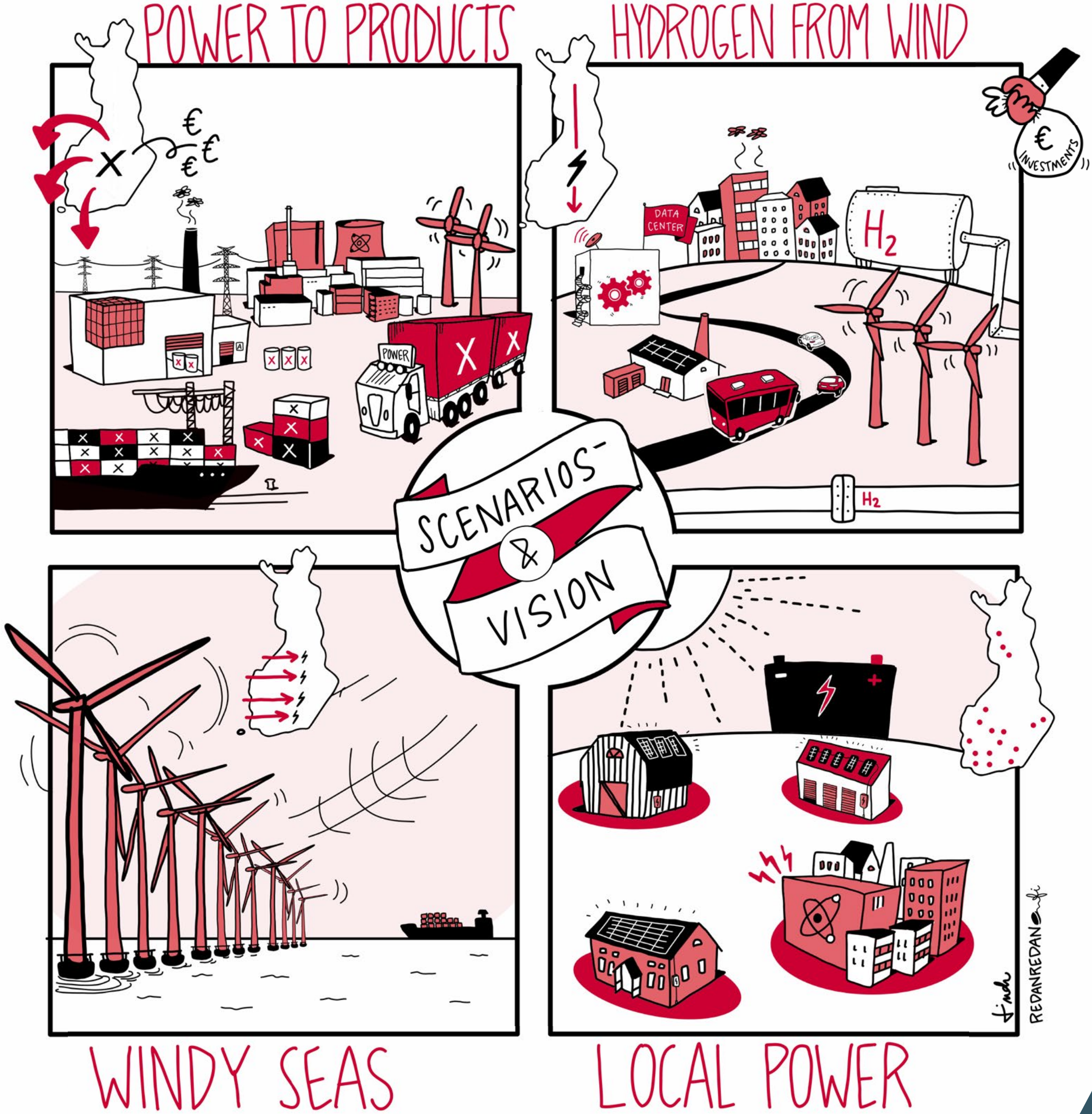

Fingrid's electricity system vision 2022 – draft scenarios for the future electricity system

FINGRID

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1 Introduction

Electricity system vision

During 2022, Fingrid will produce an electricity system vision for a carbon-neutral and competitive Finland. The vision is an update to the Network vision[1] published by Fingrid at the beginning of 2021; at the same time, the work expands beyond the long-term main grid planning perspective to address issues concerning the electricity market of the future and the management of the electricity system.

The electricity system vision presents Finland's opportunities for competing for electricity production and consumption projects, and identifies and raises for discussion challenges and opportunities that the transition to a carbon-neutral electricity system and society will bring. In our vision work, we have given ourselves permission to think big. A strong and reliable electricity main grid enables investments in both electricity-using industries and electricity production. Therefore, the long-term planning must be prepared for the realisation of even 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 unpreparedness would limit electrification development, the implementation of industrial investments and the achievement of climate targets, or lead to a deterioration in the system security of the main grid.

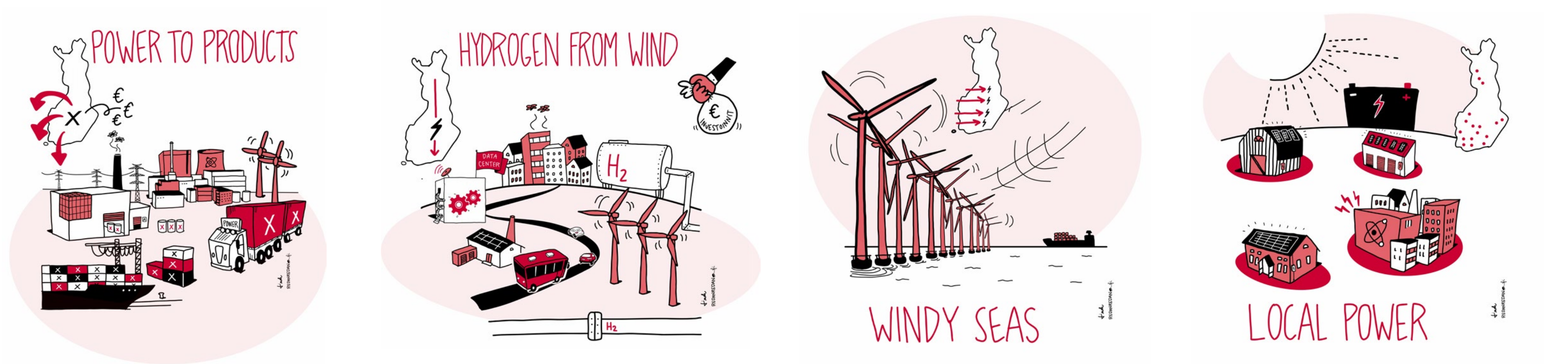
In this document, we present draft scenarios for 2035 and 2045. In addition to the scenarios, we also discuss what kinds of changes the energy transition described in the scenarios will mean for the entire electricity system. We welcome feedback from stakeholders not only on the scenarios themselves, but also on how stakeholders see the relationship between the scenarios and broader electricity system issues, such as electricity market developments, reserve supply, sufficiency of transmission capacity, and system technical issues. Fingrid will work on the scenarios and issues related to the electricity system based on the stakeholder feedback. Based on the finalised scenarios, a vision of the network investments needed in the future will be formed.

The four scenarios created 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, the development of electricity consumption, electricity generation potential, and Finland's competitiveness, as well as the system flexibility assumed in the scenarios. Section 4 discusses the effects of the future described in the scenarios on different aspects of the electricity system. After texts on various topics, we have added speech bubbles to the document, which contain questions on which we hope stakeholders will especially take a stand. Section 5 also lists all the questions asked in the speech bubbles, in addition to which the section contains instructions on how to give stakeholder feedback.

We wish you enjoyable reading moments with the future electricity system.

[1] https://www.fingrid.fi/kantaverkko/kehittaminen/verkkovisio/

Kuva 1 Scenarios of the electricity system vision



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

Power to 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

- Electricity consumption is particularly boosted by a significant increase in hydrogen production in Finland
- 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 changing production and consumption structure challenges 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. Fingrid and Gasgrid's joint project, on the other hand, examines the hydrogen economy in detail and looks more closely at the possible development paths of the hydrogen economy and the role of energy transmission systems in enabling the hydrogen economy. The Fingrid-Gasgrid joint project has developed separate scenarios from the perspective of the development of the hydrogen economy, where the focus is on sector integration of electricity and hydrogen systems . The joint project aims to find cost-effective development paths for the development of Finland's energy system.

[2] https://gasgrid.fi/wp-content/uploads/Fingrid-Gasgrid_Intermediate-report_Energy-transmission-infrastructure-as-enabler-of-hydrogen-economy-and-clean-energy-system.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 development of the energy sector and climate targets. To enable long-term vision work, the scenarios have been prepared for 2035 and 2045. The year 2035 is also interesting because of Finland's carbon-neutrality target. The main grid investments needed over the next ten years are described in the main grid development plan published in autumn 2021.[3]

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 correspondingly also require an increase in electricity production. In addition, one of the scenarios assumes the commercialisation of small modular nuclear power plants already by 2035. The scenarios have also been updated to take into account changes in energy trade between Europe and Russia following Russia's invasion of Ukraine. In this regard, the development of the situation is being monitored and, where possible, the impacts will be taken into account more closely in the final scenarios.

The most relevant variables in the scenarios in terms of electricity consumption are electricity consumption and its regional distribution for industry, hydrogen and electricity products, heating, and transport. On the electricity production side, on the other hand, 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 from production and consumption, the size 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 principles of modelling are described in Appendix 1.

In all scenarios, Finland's carbon-neutrality 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 guide it to resolve short-term challenges only. The scenarios have therefore been created in such a way as to challenge main grid planning, the structure of the electricity market, and the operation of the electricity system as a whole. The scenarios are based on the assumption of a number of developments that will allow the scenarios to materialise. Below are the main assumptions about the prerequisites for these developments:

[3] https://www.fingrid.fi/globalassets/dokumentit/fi/kantaverkko/kantaverkon-kehittaminen/kantaverkon-kehittamissuunnitelma-2022-2031.pdf

- 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, 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 network of neighbouring countries does not cause restrictions on cross-border electricity trade and, for example, the current export restriction on Fennoskan will be lifted.
- There are no new restrictions on the use of existing power plant capacity (e.g. hydro power capability to provide flexibility).
- If the acceptability of additional wind power construction is subject to restrictions, these do not simultaneously restrict the construction of both onshore and offshore wind power.
- 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 the expansion of new 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 or an unexpectedly high fall in the price of solar power 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.

The scenario modelling does not specifically take into account the impacts of the scenarios on the electricity system. Thus, the modelling of the presented scenarios does not take into account the adequacy of transmission capacity or the system-technical challenges caused by the scenarios. The sufficiency of reserves has also not been considered during the scenario creation phase. This is because the purpose of the work is to use scenarios to identify what potential challenges the energy transition described in the scenarios will pose to the operation of the electricity system from different perspectives. In this way, we can raise the challenges of the energy transition in a joint discussion and find solutions together with the sector. If we pre-limit our scenarios because of the challenge of the electricity system, a significant number of potential solutions could be missed. The effects of the scenarios on the electricity system are discussed more extensively in section 4.

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 in common the electrification of existing industrial processes and related heat production, at least along the path shown by low-carbon maps[4]. In industry, the growth in electricity consumption is particularly strong in the scenarios Power to products, Hydrogen from wind, and Windy seas, in which new electricity-intensive industries emerge in Finland, such as the electric fuel industry, the battery industry, and data centres, or electrolysis for the export of hydrogen. In the scenario Local power, 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, in the scenario Local power, electricity consumption related to heating increases only slightly, as the scenario assumes that solutions based on the use of waste heat in particular will reduce district heat 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 2019. The comparison is made with 2019, as the year 2020 does not provide as good comparison due the mild winter and influence of coronavirus pandemic.

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 scenarios Hydrogen from wind and Power to products. Offshore increases especially in the scenario Windy seas. Solar power production grows most strongly in the scenario Power to products. In all scenarios, hydro power remains at its current level. The use of fossil fuels is marginal in all scenarios.

[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/en/low-carbon-roadmaps-2035

Figure 2 **Consumption of electricity in the different scenarios.**

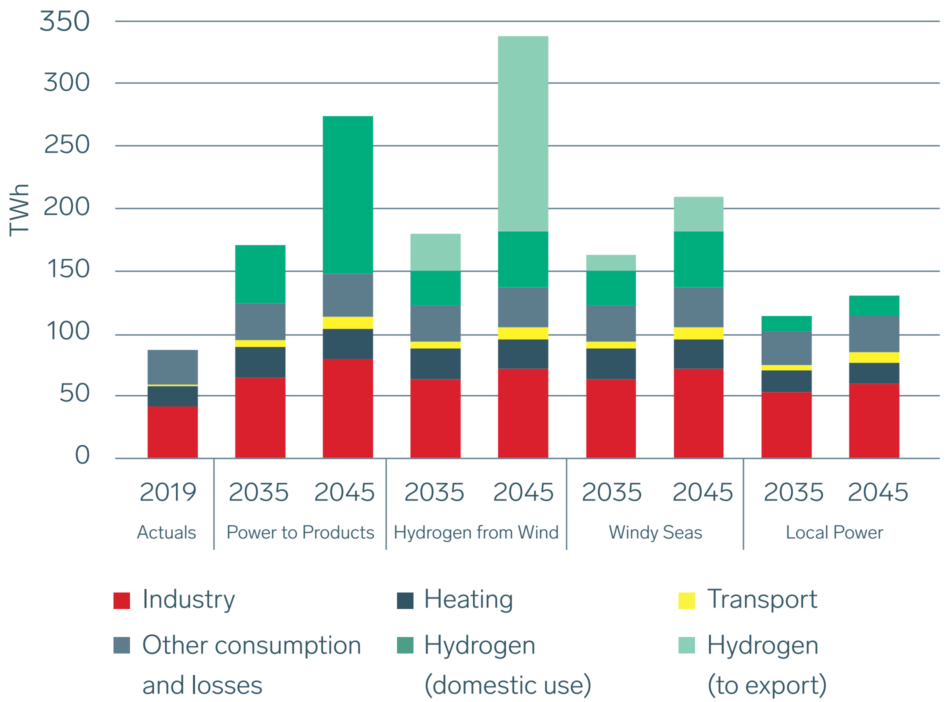


Figure 3 **Electricity production in the different scenarios.**

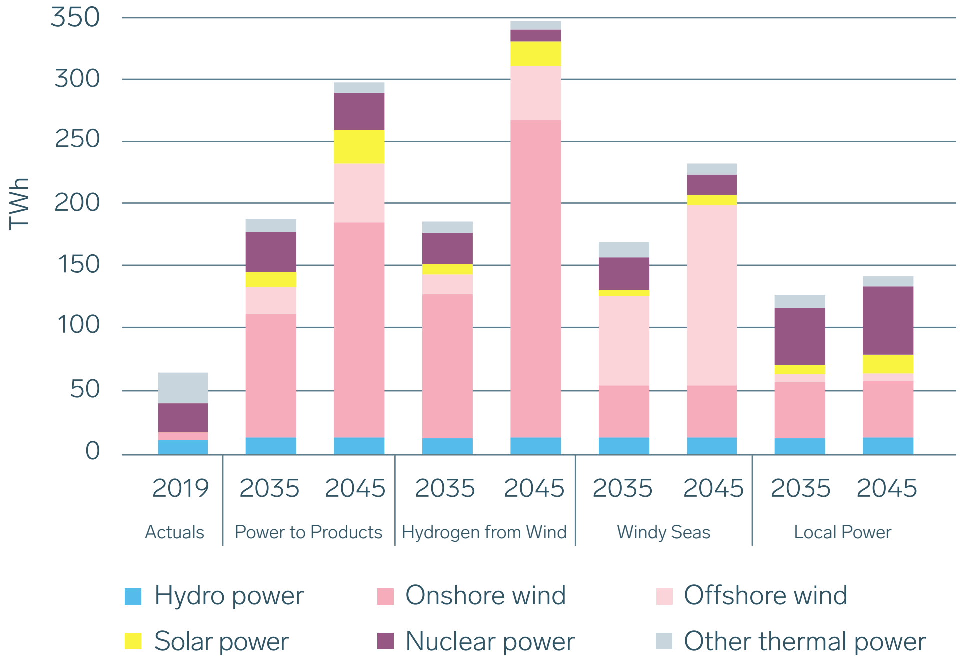


Table 2 Power balance in the different scenarios in 2035.

Power balance 2035 (TWh)	Power to products	Hydrogen from wind	Windy seas	Local power
Hydro power	14	14	14	14
Onshore wind power	99	115	42	45
Offshore wind power	21	16	71	6
Solar power	12	8	5	7
Nuclear power	32	26	26	46
Other thermal power	10	9	12	10
Total production	188	187	170	128
Total consumption	170	180	163	114
Finland's power balance (net exports)	18	7	8	14
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	14	14	14
Onshore wind power	171	253	42	45
Offshore wind power	47	43	143	6
Solar power	26	20	8	15
Nuclear power	30	10	17	55
Other thermal power	8	7	9	8
Total production	297	347	233	143
Total consumption	274	338	210	130
Finland's power balance (net exports)	23	8	23	13
Share of carbon-neutral electricity generation	100%	100%	100%	100%

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

Table 4 Production capacity in the different scenarios in 2035.

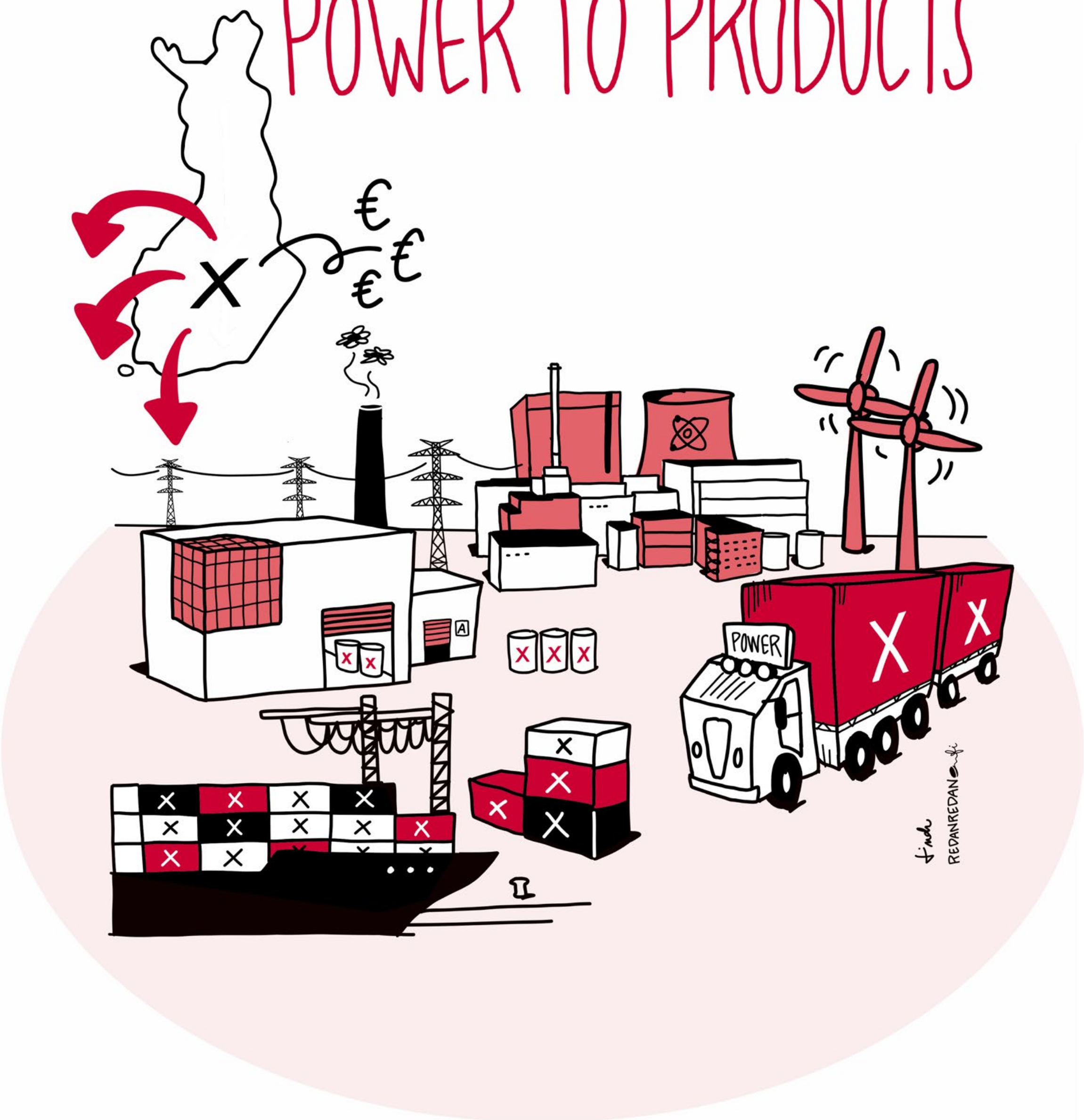
Capacity 2035 (MW)	Power to products	Hydrogen from wind	Windy seas	Local power
Hydro power	3	3	3	3
Onshore wind power	32	36	13	14
Offshore wind power	5	3	15	1
Solar power	12	8	5	7
Nuclear power	4	3	3	6
Other thermal power	5	4	4	4
Electricity storage (on the daily and intraday market)	1	1	1	3

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	3	3	3
Onshore wind power	53	76	13	14
Offshore wind power	10	9	31	1
Solar power	25	19	8	14
Nuclear power	4	2	2	8
Other thermal power	4	4	4	3
Electricity storage (on the daily and intraday market)	6	1	1	4

2.3

POWER TO PRODUCTS



In the scenario Power to products, Finland becomes a major exporting country of products made using electricity (P2X products)[6]. 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 addition, as a difference from other scenarios, Vehicle-to-Grid technology (V2G) for two-way charging is commonly used. In the scenario, P2X products are exported from Finland, not unprocessed hydrogen; thus, export links for hydrogen will not be built either.

Electricity production in Finland grows strongly with consumption. In particular, onshore wind power grows strongly, reaching 32 GW in 2035 and 53 GW in 2045. Onshore wind power is also increasingly built in eastern and northern Finland, which means that more geographically dispersed wind power produces electricity more evenly than regionally focused wind power. Less wind

[6] 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.

power is generated in southern Finland, as the number of suitable project areas is smaller than in the rest of Finland. In addition to onshore wind power, offshore wind power and more solar power than in other scenarios are built into the system, and their production profiles differ from that of onshore wind power.

The amount of hydro power remains at its current level. The old 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 does not break through commercially in this scenario. The amount of biopower decreases moderately.

Electricity consumption in the scenario Power to products is described in Table 6. Electricity production capacity and annual production are described in Table 7.

[7] SMR technology refers to a serially manufactured nuclear power plant with a modular structure, the size of which is from tens to some hundreds of megawatts, and which is used for the production of both electricity and heat in cities.

Table 6 Electricity consumption in the scenario Power to products.

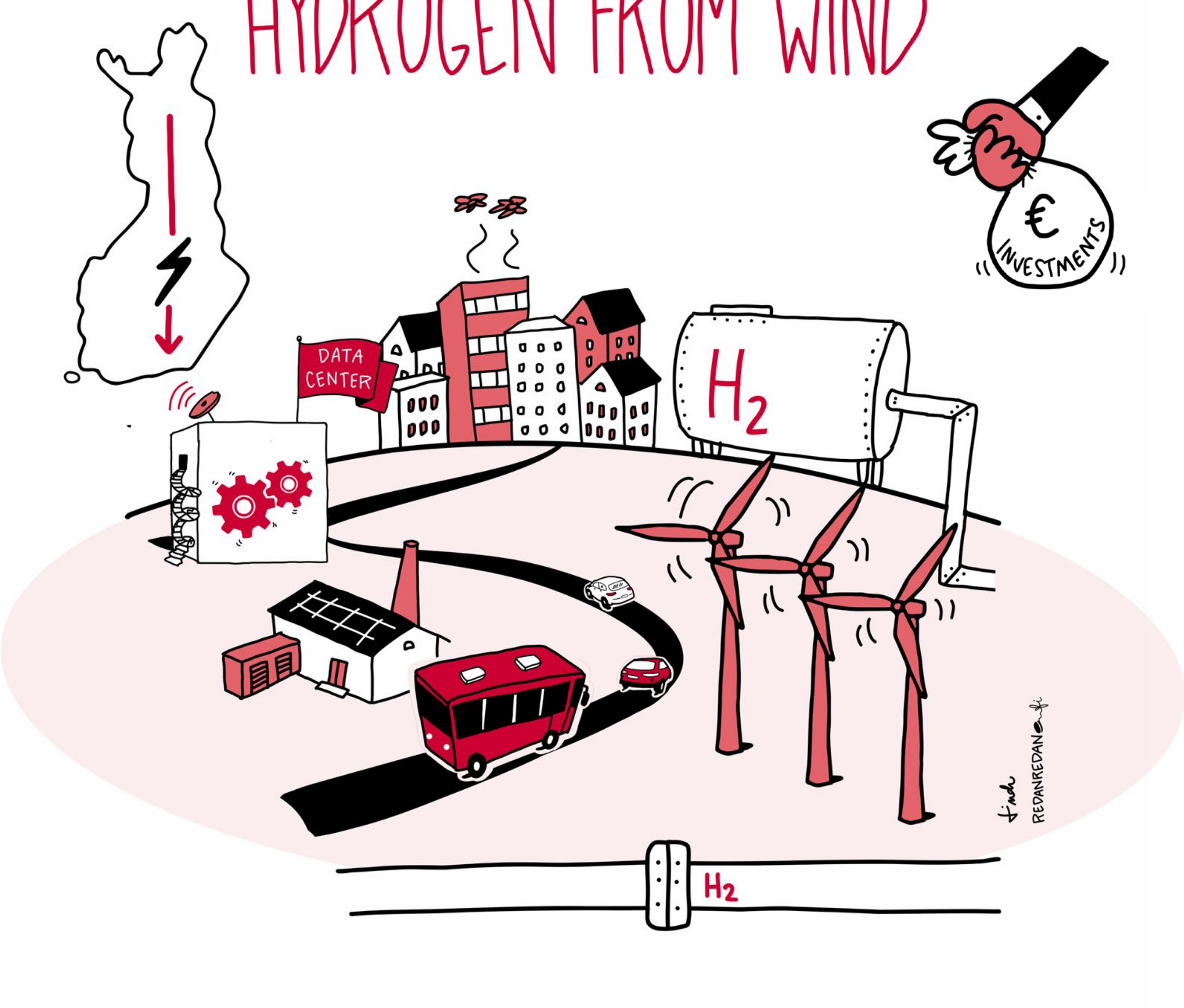
Electricity consumption in the scenario Power to products (TWh)	2019	2035	2045
Industry excl. electrolysis	41	64	79
Electrolysis	0	47	126
Heating	17	25	24
Transport	1	5	10
Other consumption and losses	28	30	35
Total	86	170	274

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

Electricity production capacities in the scenario Power to products (GW)	2019	2035	2045
Hydro power	3	3	3
Onshore wind power	2	32	53
Offshore wind power	0	5	10
Solar power	0	12	25
Nuclear power	3	4	4
Other thermal power	8	5	4
Total	16	61	100

Electricity production in the scenario Power to products(TWh)	2019	2035	2045
Hydro power	12	14	14
Onshore wind power	6	99	171
Offshore wind power	0	21	47
Solar power	0	12	26
Nuclear power	23	32	30
Other thermal power	25	10	8
Total production	66	188	297
Consumption	86	170	274
Finland's power balance	-20	18	23

2.4 HYDROGEN FROM WIND



In the scenario Hydrogen from wind, 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 both district and separate heating and transport increases. The majority of electric cars are charged smartly, but V2G technology is not widely utilised.

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: 36 GW; 2025-2035 average +2.6 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. Offshore and solar power grow strongly, while hydro power remains at its current level. The amount of nuclear and biopower declines.

Electricity consumption in the scenario Hydrogen from wind is described in Table 8. Electricity production capacity and annual production are described in Table 9.

Table 8 Electricity consumption in the scenario Hydrogen from wind.

Electricity consumption in the scenario Hydrogen from wind (TWh)	2019	2035	2045
Industry excl. electrolysis	41	63	71
Electrolysis	0	58	202
Heating	17	25	24
Transport	1	5	10
Other consumption and losses	28	29	32
Total	86	180	338

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

Electricity production capacities in the scenario Hydrogen from wind (GW)	2019	2035	2045
Hydro power	3	3	3
Onshore wind power	2	36	76
Offshore wind power	0	3	9
Solar power	0	8	19
Nuclear power	3	3	2
Other thermal power	8	4	4
Total	16	57	113

Electricity production in the scenario Hydrogen from wind (TWh)	2019	2035	2045
Hydro power	12	14	14
Onshore wind power	6	115	253
Offshore wind power	0	16	43
Solar power	0	8	20
Nuclear power	23	26	10
Other thermal power	25	9	7
Total production	66	187	347
Consumption	86	180	338
Finland's power balance (net exports)	-20	7	8

2.5

The key factor in the scenario Windy seas is a sharp increase in offshore wind power. In the scenario, Finland's electricity production focuses heavily on western Finland; a large part of onshore wind power is built there, as well as all offshore wind power and, by 2035, all nuclear power, as in this scenario, the operating time of the Loviisa units is not extended after the current permit period. A key challenge for the development of the main grid is the transmission of this electricity surplus to consumption concentrations. If the offshore wind would be located also at the gulf of Finland, it would decrease the electricity transmission need and lead to a lower variability of offshore wind production.

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 scenarios Power to products and Hydrogen from wind. The majority of electric cars are charged smartly, but V2G technology is not widely utilised.

In the scenario Windy seas, a hydrogen transmission infrastructure has been assumed inside 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 scenario Hydrogen from wind. 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 the 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 located about 10-20 kilometres from the coast, allowing the use of an AC-powered network connection. Thus the investment cost of offshore wind power is lower than when using an HVDC transmission link to connect a farm further offshore. 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 decreases when the Loviisa plant units are decommissioned. The amount of biopower decreases moderately.

Electricity consumption in the scenario Windy seas is described in Table 10. Electricity production capacity and annual production are described in Table 11.

Table 10 Electricity consumption in the scenario Windy seas.

Electricity consumption in the scenario Windy seas (TWh)	2019	2035	2045
Industry excl. electrolysis	41	63	71
Electrolysis	0	41	73
Heating	17	25	24
Transport	1	5	10
Other consumption and losses	28	29	32
Total	86	163	210

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

Electricity production capacities in the scenario Windy seas (GW)	2019	2035	2045
Hydro power	3	3	3
Onshore wind power	2	13	13
Offshore wind power	0	15	31
Solar power	0	5	8
Nuclear power	3	3	2
Other thermal power	8	4	4
Total	16	43	62

Electricity production in the scenario Windy seas (TWh)	2019	2035	2045
Hydro power	12	14	14
Onshore wind power	6	42	42
Offshore wind power	0	71	143
Solar power	0	5	8
Nuclear power	23	26	17
Other thermal power	25	12	9
Total production	66	170	233
Consumption	86	163	210
Finland's power balance (net exports)	-20	8	23

2.6

In the scenario Local power, 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 of the electricity system and market that are needed 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 the 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 6 GW in 2045. The power plants are used for combined heat and power production and are located in existing district heating systems. The operation of the Loviisa nuclear power plant continues into the 2030s. The cost of solar power decreases faster than in the other scenarios, and solar power capacity grows strongly in Finland, as well. 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.

Electricity consumption in the scenario Local power is described in Table 12. Electricity production capacity and annual production are described in Table 13.

Table 12 Electricity consumption in the scenario Local power.

Electricity consumption in the scenario Local power (TWh)	2019	2035	2045
Industry excl. electrolysis	41	52	59
Electrolysis	0	13	16
Heating	17	18	17
Transport	1	4	8
Other consumption and losses	28	27	29
Total	86	114	130

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

Electricity production capacities in the scenario Local power (GW)	2019	2035	2045
Hydro power	3	3	3
Onshore wind power	2	14	14
Offshore wind power	0	1	1
Solar power	0	7	14
Nuclear power	3	6	8
Other thermal power	8	4	3
Total	16	35	44

Electricity production in the scenario Local power (TWh)	2019	2035	2045
Hydro power	12	14	14
Onshore wind power	6	45	45
Offshore wind power	0	6	6
Solar power	0	7	15
Nuclear power	23	46	55
Other thermal power	25	10	8
Total production	66	128	143
Consumption	86	114	130
Finland's power balance (net exports)	-20	14	13

3 Scenario themes

3.1 Development of electricity demand

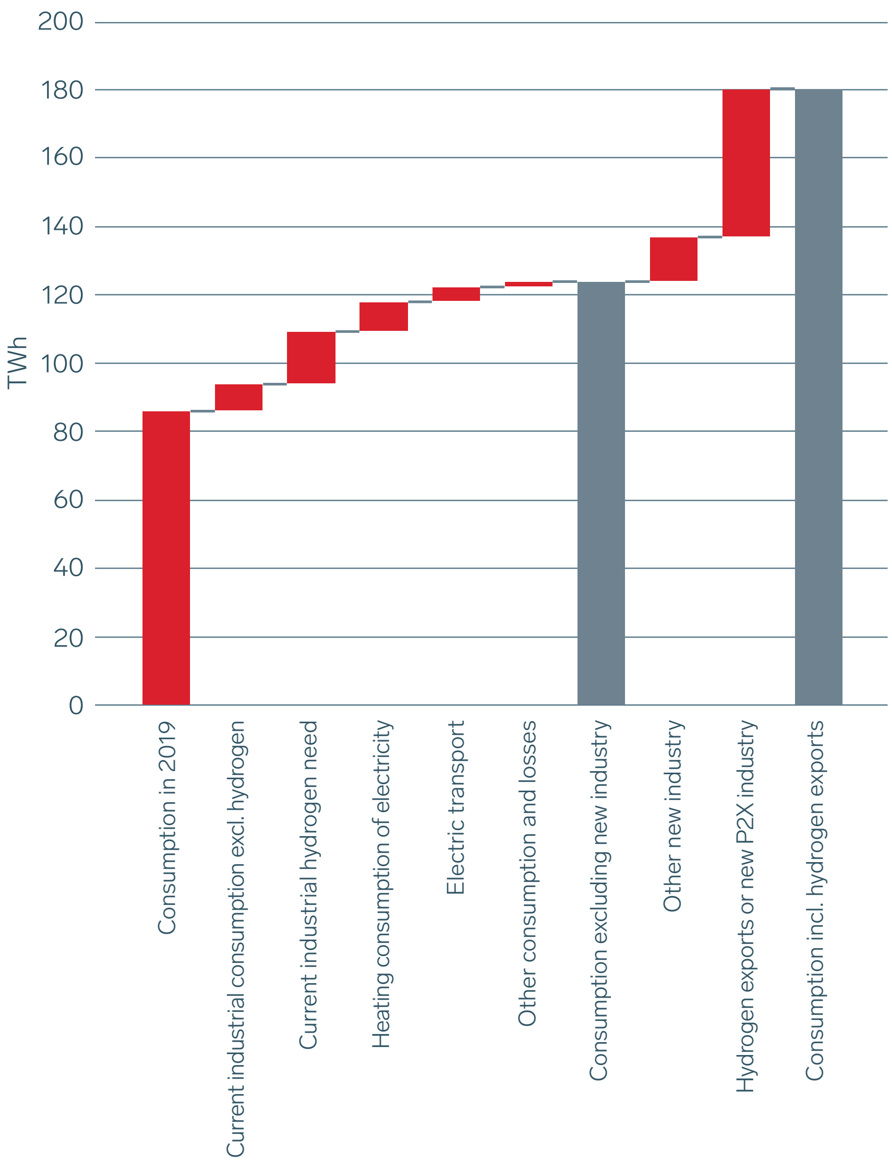
The scenarios anticipate a very strong increase in electricity consumption. Electricity consumption may even double by 2035 compared to current levels, but consumption may also remain at lower levels if one or more growth drivers do not progress. Figure 4 illustrates which components may constitute the growth required for doubling. The figure presents the development of consumption in the scenario Hydrogen from wind, but the structure is similar in the scenarios Power to products and Windy seas, although the amount and purpose of P2X production differs between the scenarios.

The growth in current industrial consumption (+8 TWh) 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.[8]

Replacing fossil fuels in district heating and separate heating of buildings would increase electricity consumption by approximately 9 TWh, although the figure depends heavily on how much of the energy is obtained from waste heat and how much the heating demand of buildings decreases as a result of climate change and energy efficiency measures. 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.

[8] 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. Efficiency coefficient of electrolysis is assumed to be 70 %.

Figure 4. Electricity consumption growth components for years 2019–2035.

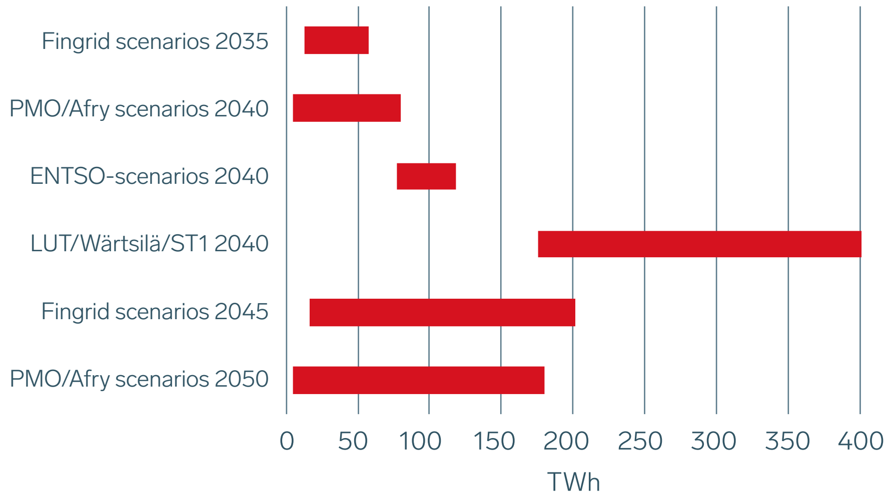


By 2035, the above changes would bring Finland's electricity consumption to a level of approximately 120–125 TWh, which would correspond to an increase of approximately 40–45 per cent compared to the current situation. In addition to this growth, it is possible – if not probable – that clean and competitively 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.[9] 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)[10]. In addition to Central Europe, a potential target for hydrogen pipeline exports is northern Sweden, where LKAB[11] 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 5 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[12] by LUT, Wärtsilä and ST1; the "Hydrogen economy – Opportunities and limitations" report[13] by the Prime Minister's Office and Afry; and the ten-year network plan of ENTSO-E and ENTSOG (TYNDP2022)[14].

Figure 5. Use of electricity for hydrogen production in the system vision scenarios compared to other parties' scenarios.



[9] 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.

[10] 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.

[11] 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

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

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

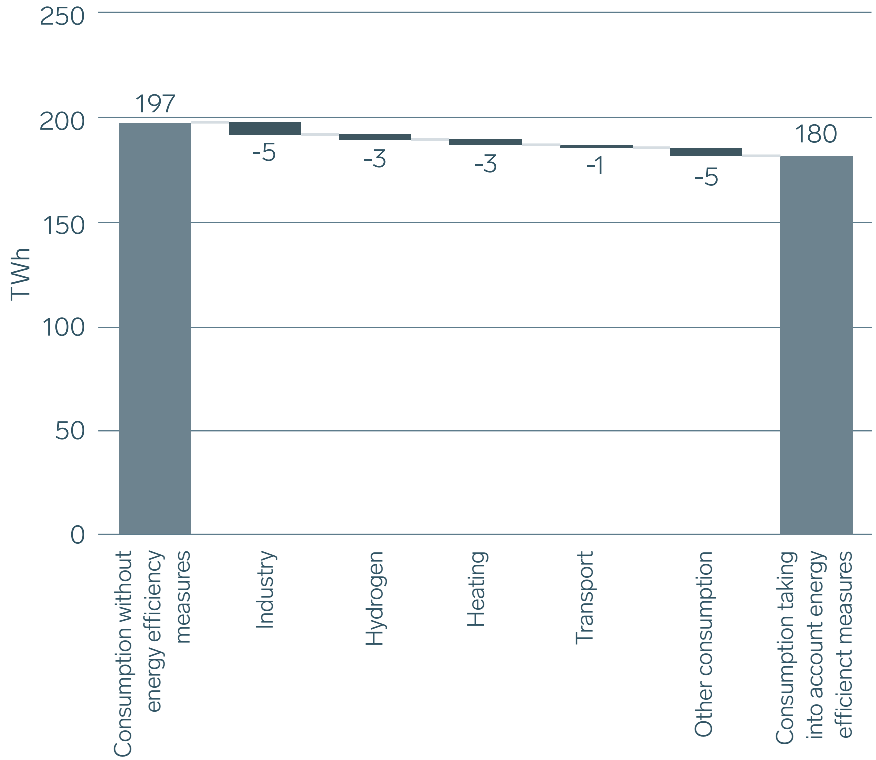
[14] https://2022.entsos-tyndp-scenarios.eu/visualisation-platform/ data retrieved 10th of February 2022.

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 lower than in the two scenarios of the Carbon-neutral Finland report. In the first of these, Finland's bio-based carbon dioxide emissions would be utilised in the manufacture of P2X products, and the electricity consumption of hydrogen production is slightly higher than in the system vision scenarios. In the second scenario of the Carbon-neutral Finland report, fossil carbon dioxide emissions are also utilised in hydrogen production, so electricity consumption is clearly higher 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 6 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. 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 6 Energy efficiency assumptions in the scenario Hydrogen from wind.

Assumption of effect of energy efficiency measures on electricity consumption 2035



[15] 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.

Finland's wind power potential is very high. Fingrid has received approximately 170,000 MW worth of inquiries to connect electricity production to the main grid, the majority of which is wind power, but the share of solar power is also growing strongly. If all the projects were to be implemented, they would generate approximately 600 TWh of renewable electricity. Naturally, not all inquiries will be realised as completed projects. However, there were about 90,000 MW of project inquiries in spring 2021, so the number of inquiries has nearly doubled by August 2022. There is also no specific reason why the potential of wind power in Finland would be lower than in Germany, which is of roughly the same size, where the potential calculated on the basis of ENTSO-E and ENTSOG's TYNDP2022 draft scenarios is close to 800 TWh.[16] Thus, 600 TWh may even be a conservative estimate for Finland.

A potential of 600 TWh is estimated to correspond to more than 10% of the total EU wind and solar power potential, using the potentials derived from the TYNDP2022 scenarios as the EU benchmark.[17] 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 in relation to the the need for electricity and hydrogen, which is not common 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. In addition, even if the production of wind and solar power in the EU was distributed in 2050 exactly in relation to current electricity consumption, and not in relation to the potential of renewables, Finland's share of production would be around 150 TWh, which would also be a massive change compared to the current situation.

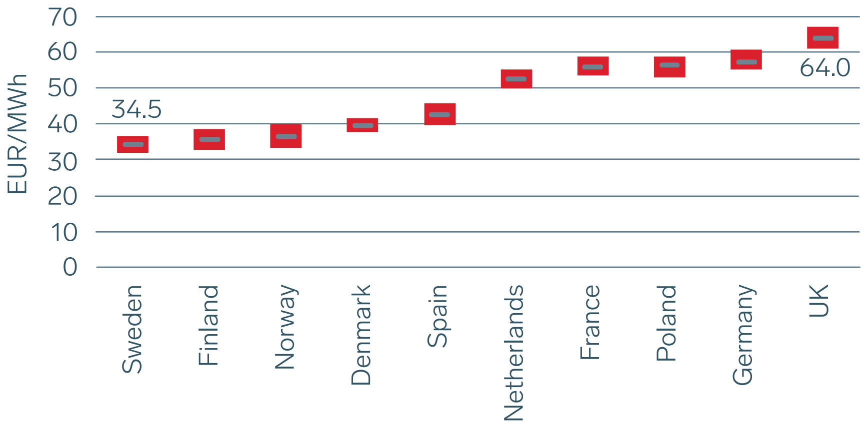
The competitiveness of Finland's electricity production is increased by the possibility of building cost-effective onshore wind power based on high power plant heights. In many other European countries, the focus has shifted to the construction of offshore wind power due, among other things, to local opposition to onshore wind power, in addition to which the costs of onshore wind power projects that can be built are higher. Renewable electricity is often procured through long-term power purchase agreements (PPAs), the pricing of which is also affected by the current and assumed price level of electricity in the market area. Thus, PPA prices also reflect the potential of the amount of renewable electricity and the cost of producing alternative (fossil) electricity, not just the cost of producing renewable energy. Figure 7 presents the price levels of PPAs reported by Bloomberg in various European countries in the first quarter of 2022. The price level in Finland appears to be remarkably affordable compared to Central European countries in particular, not only in wind power, but also in solar power.

[16] https://2022.entsos-tyndp-scenarios.eu/download/

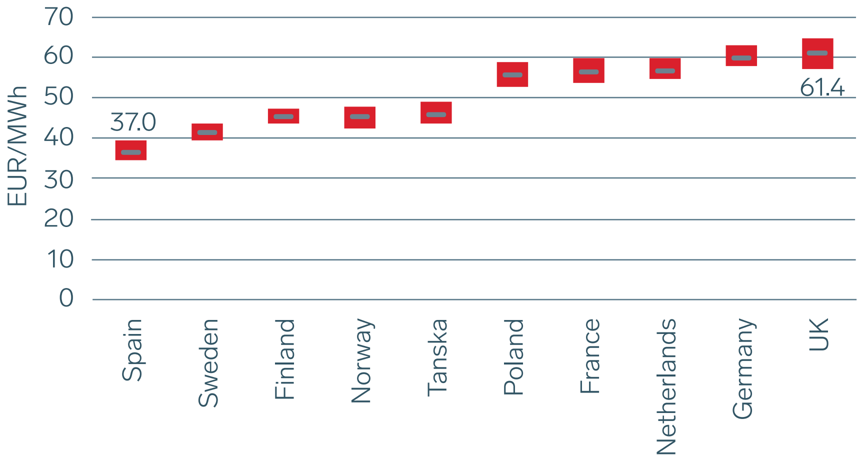
[17] In the TYNDP2022 draft scenarios for 2050, the combined production of wind and solar power was ~5000 TWh in the Distributed Energy scenario and ~4400 TWh in the Global Ambition scenario. The sum of the maximum production calculated on a country-by-country basis was approximately 5300 TWh.

Figure 7 Wind and solar power purchase agreement (PPA) prices in Q1/2022. Source: Bloomberg new energy finance[18]. The red bar represents the range, and the grey line represents the average.

Onshore wind PPA prices, Q1 2022



Solar power PPA prices, Q1 2022



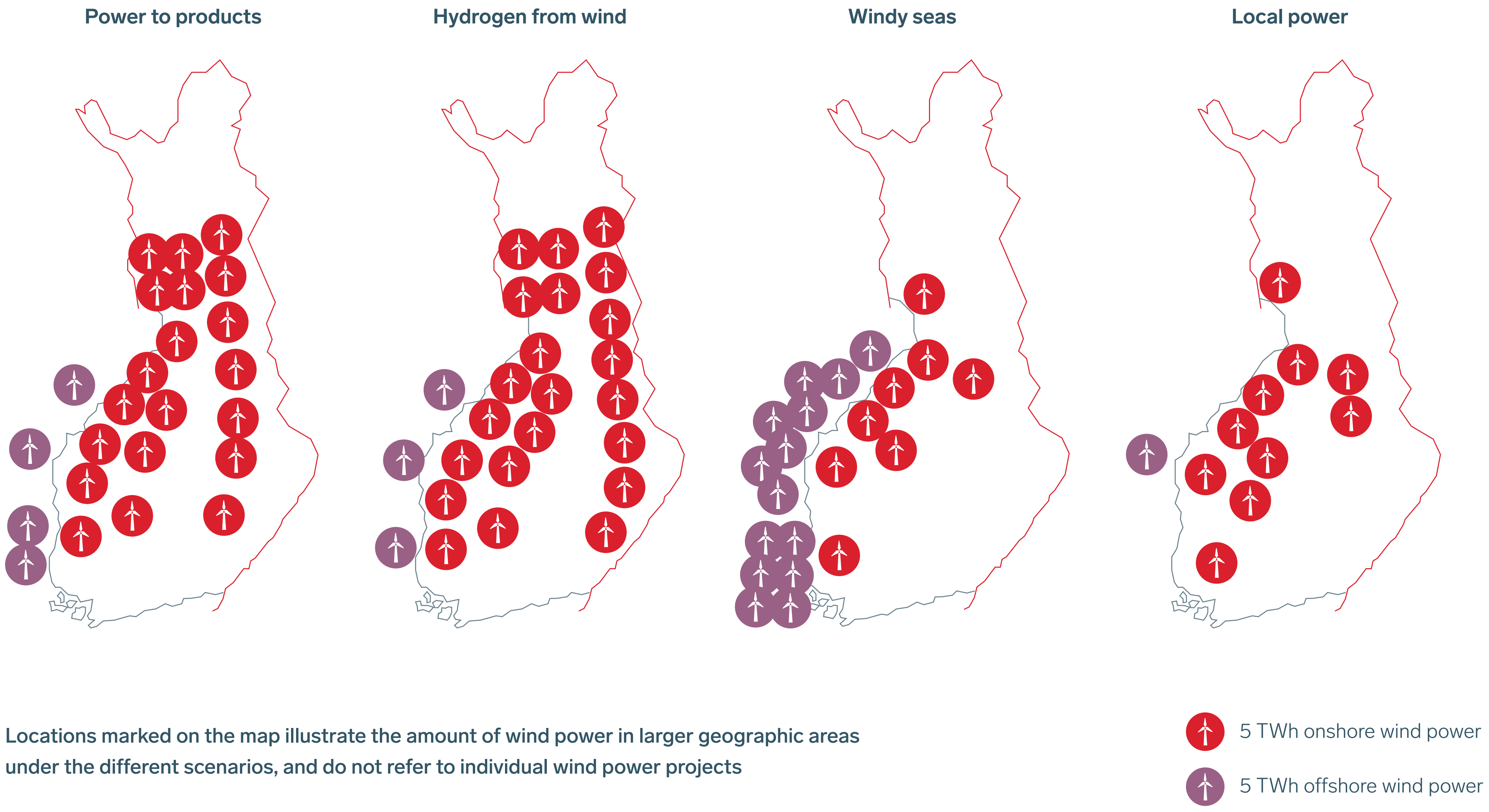
The data reported by Bloomberg on the current situation is in line with the simulated results in Fingrid's scenarios for 2035. Compared to the rest of Europe, relatively large quantities of low-cost electricity production can be built in Finland, resulting in the average marginal electricity production cost in Finland being clearly lower in the simulated scenarios than in Central Europe, despite large quantities of electricity, hydrogen and P2X products being exported from Finland at the same time.

Figures 8 and 9 illustrate assumptions about the geographical focus areas of electricity production. In the scenarios Power to products and Hydrogen from wind, onshore wind power is built extensively across Finland. The most significant part of the production is located in Ostrobothnia, Lapland, Kainuu and elsewhere in eastern Finland. In the scenario Windy seas, 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 large solar parks are concentrated. In the scenario Local power, the growing small-scale nuclear power is located 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.

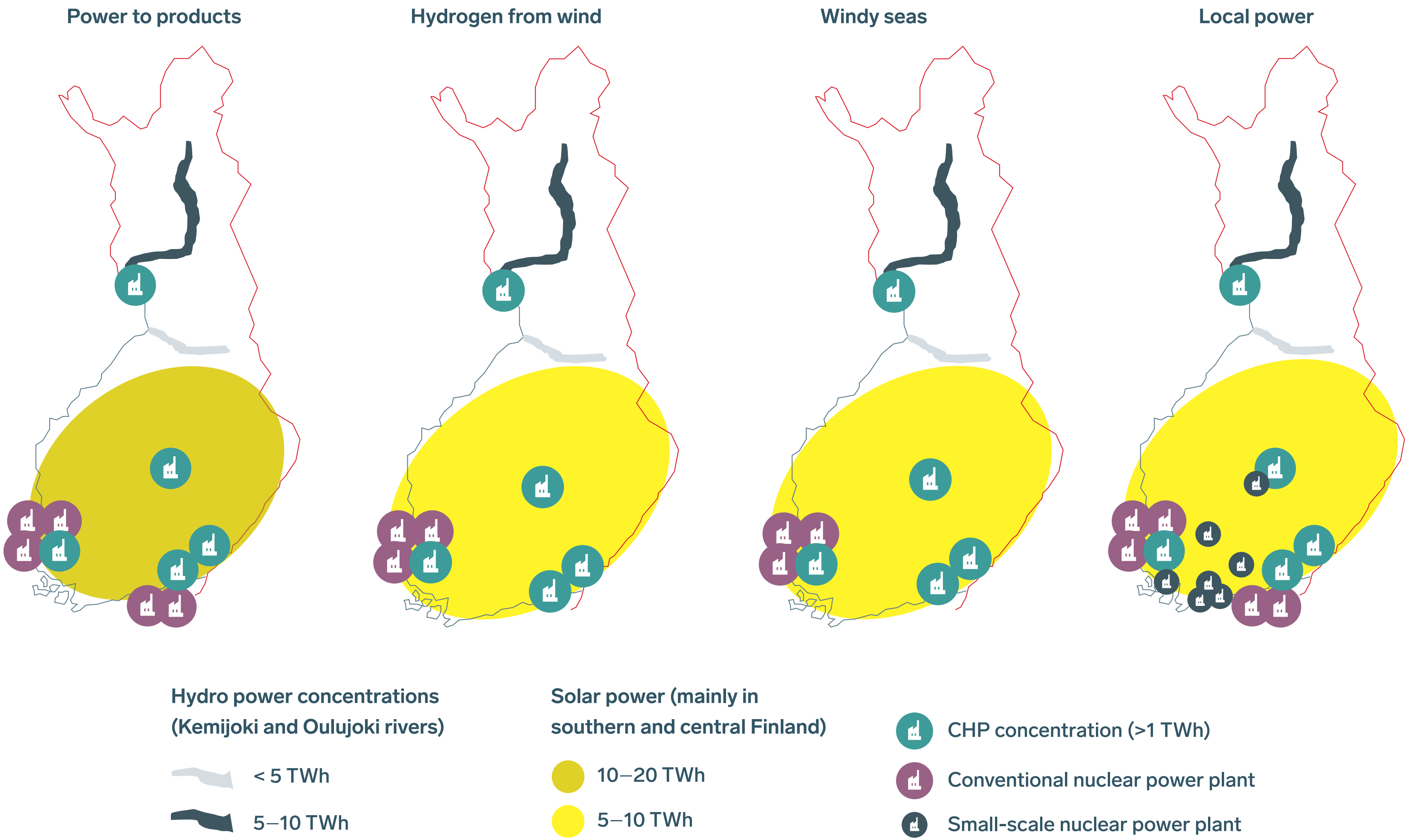
[18] https://about.bnef.com/blog/wind-and-solar-corporate-ppa-prices-rise-up-to-16-7-across-europe/

Figure 8 **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 9 Assumptions about the geographical focus areas of solar, hydro, nuclear and thermal power in 2035.



3.3 Transmission connections

The scenarios assume that, in addition to the Aurora Line (+800 MW import / +900 MW export), another new transmission connection will be built between Finland and Sweden by 2035. This connection has been in the simulations between Aurora Line 2 bidding zones FI and SE1, with a capacity of 800 MW. In the scenario Power to products, it is 1600 MW, while the connection is assumed to be implemented as a 2 x 400 kV connection. The Fenno-Skan connections are assumed to be in use, and the internal transmission restrictions of the Swedish main grid currently restricting exports are assumed to have been lifted in 2035. A commercial transmission capacity of 150 MW has been assumed between Finland and Norway's NO4 bidding zone. In addition to the existing connections, an EstLink 3 transmission connection (+700 MW) has been assumed between Finland and Estonia. In addition, in the scenario Windy seas, a new submarine cable connection to Germany (+1400 MW) has been assumed, which increases electricity exports in the scenario. By 2045, border transmission capacity to the rest of the EU is assumed to increase further. The scenarios assume that the border transmission capacity between Finland and Russia is permanently decommissioned. All assumptions made about electricity transmission connections are preliminary at this stage, and the benefits of new transmission connections will be examined in more detail in the later stages of the system vision work. Table 14 summarises the assumptions for available border transmission capacity in 2035 by scenario.

Table 14 Assumptions about available electricity transmission capacities in the scenarios in 2035.

	Power to products (MW)	Hydrogen from wind (MW)	Windy seas (MW)	Local power (MW)
FI-SE1	3,600	2,800	2,800	2,800
FI-SE3	1,200	1,200	1,200	1,200
FI-NO4	150	150	150	150
FI-EE	1,716	1,716	1,716	1,716
FI-DE	0	0	1,400	0

In terms of hydrogen transmission connections, the scenario Hydrogen from wind assumes a pipeline connection from Finland to Central Europe[19] (13 GW) and from northern Finland to northern Sweden[20] (7.2 GW). In the scenario Windy seas, a pipeline connection between northern Finland and northern Sweden has been assumed. In the scenarios Hydrogen from wind and Windy seas, a north-south pipeline connection has been assumed inside Finland, combining production and demand facilities and cross-border connections for hydrogen. In the scenarios Power to products and Local power, no cross-border connections for hydrogen or intra-Finnish pipeline connections have been assumed.

3.4 Flexibility

The significant increase in electricity consumption, as well as renewable production that varies according to the weather, increases the need for flexibility in order to maintain the power balance of consumption and production in the electricity system. The balance is maintained by increasing the ability to control production, energy storage and demand side response.

Fluctuations in[19] electricity prices create incentives especially for energy storage and demand side response. Fluctuations increase as the amount of renewable production that varies according to the weather increases. In windy hours, the need for more expensive forms of electricity production decreases, while in low-wind hours, electricity is produced by more expensive forms of production. Fluctuations in electricity prices can also encourage investment in adjustable peak power.

Figure 10 presents the duration curve of electricity price and its range according to different weather scenarios in the Power to products scenarios in 2035. Similarly figure 11 presents the median duration curve of electricity

[19] 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

[20] 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

[21] In this paragraph, price refers to the resulting marginal cost in the market simulations of the scenarios.

price in all 2035 scenarios. The figures show that electricity price vary considerably, despite the flexibility already assumed in the scenarios. Flexibility is also emphasised between scenarios: In the scenario Local power, 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 scenarios Windy seas and Hydrogen from wind, 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 scenario Power to products, where the amount of storage is smaller, the system is relatively less flexible. In the scenario Power to products, 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. As a result, in the Power to products scenario, the average production cost of electricity in Finland is also the highest of the scenarios.

Figure 10 Duration of electricity price in the scenario Power to products in 2035. The y-axis of the figure is cut for readability, the maximum of the range is multiple times higher.

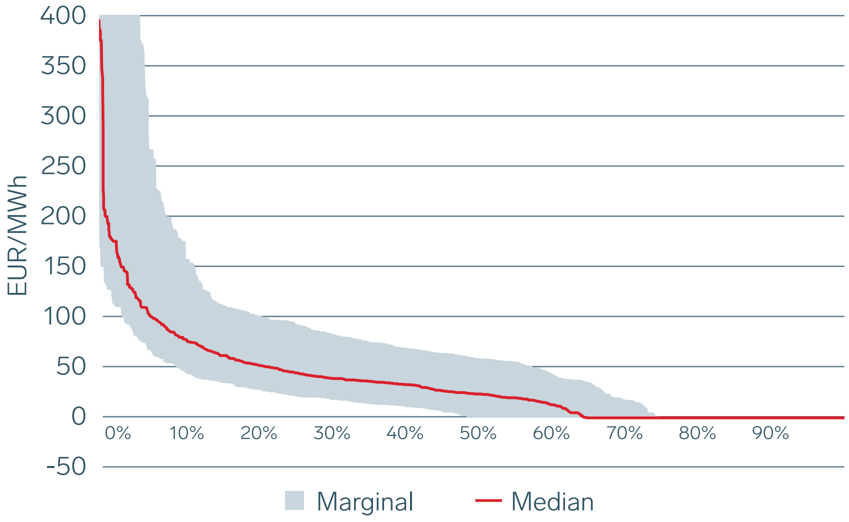


Figure 11 Duration of electricity price in the 2035 scenarios (median).

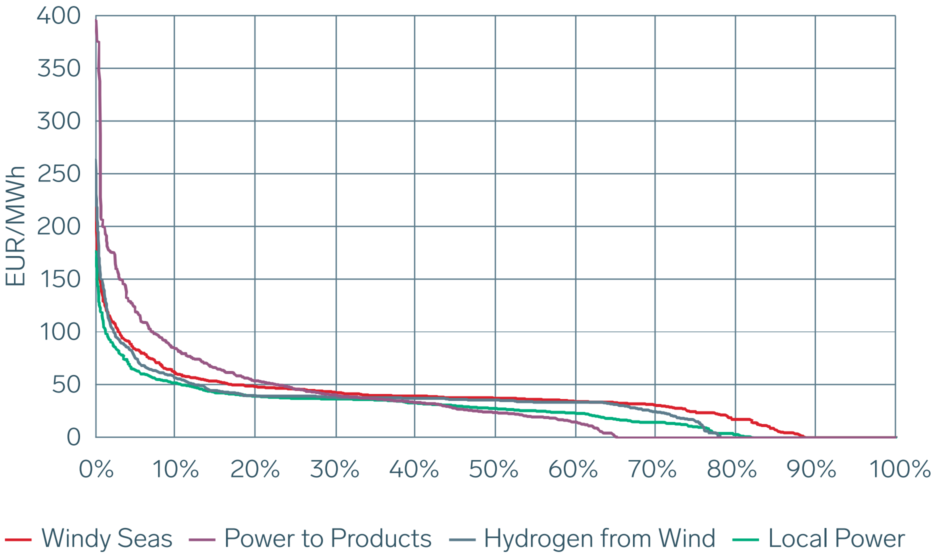
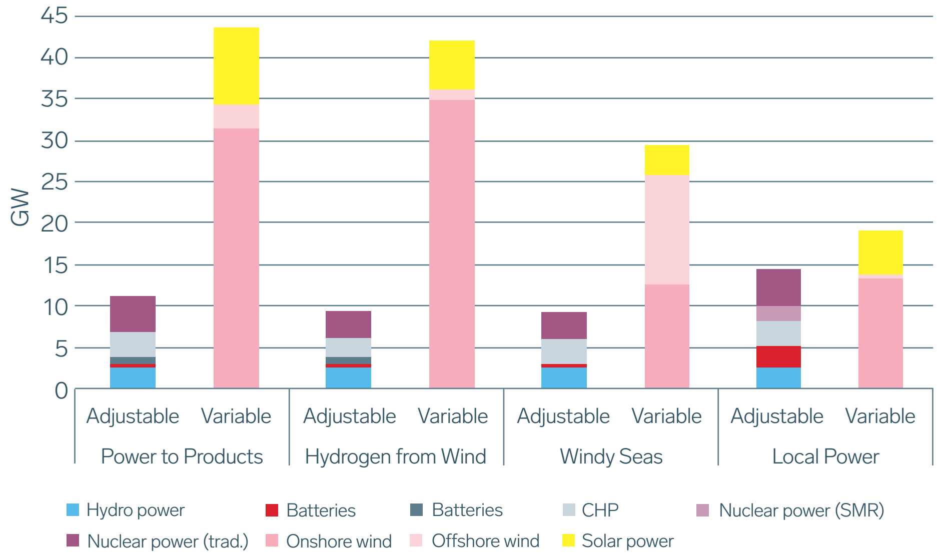


Figure 12 presents the distribution of production in the scenarios into adjustable production and electricity storage, as well as variable renewable wind and solar power. In the scenarios, flexibility and adjustable power are obtained from existing hydro, nuclear and thermal power, among others. Hydro power is very important for balancing the system, but its amount cannot be increased much. In addition, investments in new thermal power capacity are not expected to be realised to a significant extent, thereby reducing thermal power capacity and the resulting flexibility. In addition, the scenarios assume that 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.

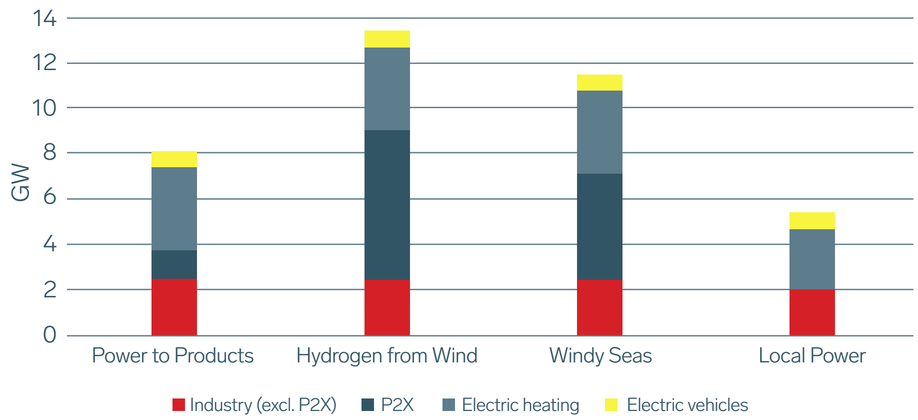
Figure 12 Hourly peak production by different forms of production and their distribution into adjustable and variable production in the scenarios in 2035.



In terms of profitability, increasing adjustable production seems challenging in the scenario analysis. Therefore, in the scenarios, new flexibility is obtained mainly from consumption. In demand side response, electricity consumption can be temporarily reduced and, at best, energy can be stored as heat or hydrogen for longer periods of time for later use.

Figure 13 presents the demand side response available in the different scenarios during a consumption peak. Demand side response is broken down into four consumption categories: Industry (excluding electrolysis), electrolysis, electric heating, and transport. The amount of demand side response available from different sources varies by scenario, depending on the underlying assumptions. The flexibility of electrolysers between the scenarios is the same, but the amount of flexibility depends on electrolysis capacity and hydrogen storage capacity. In the scenario Local power, hydrogen cannot be stored or imported, in which case the electrolysers are also not flexible. 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 scenario Local power is not as strong, which reduces flexibility.

Figure 13 Demand side response available in different scenarios during a consumption peak in 2035.



It should be noted that, in the calculation of the amount of demand side response in the figure, a situation with no demand side response at all has been used as a reference point. In other words, without flexibility, consumption would behave in accordance with the final demand profile set for it. The consumption of industry and electrolysis is uniform in nature, while the consumption of heating varies depending on the demand for heat and the required charging of electric cars. For example, the described amount of flexibility in heating is therefore only available during very cold winter frosts.

Table 15 specifies the sources of demand side response under the categories, in addition to which it breaks down demand side response into three types: cutting, restoring and storing. In the cutting type, electricity user reduces electricity consumption according to marginal price. In the restoring type, electricity user reduces electricity consumption according to the marginal price, but consumption is increased in subsequent hours by an amount equal to the cut. In the storing type, energy can be stored, for example as electricity, heat or hydrogen, and thus consumption is optimised according to price within the limits set by the storage.

The flexible part of the table reflects the flexibility potential of the total consumption of the consumption category (industry excluding electrolysis, electrolysis, heating, transport). For example, the amount of flexibility from traditional manufacturing industry does not exceed 20% of industrial consumption. However, industrial consumption can be flexible overall by up to 35%, 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.

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	20%	Several hours – days
	Electrified heating processes	Restoring	10%	Several hours – days
Electrolysis	Flexibility of electrolysers	Storing	0–100%	Several hours – days
Heating	Electric heating of households	Restoring	30%	A few hours
	Electric district heating	Cutting/ Restoring	20%	Several hours
Transport	Smart charging of electric vehicles	Storing	70%	Several hours – days

Industrial non-electrolysis demand side response comes from data centres, traditional manufacturing, and the electrification of heating processes in both old and new industrial sites. The normal hourly consumption power of industry varies between 6-8 GW per scenario in 2035, of which a total of around 2-3 GW is flexible.

Data centres are seen as potential providers of flexibility, 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/MWh 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. It is assumed to remain almost the same in relation to the amount of industrial consumption.

In industry, the amount of demand side response is estimated to increase with the electrification of heating processes in both existing and new industrial sites[22]. Heating can be electrified, for example, using large-scale industrial heat pumps and electric boilers. The marginal price for flexibility ranges from EUR/MWh 25 to around EUR/MWh 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.

Demand for hydrogen in manufacturing is assumed to be steady throughout the year, and this demand for hydrogen 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[23] and Denmark[24], 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, in the scenarios Hydrogen from wind and Windy seas, Finland also has a significant amount of hydrogen storage.

The electrical capacity of electrolysers and the unloading capacity of hydrogen storage in Finland are presented in Table 16. The unloading capacity of hydrogen storage is presented as the amount corresponding to the input capacity of the electrolyser[25]. In addition, the scenarios Hydrogen from wind and Windy seas assume a hydrogen transfer infrastructure, which contributes to the storage of hydrogen. In practice, in these scenarios, electrolysers can be flexible by 100% of their input power. In the scenario Power to products, the flexibility of electrolysers remains at less than half the capacity, and in the scenario Local power, electrolysers are not flexible at all.

Table 16 Electrical capacity of electrolysers and electricity-equivalent unloading capacity of hydrogen storage in the different scenarios in 2035.

Capacity in 2035 (GW)	Power to products	Hydrogen from wind	Windy seas	Local power
Electrolyser (input power, GW electricity)	6	11	7	1
Hydrogen storage (GWh H2)	57	150	152	0

Hydrogen can be stored in the hydrogen network, steel tanks, and salt stone cavern storage. In the scenarios Hydrogen from wind and Windy seas, the hydrogen network enables storage both in the network and in non-local storage facilities. In the scenarios Power to products and Local power, 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[26], which increases the flexibility of the system. However, in the scenarios Power to products and Local power, the construction of hydrogen storage has been restricted due to uncertainties about the potential of stone cavern storage[27] and the storage costs of steel tanks.

In addition, demand side response is estimated to increase due to the electrification of district heating and domestic heating. The peak consumption of heating varies between 5-7 GW by scenario, of which approximately half in total can be flexible[22].

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 amount of flexibility is estimated to be approximately 30% of consumption. The duration of the cut in consumption is no more than 3 hours, as the storability of heat is estimated to be low in individual buildings, 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 already have invested or will invest in separate thermal batteries[28], which contribute to the flexibility of electric heating. Flexibility is estimated to be about one fifth of heating consumption. Half of the non-produced heat is produced electronically over the next few hours, and half is replaced by biomass boiler production. Flexibility is estimated to be cost-effective and activated at relatively low prices. The maximum duration of flexibility is estimated to be 8 hours.

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 scenario Power to products, 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, including electricity use by households and services for purposes other than these categories (heating, transport), is not estimated 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 demand side response amounts.

In order to illustrate the available demand side response and variation in renewable production, the hourly balance of electricity in the scenario Hydrogen from wind is presented below for a period of two weeks during which it has been cold and wind has been variable (Figure 14). The figure shows that the variation in wind power production is very significant. In the least windy hour, production has been below 0.5 GW, while in the windiest hour, it has been over 27 GW.

[22] 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

[23] Hydrogen storage - Hybrit (https://www.hybritdevelopment.se/en/a-fossil-free-development/hydrogen-storage/)

[24] Green Hydrogen Hub Denmark - About Us - What We Do (https://greenhydrogenhub.dk/about/)

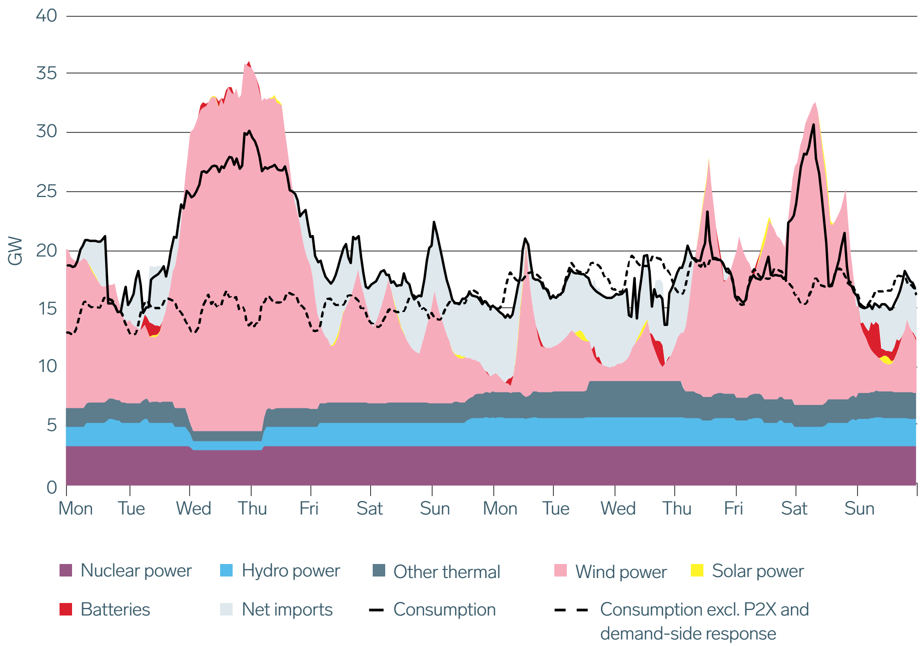
[25] The hydrogen storage unloading/output power has been converted from hydrogen energy to the input power of the electrolyser by dividing by the assumed electrolysis efficiency of 70%.

[26] 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. The capital cost of salt stone caverns is estimated by ENS.dk at circa EUR 2,000/MWh. Both storage techniques would therefore be very advantageous compared to electricity storage or hydrogen steel tank storage. 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 the ENS.dk report is available at: https://ens.dk/sites/ens.dk/files/Analyser/technology_data_catalogue_for_energy_storage.pdf

[27] 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://lkab.com/en/news/hybrit-sek-200-million-invested-in-pilot-plant-for-storage-of-fossil-free-hydrogen-in-lulea/

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

Figure 14 An example of hourly electricity production and consumption in the scenario hydrogen from wind in the first two weeks of the reference year 2035.



To utilise wind power, the rest of the system, in practice, adjusts to fluctuations in wind power production. This includes the adjustment of hydro and thermal power, demand side response, 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 response, electrolysers (P2X), in particular, operate flexibly by producing hydrogen in windy hours, when affordable electricity is available, utilising hydrogen storage and hydrogen cross-border connections.

3.5 The surrounding world

For the rest of Europe, the scenarios are based on the draft scenarios of ENTSO-E and ENTSOG's 10-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 prior to the Russian invasion of Ukraine and thus do not take into account changes in energy policy (such as the REPowerEU programme) and fuel prices that occurred as a result of the attack. However, these changes will increase the demand for clean energy (especially electricity and hydrogen). On the other hand, the changes will also improve the possibilities of producing renewable energy in Europe if, for example, the permitting of renewable energy becomes easier. In the system vision scenarios, initial data based on TYNDP2022 are used especially in continental European countries. These assumptions have not been changed as a result of the war, as comprehensive data on the changes were not available when the scenarios were prepared, and on the other hand, the estimated changes partially cancel each other out, as clean energy demand and supply both increase compared to the TYNDP2022 draft scenarios. If data becomes available later in 2022, continental Europe's assumptions can be updated in the final scenarios.

In the scenarios, Sweden's development has been explicitly sensitised so that the future development path in Sweden is similar to that in 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 scenario Power to products, which also extends the service life of Sweden's nuclear power, as in Finland. Similarly, in the scenario Hydrogen from wind, Sweden is an exporter of hydrogen despite the fact that the country will phase out nuclear power by 2045. In the scenario Local power, small-scale nuclear power plants are also built in Sweden.

Are the scenario descriptions realistic, diverse enough and challenging enough?

Is there too much or too little of a particular form of electricity production in the scenarios?

Are the assumptions about the flexibilities used to balance electricity production and consumption justified and credible? Can you identify other sources of flexibility? What factors would most effectively guide us to provide flexibility for the needs of the electricity system?

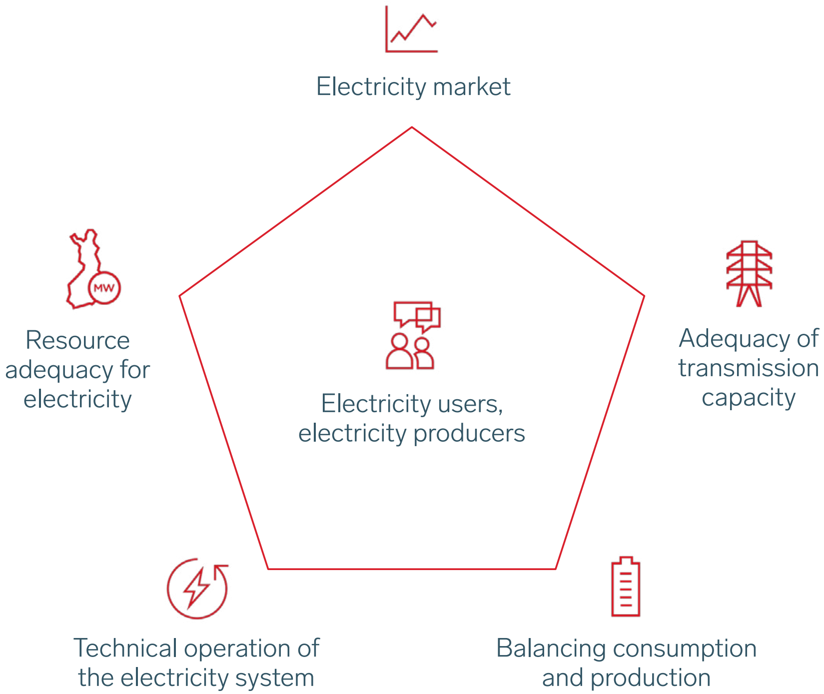
Is there a source of consumption growth that is not credible? Is one missing?

Do you think the general assumptions behind the scenarios are justified?

4 Electricity system perspectives on the scenarios

In this section, we look at the world described by the scenarios from different perspectives of the electricity system. In the vision, we use the term “electricity system” to refer to a broad concept. It covers perspectives on both the efficient functioning of the electricity market and electricity resource adequacy for the needs of society. In addition, the electricity system comprises the factors of operational security of the electricity system, including the momentary balancing of consumption and production, the adequacy of transmission capacity, and the technical operation of the electricity system.

Figure 15 Electricity system perspectives.



The scenarios illustrate a drastic change in Finland’s production and consumption structure. They challenge us to examine how the change impacts different sectors of the electricity system and whether current practices need to be changed as the operating environment changes. An increase in production that varies according to the weather and, on the other hand, a decrease in adjustable production provoke discussion about, for example, resource adequacy for electricity, the emergence and availability of new kinds of flexibility, and the sufficiency of the reserves needed to manage disturbances. In addition, the current means of managing system security are likely to change radically with the transition, as transmission needs increase and the technical characteristics of the production and consumption structure change.

In our previous system, synchronous machines that use storing energy sources have been in the majority. Adjustable production based on the storable energy sources has evened out the variation in electricity consumption, and the characteristics of synchronous machines have maintained the inherent stability of the system. In addition, the production and consumption volumes connected to the system have been isolated and predictable, which has made it possible to meet the adequacy of transmission capacity by traditional means without major challenges. The current principles prevailing in the energy sector, the functioning of the electricity market, and society’s expectations for resource adequacy for electricity and the system security of the network are mainly based on our traditional system.

However, with the carbon-neutrality targets, we have already started the transition to a new era. The energy transition has started and is accelerating. The scenarios presented in the vision describe a world where the biggest phase of the transition has taken place and we have moved to a carbon-neutral production structure, where various clean production, consumption, and storage technologies and new technical solutions are responsible for the adequate functioning of the electricity system and for meeting the needs of society as cost-effectively as possible.

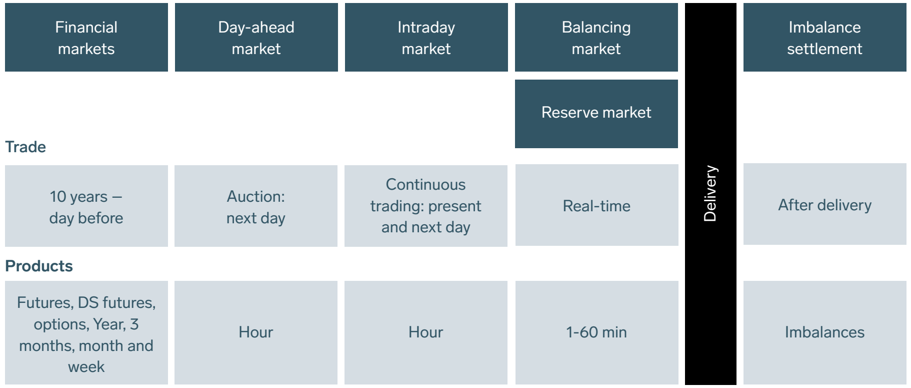
To make the world described in the scenarios a reality, the energy sector must be able to identify the challenges of implementing the transition and the most cost-effective ways to address these challenges. As the operating environment changes radically, finding the most cost-effective solutions is likely to require a review of previous 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.

In the subsections of this section, we have tried to use the scenarios to identify and describe the different changes and challenges that will result from the energy transition, as well as possible pathways to solutions. The focus regarding the system perspectives is on the change described by scenarios for year 2035. **The aim of the sections is to open up different perspectives and possible solution options for stakeholders' consideration. At the end of each topic, there are questions for stakeholders, on which we hope to receive their views in the form of feedback.**

4.1 Perspectives on the development of the electricity market

The electricity market is an essential part of the functioning of the electricity system. It allows electricity users and producers to acquire and sell electricity for their needs. In the market, a price is formed for electricity. The term "electricity market model" refers to the entity created by different electricity marketplaces and market rules within which market participants can trade in electricity. A well-functioning electricity market generates price signals that effectively create a balance between electricity supply and demand in both the short and long term. A well-functioning electricity market requires well-designed market rules. Figure 16 presents the current structure of the electricity market.

Figure 16 Current electricity market structure.



The current electricity market model is based on a single European electricity market, the development of which is governed by EU legislation. Physical trading in electricity takes place in a number of markets over different time horizons, supported by financial, meaning derivatives, markets. In a pan-European day-ahead electricity market, the demand and supply of electrical energy are balanced and electricity prices are formed for each hour of the following day. Prices are calculated by bidding zones, which are based on the physical transmission restrictions of the electricity network – Finland is one bidding zone because the main grid does not limit the transmission of electricity within the country. After the day-ahead market, electricity trading can be conducted in continuous intraday markets. In real time, the balancing of the electricity system is the responsibility of the transmission system operator responsible for the system, utilising reserves. There are several reserve products in use for different electricity system needs. Fingrid acquires the reserves from the reserve market it maintains. In Finland, the electricity market is mainly based on energy-based trading (the so-called energy-only model). Part of the reserve market maintained by Fingrid and the strategic reserve system are capacity-based.
Several changes in the electricity market are taking place during the current

decade, as changes in the operating environment and the progress of the energy transition cause the need to develop the electricity market. The Nordic reserve market is being developed on the way to European marketplaces. Alongside these, 15-minute imbalance settlement and markets will be introduced – both in the balancing power, intraday and day-ahead markets. In the Nordic countries, the calculation of transmission capacity for the electricity market will become flow-based. In addition, financial markets will be developed to meet the changing needs of market participants, for example through cross-border transmission rights products.

All four future scenarios presented in this vision work illustrate a fundamental change in the electricity system and thus also in the electricity market. In the scenarios, market price volatility increases and the occurrence of low prices is more common, while very high price spikes are also more likely to occur, when comparing to the situation before the current energy crisis. The amount of electricity transmitted in the main grid grows, challenging the sufficiency of the electricity network, and the importance of flexibility in different time spans is emphasised.

In the midst of the energy transition, it must be ensured that the electricity market model supports the change towards an emission-free energy system, with the reliability and cost-effectiveness of the system, thus enabling Finland's competitiveness. 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, and to determine the dispatching of production and consumption in the electricity system and this way balance the production and consumption in the electricity system. In addition to the role of the market so far, the change in the operating environment may also require new things from the market. 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.

Enabling the necessary investments: Achieving the carbon-neutrality targets means that our electricity system will require an exceptionally large amount of investment in a short period of time. For this reason, the risks associated with the investments and their management become even more interesting issue. The price of electricity acts as an investment signal in the electricity market. In Finland, market-based wind power investments are already well underway, and the market currently seems to enable cost-effective investments in renewable forms of energy. However, in addition to wind power and other variable electricity production, investments are also needed that ensure sufficient electricity supply to society even in those moments when production that varies according to the weather is scarcely available. These investments can take the form of storage for different forms of energy, demand side response potential, and production with adjustability. Increased volatility in electricity prices and the perceived unpredictability of the operating environment as a result of various crises and policy actions may pose investment risks.

Price caps and the growing need for hedging: The uncertainty brought about by the increasing volatility of electricity prices highlights the need for adequate hedging by market participants, which may make it necessary to develop long-term contracts, as well as the financial markets for electricity and their liquidity. As price volatility increases, there may also be occasional price spikes close to the cap prices of the day-ahead market. Price spikes can become much higher than at present, which increases, for example, the guarantee requirements of stock exchanges and, in particular, the risk level of smaller market participants. This can also make it more difficult to participate in the market and can thus have a negative impact on market liquidity and competition in the market.

Trading time and market time unit: Changes in the electricity system are reflected in changes in the electricity market. The growth of trading volumes and trading closer and closer to the moment of use, for example due to more accurate weather forecasts, are changing the functioning of the electricity market. Already in the 2020s, imbalance settlement and market time units will be shortened to 15 minutes instead of the current hour. In the future, it may be necessary to find out whether the market time unit should be even shorter. The shortening market time unit changes the operating environment of the parties operating in the electricity market and the use and profitability of their resources in the market.

Market mechanisms supporting the adequacy of transmission capacity: Based on the scenario modelling, it is clear that the amount of electricity transmitted in the main grid will increase significantly. The growing need for transmission has traditionally been met by network investments to enable a functioning market and a single bidding zone. In the future grid investments may be accompanied by other methods that are more flexible than investments, that are implemented more quickly, or that make their use more efficient, which can make use of new market mechanisms or require them. Issues related to transmission capacity adequacy are discussed in more detail in sections 4.4 and 4.5.

Reserves: Reserves are used to ensure control of the power balance and frequency of the electricity system. Reserves are acquired from the reserve market, which is part of the electricity market, and thus the related development must be coordinated with the structure of the electricity market in the future, too. It is expected that the need for reserves will increase with the energy transition, and their operational requirements will have to be changed as the technical characteristics of the electricity system change. The reserve market is discussed in more detail in section 4.3.

System services: The change in the structure of production and consumption also challenges the technical operation of the system. The characteristics needed to maintain the stability of the system - such as the availability of inertia, voltage support and short-circuit power - have not previously been an issue of particular attention, as the current electricity system has been built on the intrinsic, system-supporting characteristics of synchronous machines. In the energy transition, the situation changes, as the share of synchronous machines decreases significantly as converter-connected production increases. This change has already triggered a debate on the need to create new practices to guarantee these characteristics, which were previously taken for granted from a systemic point of view. This topic is discussed in more detail in section 4.6.

Importance of information: The importance of information related to the electricity market will become even greater in the future. Equal access to and transparency of market information is of paramount importance in order for competition to ensure the best possible functioning of market-based solutions.

In the development of the electricity market, it should be noted that changes in the market model are often time-consuming. It is therefore to be expected that development will take place step by step. The development must also take into account how the different segments of the market are strongly intertwined, so a small change in one 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 is necessary to be able 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 or in addition, for example, in the form of reserves, system services or flexibility needed for transmission management, in which case value for the flexible use of the resource can be accumulated from several different sources. In addition to the above, it is possible that, in the future, a need for a market participant's resource 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.

What kinds of electricity market structures, e.g. financial markets, physical markets, and reserve markets contribute to Finland's competitiveness in the energy transition?

Should the rules of electricity market be changed? If yes, how?

4.2 Resource adequacy for electricity

Society is dependent on the uninterrupted supply of electricity, which requires a constant balance between the production and consumption of electricity. This section discusses resource adequacy for electricity from the perspective of the day-ahead and intraday market. Resource adequacy for electricity is affected by electricity consumption and demand side response, the production capacity of available electricity, and electricity that can be transmitted by electricity transmission connections from other market areas. The sufficiency of adjustable capacity at the time of use, related to the power balance, is discussed in section 4.3 on the procurement of reserves.

Fingrid is responsible for managing the power balance during the operative situation, but is not responsible for resource adequacy for electricity. In Finland, the Ministry of Economic Affairs and Employment is responsible for energy policy related to resource adequacy for electricity, and the Energy Authority is responsible for monitoring resource adequacy for electricity. Also, The National Emergency Supply Agency plays a role in energy security of supply, for example in relation to preparedness and contingency planning and reserve storage of energy commodities. The Government has set a target level for resource adequacy for electricity on the basis of a proposal prepared by the Energy Authority.

Fingrid participates annually in the assessment of resource adequacy for electricity for the upcoming summer and winter seasons and in the medium term through ENTSO-E cooperation. The European Resource Adequacy Assessment (ERAA) is drawn up annually in cooperation with European transmission system operators, and it plays an important role in assessing the security of electricity supply of the countries. The ERAA assesses the achievement of the national targets for the security of electricity supply set by European countries over the next ten years. The assessments on resource adequacy for electricity are based on a probabilistic analysis that takes into account weather conditions affecting both demand and production, as well as unexpected failures in production plants and transmission connections. The results of the ERAA are approved by ACER, the EU Agency for the Cooperation of Energy Authorities.

Calculation of resource adequacy for electricity and loss of load

The following key indicators are used to determine resource adequacy for electricity in the assessments, which are also used to determine the target level for resource adequacy for electricity:

- Loss of Load Expected (LOLE), hours per year
- Expected Electricity Not Served (EENS), megawatt-hours per year

LOLE is the number of hours per year in which the market-based supply of electricity is not enough to meet consumption. LOLE is calculated as an average of the various combinations of simulated weather years and interruptions. EENS describes the total volume of electrical energy that will, on average, not be supplied during these hours.

4.2.1 What does resource adequacy for electricity look like in the scenarios in 2035?

Table 17 presents the indicators for resource adequacy for electricity in the scenarios in 2035, calculated using a relatively average weather year in terms of weather conditions (1999). The indicators do not take a position on resource adequacy for electricity in 2022-2034, so the situation may deviate from the scenarios, for example, so that LOLE will be higher in the coming years. The indicators show that in the scenarios Power to products and Local power, no challenges to resource adequacy for electricity are foreseen. In these scenarios, resource adequacy for electricity is promoted, for example, by the decentralisation of production: variable production is versatile onshore wind, offshore wind and solar power, which, in addition, are geographically dispersed across Finland, which means that the variation in production with renewables is lower. Domestic production capacity also includes reliable and adjustable nuclear, hydro and thermal power, and the transmission connections to be built help ensure resource adequacy for electricity.

Table 17 Resource adequacy for electricity indicators in the scenarios for 2035, weather year 1999.

Resource adequacy for electricity in 2035	Power to products	Hydrogen from wind	Windy seas	Local power
Loss of Load Expected (h/a)	0	3	4	0
Expected Electricity Not Served (MWh/a)	0	7,000	12,000	0

In the scenarios Hydrogen from wind and Windy seas, resource adequacy for electricity becomes a challenge in a few hours, when, for example, electricity production plants or transmission connections have failed to a significant extent and consumption is high. In both scenarios, the increase in consumption is enormous, but on the other hand, the system is balanced by the flexibility made possible by the hydrogen pipeline infrastructure. However, this alone is not enough to balance the electricity system in failures that occur at challenging times. In the scenario Windy seas, the factor is, for example, the one-sided geographical location of wind power in western Finland, which means that the fluctuations in wind power production are greater than in the other scenarios, and it is more difficult for the electricity system to respond to these fluctuations.

The indicators have been calculated using the historical weather year 1999 as a reference, as it reflects a fairly typical year in terms of weather conditions, including cold periods that test resource adequacy for electricity in January and February. In line with the above, resource adequacy for electricity can also vary considerably depending on weather conditions, especially in an increasingly wind power-intensive system, which is why several tens of weather years should be modelled for a more comprehensive analysis of resource adequacy for electricity.

In addition to the weather year, ten different simulations of failures in power plants and transmission connections have been used to calculate the indicators. Due to the small margin in the scenarios Hydrogen from wind and Windy seas, failures cause problems in resource adequacy for electricity in the scenarios, which in the most scarce hours lead to electricity not served. In the scenarios Power to products and Local power, the margin for failures is significantly higher, and therefore failures do not pose challenges for resource adequacy for electricity in the scenarios.

When interpreting the results, it should be noted, that the flexibility described in Chapter 3.4. is available, which means that the investments for flexibility are seen as feasible in scenarios and the investments have already taken place before b year 2035. However, the results do not take a stand on electricity adequacy before year 2035, when all the investment have not yet been implemented.

4.2.2 Developing resource adequacy for electricity in the electricity market

There are many questions of principle related to resource adequacy for electricity. Simplified, the best way to reduce the risk of an electricity shortage is to have excess capacity available from resources capable to increase generation or decrease consumption. This excess capacity, on the other hand, means costs, and the challenge is to find a cost-effective and socially acceptable balance between the risk of electricity shortages and excess capacity. Different electricity users require different access to electricity, and the resource adequacy and total price of electricity have different meanings for different parties. From the point of view of electricity adequacy, it is essential to assess: are price fluctuations and possible occasional high price spikes a sufficient means to generate the necessary investments in capacity to guarantee resource adequacy for electricity? Another question is what are the most cost-effective technologies that guarantee resource adequacy for electricity in a carbon-neutral society. Resource adequacy for electricity must also take into account aspects of security of supply, such as solutions related to the potential emergency storage of fuels.

The current energy-based electricity market generates investment signals based on the price of the energy sold. Thus, investments are made on the basis of the expected price of energy. In the system, the development and maintenance of cross-border connections are also of great importance, as they allow electricity to be transmitted from a surplus area to areas where there is a need for electrical power. It is to be expected that in an electricity market based on energy-based electricity trading, the necessary investments in production, storage and demand side response will take place on market terms in the long term, when supply and demand in a functioning market balance themselves as a result of the right price signals. The challenge, however, is the potential slowness in the current transformation, which could cause problems with resource adequacy for electricity in the short and medium term. The profitability of investments is the sum of many uncertain variables, and the investor may not have enough visibility into what kind of earning potential the new capacity will have in the energy system of the future, which may slow down the making of investments. Thus, it is possible to end up in a situation where only a long shortage of electricity or electricity shortage situations trigger investments. The key to functioning a clean energy-based electricity market model is how much we as a society trust the functioning of the energy-based market mechanism and, on the other hand, how much we tolerate the risk of potentially tightening margins and power shortages.

Alongside the energy-based market, **the capacity mechanism** can be seen as one of the ways to develop power sufficiency. The capacity mechanism is a generic term for arrangements that compensate for the availability of capacity when needed. The capacity mechanism, as such, does not take a position on technology that enables the necessary power, but the capacity mechanism may include electricity production, the ability to cut electricity consumption, and electricity storage facilities.

A capacity mechanism in which a plant receiving power compensation cannot participate in other electricity marketplaces is called a **strategic reserve**. The advantage of a strategic reserve can be considered as its low impact on the rest of the electricity market. In Finland, for example, the strategic reserve is the so-called power reserve, the cost of which was EUR 10.7 million in 2021[29]. A strategic reserve secures resource adequacy for electricity in situations in which the market-based supply of electricity is not sufficient to cover electricity consumption. The idea of a strategic reserve is that it is so rarely needed that there is no need for that capacity and therefore no profitability in a "normal" market situation, but in rare situations of scarcity, that capacity is utilised. The functioning of the strategic reserve currently in use in Finland, meaning the power reserve, must be examined in a changing operating environment. In the future, with the increase in production that varies according to the weather, it is possible that scarcity situations may last longer, and there may possibly be more operating hours for the capacity.

In the capacity market, capacity is compensated separately, but unlike the strategic reserve, capacity that receives capacity compensation can also participate in the energy-based electricity market and thus also receive compensation for the energy it sells. Depending on how the capacity market is organised, capacity bids may be submitted by existing capacity as well as by new capacity, in which case the capacity compensation may have an impact on investments in new capacity. The total cost of the capacity market depends on the total amount of capacity to be compensated, the way in which the procurement is organised, the technology, and whether existing capacity is compensated or whether it is an investment in new capacity. A capacity market is typically a larger-scale solution than, for example, a strategic reserve, and thus its total costs are typically higher.

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 regarding power adequacy. Any concerns will be addressed through the European Resource Adequacy Assessment (ERAA), the results of which will be compared with the target level[30] of security of supply set by the Member State. If necessary, the resource adequacy assessment can also be supplemented by a national resource adequacy assessment. If the adequacy assessments do not reach the set target level of security of supply, the Member State may apply a capacity mechanism.[31] A strategic reserve should be used as the primary capacity method; secondarily, production or demand side response capacity

[29] https://energiavirasto.fi/-/sahkon-toimitusvarmuus-turvataan-600-megawatin-tehoreservilla-tarjouskilpailu-kaynnissa available in Finnish

[30] In Finland, a reliability standard has been set, according to which the loss of load expected of the Finnish electricity system may not exceed 2.1 hours per year, and the expected energy not served may not exceed 1100 megawatt-hours per year. Source: Government decision on the target level for the security of electricity supply (reliability standard). MEAE/2022/36 and the Energy Authority's proposal for a reliability standard in accordance with Regulation (EU) 2019/943. 214/040000/2022.

[31] Regulation (EU) 2019/943 of the European Parliament and of the Council

can be procured from the capacity market. Both of these approaches are in use worldwide, including in the EU Member States.

An essential challenge with regard to capacity mechanisms is the definition of the conditions and principles related to the functioning of the mechanism and the correct dimensioning of the mechanism. Over-dimensioning can lead to capacity compensation being paid unnecessarily, creating overcapacity, which entails unnecessary costs for society. As electricity is an important commodity for the society, the question between the energy and capacity markets is also what kind of risk the market participants in the electricity market and, on the other hand, society can tolerate.

What challenges do you see in the scenarios from the perspective of the adequacy of electrical power?

What solutions should be considered in relation to the challenges regarding adequacy of electrical power?

4.3 Balancing consumption and production, and reserve markets

In the electricity system, the production and consumption of electricity must be in balance at all times. Finland, Sweden, Norway and Eastern Denmark form the Nordic synchronous area, with a nominal frequency of 50.0 Hz. If there is more production than consumption in the Nordic electricity system, the frequency in the entire system rises to more than 50.0 Hz. If, on the other hand, there is more consumption than production, the frequency drops below 50.0 Hz. The division of the tasks between transmission system operator and market parties for balancing the electricity system is such, that the in the market the parties try to balance their sell and purchases in relation to their production and consumption during the imbalance settlement period, which is currently one hour, but will be 15 minutes in the near future. During the imbalance settlement period, the actual production and consumption can however vary, and transmission system operators take care of balancing consumption and production with the help of reserves. In order to acquire reserves, transmission system operators maintain marketplaces where balancing service providers can offer their flexible resources. Reserves can be provided by electricity production and consumption, as well as electricity storage. The reserve products in use in Finland are shown in Figure 17.

Figure 17 Reserve products in use in Finland and their current procurement needs.

	FFR	FCR-D	FCR-N	aFRR	mFRR
	Fast Frequency reserve, Finland 18 %, Nordics total 0-300 MW (estimate)	**Frequency Containment Reserve for Disturbances,** Finland ~300 MW, Nordics total 1450 MW upwards and 1400 MW downwards	**Frequency Containment Reserve for Normal Operation,** Finland ~120 MW, Nordics total 600 MW	**Automatic Frequency Restoration Reserve,** Finland 60-80 MW, Nordics total 300-400 MW	**Manual Frequency Restoration Reserve** Reference incident + imbalances of balance responsible parties
ACTIVATED	**In large frequency deviations** In low inertia situations	**In large frequency deviations,** Needed to quickly replace production or consumption lost from the electricity system due to a disturbance	**Used all the time,** Balances normal fluctuations between production and consumption	**Used in certain hours,** Releases frequency controlled reserves	**Activated if necessary,** For larger changes in electricty production or consumption and releases faster reserves
ACTIVATION SPEED	**In a second**	**In seconds**	**In three minutes**	**In five minutes**	**In fifteen minutes** (time decreases to 12,5 min with European harmonisation)

Today, the technologies that provide reserves are hydro power, thermal power, wind power, consumption and electricity storage. The share of hydro power in 2021 remains significant in all other reserves, with the exception of the fast frequency reserve, which requires a very fast activation time. Recently, the share of electricity storage in frequency-controlled reserves has been growing. The participation of wind power in the various reserve markets is still very limited, even though its technical characteristics would allow it to participate in all reserve marketplaces. In particular, down-regulation products would be natural reserve products for wind power. Nuclear power has traditionally not participated in the Finnish reserve market, although in terms of its technical characteristics, it could be suitable for most reserve products. More detailed information on the current shares of different technologies in reserve products can be found in Fingrid's report describing supply and procurement inthe reserve market.[32]

The modelling of the scenarios of this vision has been based on the day-ahead and intraday markets and the investments generated through them, and the reserve market has not been specifically modelled. However, the scenarios challenge us to consider whether the need for reserves will change in the future described by the scenarios and where the future reserves will come from.

Although it is challenging to predict the required amount of reserves, it can be assumed that the need for reserves as a whole will increase somewhat with the energy transition. Traditionally, the balancing that takes place within the imbalance settlement period has mainly been related to random fluctuations in consumption, but as the share of variable production increases, an increasingly large part of production also varies randomly depending on the weather. This increases the need for frequency restoration reserves. It is expected that the need increases especially for automatic frequency restoration reserve (aFRR), which is used to adjust the changes occurring within a 15-minute settlement period.

On the other hand, for example switching to a 15 minute imbalance settlement period balance is expected to incentivise parties to have more accurate imbalance management, which may restrain the growth in reserve needs. The parties' own imbalance management and for example good forecasting of production and consumption influence how much the transmission system operator needs to balance production and consumption in real time.

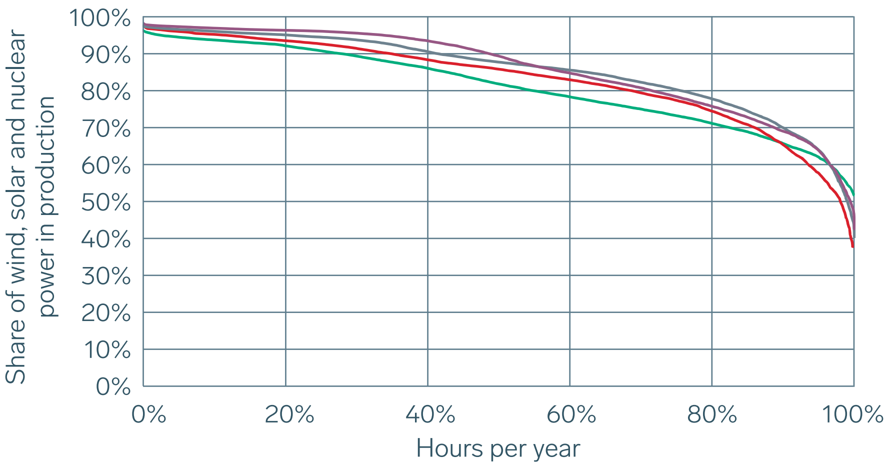
The need for the frequency containment disturbance reserve (FCR-D) and for frequency containment normal reserve (FCR-N) is not expected to increase. The dimensioning of the FCR-D is linked to the individual under- and over-frequency faults of the Nordic electricity system, the magnitude of which is not expected to increase from the current ones. The need for FCR-N may even decrease slightly in the future, as the normal fluctuation of consumption and production will become balanced more with automatic frequency restoration reserve.

The need for a fast frequency reserve (FFR) is linked to the amount of the rotating mass, inertia, of the Nordic electricity system. On the other hand, if the situations with small inertia increases significantly in the future, it may be necessary to consider other means for the frequency management needs than the additional procurement of FFR reserve. Inertia and the how the energy transition is expected to influence to the frequency control is discussed in more detail in section 4.6.

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 grows into a significant form of electricity generation. In order to cover the growing need for reserves, it would be important to explore the possibilities of nuclear, wind and solar power to participate more extensively in the reserve market. As shown in Figure 16, there are plenty of use cases in the different scenarios in which a very significant part of the electricity is generated by nuclear, solar and wind power. 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.

[32] Report on offered and procured capacity in the Finnish reserve markets - sorted by technology - Fingrid

Figure 18 Share of wind, solar and nuclear power in finnish total production for sceanarios in 2035.



In the scenarios, consumption and its flexibility also play a big role. Electricity consumption is assumed to participate in the reserve market, as it does today. In particular, in the scenarios Power to products and Hydrogen from wind, the role of electrolysers is significant. It is therefore important to explore what opportunities electrolysers have to participate in the reserve market. Below is described different ways to develop reserve markets.

From a reserve product to a reserve source: In order to obtain the widest possible supply and to activate new reserve operators, it is important that participation in the reserve market is easy and simple. Today, the reserve market consists of several different marketplaces, from which the balancing service provider can choose the most suitable products and markets on which to offer its own reserve resource. In reality, however, the same reserve resource could be suitable for several reserve products. Should the reserve market be developed so that a balancing service provider can submit alternative bids for different reserve products for the same resource? Or should reserve products be combined so that there would be fewer alternative products?

Timing of securing reserves: Currently, part of the reserve capacity is mainly acquired from the hourly market on the previous day, either before or after day-ahead market trading. In the future, consideration may be given to securing a higher share of reserve capacity before day-ahead market trading in order to maintain system security. However, this means that this flexibility is not available in the day-ahead or intraday market.

Contract periods: Participation in the reserve market requires investments, especially from new participants, and the current hourly market does not necessarily guarantee sufficient visibility for the investments to be realised. Should reserve capacity be acquired alongside the current hourly market through longer-term contracts, such as the model currently used in the yearly market for frequency containment reserves (FCR-N and FCR-D), in which the price is fixed for a longer period of time and the balancing service provider has an option to sell the reserve at a price fixed to Fingrid near the moment of delivery?

What measures can be taken to increase supply in the reserve market?

How to increase interest of market participants in short term balancing?

How do you see the division of tasks between the market participants and the transmission system operator in managing the power balance in the future?

4.4 Sufficiency of internal transmission capacity in Finland and management of transmission situations

A limited amount of electricity can be transmitted in an electricity network, subject to system security criteria. This is called transmission capacity. System security criteria refer to the conditions that must be met in order to achieve the desired level of system security. The level of system security is affected by the dimensioning principles applied by Fingrid. In Finland and other Nordic countries, the N-1 criterion is commonly used, according to which the system can withstand normal single faults and the disconnection of a failed component in a 400 kV and 220 kV looped network without interruption to production or consumption and without consequential effects. For rare faults and combinations of several faults, wider consequences are allowed. Transmission management ensures that electricity transmissions remain within defined transmission capacities.

In addition to the normal operating situation, the construction and maintenance of the electricity network requires transmission outages, in which a part of the electricity network, such as a transmission line or a power transformer, is taken out of service, as planned, for a predetermined period of time. Planned transmission outages may affect the transmission capacity of the electricity system. The aim is to schedule and plan transmission outages in such a way that their implementation causes as little inconvenience as possible to connected customers and the electricity market and is done as cost-effective as possible.

According to the Electricity Market Act, the main grid must be planned in such a way that the prerequisites for a uniform bidding area are maintained. In order for the system security criteria to be met in the future, as well, enabling one bidding zone will require significant new network investments as electricity production and consumption grow strongly. In addition, the geographical focus of production and consumption will change. With changes in consumption and production, new network investments are also likely to be needed for different local needs.

From the point of view of transmission capacity, the most challenging scenarios in the vision are Hydrogen from wind, Windy seas and Power to products. The scenario Hydrogen from wind includes a large amount of new wind power and new consumption, as well as a significant north-south transmission need, which creates a need for a strong increase in the transmission capacity of the network. In the scenario Windy seas, production is concentrated on the west coast, causing a high need for transmission from the west to the south and north directions. In the scenario Power to products, hydrogen is produced close to consumption, and no centralised hydrogen storage or hydrogen network is created. If the electricity production is located far from P2X plants, that causes a significant need for network reinforcement. In the scenario Local power, electricity production consists of several different sources, and in this scenario, production has focused close to the consumption of southern Finland, reducing the need for north-south transmission.

Figure 19 presents the need for electricity transmission in cross-section central Finland in 2035, and Figure 20 presents the corresponding need in 2045. The figures are presented as the need for electricity transmission in a situation where all energy transmission would take place as electricity. Part of the transmission need could also be covered as hydrogen if there were a hydrogen network inside the country and the electrolysers were located close to electricity generation. In this case, part of the energy needs can be transmitted as hydrogen instead of electricity over cross-section central Finland. In the scenario Hydrogen from wind, transmission needs increase up to 20 gigawatts by 2035 and to more than 40 gigawatts by 2045, while in 2021, the maximum transmission need was around 3 GW. In the scenario Power to products, the corresponding transmission needs would be 15 and 30 GW, respectively. In the scenarios Windy seas and Local power, the transmission needs would be substantially lower. If the highest (1%) percentile of transmissions (approx. 100 hours per year) could be covered by other means, the need for transmission capacity would be approximately 3-5 GW in 2035 and up to 3-10 GW lower than the maximum transmission need in 2045. An increase in transmission capacity of one gigawatt would require investments of approximately EUR 150 million in cross-section central Finland and approximately EUR 400 million in the case of a connection from Kemijoki to Uusimaa. The highest 1% of transmission situations would thus increase the need for north-south investments in the main grid by approximately EUR 0.5-2 billion in 2035, depending on the length of the connections.

Figure 19 Transmission needs over cross-section central Finland in the 2035 scenarios, if all energy were transmitted as electricity. The duration curves of all scenarios show a peak of the curves, meaning that large transmission situations rarely occur, but the transmission need is very high.

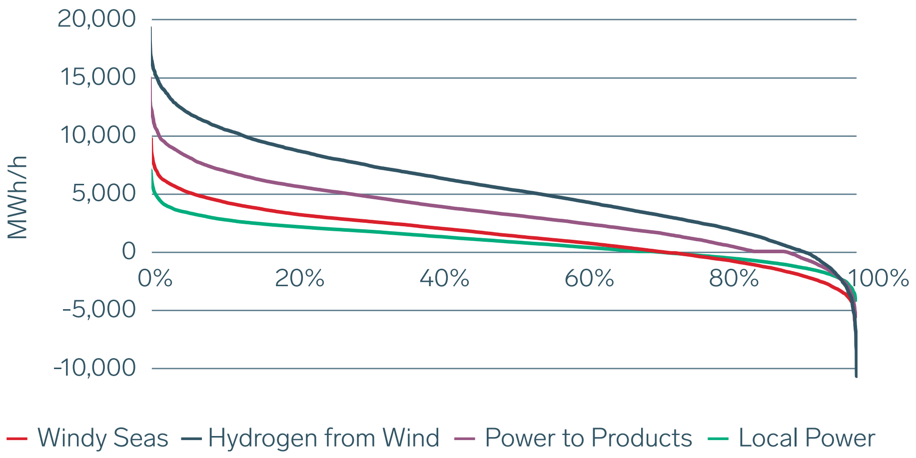
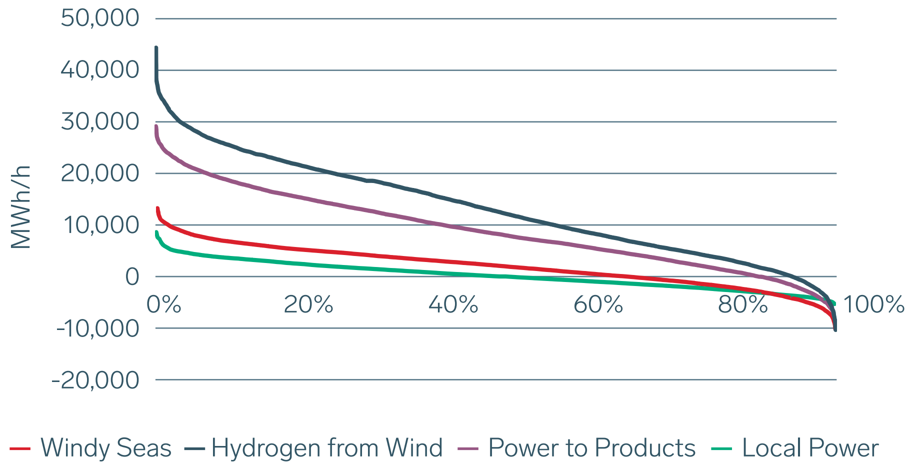


Figure 20 Transmission needs over cross-section central Finland in the 2045 scenarios, if all energy were transmitted as electricity.



As the share of variable, renewable production grows strongly and, on the other hand, electricity consumption profiles change with electrification, predictability and scheduling planned outages and managing disruptions become more difficult. To illustrate the challenges, we studied the case of the main transmission cross-sections of the main grid[33], namely the cross-sections of the Kemi-Oulujoki river and central Finland, in the event of a fault. A single transmission situation is used as the starting point for the review, illustrating the maximum north-south transmission need according to the scenario, as shown in Figure 19. The significance of an outage or failure of a single transmission connection for north-south transmission capacity decreases as the network becomes more looped and the number of parallel transmission connections increases. At the same time, the number of transmission connections to one substation increases, making the outage or failure of the station very significant, and the failure can cause a significant limitation of transmission capacity. Possible transmission capacity limitations of several thousand megawatts and in-service transmission management measures will significantly challenge the main grid, so adjustable consumption and production is a prerequisite to ensure the operation of the electricity system in cost-effectively way.

As a follow-up to the vision work, Fingrid will later examine in more detail the necessary network investments per scenario. Although scenario-specific network reinforcement needs have not yet been considered at this draft stage, it is very likely that other means will be needed alongside network investments. These possible means are discussed in section 4.5 below.

[33] A main transmission cross-section refers to the intersecting boundary of the transmission lines between regions, defined on electrotechnical grounds. Finland's two main transmission cross-sections are the Kemi-Oulujoki cross-section (P0 cross section) and the central Finland cross-section (P1 cross section).

4.5 Means to ensure sufficient transmission capacity alongside network investments

The planned network investments in transmission lines, compensation devices and Dynamic Line Rating technology will significantly increase the transmission and connection capacity of the network in the coming years and decades. However, the very strong growth in electricity demand and supply challenges Fingrid's ability to increase transmission capacity so much and so quickly that it can cover all foreseeable transmission situations. This is particularly the case if new electricity production and new electricity consumption are located far apart and are growing strongly. Based on the 2035 scenarios, it seems clear that in the high production and consumption growth scenarios (Power to products, Hydrogen from wind, Windy seas), transmission needs cannot be fully met only by network investments, and in the 2045 scenarios, the challenges become even more acute. In the event that the development of the network does not keep pace with the development of production and consumption, despite efforts, and a structural bottleneck appears in the network, it could lead to the situation, where the bidding zone division would have to be implemented in order to ensure system security.

However, network investments and bidding zone division are not the only means to address the challenges posed by growing transmission needs. There are several means to encourage consumption, production and storage investments to be located optimally for the system or to be flexible in the event of exceeding the transmission capacity of the network. On the other hand, it is important to note that the location of investments in the production, consumption and storage of electricity is influenced by several different factors in addition to the market price and the distribution price of electricity. Properly dimensioned incentives 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 addition to network investments such as transmission lines, equipment and technical solutions, the following means have been identified to ensure sufficient and cost-effective transmission capacity:

1. Redispatching and measures to ensure the availability of redispatch resources
2. Network fees that encourage co-location of production and consumption
3. Location-based network fees
4. Emphasising the importance of a connection fee
5. Flexible connection contracts
6. Bidding zone division

Internal bottlenecks in Finland can be solved **by redispatching**, which means changing the dispatching order of power plants, storage, and demand facilities. This requires that resources suitable for redispatching are available at the right points in the network. Currently Fingrid can implement redispatch via special regulation or by doing countertrade over the bidding zone borders. The availability of redispatch resources can be developed, for example, through long-term procurement contracts. At best, this would bring significant flexibility to the different parts of the network preventing the need to form bidding zones and the flexibility could be also used in the event of outages and special situations. On the one hand, if a significant part of the revenue stream of the resources to be acquired were generated by redispatching fees, the cost of the solution could become high, and on the other hand, if the redispatching corresponded to only a small share of the revenue stream of the resources, the arrangement might not significantly affect investment decisions. In addition, if redispatching were the only means to manage transmissions, the need for redispatch resources would become very high (even several thousand megawatts in 2035).

Network fees could provide an incentive to locate production and consumption at the same connection point if a higher proportion of the fee were allocated to the net use of the network (input and output fee). This would reduce the need for connections and the amount of energy transmitted in the network. This could be a viable solution, especially for hydrogen production, if EU legislation requires hydrogen production to follow renewable energy production on an hourly basis anyway. Consideration should also be given to whether the net power of the connection can be limited if, in such a case, the network had not, in principle, been dimensioned for full output/input.

For example, **the location-based network fees** in place in Sweden and the UK could provide an incentive to reduce network bottlenecks through investment. Location-based network fees are often challenged by their complexity, low predictability, and the fact that the economic impact also affects customers who are already connected to the network, even though the location cannot then be changed. In addition, the incentive of network fees in principle reduces transmission needs throughout the year, so they do not reduce peak transmission.

The connection fee currently only covers the direct costs of the connection. If the connection fee were also to cover investments in the network surrounding the connection station to a greater extent, it would encourage connections that do not increase transmission needs, such as connecting electricity consumption to areas with a production surplus or vice versa. Such a procedure would reduce transmission needs in general, but would not specifically target peak transmission situations.

Maintaining the level of system security (preparing for a failure during an outage) in the event of a planned outage of a 400 kV network may require the prior restriction of production from a specific area for the duration of the planned outage. The starting point for the restriction is the equal and non-discriminatory treatment of operators, meaning that the restriction must be directed at operators in accordance with the pro rata principle. A possible perspective on restrictions could also be to explore the possibility of **flexible connection contracts**, through which party can affect the usability of their connection. A flexible connection contract could also be applied for a fixed period, in which the operator can be restricted, for example, during the outage of an area to ensure N-1 system security until the network reinforcement for that area is completed. From the point of view of the connecting party, a flexible connection contract enables an earlier connection to the network.

Bidding zone division is the only solution that 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 (on yearly average about 0-2 EUR/MWh or about 0-5% of the average electricity price) if the transmission capacity were generally at a sufficient level (price difference 1-5% of the time). A restriction activated by a relatively small number of hours could reduce north-south network construction needs by several thousand megawatts in 2035 and even more in 2045. On the other hand, there is a risk of the bidding zone division of the market being broken down into too small parts, which could have an impact on, for example, the liquidity of price hedging products and the reserve market. Furthermore, the implementation of a north-south bidding zone division would not reduce west-east transmission needs or vice versa.

What methods could be used to support network investments to ensure sufficient transmission capacity, if network construction and technical solutions alone are not sufficient. E.g. bidding zone division, guidance through transmission or connection fees, some other means?

4.6 Technical operation of the electricity system

The technical operation of an electricity system is based on maintaining a stable frequency and voltage in all transmission and operating situations. Traditionally, electricity has been produced mainly by synchronous machines in hydro and thermal power plants, where the turbine rotates the generator rotor in sync with the network. The intrinsic properties of these synchronous machines resist frequency and voltage changes.

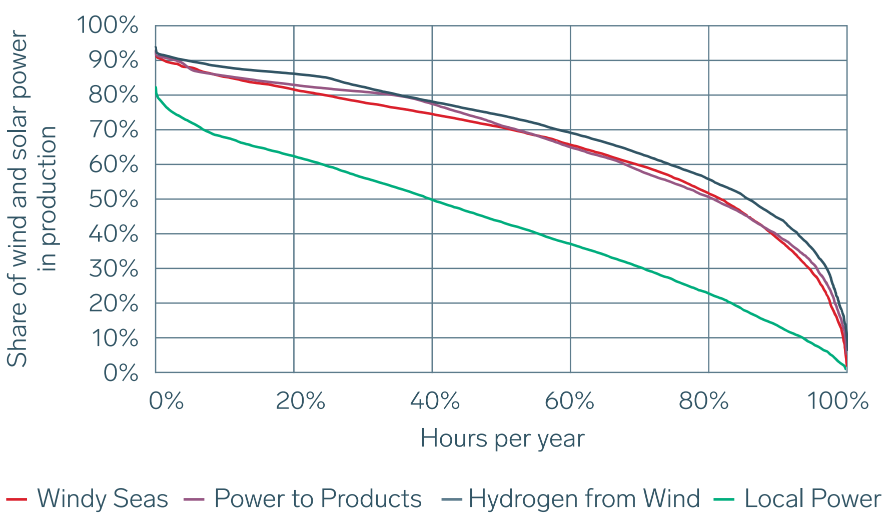
Wind and solar power plants, on the other hand, are connected to the network through frequency converters, meaning inverters. In addition to these, HVDC connections and batteries also supply electricity to the network through inverters. Unlike machines that are physically synchronized with the network, inverters do not intrinsically resist frequency and voltage changes, but their response to the electricity system is based on programmed characteristics. At present, inverters are required to have some functions similar to synchronous machines, such as fault current supply in a voltage dip and capability for voltage control. However, the operation does not fully correspond to synchronous machines, in which case, due to the differences, the technical characteristics of the inverter-dominated system differ from the synchronous machine-dominated system.

The change does not only affect the production of electricity, as the consumption structure will also become more inverter-dominated in the future. Today, much consumption equipment is connected to the electricity system without inverter-connected connection equipment, but new large consumers of the future, such as electrolysers and data centres, will be connected to the electricity system by means of an inverter, allowing the load to draw power evenly regardless of the prevailing state of the electricity system. The increasing use of heat pumps and electric cars will also increase the amount of inverter-connected consumption.

The increase in inverter-connected resources affects a number of different technical characteristics of the electricity system: frequency stability, inverter-driven stability, voltage stability, angular stability, resonant stability, electricity quality, and the protection function. Some of the technical characteristics are characterised by a system-level scale (Nordic synchronous region), while others are local phenomena.

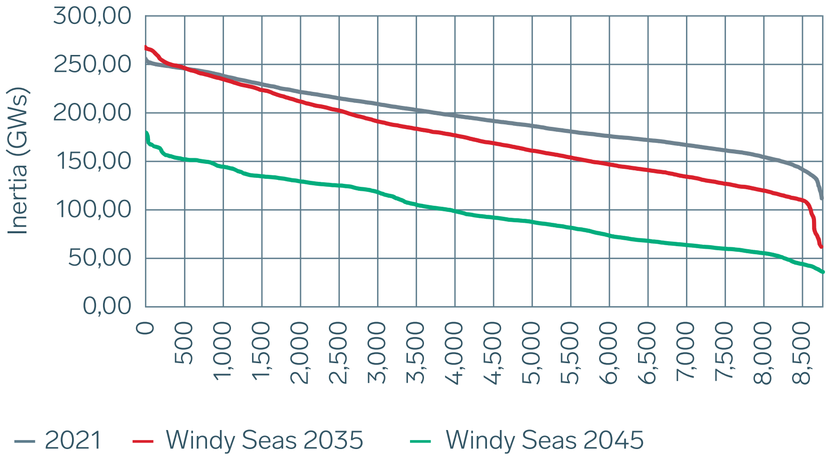
In order to operate, modern-day wind and solar power plants require a sufficiently strong network, meaning sufficient synchronous machine production that maintains the frequency and voltage of the network. However, with the energy transition, it is likely that the number of synchronous machine power plants will decrease while the number of wind and solar power plants will increase. In the presented draft scenarios, a large number of situations arise in which an increasing share of instantaneous production is generated by wind and solar power, which means that the amount of inverter-connected production increases significantly compared to the volume of synchronous machine production. Figure 21 presents the share of wind and solar power in hourly production in the different scenarios.

Figure 21 Share of wind and solar power in production in scenarios in 2035.



The inertia of the Nordic synchronous system related to frequency stability and its permanence were assessed as an example in the scenario Hydrogen from wind, which is assumed to be the most challenging scenario in terms of inertia, due to its production and consumption structure. Inertia refers to the kinetic energy stored in rotating masses in connection with an alternating current system that resists immediate frequency change. In Figure 22 inertia duration curves from simulations with weather year 1999 for year 20235 and 2045 are compared with the inertia level of year 2021.

Figure 22 Nordic inertia in the scenario hydrogen from wind.



The figure shows that the amount of inertia decreases from the current level, but in the 2035 scenario, the simulation still shows a moderate number of low inertia situations. In contrast, in 2045, the scenario Hydrogen from wind produces clearly lower inertial levels. This is especially influenced by the scenario assumption of reduction in nuclear capacity in Sweden (all capacity removed) and in Finland (only Olkiluoto 3 in use) between 2035 and 2045. The amount of inertia affects for example the maximum allowable power change in the system, and with such low inertia, situations may arise in which the power of the largest production or consumption units may have to be limited. As one remedy to the situation, a new type of reserve, FFR (Fast Frequency Reserve), has been introduced. A decrease in inertial minimums increases the frequency change rate, so solutions other than FFR may be also required to ensure frequency stability.

When electricity is transmitted on long transmission lines, transmission capacity is often limited by voltage stability or the damping of power fluctuations rather than thermal capacity. The Finnish main grid uses series compensation with long 400 kV transmission connections between northern and southern Finland and between Finland and Sweden to improve voltage and angular stability. The transmission grid on the southside of cross-section central Finland is highly meshed, and the line lengths are short, so series compensation is not a viable alternative. The situation will be weakened in the future by the decrease of thermal power production located in southern Finland, which will lead to an increase in transmissions and the loss of dynamic voltage support. In order to enable the change, a significant amount of voltage support is needed to the south of cross-section central Finland and in the Helsinki metropolitan area, which can be implemented partly with static and partly with dynamic compensation equipment. Significant consumption equipment has an impact on the stability of the electricity system, which is why the system technical requirements imposed on these installations also need to be reassessed. The voltage support required for inverter-connected production also plays a significant role in ensuring sufficient transmission capacity.

In the future, inverter-driven stability may become a limiting factor for the proportion of the system's instantaneous permissible inverter-connected production. In order to ensure that inverter-connected production does not have to be limited due to the technical function aspect, new solutions are needed that can also guarantee the technical function of the system. The various principled solutions that can be used to ensure the technical function of an inverter-dominated system are presented below. It is likely that all the solutions below will be needed, and they are not mutually exclusive.

The operation of the system can be supported by a range of t**echnical solutions built into the network.** For example, large synchronous motors without an energy source can be built into the network to balance the network, and such a synchronous compensator is planned, for example, for the Jylkkä substation, in an area where a large number of wind turbines are concentrated. Voltage support can be affected by reactive power compensators or capacitor batteries. In principle, this option means investments made by Fingrid in the network.

The procurement of services enabling the technical operation of the network can also be arranged **through the market.** For example, the FFR currently in use is one example of a service to be procured from the market. In order to guarantee the technical function of the system, the system services to be procured would probably mean new reserve products, marketplaces and contract forms. When considering the solutions, it will be important to take into account that in all cases the establishment of new marketplace is not necessarily the most effective way. For example, matters that are very local, too rarely realised, or that concern only few market participants may not be handled most effectively by the market.

A third way to solve the problem is to **expand the technical requirements for new inverter-connected interfaces.** At present, inverters are required to have some functions similar to synchronous machines, such as fault current supply in a voltage dip and capability for voltage control. In a inverter-dominated system, power park modules must also be able to create voltage in the network without a reference produced by synchronous machines.

Fingrid, together with the transmission system operators of Sweden, Norway and Denmark, launched a project at the beginning of 2022 with the aim of identifying the need for changes to the design, operation and technical requirements of the electricity system required by an inverter-dominated system, and creating a roadmap to enable scenario-based futures from the perspective of the technical function of the system.

What possible problems or solutions do you foresee for the technical functioning of the electricity system in the future according to the scenarios?

Which of the above-mentioned solutions you consider particularly desirable or challenging, why?

5 Providing feedback

We would like to receive feedback from stakeholders on the above draft scenarios, to be used as a basis for the electricity system vision work, as well as on topics concerning the electricity market and the system. The scenarios will be finalised based on the stakeholder feedback.

In addition to open feedback, we hope that stakeholders will consider the following questions:

Questions relating to the content of the scenarios:

- Are the scenario descriptions realistic, diverse enough and challenging enough?
- Is there too much or too little of a particular form of electricity production in the scenarios?
- Is there a source of consumption growth that is not credible, or is one missing?
- Are the assumptions about the flexibilities used to balance electricity production and consumption justified and credible? Do you recognise other sources of flexibility? What factors would be most effective in providing flexibility to meet the needs of the electricity system?
- Do you think the general assumptions behind the scenarios are justified?

Questions relating to the functioning of the electricity market and system:

- What kinds of common European electricity market structures (e.g. financial markets, physical markets, and reserve markets) contribute to Finland's competitiveness in the energy transition? Should the rules of electricity market be changed? If yes, how?
- What challenges do you see in the scenarios from the perspective of the adequacy of electrical power? What solutions should be implemented in relation to the adequacy of electrical power?
- What measures can be taken to increase supply in the reserve market? How to increase interest of market participants in short term balancing? How do you see the distribution of responsibilities between market participants and the TSO in managing the power balance in the future?
- What methods could be used to support network investments to ensure sufficient transmission capacity, if network construction and technical solutions alone are not sufficient e.g. bidding zone division, guidance through transmission or connection fees, some other means?
- What possible problems or solutions do you foresee for the technical functioning of the electricity system in the future according to the scenarios?
- Which of the above-mentioned solutions you consider particularly desirable or challenging, why?

Free-form feedback can be sent by email to **strateginen.verkkosuunnittelu@fingrid.fi** Please send your feedback by 15th of September 2022 at the latest.

A summary of the feedback will be prepared, and the feedback will be discussed in the final report on the electricity system vision to be published later. In addition, the feedback will be discussed with Gasgrid Finland in the cooperation project on the effects of the hydrogen economy. Please indicate clearly in connection with the feedback if your feedback may not be shared with Gasgrid Finland Oy. Feedback from individual respondents will not be published.

Appendix 1. Scenario modelling

The aim of the 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[34]. The assumptions about investment costs for both operating and maintenance costs are mainly based on TYNDP2022 scenarios, and they are described in Table 18. In some scenarios, the TYNDP figures have been deviated from when it is preferable for the scenario to allow for a certain trajectory. For example:

- Investments in onshore wind power have been limited in the scenarios Windy seas and Local power 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.

Table 18 Assumptions for investment costs for new power plants in finland for year 2035. Marginal reflects difference between different scenarios. SMR-nuclear power is used only in local power scenario[35].

All costs as real currency (2021)		Onshore wind	Offshore wind	Solar PV	SMR-nuclear power	Traditional 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
Capacity factor	%	40%	54%	10%	87%	87%
Lifetime	years	30	30	40	60	60
Levelized cost of electricity (LCOE)	EUR/MWh	21–25	26–41	26–37	29–41	79

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

[35] Cost of onshore wind is from the lower bound of the range in the scenarios Power to products and Hydrogen from wind. Cost of offshore wind is from the lower bound of the range in scenario Windy seas, from the upper bound of the range in the scenario Local power and from the middle in two other scenarios. Cost of solar power is from the lower bound of the range in scenario Local power, from upper bound in scenario Windy seas and from the middle in other scenarios. SMR-nuclear power is available only in Local power scenario. Traditional nuclear power would be available in all scenarios, but investments are not assumed to be profitable in Finland with assumed cost level.

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.

CAPEX and OPEX for wind and solar power are based on TYNDP scenarios[36] and their source data from ENS.dk[37]. For the numbers for onshore wind power, Finland's higher plant height and unit size are considered. For the traditional nuclear power plants, the ASSET study[38] has been used as a source, and for fuel costs TYNDP data is used. For SMR nuclear power costs are assumed to be such, that the investments are profitable. Thus the capital costs as well as operation and maintenance costs are about 50 % lower than for traditional nuclear power, so the capital costs are roughly in line with the long-term target of the NuScale-company (”Nth-of-a-kind”, 3 600 USD/ kW)[39]. In addition, for SMR power plant the construction time is assumed to be significantly shorter than for traditional nuclear power plant. In case SMR power plants are used for combined heat and power use, plants are assumed to receive from heat production return equal to its variable costs (12 EUR/MWh per produced MWhe), in this case net variable OPEX is 0-12 EUR/MWh depending whether the waste heat is utilized or not. SMR nuclear power plants are used only in Local power scenario. The levelized cost of electricity is calculated for each technology as real using 5 % real rate of return. Thus, in order to quantify the nominal cost in 2035, inflation would have to be added on top.

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

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

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

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

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