-efficiency measures. The scenarios estimate an increase of 7 TWh by 2035. Between 1 and 1.5 million electric and hybrid cars would consume an estimated 3–5 TWh of electricity in 2035. Other electricity consumption is estimated to decrease slightly as energy efficiency improves, but as transmissions increase, so do losses, so the electricity consumption in the "other consumption and losses" category remains stable in net terms.

[13] Hydrogen demand projection in current industries is assessed based on Business Finland's hydrogen roadmap https://www.businessfinland.fi/4abb35/globalassets/finnish-customers/02-build-your-network/bioeconomy--cleantech/alykas-energia/bf_national_hydrogen_roadmap_2020.pdf. Electrolysis efficiency assumed at 70%

Figure 10 Electricity consumption growth components in the Hydrogen from Wind scenario in 2035.

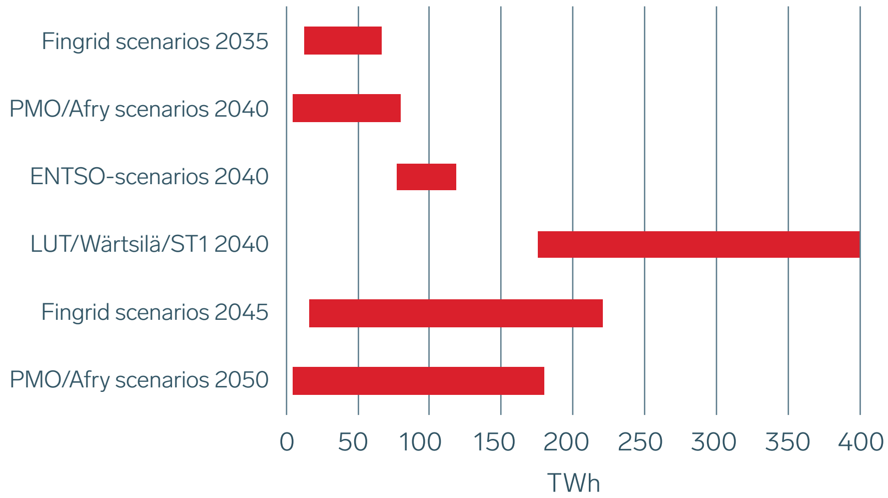


By 2035, the above changes would bring Finland's electricity consumption to a level of approximately 120–125 TWh, which would correspond to an increase of approximately 40–45 per cent compared to the current situation. In addition to this growth, it is possible – or even probable – that clean and competitively priced electricity would attract new industries to Finland. It is difficult to estimate the growth potential of new industrial consumption accurately, but the magnitude of the electricity consumption of an individual site is given, for example, by the annual electricity consumption of a large battery factory, which can be about 3 TWh.[14] A relatively small number of large sites in the electricity-intensive parts of the battery industry value chain could clearly increase electricity consumption. New data centres can also significantly increase electricity consumption.

In the scenarios, the P2X industry and related hydrogen production are the biggest drivers of growth in terms of size. Finland not only has excellent potential for clean electricity production, but also bio-based carbon dioxide for the production of P2X-processed products and a use for the waste heat generated in the process. It could also be possible to export hydrogen produced in Finland to the rest of Europe using pipeline infrastructure, which would significantly increase electricity consumption (by several dozen terawatt hours)[15]. In addition to Central Europe, a potential target for hydrogen pipeline exports is northern Sweden, where LKAB[16] alone estimates that it will need hydrogen corresponding to up to 70 terawatt-hours of electricity production, of which 20 TWh would be needed as early as 2030.

Figure 11 compares the electricity consumption related to hydrogen production in the system vision scenarios with those of other parties. The scenarios have been extracted from three different reports, which are the "Carbon-neutral Finland" report[17] by LUT, Wärtsilä and ST1; the "Hydrogen economy – Opportunities and limitations" report[18] by the Prime Minister's Office and Afry; and the ten-year network plan of ENTSO-E and ENTSOG (TYNDP2022)[19].

Figure 11 Use of electricity for hydrogen production in the system vision scenarios compared to other parties' scenarios.



[14] An example calculated based on the electricity consumption of the Northvolt Ett battery factory (360 MW, source: https://northvolt.com/manufacturing/ett/) and the assumption of 8,000 h/a operating time.

[15] The European Hydrogen Backbone study listed pipeline sizes of 1.2, 4.7 and 13 GW. For example, with a utilisation period with the maximum load of net transmission 4,000 h/a, a 4.7 GW pipeline would transmit 19 TWh of hydrogen, the production of which would require 27 TWh of electricity. Similarly, for a 13 GW pipeline, the corresponding figures would be 52 TWh of hydrogen and 74 TWh of electricity.

[16] LKAB announced that it would need 20 TWh of electricity in 2030, 50 TWh in 2040 and 70 TWh in 2050 "mainly for the production of hydrogen gas". https://www.lkab.com/en/news-room/press-releases/a-faster-pace-and-higher-targets-in-lkabs-transition-towards-a-sustainable-future/?aid=16447

[17] https://www.lut.fi/uutiset/-/asset_publisher/h33vOeufOQWn/content/lut-wartsila-ja-st1-power-to-x-ratkaisut-tulee-nostaa-suomen-energia-ja-ilmastoratkaisujen-ytimeen

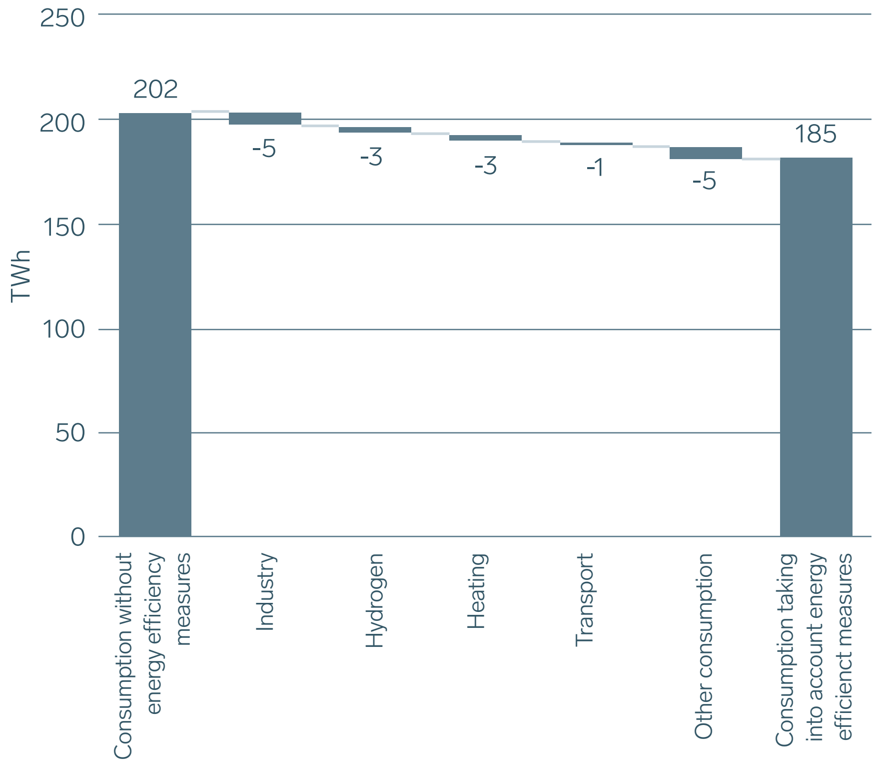
[18] https://julkaisut.valtioneuvosto.fi/bitstream/handle/10024/163901/VNTEAS_2022_21.pdf?sequence=1&isAllowed=y

[19] https://2022.entsos-tyndp-scenarios.eu/visualisation-platform/ data retrieved on 10 February 2022

Although the increase in electricity consumption related to hydrogen production is significant in the system vision scenarios – and in the Power to Products and Hydrogen from Wind scenarios, it exceeds Finland's current electricity consumption in 2045 – it is similar to or lower than the increase in the two scenarios of the Carbon-neutral Finland report. In the scenario that envisages Finland's bio-based carbon dioxide emissions being used to manufacture P2X products, the amount of electricity consumed for hydrogen production is similar to the amount in the system vision scenarios. In the second scenario in the Carbon-neutral Finland report, fossil carbon dioxide emissions are also utilised for hydrogen production, so hydrogen production consumes significantly more electricity than in the system vision scenarios. On the other hand, the scale of the system vision scenarios for the electricity consumption of hydrogen production is slightly higher than the scenarios in the report by PMO and Afry. In the Power to Products and Hydrogen from Wind scenarios, the electricity consumption of hydrogen production is roughly in line with the TYNDP2022 draft scenarios, taking into account that the ENTSO scenarios have been prepared for 2030, 2040 and 2050, while Fingrid's scenarios are for 2035 and 2045.

Although Finland's electricity consumption grows strongly in all scenarios, the effects of more efficient overall use of energy have not been forgotten. Figure 8 presents the impact of energy efficiency improvements in 2035 in the Hydrogen from Wind scenario. More efficient use of electricity takes place in all sectors, and without it, electricity consumption would be almost 10% higher.[20] The calculation only takes into account the efficiency gains in electricity use. Overall energy use will become even more efficient when we switch from fossil fuels to the use of electricity in transport and heating. For example, an electric passenger car consumes about 20 kWh of energy per 100 km, while an internal combustion engine car uses about 45 kWh over the same distance.

Figure 12 Energy efficiency assumptions in 2035 in the Hydrogen from Wind scenario.



[20] The calculation assumes an improvement in the energy efficiency of industrial electricity use by 0.5% p.a. The efficiency of electrolysis is assumed to increase to 70% by 2035. The final use of heating energy has been estimated to decrease by 0.5% p.a. due to the improvement in the energy efficiency of buildings, including the impact of global warming. In addition, energy efficiency improvements have been taken into account in heating due to the development of heat pump technology and the replacement of direct electric heating. The improved energy efficiency of electric cars has been taken into account in transport. For households, the impact of more efficient energy use of household appliances has been taken into account by about 100 GWh p.a. For services, energy efficiency has been assumed to improve by 1% p.a. Sources of the assumptions: Finnish Energy, Chemical Industry Federation of Finland, ENS.dk, Fingrid, Finnish Ministry of Transport and Communications

3.2 Competitiveness and potential of Finnish electricity production

The price and availability of clean electricity is a key factor influencing the operating environment of the electricity-intensive industries in the future. In addition, a high security of supply in the transmission and distribution of electricity is a prerequisite for the consumption and production of electricity. Due to its high onshore and offshore wind potential, Finland is in an excellent position to compete for investments in the sector. In addition to these, Nordic hydro power, nuclear power and bioenergy are resources that not all of Finland's competitors have at their disposal. The potential of solar power in Finland is also significant, especially from the perspective of the land area available. Similarly, in many Central European countries, the further construction of onshore wind power is difficult, the share of nuclear power is small or nuclear power is being abandoned, and the share of hydro power is low. In addition, the share of fossil production in the electricity and energy system is substantially higher in many European countries than in Finland, and greater share of new built renewable energy is needed to substitute the old production.

Finland's wind power potential is very high. In the beginning of 2023 Fingrid has received almost 250,000 MW enquiries for the connection of electricity production to the main grid. About two-thirds of the projects are onshore wind power, which offers excellent cost-competitiveness by European comparison. The proportions of solar power and offshore wind power are also rising sharply. If all the projects were to be implemented, they would generate almost 800 TWh of renewable electricity. Naturally, not all the enquiries will be realised as completed projects. However, there were about 90,000 MW of project enquiries in spring 2021, so the number of enquiries nearly doubled by the beginning of 2023. There is also no reason why the wind or solar power potential in Finland should be any lower than that in Germany, which has a similar territorial area and a much higher population density. Germany aims to have approximately 600 TWh of wind and solar power production in 2030 and almost 900 TWh of wind power in 2035[21].

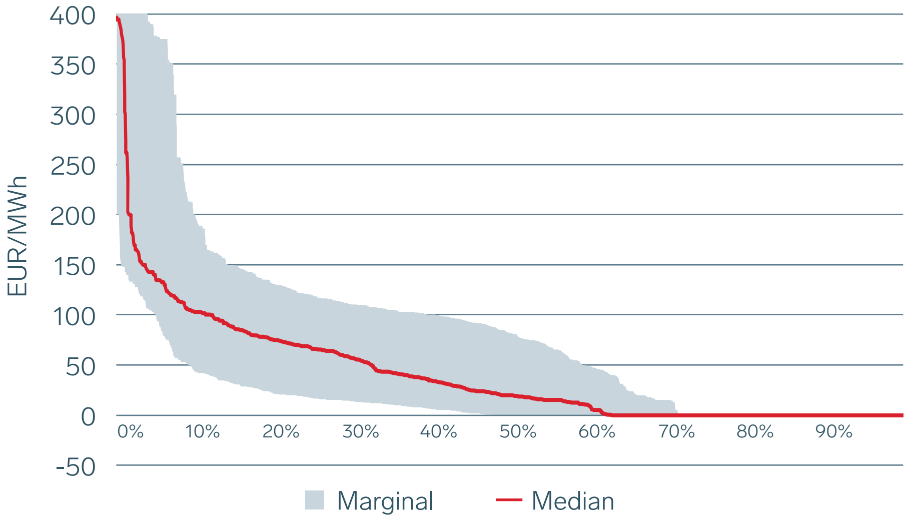
A potential of 800 TWh is estimated to correspond to more than 15% of the total EU wind and solar power potential, using the potentials derived from the TYNDP2022 scenarios as the EU benchmark[22]. Correspondingly, Finland accounts for just over 3% of the EU's current electricity consumption. For Finland, the potential of wind and solar power is many times higher than the need for electricity and hydrogen, which is uncommon in Europe, based on the TYNDP2022 scenarios. In the long term, many EU countries need clean imported electricity, imported hydrogen, or imported products made from these, and Finland, as an EU country, is well placed to export these to other parts of Europe. Despite relatively large exports of energy and energy-intensive products, the simulated scenarios foresee a much lower average electricity price[23] in Finland than in Central Europe.

3.3 Flexibility

In the electricity system, flexible electricity generation has traditionally evened out fluctuations in electricity consumption. Hydro power and thermal power plants using stored fuels have offered the necessary flexibility. In the scenarios, a significant increase in electricity consumption and renewable production that varies according to the weather, along with a decrease in fossil-fuelled thermal power generation, increase the need for flexibility in order to maintain the balance between consumption and production in the electricity system. In the scenarios, larger volumes of energy storage and demand-side response provide flexibility in addition to the balancing capacity of production. This section presents the assumptions made in the scenarios regarding the flexibility available in the day-ahead market.

Fluctuations in[23] electricity prices create incentives, especially for energy storage and demand-side response. Price fluctuations increase as the amount of weather-dependent renewable production increases. For example, at windy times, there is less need for more expensive forms of electricity, and the electricity price decreases. Conversely, when there is not much wind, electricity is

Figure 13 **The electricity price duration in the Power to Products scenario**[24]



produced using more expensive forms of production, causing the electricity price to rise. Flexible consumption behaviour and the use of storage facilities can, for example, help to avoid using electricity when prices are higher, yielding savings for consumers. This encourages flexible consumption patterns according to price fluctuations. Fluctuations in electricity prices can also encourage investments in adjustable peak power.

Figure 13 presents a duration curve of the electricity price and its range according to different weather scenarios in the Power to Products scenario in 2035. Similarly, Figure 14 presents a median duration curve of the electricity price in all the scenarios for 2035. The figures show that the electricity price varies considerably, despite the flexibility already assumed in the scenarios.

Flexibility is also emphasised between scenarios (Figure 14): In the Local Power scenario, the amount of electricity consumption and variable production is lower and the system is relatively more flexible, which helps to even out the variation in production costs. In the Windy Seas and Hydrogen from Wind scenarios, the flexibility of the hydrogen system (hydrogen storage, pipeline connections) evens out the variation in production costs despite the high share of variable renewable electricity production. In the Power to Products scenario, where the amount of storage is smaller, the system is relatively less flexible. In the Power to Products scenario, both very high and very low marginal production costs are seen in several hours of the year, which means that low-cost electricity cannot be fully utilised.

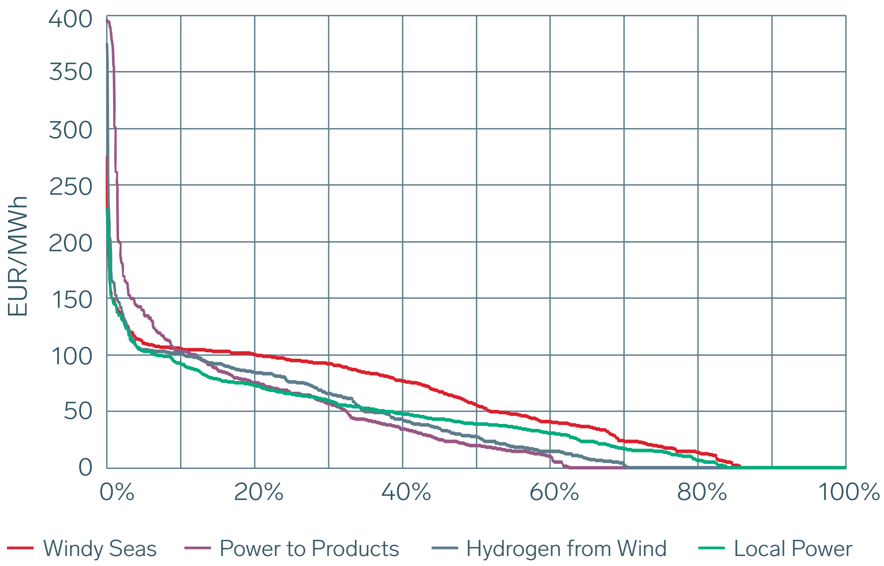
[21] https://www.bmwk.de/Redaktion/EN/Downloads/Energy/0406_ueberblickspapier_osterpaket_en.pdf?__blob=publicationFile&v=5

[22] In the TYNDP2022 draft scenarios for 2050, the combined production of wind and solar power was ~5,000 TWh in the Distributed Energy scenario and ~4,400 TWh in the Global Ambition scenario. The sum of the maximum production calculated on a country-by-country basis was approximately 5,300 TWh.

[23] Price refers to the resulting marginal cost in the market simulations of the scenarios.

[24] The y-axis of the graph is truncated for readability; the upper bound of the range extends many times higher in the figure.

Figure 14 **The electricity price duration in the 2035 scenarios (median).**



In the scenarios, not all of the weather-dependent renewable production can be profitably exploited under all circumstances. The model assumes that producers reduce their production with renewables when the electricity price is low in order to balance supply and demand. In such a case, low-cost renewable electricity is lost. However, it may not be cost-effective to use all the available energy at all times, as it would require additional investments in storage facilities, for example, which may be more expensive than simply not using the surplus electricity.

Table 14 shows the amount of renewable energy limited on market terms during the year in relation to the total energy that could be produced with renewables during the year. The renewable energy capacity is very high in the Power to Products and Hydrogen from Wind scenarios, highlighting the limitation of production. Renewable production is, nevertheless, profitable in relation to the cost assumptions. In the Power to Products scenario, the amount of storage is limited, leading to a larger market-based decrease in production. In the Windy Seas and Local Power scenarios, the renewable capacity is slightly lower, and production can be utilised effectively with the help of the demand-side response and transmission links envisaged in these scenarios.

Table 14 Market-based limitation of renewable electricity production in the scenarios.

Market-based limitation of energy production during the year as a proportion of total production without any limitations (%)	Power to Products	Hydrogen from Wind	Windy Seas	Local Power
2035	10%	8%	1%	< 1%
2045	4%	2%	1%	< 1%

Figure 15 presents the distribution of production in the scenarios into adjustable production and grid energy storage, as well as variable renewable wind and solar power. In the scenarios, flexibility and adjustable power are obtained from existing hydro and thermal power, among others, while nuclear power provides a steady rate of production. The forms of production mentioned above provide approximately 10 GW in the scenarios. Hydro power is very important for balancing the system, but the scenarios assume that the amount cannot be increased much. In contrast, the Hydrogen from Wind scenario assumes a decrease in the volume of hydro power, reducing the peak power available from hydro power to approximately 1.7 GW, instead of the 2.5 GW used in the other scenarios. Due to the lower hydro power, additional wind power and hydrogen-powered electricity production capacity was added to the Hydrogen from Wind scenario. Hydrogen from Wind scenario also requires the flexibility provided by hydrogen storage and grid energy storage facilities for short-term flexibility.

The Power to Products and Hydrogen from Wind scenarios also assume the construction of some new generator power plants. The scenarios assume that these adjustable peak power plants can boost their profitability by generating income from revenue sources such as the reserve market in addition to the electricity wholesale market. Otherwise, no major investments in new thermal power capacity are assumed. In addition, the scenarios assume that mainly it is not worthwhile for conventional nuclear power plants to adjust on the wholesale market, so the plants are assumed to participate in the wholesale market mainly at full capacity. In energy storage, electric batteries work well for short-term flexibility lasting a few hours, but are not a cost-effective solution for longer-term flexibility.

In terms of profitability, increasing the volume of adjustable production by a significant amount seems challenging in the scenario analysis. For this reason, new flexibility is obtained mainly from consumption in these scenarios. In demand-side response, electricity consumption can be temporarily reduced and, at best, energy can be stored as heat or hydrogen for longer periods for later use.

Figure 16 presents the demand-side response available in the scenarios during a consumption peak. Demand-side response is split into four categories: industry (excluding electrolysis), electrolysis, electric heating, and transport. The amount of demand-side response available from different sources varies according to the scenario, depending on the underlying assumptions. The amount of flexibility provided by electrolysers depends on the electrolysis capacity and hydrogen storage capacity. In the Local Power scenario, hydrogen cannot be stored or imported, so the electrolysers are inflexible. The flexibility of the rest of industry is relatively the same in the scenarios, but higher total industrial consumption increases the amount of flexibility. In the case of electric heating and transport (electric cars), the assumptions about flexibility are also proportionally the same between the scenarios. Compared to the other scenarios, the electrification of heating in the Local Power scenario is not as strong, which reduces flexibility.

Figure 15 Hourly peak production by different forms of production and their distribution into adjustable and variable production in the scenarios in 2035.

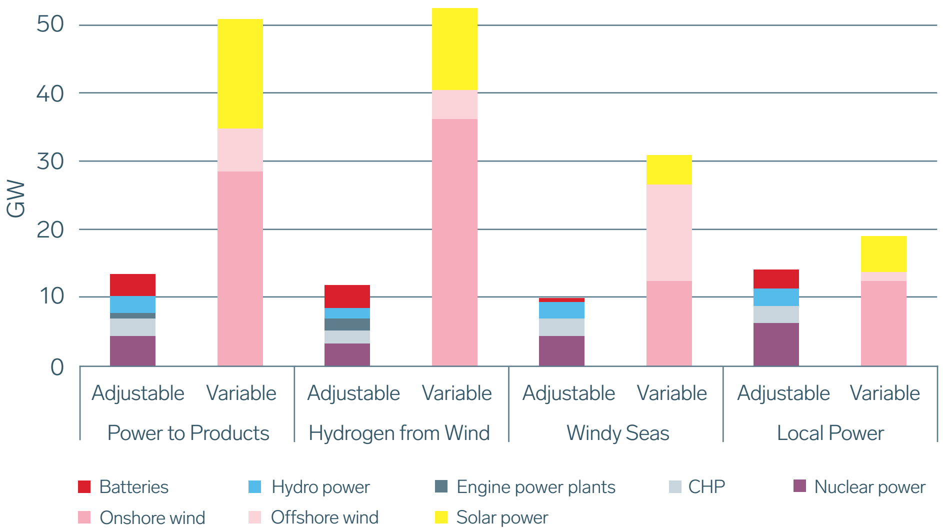
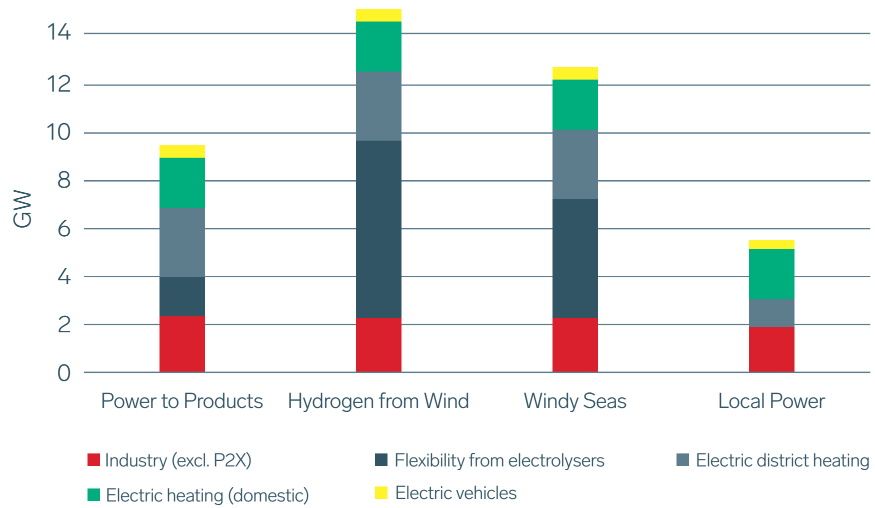


Figure 16 Demand-side response available in different scenarios during a consumption peak in 2035.[25]



[25] The calculation of the amount of demand-side response in the figure is based on a comparison with a situation in which the category is at its maximum consumption and would not provide any flexibility. For example, industrial consumption is even by nature, and the presented flexibility is available throughout the year. In contrast, the energy consumption of heating varies depending on the demand for heat, and the flexibility available from it fluctuates accordingly.

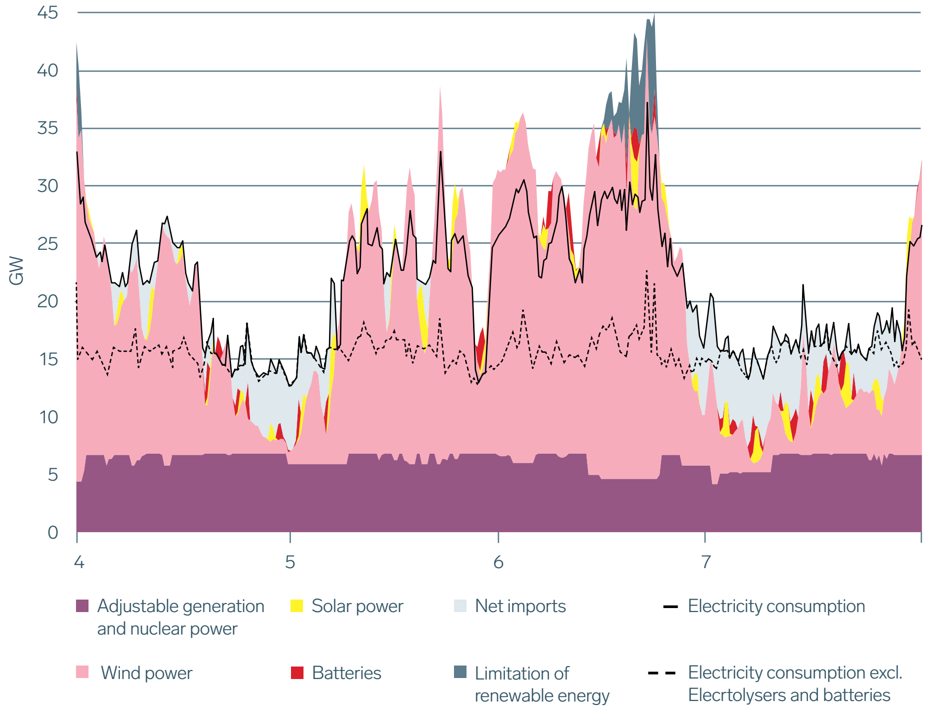
Table 15 Sources of demand-side response in the scenarios. Flexible share presented for 2035.

Category	Source	Type	Flexible share	Duration
Industry (excl. electrolysis)	Data centres	Cutting	5%	Hour
	Traditional manufacturing industry	Cutting	18%	Several hours – days
	Electrified heating processes	Restoring	9%	Several hours – days
Electrolysis	Flexibility of electrolysers	Storing	0–100%	Several hours – days
Heating	Electric heating of households	Restoring	40%	A few hours
	Electric district heating	Cutting	85%	Several hours – days
Transport	Smart charging of electric vehicles	Storing	70%	Several hours – days

Table 15 specifies the sources of demand-side response under the categories and breaks down demand-side response into three types: cutting, restoring, and storing. The cutting type requires electricity users to reduce their consumption when a threshold price is surpassed. The restoring type requires electricity users to postpone their consumption if the price difference leads to greater savings than the flexibility threshold price. In the storing type, energy can be stored, for example as electricity, heat or hydrogen, so electricity consumption is optimised according to price within the constraints of storage and final demand (for example, heat or hydrogen). Appendix 2 describes the assumptions described in the table in more detail.

In order to illustrate the available demand-side response and variation in renewable production, the hourly balance of electricity in the Hydrogen from Wind scenario is presented below for a four-week period of low temperatures and varying wind conditions (Figure 17). The figure shows that the variation in wind power production is very significant. In the least windy hour, production is below 1 GW, while in the windiest hour, it is close to 40 GW. During the windiest hours, production is also limited to maintain balance in the power system.

Figure 17 An example of hourly electricity production and consumption in the Hydrogen from Wind scenario in the reference year of 2035, based on four winter weeks in climate year 2009.



To utilise wind power, the rest of the system, in practice, adjusts to fluctuations in wind power production under the scenarios. This includes the adjustment of hydro and thermal power, charging and discharging grid energy storage facilities, demand-side flexibility, and the use of electricity transmission connections for both imports and exports. Of these, consumption varies most over the period under review. In demand-side flexibility, electrolysers (P2X) are especially flexible in that they do not produce hydrogen when there is no wind and, consequently, no cheap electricity available.

The substantial increase in consumption foreseen by the Windy Seas, Power to Products and Hydrogen from Wind scenarios is based on a significant rise in wind power production, enabling a competitive average electricity price. However, this calls for flexibility in the types of electricity consumption that are most reliant on low-cost electricity in the scenarios. The scenarios assume that flexibility can be obtained from controlled production and grid energy storage facilities, but the scenarios assume that consumption provides a significant proportion of the flexibility.

3.4 The surrounding world

For the rest of Europe, the scenarios are based on the draft scenarios of ENTSO-E and ENTSOG's ten-year network plan (TYNDP2022), data from Nordic TSOs, and Fingrid's own calculations on the profitability of forms of electricity and hydrogen production and storage. The TYNDP2022 scenarios are based on the operating environment before Russia invaded Ukraine. For this reason, the source data for the scenarios was updated to account for factors such as the rise in fossil fuel prices in relation to the prices used in the TYNDP scenarios. The prices of coal and natural gas used in the scenarios are based on values provided in the context of the EU REPower plan[26].

The scenarios assume that Sweden's future development will be similar to that of Finland. Sweden, like Finland, has good potential for increasing clean electricity production, so it was decided to look at scenarios in which clean energy production and demand increase in both Finland and Sweden. Sweden's electricity and hydrogen use increases in all scenarios, but the growth is particularly high in the Power to Products scenario, which also extends the service life of Sweden's nuclear power, as in Finland. Correspondingly, under the Hydrogen from Wind scenario, large quantities of hydrogen are produced in Sweden while the nuclear and hydro power capacities decrease. In the Local Power scenario, small-scale nuclear power plants are also built in Sweden.

[26] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=SWD%3A2022%3A230%3AFIN&qid=1653033922121

4 Main grid strengthening needs under the scenarios

The need to transmit electricity from north to south will increase significantly under all the scenarios compared with today. The need for electricity transmission increases the most under the Hydrogen from Wind and Power to Products scenarios, which foresee the greatest increases in consumption and a larger proportion of electricity production in northern and eastern Finland than the other scenarios. Under the Hydrogen from Wind and Windy Seas scenarios, some of the electricity transmission needs can be covered by transmitting hydrogen instead of electricity. Under the Local Power scenario, the need for transmission is much lower than in the other scenarios due to lower overall electricity consumption and a greater proportion of electricity consumption being located in southern Finland. Under the Windy Seas scenario, the growth in the need for transmission is offset by the fact that a significant proportion of the offshore wind power is assumed to be below cross-section Central Finland, between Vaasa and Turku. In the Windy Seas scenario there is also significant transmission need from west coast to inland, however the pressure on transmission need is decreased due submarine cable connection, included in the scenario, that enables electricity export from west coast to Germany. In addition, without the new consumption located in west coast, the pressure for transmission need towards inland would grow even more.

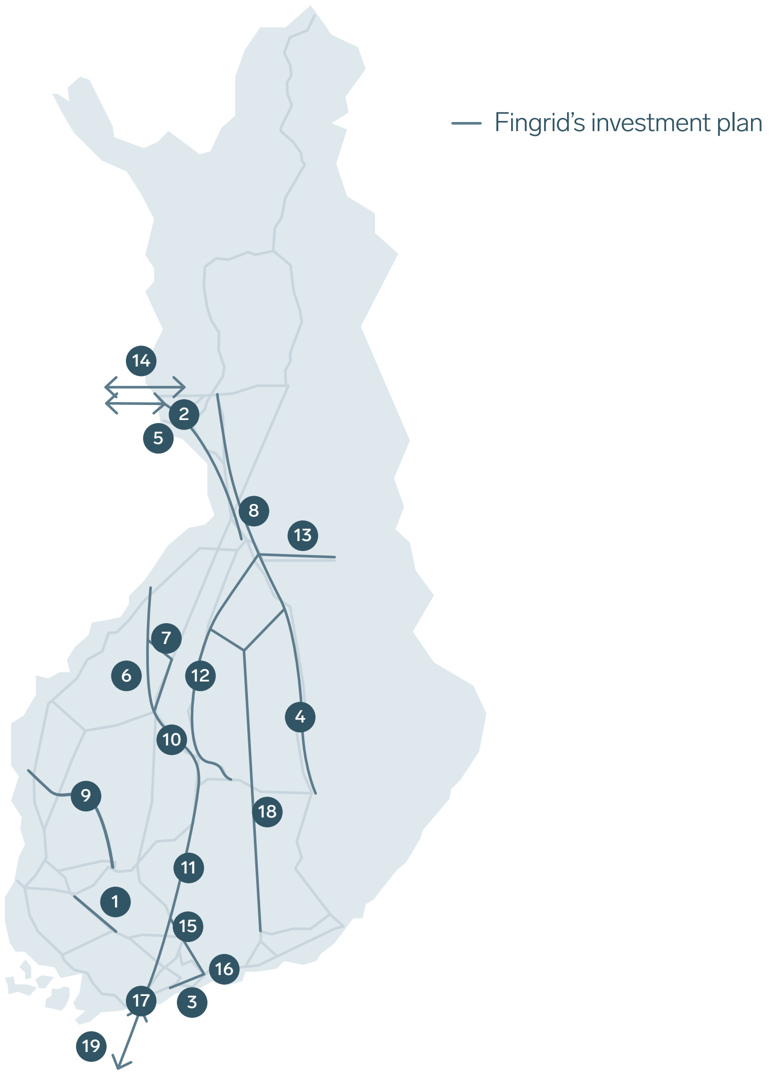
When the scenarios were created, market modelling assumed there would be no restrictions on transmission capability within the bidding zone. In reality, however, the transmission capacity of the physical electricity grid is limited. Network analyses of the scenarios seek to identify the need to strengthen the grid to yield adequate transmission capacity to cover the needs foreseen in the scenarios. A further aim of the analysis is to identify strengthening needs arising under several scenarios and, therefore, serve several possible future development outlooks. Sections 4.2–4.6 present the strengthening needs identified in each scenario and in several scenarios.

In addition to the existing main grid, all the scenarios are based on 400 kV strengthening in accordance with Fingrid's present investment plan. Figure 18 shows the investment plan. Therefore, the analysis covers the strengthening needs required under each scenario in addition to the present investment plan. In terms of the investment plan and the strengthening needs in each scenario, it is worth remembering that the grid is built in phases, one connection at a time. Fingrid builds the grid based on customer needs. As it is only possible to build a limited number of new connections and such connections take time to build, construction to strengthen the main grid takes place first in the places where there is a need for tangible projects that are feasible also from the perspective of permission. The need for electricity transmission may change during the implementation of the investment plan, and every investment decision is considered separately in light of the latest information on the necessity of each connection.

Network reinforcements in accordance with the investment plan 2023–2033

1	Huittinen Forssa (2025)
2	Aurora Line (2025)
3	Helsinki cable link (2026)
4	Strengthening the Lake Line, Nuojuankangas–Huutokoski (2026)
5	Raising the capacity between Svartby and Keminmaa (2026)
6	Jylkkä–Alajärvi x2 (2027)
7	Ullava – Halsua – Alajärvi (2027)
8	Petäjäskoski–Nuojuankangas (2027)
9	Kristinestad–Nokia (2028)
10	Alajärvi–Toivila (2028)
11	Extending the Forest Line, Toivila–Hikiä x2 (2028)
12	Strengthening the Forest Line, Nuojuankangas–Vihtavuori (2030)
13	Nuojuankangas–Seitenoikea (2030)
14	Aurora Line 2 (2030)
15	Hausjärvi–Anttila (2030)
16	Länsisalmi–Anttila (2030)
17	Hikiä–Kynnar–Ingå (2031)
18	Ridge Line x2 (2032)
19	Estlink 3, HVDC link (2033)

Figure 18 Fingrid's investment plan for the main power grid.



4.1 The network calculation process

A baseline model was created in the calculation software to prepare network analyses for the system vision. The baseline model describes the existing main grid and the network reinforcements in accordance with Fingrid's investment plan. The baseline model also contains a rough model of the network connections required for new electricity production by adding, among other things, the necessary 400/110 kV transformers. The connections for new electricity production facilities were not modelled in detail, nor are they discussed in more depth in this report.

The common baseline model is used for creating simulated network operating situations for each hour of the year in each scenario, utilising the market simulation results. Analysing the situations throughout the year helps to identify the challenges of the scenarios, which are addressed by adding the necessary main grid reinforcements to the model to provide sufficient transmission capacity.

The aim of network analysis is to identify a main power transmission grid with N-1 redundancy[27] in the various scenarios. 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. The need for shunt compensation was not examined in detail because it is local in nature. The assumption concerning the investigated network solutions was that the amount of shunt compensation required will be significantly higher than at present, but the exact amount or location was not specified. Another reason for excluding shunt compensation from this analysis is that the implementation is substantially faster than constructing a transmission line. The network analysis assumes that new lines would conform to Fingrid's basic solution for the 400 kV network, built with portal towers carrying 3-Finch conductors.

The vision work identified needs for strengthening in the specific scenarios in addition to the investment plan. These network strengthening needs describe the need to transmit electricity between substations. For the sake of presentation, the reinforcements needed to secure the necessary transmission capacity are presented on the existing transmission line rights-of-way in sections where the network has already been built. The practical feasibility of building the transmission line, including factors such as the exact route or land-use perspectives, were not examined. When considering the need to strengthen the grid, it should also be noted that in reality, the grid is built in phases. As such, the solutions presented in the vision may require connections or lines to underpin system security during phased construction, and these were not identified in the scenario work. Land use considerations may also limit the locations of transmission lines. When examining the network reinforcements presented in the vision work, it should also be noted that the scenarios include assumptions about the future locations of consumption and production that naturally affect the proposed reinforcements. Furthermore, the assumptions in the scenarios concerning cross-border connections described in section 2.8 also influence the results.

4.2 Scenario-specific analysis: Local Power

In the Local Power scenario, the electricity transmission need increases from the current level, especially in the north–south direction. This scenario also envisages a need to transmit power out of surplus areas, especially the southern parts of Ostrobothnia. However, the transmission capacity required in the main grid is substantially lower than in the other scenarios, and Fingrid's present investment plan would be enough to cover most of the electricity transmission capacity in the Local Power scenario. This scenario foresees less electricity-intensive consumption arising in Finland than in the other scenarios, so the growth in consumption and production is more moderate, thereby reducing the need for transmission capacity. Decentralised production, such as solar power systems on individual properties, also reduces the need for transmission capacity. In addition, the SMR nuclear power plants built in several large towns and cities in southern Finland under this scenario would enable electricity to be produced near where it is consumed, thereby limiting the growth in the required north–south transmission capacity.

The clearest investment needs identified in addition to the investment plan are an increase in the capacity of the 400 kV line between Seinäjoki and Alajärvi and a replacement of the Hirvisuo series capacitor with an installation capable of withstanding higher power loads. Furthermore, the minimum requirements under this scenario are changes to the switching arrangements on the lines between Seinäjoki and Ulvila and between Petäjävesi and Toivila. In addition, the River Line and the Seinäjoki-to-Ulvila route require Dynamic Line Rating (DLR) technology[28] or other means of ensuring control during the toughest transmission situations. If the need for electricity transmission on the Seinäjoki–Ulvila and Petäjävesi–Toivila connections continues to increase by more than stated in the scenario, new 400 kV lines will be needed on these sections. An increase in the load or production in the Kontiolahti region could also necessitate a new 400 kV line between Huutokoski and Kontiolahti or a significant need to strengthen the 110 kV network in the Kontiolahti area.

Figure 19 shows the network strengthening requirements under the Local Power scenario. The need for new lines under the scenario (in addition to the investment plan) is limited to approximately 100 km of new 400 kV lines if situations with the highest load can be handled using DLR and line arrangements and production and consumption, and the consequent need for additional transmission capacity, are not expected to continue increasing immediately after 2035. Otherwise, this scenario will require all the reinforcements mentioned above at a minimum, which translates into a total of over 400 km of new 400 kV lines.

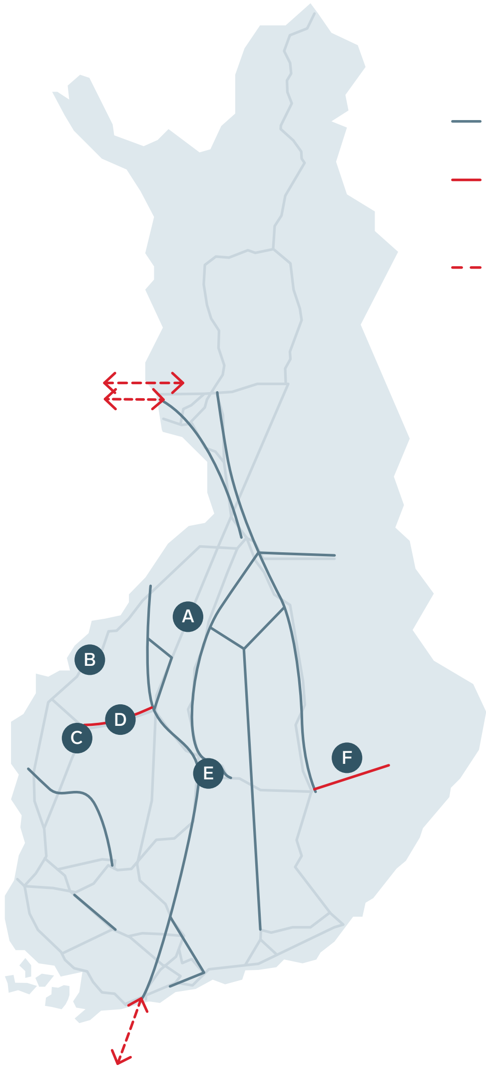
[27] N-1 redundancy means that the system can withstand the usual individual defects and the disconnection of the failed component. N-0 redundancy, on the other hand, means that the system is durable in an intact state before any faults arise.

[28] Dynamic Line Rating technology refers to the dynamic current-carrying capacity of transmission lines depending on the prevailing weather conditions, such as temperature and wind. The DLR device measures the current-carrying capacity of the line in real time in different weather conditions.

Additional strengthening needs under the Local Power scenario

A	Pikkarala–Alajärvi: Using DLR and/or other transmission state management techniques
B	Improving the loadability of the series capacitor in Hirvisuo
C	Seinäjoki–Ulvila: Using DLR and/or other transmission state management techniques
D	Seinäjoki–Alajärvi: capacity strengthening needed on the existing connection
E	Petäjävesi–Toivila: second connection for this section in addition to the one in the investment plan or change in the switching arrangements of the lines
F	Huutokoski–Kontiolahti: new 400 kV connection or, alternatively, strengthening of the 110 kV network in the region

Figure 19 Additional strengthening needs under the Local Power scenario.



— Fingrid's investment plan

— New strengthening required under the scenario

- - New cross-border connection assumed in the scenario in addition to the existing ones

4.3 Scenario-specific analysis: Windy Seas

Under the Windy Seas scenario, wind power is assumed to be distributed relatively evenly across the entire west coast of Finland, from the tip of the Bay of Bothnia to the mouth of the Gulf of Finland. In the network analysis, the 400 kV main grid connection substations for offshore wind power are assumed to be near the coast, and the individual connections do not exceed 1 GW. The scenario anticipates approximately 15 GW of new offshore wind power. No special effort is made to optimise offshore wind power connections in relation to the locations of major consumption facilities under this scenario. Instead, wind power is expected to connect to the main grid at the nearest point on the coast. Optimising the locations of offshore wind power connections so that they are close to consumption facilities would probably reduce the pressure for new main grid investments.

Figure 20 presents the strengthening needs arising under the Windy Seas scenario. In this scenario, the necessary network reinforcements are naturally concentrated on the west coast. New transmission lines will be necessary in many places along the Coastal Line from Oulu to Ulvila. Network loads will be particularly high from the Ulvila–Rauma region to Uusimaa and the Helsinki metropolitan area. A second 400 kV connection has been added alongside the existing Rauma–Lieto–Salo–Ingå connection to cater for this. In addition, the existing Lieto–Salo–Ingå connection requires increased capacity.

Strengthening the Coastal Line alone will not be enough to cope with the required power transmission. Additional connections will be needed from the west coast to inland regions, and the existing ones must be strengthened, including a new Valkeus–Lumijärvi connection, a second Kristinestad–Honkajoki connection in addition to the one already in the investment plan, and an increase in the capacity of the River Line from Oulu to Alajärvi, and additional capacity from there onwards to Ulvila. In the north, additional capacity will be required to reinforce the Kemi-Oulujoki cross-section between Keminmaa and Oulu.

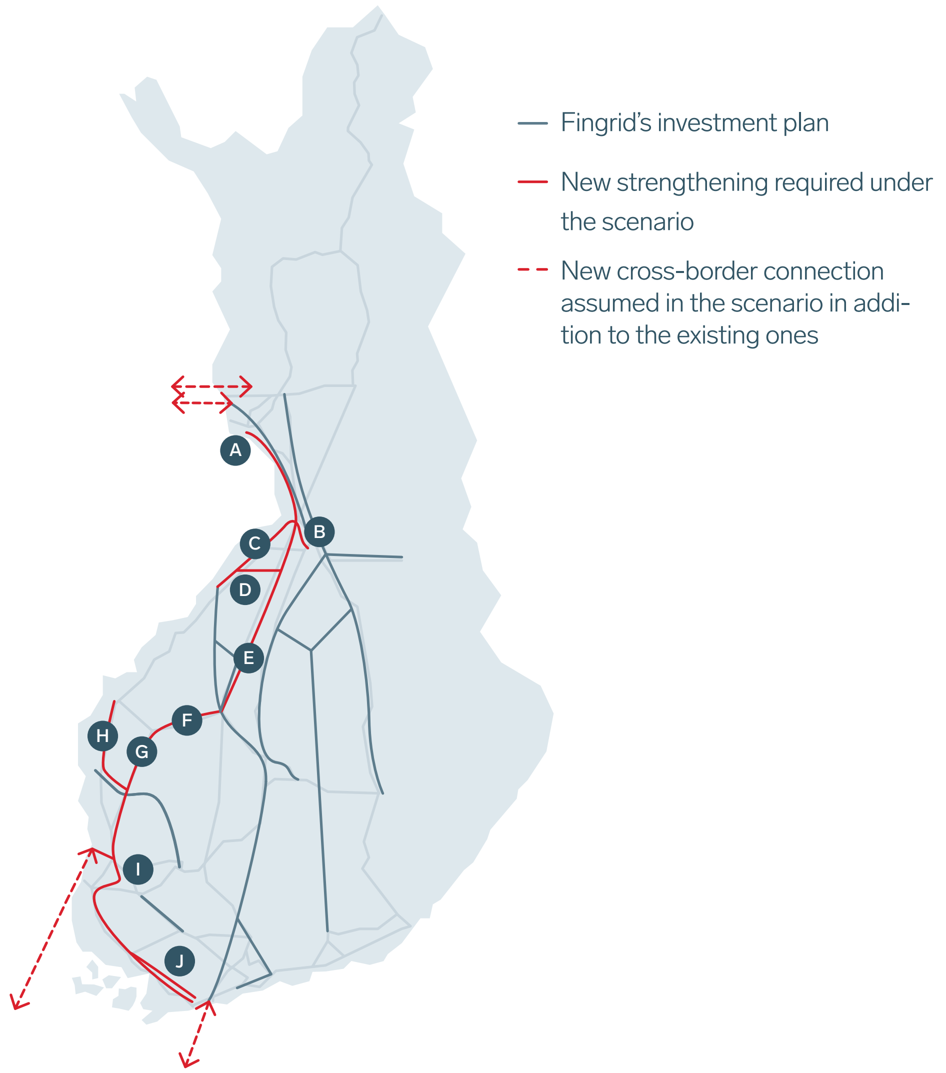
In addition to the connections in the investment plan, a new 400 kV transmission line extending approximately 1,500 km will be needed under the Windy Seas scenario. The Windy Seas scenario only accounts for the network reinforcements required in mainland Finland and not the connecting lines to offshore wind power plants.

The Windy Seas scenario differs from the other scenarios, as it includes a submarine cable connection (1,400 MW) from the Pori region to Germany. In the weather year used as a basis for the network analysis, this connection would mainly transmit electricity from Finland to Germany at almost 10 TWh/a. This would significantly reduce the need to reinforce the grid on the west coast. If the scenario came to fruition without the submarine cable to Germany, it would probably be necessary to reinforce the electricity transmission capacity on the west–east axis. On the other hand, if significant concentrations of consumption arise along the west coast near offshore wind power connections, it could have the same effect to reduce the transmission need on the west-east axis as the submarine cable.

Additional strengthening needs under the Windy Seas scenario

A	Keminmaa–Pikkarala: capacity strengthening needed on the existing connection
B	Pikkarala–Pyhänselkä: second connection alongside the existing one
C	Pikkarala–Siikajoki: new connection, Siikajoki–Jylkkä: second connection alongside the existing one
D	Valkeus–Lumijärvi: new connection
E	Pikkarala–Alajärvi: capacity strengthening needed on the existing connection
F	Seinäjoki–Alajärvi: capacity strengthening needed on the existing connection
G	Seinäjoki–Ulvila: capacity strengthening needed on the existing connection
H	Tuovila–Åback–Honkajoki: second connection alongside the existing one and the one in the investment plan
I	Ulvila–Rauma: new connection, Rauma–Lieto: second connection alongside the existing one
J	Lieto–Salo–Ingå: capacity strengthening needed on the existing connection and one new connection

Figure 20 **Additional strengthening needs under the Windy Seas scenario.**



4.4 Scenario-specific analysis: Power to Products

Two special characteristics of the Power to Products scenario are a substantial increase in wind power capacity in eastern Finland and the modelling of Aurora Line 2 as a dual 400 kV connection instead of a single connection. Wind power will also arise in northern Finland. However, the wind power in northern Finland will be concentrated further south than in the Hydrogen from Wind scenario, and the most significant wind power hubs are expected to be in the southern parts of Lapland, Sea Lapland, and north Ostrobothnia. The construction of Aurora Line 2 as two circuits and the increase in wind power capacity in northern Finland will exert pressure to increase the north–south transmission capacity so that the surplus from the north can be transmitted to the south. Wind power in eastern Finland will create a need for significant investment in the east to connect the wind power plants to the main grid and transmit electricity to the south.

Figure 21 shows the connections required under the scenario. The scenario calls for two new 400 kV connections from Pirttikoski to Seitenoikea and Pyhänselkä. Two 400 kV will be needed from Seitenoikea to Yllikkälä via Kontiolahti. These connections would like the wind power in eastern Finland to the main grid and transmit the surplus to the south. Lateral connections would also be needed to increase the east–west transmission capacity and improve the network's fault tolerance. A second 400 kV connection will be needed along the Yllikkälä–Koria–Kymi–Anttila route to transmit the future surplus from eastern Finland to the Helsinki metropolitan area.

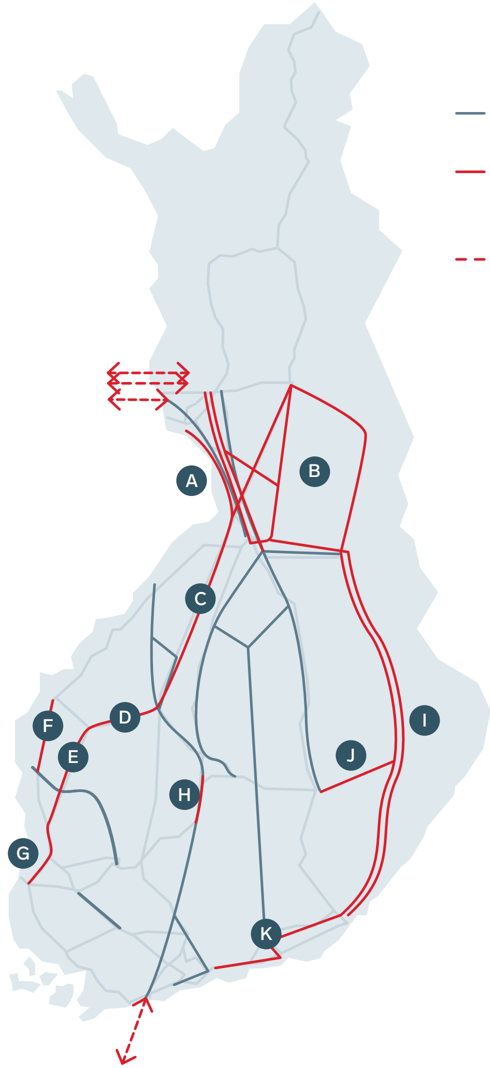
Modelling the Aurora Line 2 connection as a dual 400 kV connection and raising the wind power capacity in northern Finland increase the pressure to boost the transmission capacity over the Kemi–Oulujoki cross-section. For this reason, the scenario calls for additional capacity on the existing lines over the Kemi-Oulujoki cross-section, and there will be a need for a second 400 kV connection on the Petäjäskoski–Herva–Nuojuankangas route in addition to the one in the investment plan.

With the improvements included in the investment plan, the grid in central Finland will be almost strong enough to cover the needs of this scenario, thanks to the doubling of the Forest Line and the Ridge Line connections, only Petäjävesi – Toivila connection requires strengthening. The scenario calls for additional capacity on the Pikkarala–Uusnivala–Alajärvi lines, the Alajärvi–Seinäjoki–Ulvila line, and the Åback–Kärppiö–Tuovila line. A new Ulvila–Rauma connection will be needed on the west coast. These changes will increase the transmission capacity over cross-section Central Finland and enable the surplus from the west coast to be transmitted to other parts of Finland. An N-1 redundant network satisfying the transmission conditions of all the scenarios would require a total of approximately 3,800 km of 400 kV transmission lines on top of the investment plan.

Additional strengthening needs under the Power to Products scenario

A	Keminmaa–Pikkarala: capacity strengthening needed on the existing connection Petäjäskoski–Nuojuankangas: second connection alongside the one in the investment plan Petäjäskoski–Isokangas–Pyhänselkä: capacity strengthening needed on the existing connection
B	Pirttikoski–Pikkarala: capacity strengthening needed on the existing connection Pirttikoski–Pyhänselkä: new connection Pirttikoski–Seitenoikea: new connection In addition, belt lines needed between the new connections
C	Pikkarala–Alajärvi: capacity strengthening needed on the existing connection
D	Seinäjoki–Alajärvi: capacity strengthening needed on the existing connection
E	Seinäjoki–Ulvila: capacity strengthening needed on the existing connection
F	Tuovila–Åback: capacity strengthening needed on the existing connection
G	Ulvila–Rauma: new connection
H	Petäjävesi–Toivila: second connection alongside the existing one
I	Connection to the east, new connection needed (x2)
J	Kontiolahti–Huutokoski new connection needed
K	Yllikkälä–Koria–Kymi–Anttila: second connection alongside the existing one

Figure 21 Additional strengthening needs under the Power to Products scenario.



4.5 Scenario-specific analysis: Hydrogen from Wind

The Hydrogen from Wind scenario envisages significant quantities of new wind power and consumption connecting to the main grid. Most of the wind power will be located further north in Finland and consumption further south. The scenario requires significant network strengthening to enable the north–south power transmission. This scenario also assumes that wind power would be built in eastern Finland, necessitating a 400 kV connection to eastern Finland, as in the Power to Products scenario. Figure 22 shows a network solution that meets the transmission needs arising under the scenario.

This scenario assumes that a significant proportion of the wind power will be built further north than in the other scenarios. Two 400 kV ring connections will be needed to connect the wind power in the north. The network solution calls for a grand total of twelve 400 kV transmission lines crossing the Kemi–Oulujoki cross-section to transmit power to the south. Five of the lines are already included in the network solution for the existing network and the reinforcements to be built under the investment plan. Altogether sixteen 400 kV transmission lines to cross-section Central Finland will be needed. These investments would enable north–south transmission in accordance with the scenario. The Petäjäskoski–Nuojuankangas–Toivila–Hikiä section of the Forest Line would be under the greatest pressure for electricity transmission. In this scenario, the new reinforcements required on this connection would be highly challenging in terms of land use, as it would be difficult to build several lines along the Forest Line's right-of-way due to the density of residential settlements.

The most significant surplus areas in the scenario are northern Finland, eastern Finland and the west coast. New transmission lines over the main cross-sections and increased capacity on the Pikkarala–Alajärvi route enable the transmission of large power volumes. In addition, the construction of the eastern Finland loop enables the substantial surplus to be transmitted to southern Finland. As the need for electricity transmission over the main cross-sections increases, more and more transmission lines will need at least two circuits.

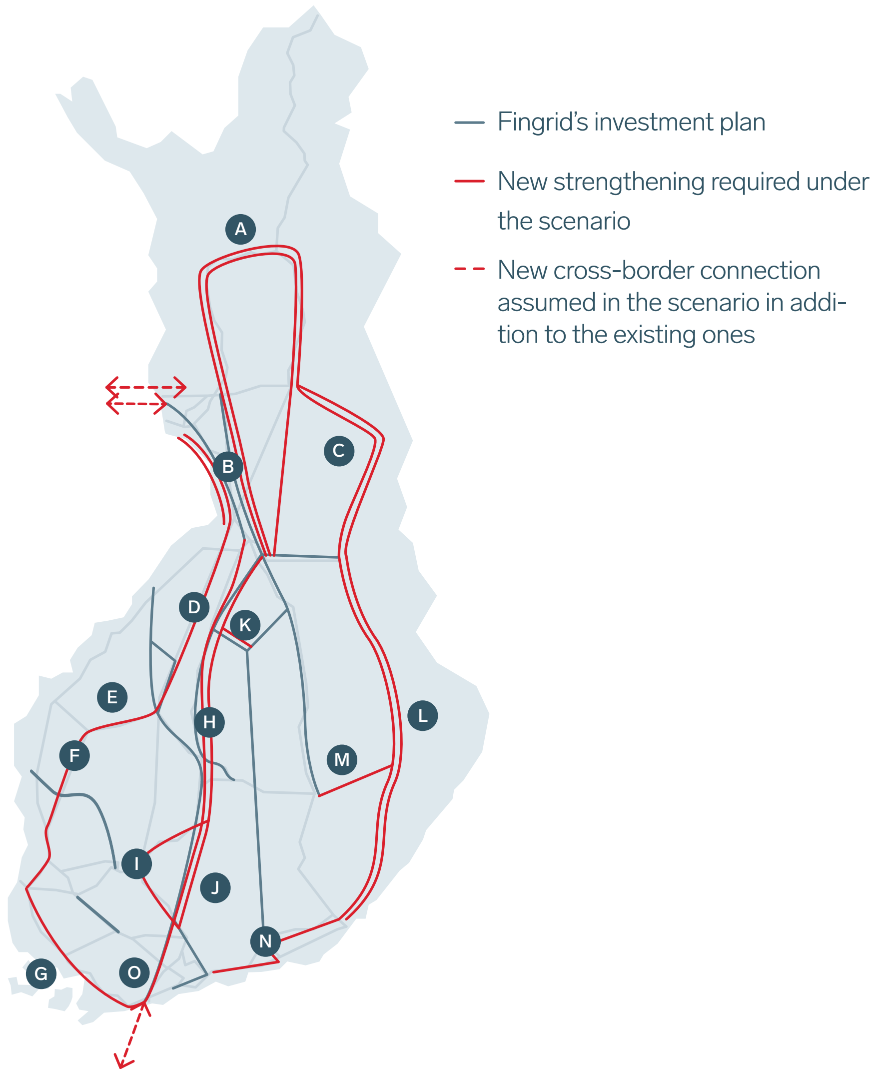
In southern Finland, the Koria–Anttila and Hikiä–Anttila connections will be under particular pressure towards the Helsinki metropolitan area. On the west coast, the Ulvila–Rauma–Lieto link will need to be strengthened. These investments will enable the transmission of wind power to satisfy the needs of the hydrogen industry. Two 400 kV circuits between Hikiä and Ingå and a new line alongside the existing Lieto–Salo–Ingå connection would enable a substantial rise in industrial consumption in Ingå, as well as increasing exports of electricity to the Baltic countries via the Estlink 3 connection.

Of all the scenarios, Hydrogen from Wind foresees the greatest growth in consumption and production, reflected in a significant increase in the need for connectivity. An N-1 redundant network satisfying all the transmission conditions in this scenario would require more than 6,100 km of 400 kV transmission lines on top of the investment plan.

Additional strengthening needs under the Hydrogen from Wind scenario

A	Lapland loop: new connection needed (x2)
B	Petäjäskoski–Nuojuankangas: new connection needed (x2) Simo–Pikkarala: new connection needed Herva–Pyhänselkä: new connection in addition to the one in the investment plan
C	Pirttikoski–Nuojuankangas: new connection needed Pirttikoski–Seitenoikea: new connection needed (x2)
D	Pikkarala–Alajärvi: capacity strengthening needed on the existing connection
E	Seinäjoki–Alajärvi: capacity strengthening needed on the existing connection
F	Seinäjoki–Ulvila: capacity strengthening needed on the existing connection
G	Ulvila–Rauma–Laitila–Lieto–Ingå: second connection alongside the existing one
H	Reinforcement of the Forest Lines, three new connections needed in addition to Forest Line 1 and Forest Line 2. Also includes the strengthening of Petäjävesi–Toivila.
I	Toivila–Kangasala–Laviavuori–Hikiä: second connection alongside the existing one
J	Toivila–Hikiä: two new connections in addition to the one in the investment plan
K	Belt line between the Pysäysperä substation and the Ridge Line
L	Connection to the east, new connection needed (x2)
M	Kontiolahti–Huutokoski: new connection needed
N	Yllikkälä–Koria–Kymi–Anttila: second connection alongside the existing one
O	Hikiä–Ingå: second connection in addition to the one in the investment plan

Figure 22 Additional strengthening needs under the Hydrogen from Wind scenario.



4.6 Strengthening needs under several scenarios

As the above descriptions of the specific scenarios indicate, the scenarios and the associated network solutions differ from each other. Figure 23 shows the necessary reinforcements arising in at least three scenarios. Although three scenarios lead to a significant increase in the required transmission lines, few of the requirements are common to several scenarios. This is because the network reinforcements in Fingrid's investment plan were assumed to be included in the baseline network used for all the scenarios. The investment plan already covers much of the growth envisaged in the scenarios. A further reason for the difference between the reinforcements required under the various scenarios is that the scenarios naturally differ from each other in terms of the volume and location of production and consumption.

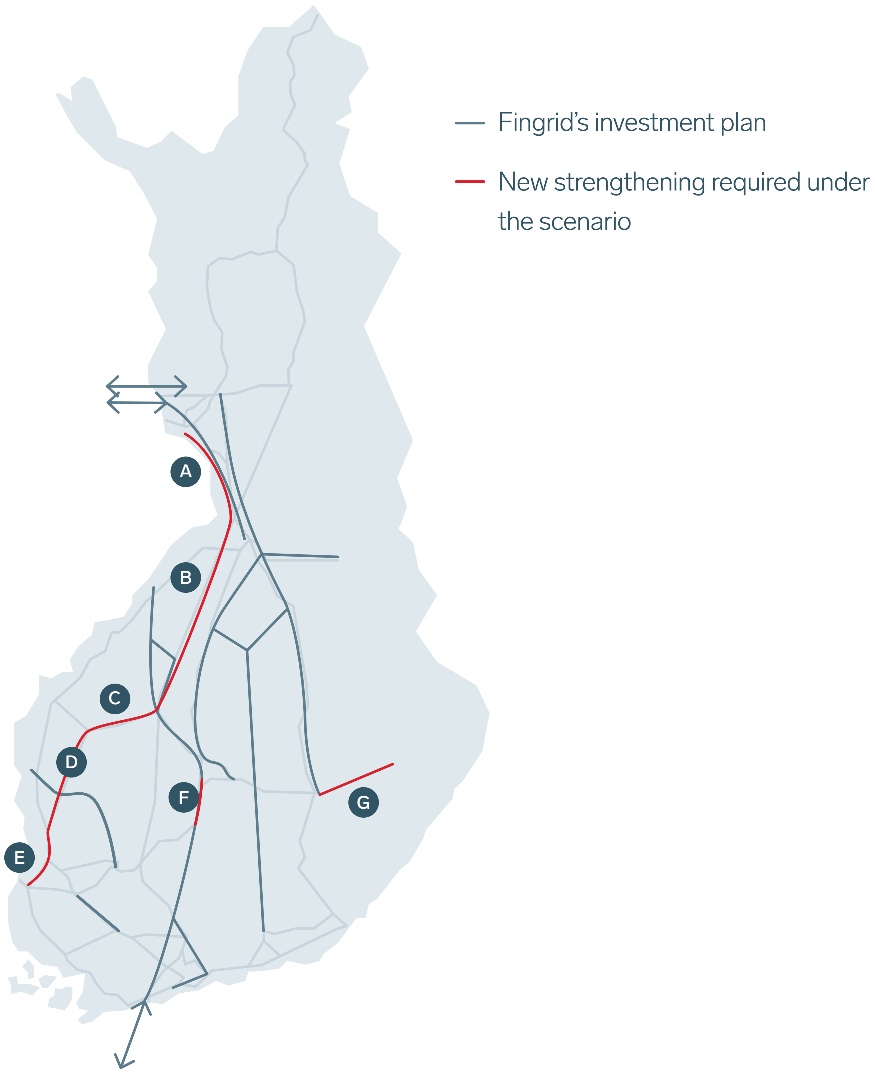
The need for additional capacity on the Keminmaa–Pikkarala section was most apparent in the Windy Seas and Power to Products scenarios. The Hydrogen from Wind scenario highlighted the Simo–Pikkarala section in the same area, mainly due to the location of wind power, but under further analysis, an increase in the capacity between Keminmaa and Pikkarala was found to facilitate transmission over the Kemi–Oulujoki cross-section. The need for additional capacity on the River Lines and a connection extending from Seinäjoki to Ulvila was most apparent in the Windy Seas, Power to Products and Hydrogen from Wind scenarios. The Local Power scenario also highlighted these routes, although some sections of the line could be assumed to be just about sufficient with the help of DLR or other transmission management solutions.

The reinforcement of the Petäjävesi–Toivila route was important under the Power to Products and Hydrogen from Wind scenarios. The Local Power scenario also highlighted this section of the line, although changes to the switching arrangements on these lines would also be sufficient. Three scenarios also examined the Huutokoski–Kontiolahti route, but the need for a connection under all three scenarios was strongly dependent on consumption and production trends in eastern Finland.

Strengthening needs under several scenarios

A	Keminmaa–Pikkarala: capacity strengthening needed on the existing connection
B	Pikkarala–Alajärvi: capacity strengthening needed on the existing connection
C	Seinäjoki–Alajärvi: capacity strengthening needed on the existing connection
D	Seinäjoki–Ulvila: capacity strengthening needed on the existing connection
E	Ulvila–Rauma: new connection
F	Petäjävesi–Toivila: second connection alongside the one in the investment plan
G	Huutokoski–Kontiolahti: new connection needed (strongly dependent on increases in consumption and production in eastern Finland)

Figure 23 Strengthening needs under several scenarios.



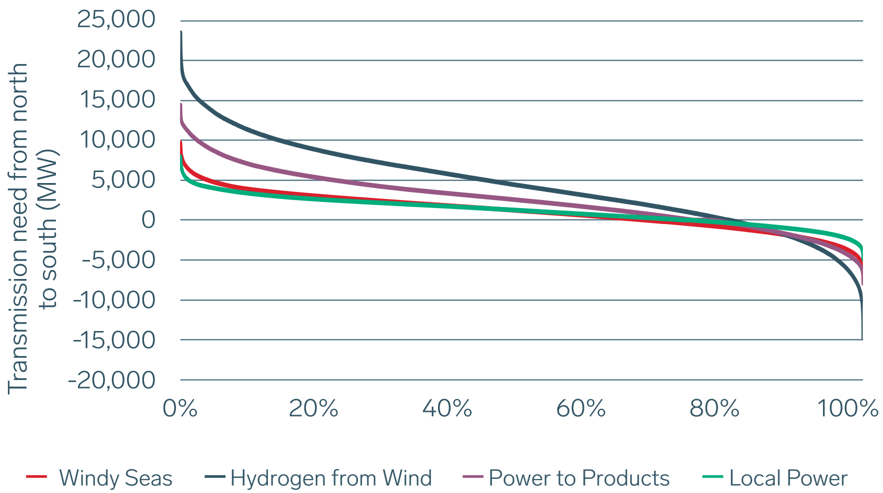
4.7 Ensuring sufficient transmission capacity

Fingrid's investment plan for 2033 includes approximately 3,200 km of new 400 kV lines. The present investment plan already enables a substantial increase in production and consumption. The analyses of the individual scenarios show that in the high-growth scenarios (Windy Seas, Power to Products and Hydrogen from Wind), significantly more would need to be invested into transmission lines to cover all possible transmission situations and take into account faults and outages.

The high-growth scenarios call for reinforcements ranging from 1,500 km to over 6,000 km, depending on the scenario, in addition to the reinforcements included in the investment plan referred to above. The high-growth scenarios represent a significant challenge in terms of network construction. The pace of network construction under the present investment plan is already faster than ever before, and it would be challenging to increase the pace for reasons such as the availability of labour and the duration of permit applications. Furthermore, building so many transmission links may not be efficient or optimal from the standpoint of cost land use.

A significant proportion of the reinforcement is only necessary when transmission volumes are highest, a situation that accounts for just a fraction of the total number of hours in the year. The highest transmission volumes are very leptokurtic, corresponding to several GW of additional transmission requirements in the scenarios. Figure 24 shows the total transmission requirement (electricity + hydrogen) at cross-section Central Finland (P1) in 2035. The graph shows that under all the scenarios, the peak of the duration curve is very sharp and is especially pronounced in the high-growth scenarios. The need for transmission increases to approximately 23 GW in the Hydrogen from Wind scenario and approximately 14 GW in the Power to Products scenario. The peak transmission requirement in the Windy Seas scenario is approximately 10 GW, and in the Local Power scenario, it is approximately 8 GW. The network solutions described in sections 4.2–4.5 were designed to cope with the situation in every hour of the year, including the hours at the peak of the duration curve, with the grid in an intact state and in the case of an ordinary, individual fault. If other techniques could be used to handle the top 1% of the transmission situations shown in Figure 24, it would reduce the required transmission capacity by about 6 GW in the Hydrogen from Wind scenario, about 3 GW in the Power to Products scenario, 3.5 GW in the Windy Seas scenario, and about 3 GW in the Local Power scenario. Covering the top 1% of transmission situations by means other than network investments would reduce the required capacity by approximately 3–6 GW, depending on the scenario. This would have a major impact on the number of kilometres of lines required.

Figure 24 Transmission needs over cross-section central Finland in the 2035 scenarios if all energy were transmitted as electricity.



The high transmission situations require very large volumes of production/imports in northern Finland and high consumption/exports in southern Finland. The following factors serve to increase the likelihood of a high transmission situation:

- Low temperatures raising electricity consumption.
- Large volumes of wind power production.
- Faults in production capacity in southern Finland, such as a fault at a large nuclear power plant.
- A low electricity price due to high wind power production, resulting in a lack of demand-side flexibility and not particularly high levels of combustion-based electricity production, although the price is positive, so it is not worth reducing the amount of wind power production capacity.
- The price is lower than in recent hours/days in general, leading to high price-dependent electricity consumption (such as charging electric vehicles, electric district heating and hydrogen production) and high consumption for charging grid energy storage facilities.
- Electricity is imported from northern Sweden and exported to southern Sweden and Estonia.

In other words, a significant share of the peak transmission requirement arises due to price optimisation factors (import/export/consumption scheduling). The transmission peaks over the main cross-sections could be effectively managed by altering the dispatching of production and consumption, for example, by introducing separate bidding zones. If Finland had a hydrogen network, division in separate bidding zones would provide a price signals. Electricity transmission could be lowered when needed by price signal raising hydrogen production in northern Finland and reducing it in southern Finland. Furthermore, the price signal affects the optimisation of flexible consumption and electricity imports and exports. If necessary, it can also increase the volume of controllable electricity production in southern Finland. The alternative is to reconfigure the redispatching of production and consumption during transmission peaks, but it is first necessary to verify that the adjustable capacity is sufficient.

Figure 25 shows the change in the electricity transmission requirement at cross-section Central Finland under the Hydrogen from Wind scenario when the market solution takes into account the 11-GW maximum for electricity transmission at cross-section Central Finland and 7-GW maximum for electricity transmission over the Kemi—Oulujoki cross-section. Figure 26 shows the total change in the transmission requirement for electricity and hydrogen. Electricity transmission would be significantly limited in the top 10 per cent of hours in the year, but the total transmission requirement would not substantially change, as energy would be transmitted in the form of hydrogen rather than electricity, thanks to the 13 GW hydrogen transmission connection assumed in this scenario.

In the simulation, the locations of production and consumption facilities were not changed. In other words, the benefit would arise purely from optimising the same resources. Some of this optimisation capability is based on the scenario's assumption that significant amounts of hydrogen production would be located along the tentative pipeline transmission network, including the area to the north of cross-section Central Finland. When the transmission restrictions were considered in the Hydrogen from Wind scenario, the simulated annual price difference arising in the bidding zones on either side of cross-section Central Finland was approximately EUR 0.2/MWh (or approximately 0.5% of the average annual electricity price) in 2035. The simulation was carried out using the average weather year.

The situation presented above was also studied using network analysis tools for the Hydrogen from Wind scenario. Without the limitations described above, more than 6,100 km of new lines would be needed in this scenario. If the transmission capacity were limited in advance, cutting the most challenging 10th percentile of transmission situations would reduce the length of new lines required by more than 2,300 km.

Figure 25 **Change in the electricity transmission requirement at cross-section central Finland in the Hydrogen from Wind scenario if measures are taken that take into consideration the transmission capacity of the electricity network.**

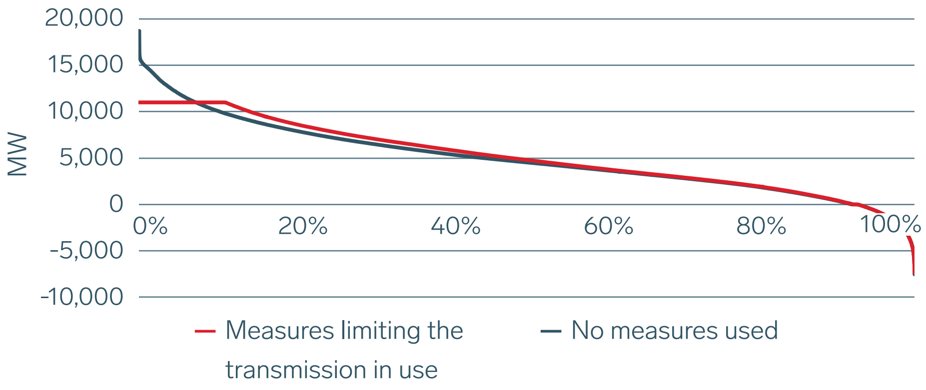
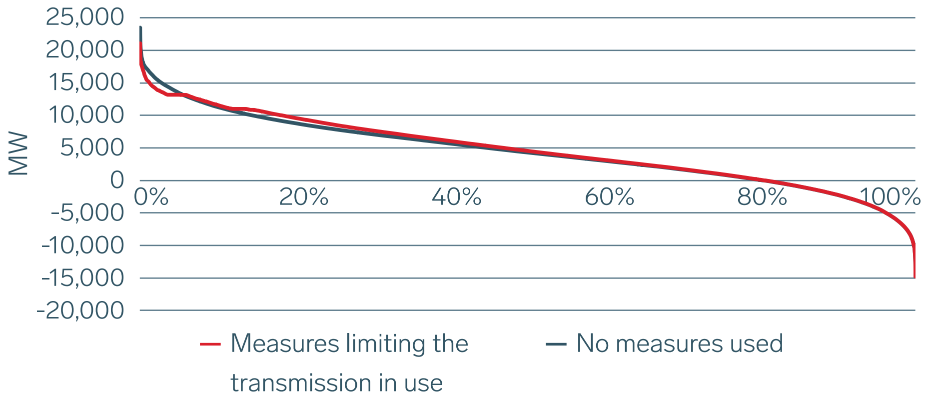


Figure 26 **Change in the combined electricity and hydrogen transmission requirement at cross-section central Finland in the Hydrogen from Wind scenario if measures are taken that take into consideration the transmission capacity of the electricity network.**



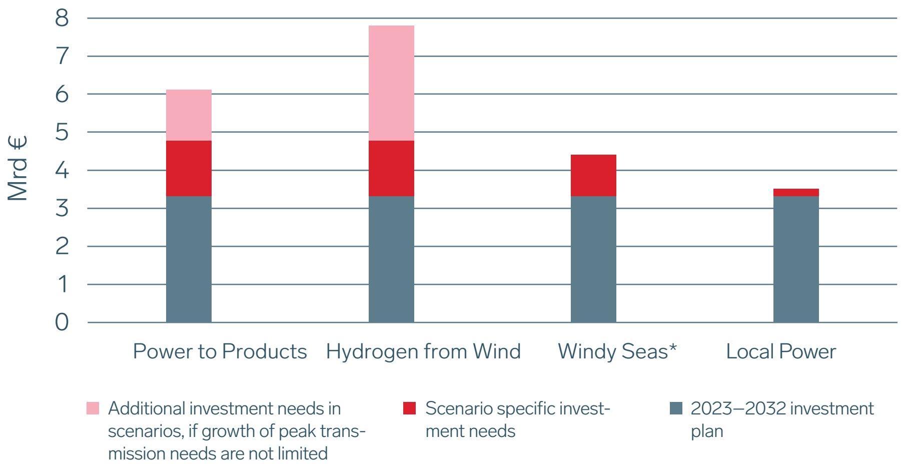
4.8 Investment costs

Figure 27 presents an order-of-magnitude estimate of the electricity network investment costs required by the scenarios in 2035. In addition to the 2023–2032 investment plan, which was included in all the scenarios and is valued at approximately EUR 3 billion, approximately EUR 0.2–1.5 billion of additional investments would be required to strengthen the 400 kV network by 2035. The estimate of the additional investments required for new 400 kV network and substations in the scenarios is approximate and contains uncertainties related to the sum of investments in compensation and transformer capacity, for example. Furthermore, the figures do not consider the need to strengthen 110 kV networks or invest in replacements in the period after the investment plan. These factors are likely to give rise to investment requirements in the future. The figures also exclude investment costs in cross-border connections for submarine cable to Germany in Windy Seas scenario and another circuit doubling Aurora Line 2 in Power to Products scenario, which are not included in the investment plan. The numbers also do not include estimates of future cost inflation.

The investment costs referred to above assume that the need for investment will be reduced by taking action to curb the growth of peak transmission requirements. If no effort is taken to curb the growth in peak transmission needs, investment costs will rise by approximately EUR 1.5–3.0 billion, especially under the Power to Products and Hydrogen from Wind scenarios, which envisage large increases in electricity production and consumption. It would also be necessary to execute projects much more quickly than at present. This would be challenging, given that the pace of construction in the coming ten years will be faster than ever before.

The presented figures assume that offshore wind power can be constructed without extending the main grid into the sea. If such an extension were necessary, the investment costs would increase substantially. 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 cost of marine transmission infrastructure were EUR 350–1,000/kW, the Windy Seas scenario would require EUR 5–15 billion in marine network investments to cater for the additional 15 GW of offshore wind power. The estimated investment costs under the Windy Seas scenario do not include the costs of the submarine cable link to Germany, which is assumed under the scenario. In the Windy Seas scenario, the cable link to Germany would also reduce the need for transmission on the west–east axis. Without the cable link to Germany or significant concentrations of consumption close to the connection points for offshore wind power, the investment costs could be higher than presented in this scenario.

Figure 27 Order-of-magnitude estimate of the electricity network investment costs required by the scenarios in 2035.

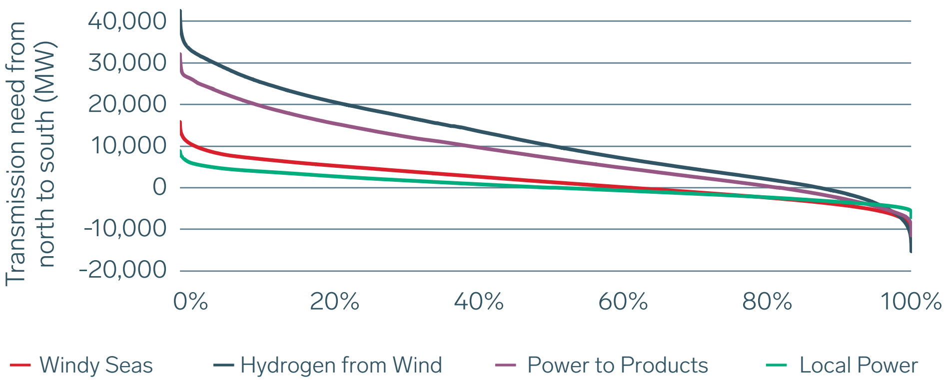


* Windy Seas scenario does not include investment costs required by the network connections built on the sea nor the submarine cable link to Germany assumed in the scenario.

4.9 Main grid transmission requirements after 2035

The transmission requirement will continue to increase up to 2045 under all the scenarios unless production and consumption are built closer together. Figure 28 shows the combined transmission requirement (electricity + hydrogen). The need for transmission increases to more than 40 GW in the Hydrogen from Wind scenario and more than 30 GW in the Power to Products scenario. However, the required capacity decreases by more than 8 GW in the Hydrogen from Wind scenario and more than 5 GW in the Power to Products scenario if the most challenging 1% of transmission situations can be handled by means other than raising the transmission capacity. The peak transmission requirement in the Windy Seas scenario is 16 GW and the 99th percentile of transmission is 11 GW, so the saving in the capacity requirement is also significant in this scenario if other solutions can be developed to handle the top 1% of transmission situations. The peak transmission requirement in the Local Power scenario is approximately 9 GW and the 99th percentile of transmission is just over 6 GW.

Figure 28 Transmission needs over cross-section Central Finland in the 2045 scenarios if all energy were transmitted as electricity. The duration curves are leptokurtic in all the scenarios.



5 Demands placed on the power system if the scenarios come to fruition

An increase in electricity production that varies according to the weather and, on the other hand, a decrease in controllable production provoke discussion about the adequacy of electricity, the electricity price, the emergence and availability of flexibility, and the sufficiency of the reserves needed to manage disturbances and frequencies. In addition, as the volume of the power system grows and the structure of production and consumption changes, the adequacy of the transmission capacity and the prerequisites, procedures and policies for managing system security will also become relevant topics of debate. These factors are likely to call for significant changes as transmission requirements increase and the technical characteristics of the production and consumption structure change. As the operating environment changes radically, finding the most cost-effective solutions requires a review of the established practices and principles, new technical solutions, new marketplaces and mechanisms, a reform of the technical requirements of the system, a redefinition of the various responsibilities, and new regulation.

Fingrid will use the scenarios to understand the evolving operating environment and prepare itself to facilitate the realisation of the potential of even the high-end scenarios. However, the energy transition will affect the entire sector, and we hope the scenarios serve parties across the energy field and help them consider the future changes required in their sectors.

We provided extensive background information on the various power system themes in a draft report we published in August 2022, and we have asked stakeholders for their views on different topics. A summary of our stakeholders' insights is available here: https://www.fingrid.fi/ajankohtaista/tiedotteet/2022/fingrid-kiittaa-arvokkaasta-palautteesta-sahkojarjestelmavision-luonnosraporttiin/

We hope that the energy sector will continue to discuss the prerequisites for Finland's competitiveness and the development of the electricity market and that the discussion will lead to action that will enable us to implement a dramatic transformation of the power system. The following sections cover the key themes for enabling the realisation of the scenarios for the entire power system.

5.1 System flexibility

5.1.1 Flexibility in the wholesale market

Society is dependent on the uninterrupted supply of electricity, which requires a constant balance between the production and consumption of electricity. From the standpoint of the operating conditions of electricity users, average electricity prices should be at least moderate in comparison with our competitor countries. In the scenarios, Finland gains a particular competitive advantage by exploiting its abundant renewable electricity production potential. The system must be highly flexible according to the availability of electricity to capitalise on the competitive advantage of weather-dependent electricity production. The adequacy of electricity rarely becomes a challenge as a result of the flexibility assumed in the scenarios, and the average electricity price remains affordable.

In the scenarios, the majority of the flexibility comes from electricity consumption, especially new consumption from the electrification of different sectors. Longer-term flexibility relies on the storage of heat and hydrogen or products made using hydrogen. Some flexibility is provided by new generator plants powered by hydrogen or hydrogen derivatives in these scenarios, but plants like these also need the capacity to store hydrogen or fuels made from hydrogen. Finland's diverse electricity production structure is also an important competitive advantage, as it enables energy to be produced irrespective of the weather, and production can be controlled. Section 3.3 and Appendix 2 examine the flexibility assumed in the scenarios.

System flexibility is essential to realise the scenarios. Flexibility balances out price peaks and enables electricity to be used when it is cheap. If the necessary flexibility cannot be achieved cost-effectively, it will not be possible to exploit the competitive advantage of weather-dependent energy production to the full in these scenarios. In practice, a lack of flexibility would probably mean higher electricity prices on average and more frequent challenges in terms of the adequacy of electricity. This would negatively affect the electrification of various sectors and Finland's attractiveness from the perspective of consumption investments, thereby slowing the exploitation of Finland's competitive advantage and the potential of the scenarios. Weaker adequacy of electricity and higher electricity prices would also affect end-consumers.

Flexibility plays an important role in the electricity market. Today's electricity market is based on energy and marginal pricing, producing investment signals based on the assumed price of electrical energy to aid market participants in making independent decisions. In an electricity market based on energy-based electricity trading, the necessary investments in production, storage and demand-side response must be made more cost-effectively on market terms in the long run when supply and demand in a functioning market balance themselves as a result of price signals. Ultimately, it does not matter which sources of flexibility are used, as the market is assumed to identify the most cost-effective ways of ensuring flexibility.

The challenge, however, is uncertainty and the slow rate of investments to enable flexibility during the current transformation, which could cause problems in balancing the power system and ensuring the adequacy of electricity in the short and medium terms. The profitability of investments is the sum of many uncertain variables, and investors may not have enough visibility into the earning potential of new investments to facilitate flexibility in the energy system of the future, which may slow down or impede investment decisions. This could result in a situation where a long-term scarcity of electricity would be necessary to trigger investments in flexibility. Furthermore, investments take time to implement, potentially leading to years of delays before a balance is struck in the market. Uncertainty highlights the need for adequate hedging by market participants, which may make it necessary to develop long-term contracts, as well as financial markets for electricity and their liquidity.

However, if it is not possible to achieve flexibility using the existing energy-based market model, we may end up in a situation where it is necessary to consider using capacity mechanisms or other systems to guarantee the necessary investments in order to ensure the adequacy of electricity. A capacity mechanism is a general term referring to systems in which compensation is paid for capacity in addition to or instead of the amount of energy produced. The capacity mechanism does not dictate the technology that should be used to enable the necessary capacity. Rather, the capacity mechanism may include grid energy storage, electricity production, and the ability to cut electricity consumption.

The application of capacity mechanisms is regulated by the EU Regulation on the Internal Market for Electricity, according to which, for the application of a capacity mechanism, Member States must have evidence of concerns about the adequacy of electricity. An essential challenge of capacity mechanisms is the definition of the conditions and principles related to the functioning of the mechanism and the correct dimensioning of the mechanism. If the need for capacity is estimated to be higher than needed, it will lead to oversized capacity and, consequently, excess costs for electricity users. The burning question is who should pay for the capacity. Ideally, the cost should only be borne by the electricity users who need a stable electricity supply and are unable to be flexible when needed. A separate market mechanism would also be needed for acquiring capacity.

5.1.2 Availability of reserves

Reserves capable of flexibility are also needed in the reserve market. The modelling of the scenarios of this vision has been based on the day-ahead and intraday markets and the investments generated through them. The reserve market and the capacity needed on the market have not been specifically modelled. Although the amount of necessary reserves was not modelled in the scenarios, it can be assumed that the energy revolution will increase the need for reserves.

Traditionally, balancing within an imbalance settlement period has mainly been related to occasional fluctuations in consumption. However, as the share of variable production grows, an increasingly larger share of production also varies according to the weather. This increases the need for frequency containment reserves, and the need is expected to shift from the slower manual Frequency Restoration Reserve (mFRR) towards automatic Frequency Restoration Reserves (aFRR), which can be used to balance out changes occurring within a 15-minute imbalance settlement period.

On the other hand, the transition to the 15-minute imbalance settlement period is expected to encourage operators to engage in more accurate balance management in the future, which is expected to curb the growth in the need for reserves. In the future, balance management conducted by operators in-house and, for example, the control of production and consumption may affect the need for the transmission system operator to balance out production and consumption in real time.

In the future described in the scenarios, the amount of thermal power will decrease and the production capacity of hydro power is not expected to increase in Finland. Traditional nuclear power is included in all scenarios, and wind power becomes the most significant form of electricity generation. All possible resources should be encouraged to contribute more widely to the offering of reserve services in order to cover the growing need for reserves. Even today, there are operational situations in which a very substantial share of electricity is produced from nuclear, solar and wind power, and this trend is set to intensify in the scenarios. Especially in situations where electricity production in Finland is almost exclusively nuclear and wind power, the participation of these forms of production in the reserve market is necessary.

Electricity consumption is assumed to participate in the reserve market in the future. Demand-side already accounts for a significant share of the resources participating in Fingrid's reserve market. It is important that new consumption in the future also offers flexibility in the reserve market. For example, it is important to attract new types of consumption, such as electrolysers, to the reserve market. Electrolysers play an important role in enabling flexibility under the Power to Products and Hydrogen from Wind scenarios in particular.

Fingrid is responsible for managing the system's power balance in operation and developing the reserve market. However, Fingrid is not responsible for the adequacy of electricity, nor does it participate in the formation of electricity prices other than by ensuring that the maximum possible transmission capacity is available to the market. The Ministry of Economic Affairs and Employment is responsible for Finland's energy policy, but every party in the energy sector has a duty to contribute to the development of the electricity market model. We hope that stakeholders will study the scenarios presented in the vision and consider the implications of the scenarios for their own activities, especially in terms of implementing flexibility. Ultimately, market participants are the ones who can actually implement flexibility.

5.2 New solutions are needed in addition to network construction to ensure adequate transmission capacity

The network investments featured in Fingrid's investment plan will raise the grid's transmission and connection capacity considerably in the coming years and decades. However, it is apparent from the need for network reinforcement under the 2035 scenarios, discussed in section four, that the steep and rapid rise in electricity consumption and production in the high-growth scenarios will challenge Fingrid's opportunities to increase the transmission capacity quickly enough and by such a quantity that it could cover all the foreseeable transmission situations. This is particularly relevant in the event that new electricity production and consumption facilities are located far from each other, their growth is sudden and sharp, and it is impossible to optimise momentary production and consumption according to grid loads during the most challenging transmission situations. The "tail" of the transmission duration curve is especially challenging. For example, if 1–10% of the most difficult transmission situations could be covered by means other than network construction, it would have a major impact on the investment required in the grid.

5.2.1 Technical solutions

It is possible to respond to the growing need for electricity transmission through network construction and by seeking means to increase the utilisation rate of the existing network and new parts of it. DLR technology and series and shunt compensation[29], which are already in use, are good examples of means of boosting the transmission capacity of the existing network. DLR technology is used in the existing network on the lines passing through the Kemi–Oulujoki cross-section and on some of the lines passing through cross-section Central Finland. Fingrid will also consider the impact of DLR as one of its planning principles, so the impact on the transmission capacity can be considered when lines are planned. Construction land use also requires new, more efficient solutions. At least two 400 kV circuits are required on an increasing number of the connections identified in the scenarios. At present, Fingrid's basic network construction solutions are to have a 400 kV circuit on one tower, and 400 kV and 110 kV circuits on shared towers. At present, Fingrid does not usually install two 400 kV circuits on shared towers, but it is likely to become more necessary in the future. From the standpoint of mitigating the environmental impacts and land use, it is important to strive to enable the construction of two 400 kV circuits on joint towers when the electricity transmission requirement calls for several 400 kV circuits along the same connection. Installing two 400 kV circuits with a shared tower solution requires less land than two parallel circuits. In autumn 2023, Fingrid will initiate the environmental impact assessment of the Hausjärvi–Anttila connection to study the environmental impact of a joint tower solution with two 400 kV circuits depending on future electricity transmission needs.

5.2.2 Location of consumption and production and flexibility

However, the technical solutions referred to above are not enough on their own to increase the transmission capacity. In terms of realising the high growth potential, it is important to encourage consumption, production and grid energy storage investments to be located optimally with regard to the system or, alternatively, to provide flexibility in the right parts of the network if the grid's transmission capacity is exceeded. The network and connection fees could be adjusted to incentivise investments in certain geographical locations. On the other hand, it is important to note that several factors influence the locations of electricity production, consumption and storage investments, and the nudging effect of network and connection fees may be less significant than other cost factors.

In addition to influencing the geographical location of investments, a further important factor is to ensure the flexibility of production and consumption according to transmission management needs. Even if production and consumption are geographically far apart, situations with the greatest transmission needs are manageable if production and consumption facilities can be flexible whenever necessary. For example, in the event of very high north–south transmissions, production should be reduced or consumption increased in the north and vice-versa in the south to manage the bottleneck. Regional network bottleneck management may also be necessary. Bottlenecks can be managed by altering the dispatching arrangement after the daily and intraday market, for example, using special regulation. However, this requires suitable resources to be available at the right points in the network and the necessary flexibility both directions. Even today, finding enough up-regulation capacity in the south is a challenge. It is important to have flexible resources available at short notice, especially in the event of unforeseen faults.

It may also be necessary to limit production in advance in certain areas to preserve system security, for example, during a planned outage. Limitations are ordered on the principle of equal and non-discriminatory treatment. One perspective on limitations in circumstances where the full connection capacity cannot be granted to a new network connection in all network operating situations is to explore the possibility of flexible connection contracts. A flexible connection contract would mean that the capacity of a new network connection could be limited, subject to certain conditions, if it is not possible to grant access to the full connection capacity. Flexible connection contracts could apply for a fixed term until the necessary grid reinforcements are completed to enable the full connection capacity. From the point of view of the connecting party, a flexible connection contract enables an earlier connection to the network.

Dividing Finland into different bidding zones is the most dramatic solution for managing production and consumption. Bidding zone division solves the problem, even if the increase in transmission needs has already exceeded the transmission capacity of the network and other means no longer help. Based on the simulations carried out in the system vision scenarios for 2035, dividing Finland into two bidding zones according to cross-section Central Finland would cause relatively moderate price differences if the transmission capacity were generally sufficient. Similar conclusions were reached in a master's thesis written for Fingrid in 2022 to study the impacts of bidding zone division[30]. However, the risk of a bidding zone division is that the market is broken down into parts that are too small. This could impact, for example, the liquidity of price-hedging products and the reserve market. However, the bidding zone division is a rigid solution, and dividing Finland into bidding zones along the north–south axis would not reduce the need for electricity transmissions in other directions, such as along the west–east axis. Furthermore, a bidding zone division may not address all transmission situations, and momentary bottlenecks could still arise regionally. Alongside a bidding zone division, it may be necessary to examine the possibilities of more dynamic models that take better account of the network's limitations at the time of use.

As the system expands, properly implemented incentives to control production and consumption in the network would allow for sufficient investment to support the adequacy of transmission capacity without too much impact on operators, for whom flexibility according to the needs of the network would be expensive or inconvenient. Furthermore, if a hydrogen network is built in Finland in addition to the electricity network, it is important that the market guides the transmission of both infrastructures in line with society's overall optimum. In the best case, the hydrogen and electricity systems could work well together in an optimal way for society.

[29] Further information about shunt compensation and the use of DLR technology (only in Finnish) https://www.fingrid.fi/ajankohtaista/tiedotteet/2022/rinnakkaiskompensointi-kasvattaa-sahkon-siirtokykya-pohjois--ja-etela-suomen-valilla/ and https://www.fingrid.fi/globalassets/dokumentit/fi/yhtio/tki-toiminta/raportit/voimajohtojen-dynaaminen-kuormitettavuus.pdf

[30] https://trepo.tuni.fi/bitstream/handle/10024/142016/SalviValtteri.pdf?sequence=2

5.3 Ensuring the technical operation of the system

The challenges for the technical operation of the power system include the increasing volume of wind and solar power connected to the grid via power converters so that these forms of production become the dominant ones and the shift in the consumption structure so that it is increasingly dominated by power converters. The technical operation of an electricity system is based on maintaining a stable frequency and voltage in all transmission and operating situations. Traditionally, electricity was produced mainly at hydro and thermal power plants using synchronous machines, whose inherent properties resist changes in frequency and voltage. Unlike machines that are physically synchronised to the network, new forms of production and consumption connect to the network via power converters, which do not intrinsically resist frequency and voltage changes. Instead, their response to the electricity system is based on programmed characteristics.

In order to operate, modern-day wind and solar power plants require a sufficiently strong network with enough synchronous machines and other grid forming equipment that maintains the frequency and voltage of the network. As the energy revolution proceeds, the number of wind and solar power plants is growing while the number of synchronous machine plants is declining. In the presented scenarios, situations often arise in which wind and solar power generate an increasing share of instantaneous production, which means that the amount of converter-connected production increases significantly compared to the volume of synchronous machine production.

The increase in converter-connected resources affects a number of different technical characteristics of the electricity system: frequency, voltage, angle and resonance stability, converter-driven stability, electricity quality, and the protection function. Some of the technical characteristics are of a system-level scale (Nordic joint operation, also known as the synchronous region), while others are local phenomena.

The increase in converter-connected production and the removal of synchronous machines also reduce the system's inertia. For example, the amount of inertia affects the maximum allowable power change in the system. When inertia is low, it may be necessary to limit the power of the largest production or consumption units. A new type of reserve – the Fast Frequency Reserve (FFR) – has been introduced to remedy this situation. A decrease in inertial minimums increases the frequency change rate, so solutions other than increasing the amount of fast frequency reserves may also be required to ensure frequency stability.

Although the scenarios describe 2035, the transition towards a converter-dominated system has already begun, and the rate of change is accelerating. The accompanying phenomena and challenges for the technical operation of the system are new, and there are no established methods for resolving or even identifying all the challenges.

However, technical functionality must be ensured in the system of the future. Fingrid works with various experts to understand and resolve the challenges. Cooperation with main grid connecting parties also plays an important role in ensuring that connected installations continue to meet the system requirements in the future. Fingrid is also involved in an ongoing Nordic cooperation project aiming to identify the technical challenges posed by the growth in converter-connected production in the Nordic countries and identify potential solutions to resolve the challenges affecting the Nordic synchronous area.

Although the future solutions – and indeed, some of the challenges – are yet to be identified, the solutions must address a combination of the requirements on connecting parties, the contract terms, capabilities procured in the market to support the system, and technical network solutions. System security is a common concern for all connecting parties, and connecting parties should also participate in maintaining system security. At present, power converters are required to have some features for supporting network operations similar to synchronous machines, such as fault current supply in a voltage dip and the capability for voltage control. In a converter-dominated system, power park modules must, however, also be able to create network voltage without a reference produced by synchronous machines. Equipment connecting to the network must comply with Fingrid's grid code specifications for power generating facilities, which will be updated according to the system needs as further insight into the system needs is obtained. Reasonable system requirements may also be imposed on old connections.

In addition to the requirements for connecting parties, services that support the system can also be purchased in the market. This means defining the new capabilities to be purchased in the market, the marketplaces and the procurement rules. The system's operation can also be supported with a wide range of technical solutions built into the network. In the future, significantly more will be invested in various installations to support the system in addition to conventional network construction. For example, a synchronous compensator is under construction in the Jylkkä substation area, where a large amount of wind power is concentrated. The synchronous compensator will stabilise the network voltage and frequency.

5.4 Electricity market trends

As the energy revolution proceeds, efforts must be made to ensure that the electricity market model supports the shift towards a carbon-neutral energy system, system reliability and cost-effectiveness while facilitating Finland's competitiveness. All the requirements presented above for the realisation of the scenarios are linked to the electricity market. The change challenges the current electricity market model from several perspectives: even in a changing operating environment, the market should be the most efficient way to carry out trading between electricity sellers and buyers in both the short and long term. At the same time, the market should determine the dispatching of production and consumption, thereby balancing production and consumption in the power system. The electricity market should also convey price signals, which are the basis for reacting to short-term balancing needs in the power system and making the investments necessary to enable system flexibility and reliability. The change in the operating environment may require new things from the electricity market rules. From the point of view of the overall efficiency of the system, it is justified to consider whether future market solutions should, for example, guide the geographical location of electricity production and consumption and encourage the implementation of sector integration or, for example, the production of system services required by the electricity system.

The basis of the present electricity market model – a pan-European day-ahead market based on marginal pricing – has effectively ensured competitiveness, the security of the energy supply, and sustainability. There is room for improvement in the present organisation of the electricity market, but the electricity market model is not to blame for the current energy crisis – it is due to Europe's dependence on Russian gas. Any changes made to the electricity market must look beyond the immediate crisis, and the fundamentals of a functioning system should not be scrapped.

In the development of the electricity market, it should be noted that changing the market model is often time-consuming. It is, therefore, to be expected that development will take place step by step. Several electricity market changes will take place this decade. For example, the Nordic reserve market is being developed on the road towards European marketplaces, the market time unit is decreased from one hour to 15 minutes, first in imbalance settlement and then in the balancing energy market, and the other markets will follow suit. In addition, the calculation of transmission capacity submitted to the electricity market will change in the Nordic countries to flow-based calculation[31]. This will affect the market through market coupling. In addition, financial markets will be developed to meet the changing needs of market participants, for example, through cross-border transmission rights products.

The development must also take into account how the different segments of the market are strongly intertwined, so several small changes together can have a great impact on the whole. In addition, we are part of the European common market, and many of the rules of the market are laid down at EU level. Any changes must also take into account the effects on the whole in the EU's internal market area. Changes to the market model must therefore be carefully designed, justified and holistic in order to maintain a stable and predictable market environment. At the same time, it must be possible to make the changes that have been identified as necessary.

The scenario modelling used as the basis for the vision work is based on the operation of the current day-ahead and intraday market. Thus, in the scenarios, the earnings of electricity market participants only take into account the income and profitability received in the day-ahead and intraday markets. In the future, it may be possible for a market participant's resource to be more strongly involved in generating value alongside the wholesale market, for example, in the form of reserves, system services or flexibility needed for transmission management, in which case value for the use of the resource can be accumulated from several different sources. In addition to the considerations mentioned above, it is possible that, in the future, a need for a market participant's flexibility capacity may also arise, for example, in connection with the transmission management of distribution networks or, for example, in the balance management of balance responsible parties.

[31] The flow-based method is a method for calculating the transmission capacity based on transmissions. Further information about the method: https://www.fingrid.fi/sahkomarkkinat/markkinoiden-yhtenaisyys/sahkomarkkinoiden-kehityshankkeet/siirtokapasiteetinlaskenta/

Appendix 1. Scenario modelling

The aim of scenario modelling is to predict how the current wholesale electricity market would function and what kinds of investments would be made on market terms in the production of electricity and hydrogen if the operating environment developed as described in the scenario. Production capacities and volumes have been determined so that the operating margin from the wholesale market for new investments in wind and solar power, electrolysers and hydrogen storage would cover the levelised investment costs, as well as the return on capital requirement (assumed in real terms of 5%) either through wholesale (energy-only) or PPAs. Other marketplaces have not been taken into account in the modelling, with certain exceptions[32]. The assumptions about investment costs for both operating and maintenance costs are mainly based on the TYNDP2022 scenarios in ENTSO-E's ten-year network plan, and they are described in Table 18. It was necessary to deviate from the TYNDP figures in some scenarios when it was preferable for the scenario to allow for a certain trajectory. For example:

- Investments in onshore wind power have been limited in the Windy Seas and Local Power scenarios in order to describe alternative developments to an onshore wind power-dominated system.
- In the Power to Products scenario, profitable hydrogen storage investments based on cost assumptions have not been fully implemented, in order to make hydrogen production less flexible in the scenario.
- In the Local Power scenario, a very aggressive cost reduction was assumed for SMR nuclear power plants in order to make them commercially viable.

For wind and solar power, CAPEX and OPEX are based on the TYNDP scenarios[34] and the underlying ENS.dk data[35]. The figures for onshore wind power account specifically for the higher turbine heights and unit sizes in Finland. The ASSET study[36] provided the source data on conventional nuclear power, and the fuel costs were sourced from the TYNDP data. For SMR nuclear power plants, the costs were assumed at a level that would make the investments viable. As such, the costs of capital, operation and maintenance are about 50% lower than for conventional nuclear power, and the cost of capital is roughly in light with NuScale's long-term target ("Nth-of-a-kind", USD 3,600/kW)[37]. In addition, SMR plants are assumed to have a considerably shorter construction time than conventional nuclear power plants. If SMR plants are used for CHP production, their heat production is assumed to generate a return corresponding to the plant's variable costs (EUR 12/MWh per megawatt-hour of electricity produced), so the net variable OPEX is EUR 0–12/MWh, depending on whether the waste heat is utilised. SMR power plants are only used in the Local Power scenario. The levelised cost of electricity was calculated in real terms for all the technologies using a 5% real return requirement. Consequently, the nominal cost of electricity in 2035 is adjusted for inflation.

The modelling covers the Baltic Sea region and the majority of Central and Western Europe. Thus, for example, the import of electricity to Finland requires that the neighbouring regions have production resources available at the time of import that are cheaper than Finnish capacity and beyond their own needs. Elsewhere in Europe, efforts have been made to take into account the minimum targets set for renewable electricity production and to assume that these investments will be supported if necessary, as well as, on the other hand, the maximum amounts for renewable electricity production, which these countries have been expected to be able to achieve at their highest. In particular, the latter restriction is often restrictive, reflecting the challenges of resource sufficiency in renewable electricity generation in Central Europe. The optimisation of production, consumption and storage takes place in the region-wide common market modelled in the calculation model, in the simulations of which perfect competition and complete information over a 10-day time horizon are assumed.

Table 16 Assumptions about the production costs of new power plant investments in Finland in 2035. The range is given for different scenarios. SMR nuclear power is only available in the Local Power scenario[33].

All costs in 2021 money		Onshore wind power	Offshore wind power	Solar	SMR nuclear power	Conventional nuclear power
CAPEX	EUR/kW	900–1,100	1,500–2,200	300–400	3,000	6,000
Fixed OPEX	EUR/kW/a	9–11	29–37	6–8	56	112
Variable OPEX	EUR/MWh	1.3	2.6	-	0–12	12
Load factor	%	40%	54%	10%	87%	87%
Service life	years	30	30	40	60	60
Levelised Cost of Electricity (LCOE)	EUR/MWh	21–25	26–41	26–37	29–41	79

[32] The revenue stream received by electrolysers and SMR nuclear power plants from waste heat has been taken into account. In addition, the Hydrogen from Wind scenario assumes that peak power investments necessary for power sufficiency receive other revenue generation, as the wholesale market return is not sufficient for investments in the scenario.

[33] The cost of onshore wind power is towards the bottom of the range in the Power to Products and Hydrogen from Wind scenarios. The cost of offshore wind power is towards the bottom of the range in the Windy Seas scenario, towards the top of the range in the Local Power scenario, and in the middle of the range in the two other scenarios. The cost of solar power is towards the bottom of the range in the Local Power scenario, towards the top of the range in the Windy Seas scenario, and in the middle of the range in the other scenarios. SMR nuclear power is only available in the Local Power scenario. Conventional nuclear power would be available in all the scenarios, but it is not profitable to invest in it at this cost level in Finland.

[34] https://2022.entsos-tyndp-scenarios.eu/wp-content/uploads/2022/04/TYNDP_2022_Scenario_Building_Guidelines_Version_April_2022.pdf

[35] https://ens.dk/sites/ens.dk/files/Statistik/technology_data_catalogue_for_el_and_dh_-_0009.pdf

[36] https://ec.europa.eu/energy/sites/ener/files/documents/2018_06_27_technology_pathways_-_finalreportmain2.pdf

[37] https://www.nuscalepower.com/newsletter/nucleus-spring-2020/featured-topic-cost-competitive

Appendix 2. Assumptions about demand-side response

The flexible share in Table 15, presented in section 3.3., describes the flexibility potential as a share of the total consumption of the consumption category. For example, the flexibility provided by traditional manufacturing industry does not exceed 18% of industrial consumption. However, industrial consumption can be flexible overall by up to 32%, taking into account the flexibility of data centres and electrified heating processes. In addition, the duration of demand-side response available from different sources varies from one hour to several days. In these scenarios, the normal hourly consumption power of industry is approximately 6–7 GW in 2035, of which a total of around 2 GW is flexible.

Data centres are seen as potential flexibility providers, as they have a battery to ensure a steady power supply and possibly also reserve power. However, flexibility is estimated to be mostly less than an hour. For an hour, it is estimated that about one third of the average data centre power is available. Overall, this represents approximately 5% of industrial consumption.

The demand-side response of traditional manufacturing is estimated to come from production restrictions, whereby a factory reduces its production during periods of high prices. The factory does not increase production in the hours after the restrictions, so the consumption is cutting in type. Industry reduces its consumption in stages by running processes at lower power or shutting them down as prices rise to between EUR 150-1,500. The amount of demand side response has been estimated based on the historical bid curves of the electricity exchange, and it has been assumed that this flexibility originates in industry. According to this assumption, flexibility would, at its highest, be about one fifth of industrial consumption. The amount of flexibility is assumed to be the same relative share of industrial consumption in 2035 and to increase slightly thereafter.

The electrification of industrial heating processes is expected to increase the amount of demand-side response in existing and new industrial facilities[38]. Heating can be electrified, for example, using large-scale industrial heat pumps and electric boilers. The marginal price for flexibility ranges from EUR 25 to around EUR 200, depending on how significant the inconvenience and costs of flexibility are. Typically, industrial processes require heat on a continuous basis, and shutdowns are costly, but in biomass drying, for example, flexibility would be cheaper. In total, the flexibility of industrial heating processes represents approximately 10% of industrial consumption. Flexibility varies from several hours to 24 hours. The simulation result shows that in the average weather year (1999), industry is flexible for 5–10% of the hours in the year, depending on the scenario. This equates to 400–800 hours. The majority of this flexibility is restorable by nature, meaning that industrial consumers shift their consumption from higher-priced hours to lower-priced ones.

Demand for hydrogen in manufacturing is assumed to be steady throughout the year and must be met, meaning that hydrogen must be evenly available every hour of the year. However, hydrogen production with an electrolyser may be flexible if there is a storage facility for hydrogen, in which case hydrogen production can be optimised to the most affordable hours of electricity prices. Significant hydrogen storage capacity is already planned in Sweden[39] and Denmark[40], for example. In addition, Central Europe has significant potential for hydrogen storage in salt stone caverns. Any hydrogen networks that may be built can also serve as hydrogen storage facilities. Based on this, Finland also has a significant amount of hydrogen storage in the Hydrogen from Wind and Windy Seas scenarios.

Table 17 shows the capacity of electrolysers in terms of electrical power, the storage capacity of hydrogen storage facilities in terms of hydrogen, and the average peak operating time of electrolysers as an average of the simulated weather years. The Hydrogen from Wind and Windy Seas scenarios assume the existence of a hydrogen transmission infrastructure, which also increases the hydrogen storage capacity. In practice, electrolysers can be flexible by 100% of their input power in these scenarios. In the Power to Products scenario, the flexibility of electrolysers is about half the input power, and in the Local Power scenario, electrolysers are not flexible at all.

Table 17 Information about hydrogen production and storage in different scenarios in 2035.

	Power to Products	Hydrogen from Wind	Windy Seas	Local Power
Electrolyser (input power, GW of electricity)	7.2	11.0	7.5	1.4
Hydrogen storage facility (GWh H2)	16	150	152	0
Peak operating time of electro-lysers (hours per year)	~6,500	~5,900	~5,800	~8,700

Hydrogen can be stored in the hydrogen network, steel tanks, and salt stone cavern storage. In the Hydrogen from Wind and Windy Seas scenarios, the hydrogen network enables storage both in the network and in non-local storage facilities. In the Power to Products and Local Power scenarios, the hydrogen network is not built, which is why storage must be carried out close to where the hydrogen is used. In all scenarios, building hydrogen storage is profitable with the cost assumptions used[41], which increases the flexibility of the system. However, in the Power to Products and Local Power scenarios, the construction of hydrogen storage has been restricted due to uncertainties about the potential[42] of stone cavern storage and the storage costs of steel tanks.

In addition, demand-side response is expected to increase due to the electrification of district heating and domestic heating. In these scenarios, the peak heating consumption varies between 6 GW and 9 GW. Approximately 1–3 GW of this consumption is provided by electric district heating boilers, which are assumed to be flexible according to the electricity price. Approximately 2 GW of the remaining 5–6 GW of peak heating consumption is flexible.

In domestic electric heating, consumption can be temporarily reduced, but consumption must be restored within the next few hours, as individual buildings are not assumed to have other forms of heat production in reserve. The maximum flexibility is estimated to be approximately 40% of consumption. The duration of the cut in consumption is no more than 3 hours, as individual buildings are assumed to have a low heat storage capacity, especially if the heating is based on air circulation instead of water circulation.

In district heating, the network acts as a heat storage facility, and heat can also be produced by other means, such as by a boiler using biomass, which enables the flexible running of heat pumps and electric boilers. In addition, many district heating networks have already invested or are currently investing in separate thermal batteries[43], which contribute to the flexibility of electric heating. Heat pumps in district heating are assumed to offer a maximum of 30% of their power in flexibility when the price exceeds EUR 75/MWh. Electric boilers are assumed to produce heat only when the price is below EUR 15/MWh. When the price is higher than this, heat is assumed to be produced by other means. Therefore, electric boilers are flexible with 100% of their input power.

Demand side response is also obtained from electric transport, where the batteries of electric cars can be charged smartly, so that charging is optimised according to the price of electricity, for example. The majority of electric cars, almost 70%, are estimated to use smart charging in 2035, and the share is estimated to reach 80% by 2045. The duration of flexibility can be up to days, as the battery capacity of an electric car is sufficient for several days of average driving. Without flexibility, electric cars are charged at a peak of 0.5–1 GW in 2035. As a result of smart charging, 70–80% of charging is optimised, and charging power can reach up to 6–8 GW during hours when cheap electricity is available. In addition, in the Power to Products scenario, some of the batteries of smartly charging electric cars can supply electricity to the network using so-called V2G (Vehicle-to-Grid) technology.

In addition to these consumption categories, other consumption, such as electricity use by households and services for purposes other than these categories (heating, transport), is not expected to provide significant demand-side response. Batteries placed in households and service buildings have been included in the calculation model as battery storage capacity, and therefore the flexibility they provide is not included in the proposed amounts of demand-side response.

[38] Estimates of the flexibility of heating processes are based on a Government (2021) report: Impact of the carbon-neutrality target on the electricity system. https://julkaisut.valtioneuvosto.fi/bitstream/handle/10024/162705/VNTEAS_2021_4.pdf

[39] https://www.hybritdevelopment.se/en/a-fossil-free-development/hydrogen-storage/

[40] https://greenhydrogenhub.dk/about/

[41] In a study by Gasgrid Finland and Guidehouse, the cost of a quarried rock cavern is estimated to be about 3 times higher than that of salt stone cavern storage. ENS.dk estimates the capital cost of salt stone caverns at EUR 2,000/MWh. Both storage techniques would therefore be very advantageous compared to electricity storage or storing hydrogen in steel tanks. The Gasgrid and Guidehouse report is available at: https://gasgrid.fi/wp-content/uploads/Gasgrid_Study-on-the-Potential-of-Hydrogen-Economy-in-Finland_ENG-FINAL.pdf and ENS.dk report is available at: https://ens.dk/sites/ens.dk/files/Analyser/technology_data_catalogue_for_energy_storage.pdf

[42] Stone cavern storage of hydrogen is only in the pilot phase, which makes it difficult to assess its local suitability and actual costs. The Luleå pilot project is an example: https://www.lkab.com/en/news-room/news/hybrit-sek-200-million-invested-in-pilot-plant-for-storage-of-fossil-free-hydrogen-in-lulea/

[43] Thermal batteries of different sizes already exist or are planned for district heating networks, at least in Espoo, Helsinki, Vantaa, Lappeenranta and Vaasa.

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