RESOURCE ADEQUACY ASSESSMENT

RESOURCE ADEQUACY ASSESSMENT UNTIL 2033

Report to Energy Authority

03/2023

CONTENT

EXECUTIVE SUMMARY

This study has been carried out to obtain information on the Finnish electricity system resource adequacy for the years 2023-2033 and estimate the need for reserve capacity for the years 2023-2025. National legislation requires a biennial evaluation of resource adequacy, which this study fulfills. The assessment of the resource adequacy is based on the evaluation of the results in relation to the nationally set threshold for Loss of Load Expected (LOLE). LOLE value indicates the average expected number of hours in a year when resources are insufficient to meet the demand. The threshold for resource adequacy set by the Finnish government is 2.1 hours a year. This study has been completed by following the European Union Agency for the Cooperation of Energy Regulators (ACER) methodology for the European resource adequacy assessment (ERAA).

Three scenarios were developed for the study, base scenario and two scenarios for the sensitivity analysis. The base scenario was modelled for the years 2023-2033 and sensitivity analyses for 2023-2025. The base scenario provides the best estimate of the development of demand, supply, interconnector, and demand side response in the Finnish electricity system until 2033. In the first sensitivity analysis scenario, the nuclear power plant Olkiluoto 3 has a 10% unpredictable unavailability rate compared to the 2% in the base scenario to reflect the possibility that the reliability of the power plant can be lower in the first few years of the operation. In the second sensitivity analysis, Olkiluoto 3 is not in operation during the years 2023-2025, which also increases the interconnection capacity between Sweden and Finland with 300MW. All other background assumptions in the sensitivity analysis scenarios regarding the electricity system are the same as they are in the base scenario.

Results for the base scenario reveal that the average expected LOLE in 2023 is 33 hours, less than 2 hours 2024-2029 and year by year increasing hours in 2030-2033. Almost all of the LOLE in 2023 occur in the first months of the year when Olkiluoto 3 is not in operation. After the year 2029 industrial electrification is expected to rapidly increase and the share of renewable electricity in the power generation mix significantly grow. Increased demand combined with variable electricity production creates electricity system that is extremely tight during some hours, and thus result higher LOLE.

The results from the sensitivity analysis 1 show that having lower availability in Olkiluoto 3 results a slight increase in LOLE compared to the base scenario. The LOLE hours during the 1.11.2023-31.10.2024 reserve period were 2.16 hours, which is a 0.72 hour increase from the base scenario. LOLE hours during the 1.11.2024-31.10.2025 reserve period were 2.72 hours, which is a 0.89 increase from the base scenario

The results from the sensitivity analysis 2 highlight the importance of the Olkiluoto 3 for the resource adequacy in Finland. Without the nuclear power plant producing electricity, there was a significant increase of LOLE compared to the base scenario. LOLE for the 1.11.2023-31.10.2024 reserve period were 10.54 hours, which is an 8.38 hour increase from the base scenario. LOLE hours for the 1.11.2024-31.10.2025 reserve period were even slightly higher.

This study has also assessed the necessary reserve capacity for the period 1.11.2023-31.10.2025 to fulfill the 2.1 national threshold for LOLE for the base scenario and sensitivity 1 scenario. In the base scenario, no reserve capacity was found to be necessary as LOLE hours were lower than 2.1. For the sensitivity scenario 1, it was found that for the reserve period 1.11.2023-31.10.2024, the reserve capacity of 50MW would bring the LOLE value down to 2.04 hours and thus, would be sufficient to fulfill the resource adequacy. For the reserve period 1.11.2024-31.10.2025, the reserve capacity of 150MW would bring the LOLE value down to 1.91 hours and would be thus, slightly higher capacity than is sufficient to fulfill the resource adequacy requirement.

ABBREVIATIONS

ACER - Agency for the Cooperation of Energy Regulators

BID3 - AFRY Electricity market model

CHP - Combine Heat and Power

CONE - Cost of New Entry

DSR - Demand Side Response

EAC - Equivalent Annualized Cost

EENS - Expected Energy Not Served

ERAA - European Resource Adequacy Assessment

EVA - Economic Viability Assessment

GW - Gigawatt

GWh - Gigawatt hour

IAEA - International Atomic Energy Agency

LOLE - Loss of Load Expected

MW - Megawatt

MWh - Megawatt hour

1. BACKGROUND

According to the national power reserve legislation (117/2011 and 146/2022), the Finnish Energy Authority must complete a resource adequacy assessment that follows the EU internal market regulation (943/2019) at least every two years. The aim of this study is to provide information to the Energy Authority about the national Resource Adequacy during the years 2023-2033 and assess the required need for reserve capacity. To support the resource adequacy assessment, this report also reviews the Cost of New Entry (CONE) values for potential new entries.

EU Agency for the Cooperation of Energy Regulators (ACER) sets a methodology for the European Resource Adequacy Assessment (ERAA) and CONE value evaluation. This study is done in line with the set methodologies. The ERAA is interpreted in the context of the national reliability standard, which for Finland is a maximum of 2.1-hour annual Loss of Load Expected. The need for reserve capacity is assessed based on the ACER methodology and in relation to the national reliability standard. Results for the adequacy assessment are presented as loss of load expected (LOLE) and expected energy not served (EENS) for 2023-2033.

2. METODOLOGY

The assessment has been completed in line with the European Resource Adequacy Assessment and Cost of New Entry methodologies adopted by ACER[1]. In the methodology and completion of this study, particular diligence has been applied during the scenario framework, economic value assessment and ensuring consistency with the reliability standard. In the overall methodology there are a few minor deviations, from the NRAA methodology. The deviations have been preemptively agreed on with the Finnish Energy Authority, and they have been described in the following chapters.

Construction of the scenarios modelled in this study has been done according to the ERAA methodology Article 3. National demand, supply and grid outlooks for each year of the studied time period have been prepared. National policies and known trends have been accounted for in detail in the development of the scenario framework. In this study, the base scenario is seen to be sufficient to present the scenario developments for the 2023-2033 timeframe. For a 2023-2025 there is seen to be two scenarios on which sensitivities are necessary to reflect the various potential outcomes for the period. Both sensitivities are related to Olkiluoto 3 availability.

A fundamental part of the ERAA methodology is the Economic viability assessment (EVA). The purpose of the EVA is to assess the likelihood of retirement, mothballing, new build of generation assets and measures to reach energy efficiency. AFRYs electricity market modelling tool, BID3 has an EVA module (Autobuild) which has been used to build the base scenario used in this study. The two sensitivity analysis modelled in this study have been built on the base scenario, and so EVA is also indirectly applied to the sensitivity scenarios.

AFRY Autobuild module capacity optimisation develops scenarios of new build, retiral and mothballing automatically. The module uses Bender's or Dantzig Wolf decomposition to solve multiple sub problems and recombine the optimisation of thermal new build, renewables new build, interconnector new build and thermal plant retiral/mothballing. Autobuild module builds scenarios for single years, multiple future years, and multiple weather patterns and optimizes them to a finalized scenario built based on economic value assessment. The module runs a series of iterations, converging on a cost optimal solution that minimises both capex, opex and variable costs of generation. The results of the EVA are presented in the scenarios of this study, as the scenarios are based on the EVA.

The probabilistic assessment for calculating the supply reliability indicators is done by using the Monte Carlo method. The methodology considers the market availability of different generation technologies and transmission capacity based on a combination of planned and unplanned outages. The Monte Carlo method is a commonly used method that is based on probabilities, and can be used to test a sufficiently large number of possible scenarios for unplanned outages that affect the availability of power plants and interconnectors. Monte Carlo simulations are modelled by using AFRY's BID3 electricity market model.

2.1 BID3 electricity market model

BID3 is AFRY's own electricity market model covering the whole of European electricity generation and transmission interconnections. The BID3 electricity market model has been used for several studies similar to this resource adequacy assessment, including studies done for European transmission system operators.

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[1] https://www.acer.europa.eu/electricity/security-of-supply/european-resource-adequacy-assessment

In this resource adequacy assessment, BID3 has been used to model regionally the Nordic and Baltic countries (Finland, Sweden, Norway, Denmark, Estonia, Latvia, Lithuania). Electricity inflows from other countries, that have interconnectors to the modelled areas have been taken into account. The model determines the electricity production of the plants and the transmission of electricity from cross-border interconnections according to their availability and profitability on an hourly basis.

As per the ERAA methodology, the BID3 electricity market model accounts for the impact of climate conditions on demand and generation with hourly profiles for 20 weather years (1999-2018). By accounting for weather conditions over 20 years confirmation on potential power shortages, for example in very cold and windless conditions year is possible. In this work, the 20 weather years are considered to be representative of future weather developments in the Nordic countries. Climate change is predicted to change the climate in Finland to a warmer and rainfall, of which recent years have been good examples. Finland's National Climate Change Adaptation Plan describes developments in more detail[2]. The 20 weather years used are considered to represent a sufficiently long sample of different weather conditions. The used weather years are also considered to weight recent climate enhanced demand profile developments, by for example highlighting the share of electric heating according to temperature, and thus its use is well justified.

The calculation is based on the nominal capacities of the electricity generation plants, electricity transmission interconnection capacities, electricity demand and their evolution in terms of the period 2023-2033. The available capacity of the different technologies is estimated both in terms of anticipated unavailability and unpredictable unavailability.

2.2 Availability assumptions of the production units and interconnectors

The availability assumptions for supply are based on predictable unavailability and unpredictable unavailability. Both types of unavailability are considered in the modelling. Predictable is accounted for by preset profiles and unpredictable unavailability by preset assumptions for different production types which are randomly applied by the Monte Carlo simulations.

Predictable unavailability

Predictable unavailability in the modelling, for example power plant annual maintenance breaks, are based on plant historical availabilities by production type. Historical availability is based on production type and interconnection data collected by AFRY. A production type and interconnector averages are formed based on the historical data. In general, the largest impacts of predicted unavailability on the electricity system and so the resource adequacy come from the annual maintenance breaks of nuclear power plants. The maintenance breaks typically occur during warmer months, and so the capacity of all other production types can match the demand and no resource adequacy issues are generally caused by predictable unavailability.

The ERAA methodology uses ENTSO-E's predicted unavailability profiles. The methodology used in this study differs slightly from this, although the methodologies used for determining the profiles are very similar. In the ERAA methodology, for the first three years the predictable unavailability profiles are based on profiles determined by ENTSO-E and transmission system operators’, which have been determined in a similar manner to the AFRY profiles by using historical data. From the fourth year onwards, optimized profiles which consider the most challenging periods for resource adequacy are used. Even though

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[2] https://mmm.fi/documents/1410837/5120838/Kansallinen+ilmastonmuutokseen+sopeutumissuunnitelma+2022.pdf/1716aa76-8005-4626-bae0-b91f3b0c6396?t=1501159291000

the ERAA availability profiles are not used in this study directly, the methodology used by AFRY for determining the used profiles is very similar. In addition, predictable annual maintenances occur in moments which are not challenging for the electricity system and so are not seen to significantly impact the results.

Unpredictable unavailability

Unpredictable unavailability, or forced outage rate, describes the ratio between failure hours and total annual service hours. Unpredictable unavailability assumptions for different plant types and transmission links can be found in Annex 1 and are based on the assumptions of the ENTSO-E MAF 2020 report. Deviating from the ENTSO-E values, a 2% rate for unforeseen unavailability has been used for Finnish nuclear power plants. Based on historical data, Finnish nuclear powerplants have had a lower unpredictable unavailability rate than a broader 5% average, used by ENTSO-E. The used 2% rate is based on IAEA (2022) statistics[3]. In line with ENTSO-E, renewable power generation profiles are considered to already account for outages for wind and solar power.

In the Monte Carlo method, the same year is modelled several times, and each time the power plant and interconnection unforeseen unavailability is assigned randomly. In this way, multiple Monte Carlo simulations can account for different unpredictable unavailability of different power plants and transmission links.

Other constraints

In addition to the predicted and unpredicted unavailability, the modelling done with BID3 considers other constraining factors related to combined heat and power (CHP) production as well. The heat generation need of CHP is accounted for and CHP plants have a so called ‘must run’ profile. The model also considers the possibility for separate electricity production for CHP plants that can do so.

2.3 Reported key figures

Two key resource adequacy indicators are reported as a result of the modelling. The indicators are reported as an average of the modelled weather years (1999-2018) and random outage years.

The first indicator, and the more significant one is Loss of Load Expected, h/a (LOLE). The indicator describes the number of hours in a year where electricity generation deficiency occurs. The value is based on probability-based modelling, and so is only an average of the modelled simulations and weather years. Actual amount may vary significantly from year to year, depending on factors such as winter temperatures, wind and water conditions, and unforeseen failures of power plants and transmission lines. The second indicator is Expected Energy not Served, GWh/a (EENS) and it presents the amount of electric energy that is not supplied during the hours where electricity generation deficiency occurs. EENS value also represents a probability-based average, while actual amount may vary greatly depending on weather conditions and unforeseen failures.

In summary and as per the ERAA methodology, Monte Carlo simulation of outages combined with weather patterns provide basis for economic dispatch for LOLE (Loss of Load Expected, h/a) and EENS (Expected Energy Not Served, GWh/a) calculation. The amount of Monte Carlo simulations is shown in Annex 3 and the impact of different weather years on the reported average LOLE and EENS values is shown in Annex 4. In addition to the resource adequacy assessment, calculation of required power reserve is conducted for the reserve periods 1.11.2023-31.10.2024 and 1.11.2024-31.10.2025.

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[3] https://www.iaea.org/publications/15212/operating-experience-with-nuclear-power-stations-in-member-states

3. CONE VALUES

A part of performing national resource adequacy assessment in accordance with the ACER methodology[4] is determining values for cost of new entry (CONE). CONE values include estimates for fixed and variable cost for technologies which can provide resource adequacy benefits and have a potential of new investments to be made. CONE values for the Finnish market have been determined in a previous study[5] and the scope of this study is to review the values and update them for selected technologies if needed. CONE values impact the reliability standard, which then impacts the need for reserve capacity, which is why ensuring the up-to-date information of the CONE values is necessary.

3.1 Review of existing CONE values

Reviewing the CONE values was done by first assessing the reference technologies for which values are calculated. CONE calculation in accordance with the ACER methodology, is based on identifying candidate technologies for new entries and then performing the calculations for selected reference technologies. Reference technologies reflect technologies for which investment decisions are likely to be made by rational private investors in a considered geographic area. ACER methodology defines reference technologies as standard technology in which reliable and generic cost information can be found and a potential new entry determined by weather capacity is developed in recent years and if future development is legal in the given region.

Assessment of the CONE values completed in this study was done by reviewing the long list of candidate technologies presented in the previous study and evaluating if the list was complete. The list was concluded to miss electrolysis as a potential demand side response (DSR) technology.

After completion of the list of candidate technologies, analysis whether the technologies in the list are reference technologies was performed. The previous analysis was deemed to be accurate apart from missing electrolysis. Electrolysis is a standard technology and a potential new entry, and it was added as a reference technology. Table 1 presents an updated list of all the reference technologies.

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[4] https://www.acer.europa.eu/electricity/security-of-supply/european-resource-adequacy-assessment

[5] https://energiavirasto.fi/documents/11120570/13026619/Energiaviraston+p%C3%A4ivitetty+ehdotus+valtioneuvostolle+luotettavuusstandardista.PDF/35ac4bfd-11de-74f7-eff9-3a66be9bdcc5/Energiaviraston+p%C3%A4ivitetty+ehdotus+valtioneuvostolle+luotettavuusstandardista.pdf?t=1647937046571

Table 1 - Reference technologies

Power generation

- Nuclear power plants
- Biogas engines
- Biomass-fired power plants
- Waste-to-Energy plants
- Capacity raise with auxiliary cooling and/or heat storages
- Residential rooftop PV
- Commercial PV
- Onshore wind power
- Offshore wind

Power storages

- Buildings-grid connected battery storages
- Utility-grid connected storages

Demand side management

- Electric heating and other loads
- HVAC, lighting, and other loads
- Electrolysis

CONE value review was done for the technologies that were determined to be a reference technology. CONE values for all other technologies except for electrolysis were calculated in the previous report. Assessing if the values required updating was done by reviewing if any significant changes have occurred in any of the variables included in the CONE calculation formula. Based on the assessment, it was determined that values for biomass-fired power plants and offshore wind need to be updated and value for electrolysis needs to be calculated.

Industrial power consumption was identified as a potential new entry in the previous report, and it is considered as such in this report as well. CONE value for the technology was not calculated previously as no reliable and generic cost information is available for future capacity increase. The status has not changed, and therefore industrial power consumption is not acceptable as a standard technology. Selected technologies need to be standard for calculating CONE values, therefore CONE value for industrial power consumption as a DSR is not calculated in this report.

3.2 Calculation of updated CONE values

Calculation of CONE values have done according to the ACER methodology[6]. CONE value consists of values for fixed and variable costs. First fixed cost has been calculated as a ratio between equivalent annualised cost (EAC) and the de-rating capacity factor.

For each reference technology, the EAC is calculated using the following formula:

$$EAC = \left[\sum_{i=1}^{X} \frac{CC(i)}{(1+WACC)^{i}} + \sum_{i=X+1}^{X+Y} \frac{AFC(i)}{(1+WACC)^{i}}\right] \cdot \frac{WACC \cdot (1+WACC)^{X+Y}}{(1+WACC)^{Y}-1}$$

Where:

- i represents each year over the construction period and economic lifetime;

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[6] https://www.acer.europa.eu/sites/default/files/documents/Individual%20Decisions_annex/ACER%20Decision%2023-2020%20on%20VOLL%20CONE%20RS%20-%20Annex%20I_1.pdf

- X is the construction period (in years) defined according to Article 11;
- Y is the economic lifetime (in years), defined according to Article 11;
- $CC(i)$ is the best estimate of the capital costs incurring each year of the construction period (in local currency per MW), defined according to Article 13;
- $AFC(i)$ is the best estimate of the annual fixed costs incurring each year during the economic lifetime (in local currency per MW), defined according to Article 13; and
- $WACC$ is the best estimate of WACC as defined in Article 14.

The $\text{CONE}_{\text{fixed}}$ for a given reference technology ($CONE_{\text{fixed,RT}}$) shall be calculated as the ratio between the EAC and the de-rating capacity factor:

$$CONE_{fixed,RT} = \frac{EAC_{RT}}{K_{\mathrm{d,RT}}}$$

Where:

- EAC_{RT} represents the EAC of a given reference technology calculated according to the formula mentioned in paragraph (1) (in local currency per MW); and
- $K_{\text{d,RT}}$ is the de-rating capacity factor of the reference technology, defined according to Article 12.

Variables used for calculation of fixed and variable CONE values were researched as a literature review and are presented in **Error! Reference source not found.** and Table 3. Following, in Table 4 the calculated CONE values are presented.

Table 2 – Values used in $\text{CONE}_{\text{fixed}}$ calculation

Technology	CAPEX, k€/MW[7,8]	Annual fixed cost, k€/MW[4,9,10]	Economic lifetime, y[4,11]	Construction time, y[4,12]	WACC, % [13,14,15]	De-rating factor, %[16,17,18]
Biomass-fired power plants	2380	66	25	5	7 %	93.60 %
Offshore wind	2120	111	27	2.5	6.90 %	13.00 %
Electrolysis	550	27.5	20	1	6 %	84.14 %

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[7] https://ens.dk/en/our-services/projections-and-models/technology-data/technology-data-generation-electricity-and

[8] https://www.iea.org/reports/electrolysers

[9] https://www.nrel.gov/docs/fy21osti/78471.pdf

[10] https://iea.blob.core.windows.net/assets/a02a0c80-77b2-462e-a9d5-1099e0e572ce/IEA-The-Future-of-Hydrogen-Assumptions-Annex.pdf

[11] https://www.sciencedirect.com/science/article/pii/S0360319920310715?via%3Dihub

[12] https://www.iea.org/reports/electrolysers

[13] https://energy.ec.europa.eu/documents_en?f%5B0%5D=document_title%3ASubsidies%20and%20costs%20of%20EU%20energy

[14] https://www.ise.fraunhofer.de/content/dam/ise/en/documents/publications/studies/EN2021_Fraunhofer-ISE_LCOE_Renewable_Energy_Technologies.pdf

[15] https://www.sciencedirect.com/science/article/pii/S0360319921034406

[16] https://www.emrdeliverybody.com/Capacity%20Markets%20Document%20Library/Auction%20Guidelines%202020_T-1_T-3_T-4.pdf

[17] https://www.emrdeliverybody.com/Prequalification/EMR%20DB%20Consultation%20response%20-%20De-rating%20Factor%20Methodology%20for%20Renewables%20Participation%20in%20the%20CM.pdf

[18] https://www.sciencedirect.com/science/article/pii/S1364032114008284

Table 3 – Values used in $\text{CONE}_{\text{variable}}$ calculation

Technology	Fuel cost €/MWh[19]	Other variable OPEX €/MWh[4,11,20]	Minimum activation price for DSR €/MWh[21]
Biomass-fired power plants	27	1.73	-
Offshore wind	-	5	-
Electrolysis	-	1.6	150

Table 4 - CONE values

Technology	$\text{CONE}_{\text{fixed}}$ k€/MW	$\text{CONE}_{\text{variable}}$ €/MWh
Biomass-fired power plants	321	29
Offshore wind	2462	5
Electrolysis	193	157

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[19] https://www.ea-energianalyse.dk/wp-content/uploads/2020/02/1280_analysis_of_biomass_prices.pdf

[20] https://theicct.org/wp-content/uploads/2021/06/final_icct2020_assessment_of-_hydrogen_production_costs-v2.pdf

[21] https://www.svk.se/siteassets/om-oss/rapporter/2021/langsiktig-marknadsanalys-2021.pdf

4. SCENARIOS

The study consists of three different scenarios for the Finnish electricity system during the years 2023-2033. The first scenario is the base scenario, which is based on AFRYs best view on the electricity system development in terms of demand, interconnector capacity, and supply. The scenario for supply is completed by using AFRYs economic viability assessment (Autobuild) module. The EVA completed by the Autobuild module accounts for Finnish national targets for the electricity system development. In addition to financial data, expected national developments are used as inputs for the Autobuild simulations. The national developments and targets are partially based on a study conducted for the Finnish Prime Minister's office about the impacts of carbon neutrality targets on the Finnish electricity system[22]. Scenario assumptions have been done as per the ERAA methodology by considering the national supply and demand outlooks through expected project outlooks and existing and planned national policies.

In addition to the base scenario, two sensitivity scenarios were created. In the first sensitivity scenario, Olkiluoto 3 nuclear power plant has a 10-percentage unpredictable unavailability rate during 2023-2025. The higher rate is based on the assumption that the power plant has a higher forced outage rate during the first years of production, compared to the historical data on Finnish power plants having a low forced outage rate of only 2%. In the second sensitivity scenario, Olkiluoto 3 is not in production at all during 2023-2025. Olkiluoto 3 is announced to begin full commercial electricity production on 17.3.2023, but due to the importance of the power plant for the resource adequacy and historical complications with the commissioning, the unavailability was modelled to reflect the worst-case scenario regarding the power plant.

4.1 Base scenario

In the base scenario, electricity production capacity increases with 5 GW between 2023 and 2033. The increase in capacities by different power plant types is presented in Figure 1. The capacities shown in the graph present the average production capacities for each year. Current reserve capacity is included in the figure.

While the gross production capacity in Finland increases during the represented years, there are changes in the share of the capacity mix that a given technology represents. CHP and condensing power share of the generation mix decreases from 40% in 2023 to 25% in 2033. On the contrary, the share of wind and solar power increases from 27% in 2023 to 48% in 2033.

Nuclear and hydropower are seen to be stable through the analysis period after Olkiluoto 3 is included in the 2023 capacity mix and no new hydropower projects are seen in the pipeline. The capacities of CHP and condensing power are seen to decline by ~ 25 % through the period. The decline is mainly caused by decommissioning of all coal CHP plants by 2029. In addition, it is projected that other CHP plants are being replaced by more carbon neutral technologies such as heat pumps and other methods of production and sourcing of heat as the existing boilers come to the end of their technical lifetime.

Wind and solar power capacities are seen to increase significantly. In the end of 2022, there was 5.7 GW of wind power production capacity in Finland. There was also 66 GW of additional onshore and offshore wind power capacity in some phase of the planning and construction pipeline[23]. While most of the 53 GW additional capacity may not realize as commissioned power plants, the volume of the projects even in early stages of planning

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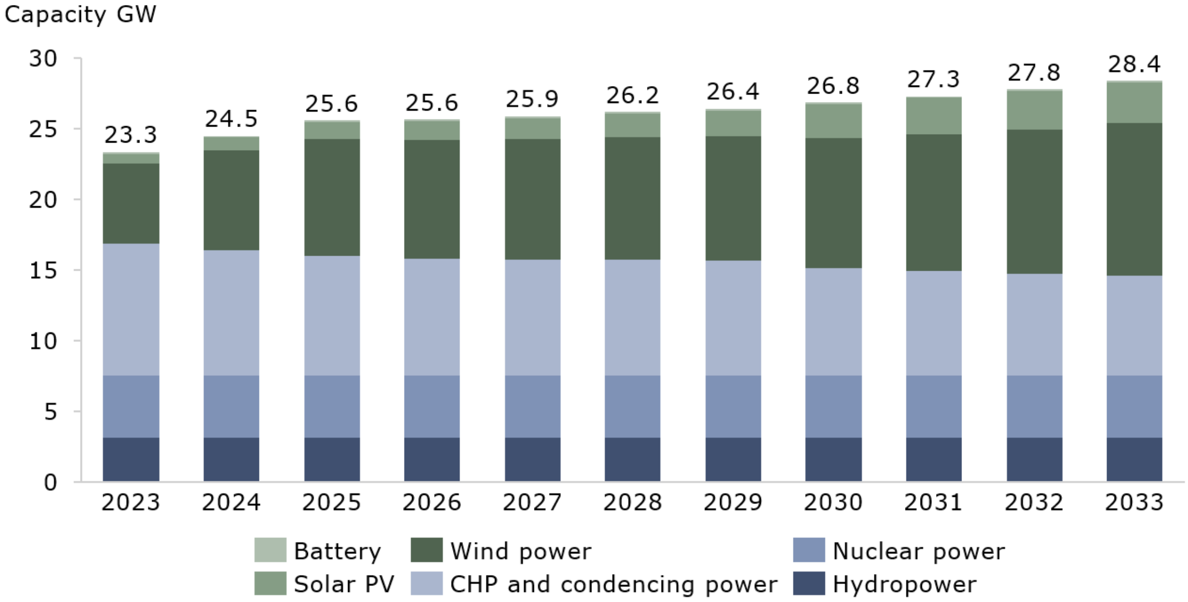
[22] https://julkaisut.valtioneuvosto.fi/handle/10024/162705

[23] https://tuulivoimayhdistys.fi/tuulivoima-suomessa

show the wind power potential that exists in Finland and the significant amount of increase by 2025 and by 2033 in capacity in the base scenario is justified.

Solar power capacity growth is expected to accelerate as investment costs are decreasing, making solar profitable in Finland. At the end of 2022, there was already 606 MW of installed solar power capacity in the Finnish electricity system[24]. Developers are constantly announcing new large-scale projects, and according to AFRY analysis, current publicly announced projects have a nominal capacity of 2.5 GW. Out of the publicly announced projects, 0.4 GW have been awarded government support.

Figure 1 - Nominal electricity production capacity between 2023 and 2033 in the base scenario



Electricity demand in Finland is expected to have a stable growth until 2030. From 2030 onwards, especially the industrial electrification is expected to increase the demand[25]. The projected annual demand in 2023-2033 is presented in Figure 2.

The modelled results are an average of the modelled weather and random outage years. Actual realized demand may differ, as the real weather patterns are not necessarily aligned with the probabilistic based modelled average. In the modelling, demand varies between different weather years, especially because of temperature changes. In colder weather years, the consumption tends to be higher while in warmer weather years the consumption generally decreases. The impact of the weather and temperature patterns on the demand in the Finnish electricity system cannot be disregarded, which is why the results are an average of the 20 modelled weather years.

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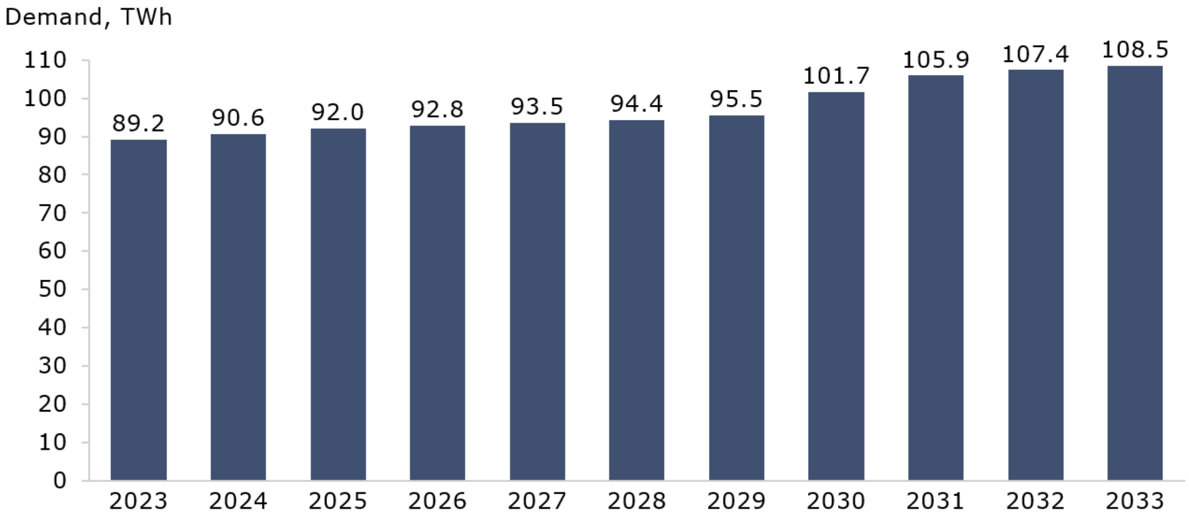
[24] https://data.fingrid.fi/open-data-forms/search/fi/?selected_datasets=267

[25] https://julkaisut.valtioneuvosto.fi/handle/10024/164567

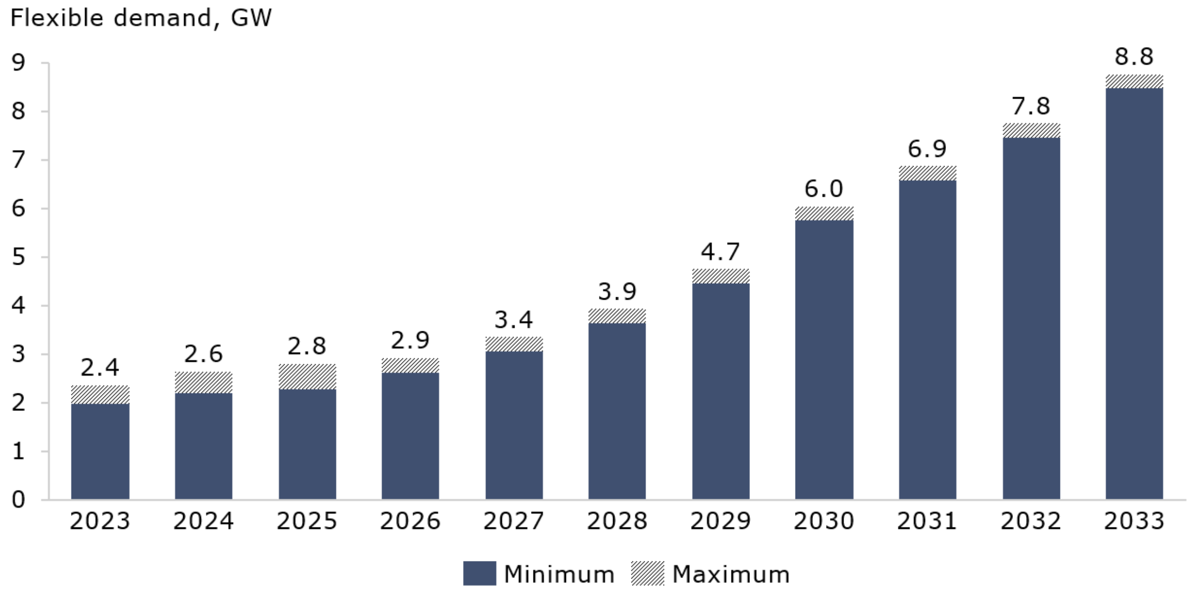
Figure 2 - Electricity consumption between 2023 and 2033 in the base scenario



Electricity consumption is also impacted by the electricity price, as some of the demand is estimated to be price responsive. In the modelling, demand side response (DSR) is divided into two categories. Some of the DSR, for example the consumption of the electric vehicles is expected to be flexible DSR, meaning that the same demand exists but the consumption is timed for hours that have a cheaper electricity price. The other category is price threshold DSR, were high electricity price decreases the electricity consumption. Price threshold DSR can be applied for example in some industrial and heating related electricity consumption.

Figure 3 shows the total maximum flexible demand in 2023-2033. Demand flexibility is expected to grow significantly in the assessed timeframe. Main drivers of increased flexibility are increasing electrification and increasingly varying electricity prices. Four main types of DSR are considered in AFRY scenarios: electric vehicles, residential, industrial and commercial demand side response, heat flexibility, and flexible electrolysis.

Figure 3 - Demand side response between 2023 and 2033 in the base scenario



Interconnection capacities at the end of each year used in the base scenario are presented in Figure 4. While there is existing interconnector capacity from Russia to Finland, this is not accounted for in the base scenario, as no electricity flows are expected from Russia during the modelled period. The transmission capacity between Sweden and Finland in the beginning of 2023 is 300 MW higher than shown in the graph, but it will be decreased to the presented value when Olkiluoto 3 is in production.

The main change during the considered period is increased transmission capacity between Sweden and Finland in 2026, as 'Aurora line' is commissioned. The increase in interconnector capacity is 800 MW. In addition to the Aurora line, 150 MW of capacity is commissioned from norther Norway to Finland in 2027. The analysis for interconnection transmission capacities and their increases are based on Fingrid network development plan[26].

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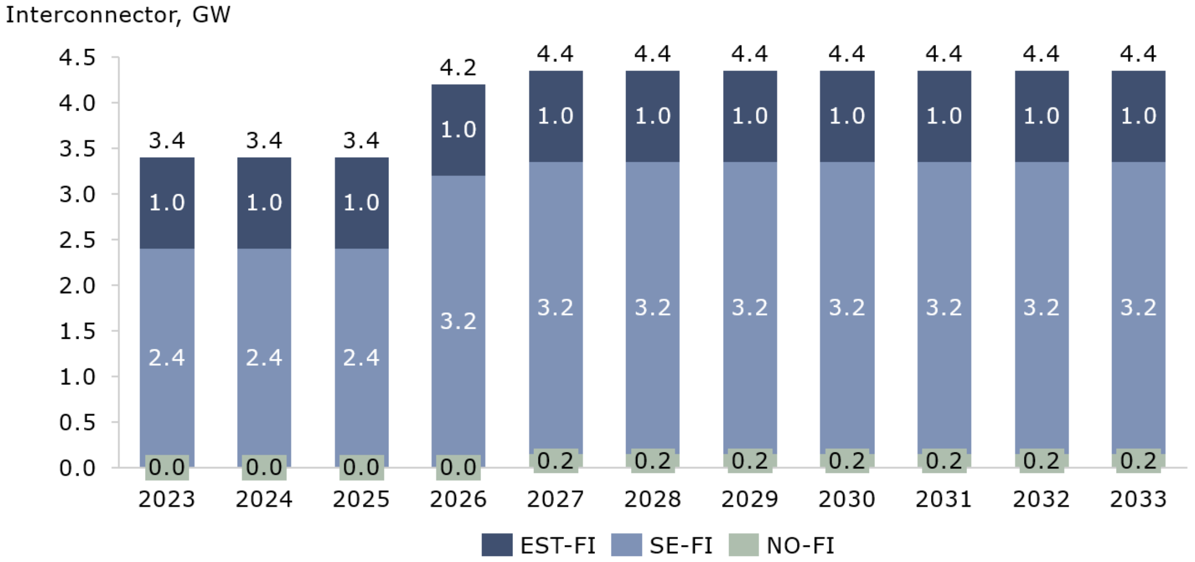
[26] https://www.fingrid.fi/kantaverkko/kehittaminen/kehittamissuunnitelma/

Figure 4 - Interconnection capacity between 2023 and 2033 in the base scenario



4.2 Sensitivity analysis 1

Sensitivity analysis 1 is a scenario where Olkiluoto 3 has a 10 % unpredictable forced outage rate during 2023-2025, compared to the 2 % in the base scenario. No other changes from the base scenario have been made to the sensitivity analysis 1 scenario and the supply, demand, demand flexibility and interconnection capacities remain the same as presented in 4.1. The sensitivity analysis is only done for years 2023-2025.

While IAEA[27] data shows that Finnish nuclear plants have historically had high reliability, there is a possibility that the reliability of the power plant is lower in the first few years of the operation. Historical data from the operational Finnish nuclear power plants shows that they all have had a lower availability factor during the first few years of operation compared to the later years[28]. While the availability factor includes predictable and unpredictable unavailability, the overall availability suggests a higher unpredictable availability as annual maintenance breaks are stable and predictable.

Sensitivity 1 scenario is created to model the possible scenario of Olkiluoto 3 having unpredictable issues during the first few years of operation. The results will give an understanding on the importance of the reliability of the Olkiluoto 3 on the resource adequacy.

4.3 Sensitivity analysis 2

Sensitivity analysis 2 is a scenario where Olkiluoto 3 is delayed and will not be producing electricity at all during 2023-2025. While the current information is that Olkiluoto 3 will continue test production on 15.3.2023 and commercial production will start on 17.4.2023, there has been historically and recently significant delays on the start of the production[29].

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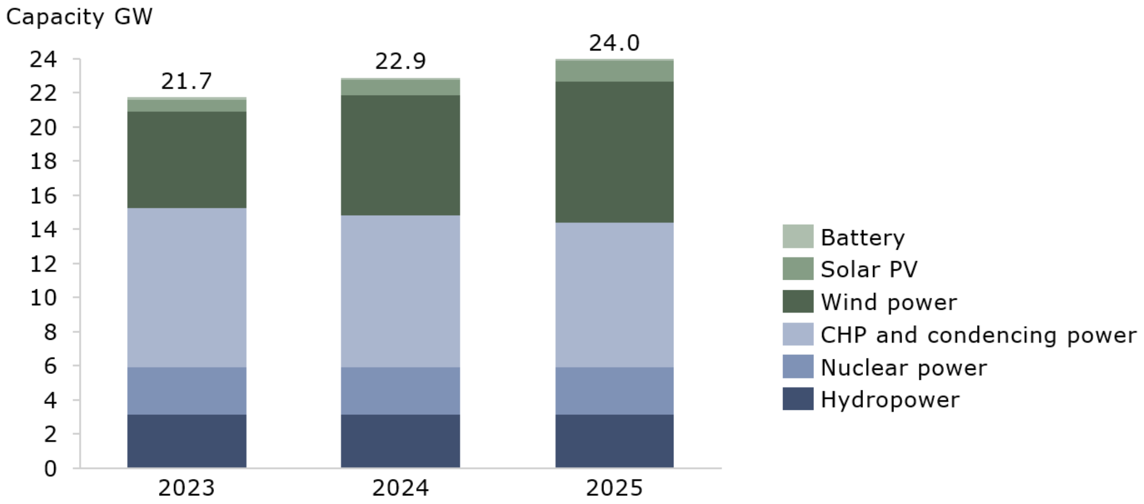
[27] https://www.iaea.org/publications/15212/operating-experience-with-nuclear-power-stations-in-member-states

[28] https://pris.iaea.org/PRIS/CountryStatistics/CountryDetails.aspx?current=FI

[29] https://www.tvo.fi/tuotanto/laitosyksikot/ol3/ol3ennusteet.html

The sensitivity analysis is performed for years 2023-2025, and the nominal production capacities without Olkiluoto 3 are presented in Figure 5.

Figure 5 – Nominal electricity production capacity between 2023 and 2025 in the sensitivity 2 scenario



The aim of the sensitivity analysis 2 is to gain an understanding of the Olkiluoto 3 power plants importance on the Finnish national resource adequacy. While the scenario is not as likely as sensitivity 1, it is important to understand more drastic scenarios and their possible implications. Whether Olkiluoto 3 is connected to the grid or not influences the transmission capacity between Sweden and Finland as well. When Olkiluoto 3 is in production with more than 1000 MW capacity, the maximum SE1-FI interconnector capacity is 1200 MW. When the power plant is producing with 0-1000 MW, the maximum SE1-FI transmission capacity is 1500 MW.

5. RESULTS

Modelling of the three scenarios, the base and two sensitivity analysis, was done according to the methodology described in chapter 2. As a result of the methodology, two key indicators for the resource adequacy are presented. The indicators are presented as an average of the modelled weather years.

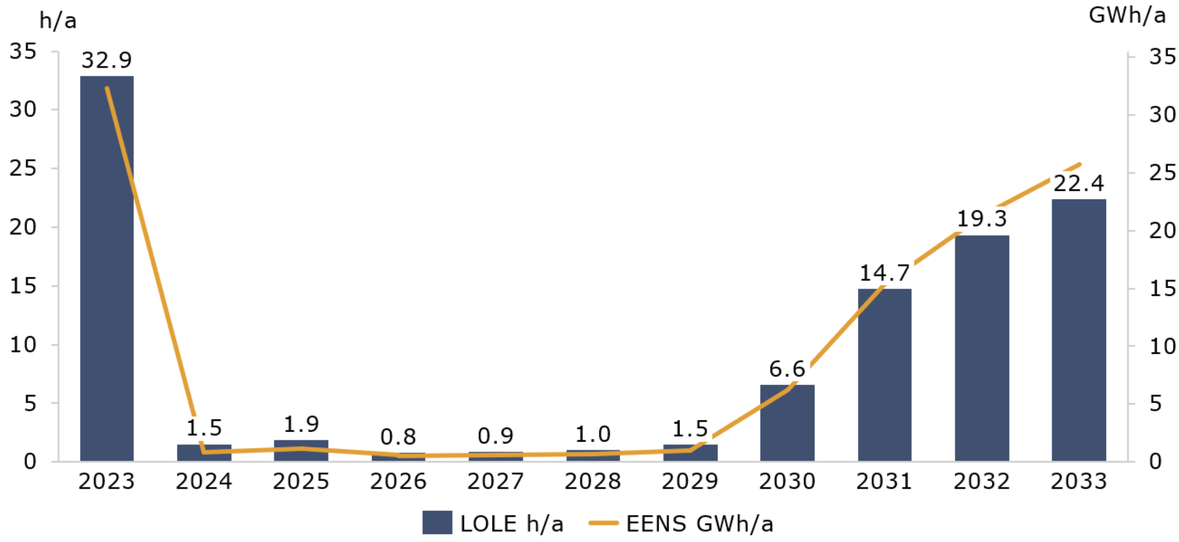
1. Loss of Load Expected, h/a (LOLE)
2. Expected Energy Not Served, GWh/a (EENS)

The Finnish government has set the standard for LOLE hours to be maximum 2.1 hours per year[30]. The results in all three scenarios are interpreted in relation to the set standard. In addition, the reserve capacity is calculated with the aim of having LOLE hours under the set threshold.

5.1 Base scenario

The Loss of Load Expected and Expected Energy Not Served values in the base scenario are presented in Figure 6 and Table 5. There are significant LOLE hours in 2023, but the modelling results show that most of them occur in the first three months of the year, when Olkiluoto 3 is not producing electricity. The loss of load hour for the first three months of 2023 is 32.8 and for the last 9 months only 0.02 hours.

Figure 6 - LOLE and EENS between 2023 and 2033 in the base scenario



During the years 2024-2029 the LOLE and EENS values are low, and there are no significant adequacy issues. Low values after the first three months of 2023 indicate the importance of Olkiluoto 3 for the resource adequacy in Finland. In 2026 additional transmission capacity between Sweden and Finland can be seen further lowering the LOLE value by 1.1 hours from 2025 and making the resource adequacy even more sufficient.

After 2030 LOLE and EENS values start increasing again. Around 2030 industrial electrification is expected to increase as well as the share of renewables in the electricity

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[30] https://valtioneuvosto.fi/paatokset/paatos?decisionId=0900908f807a154a

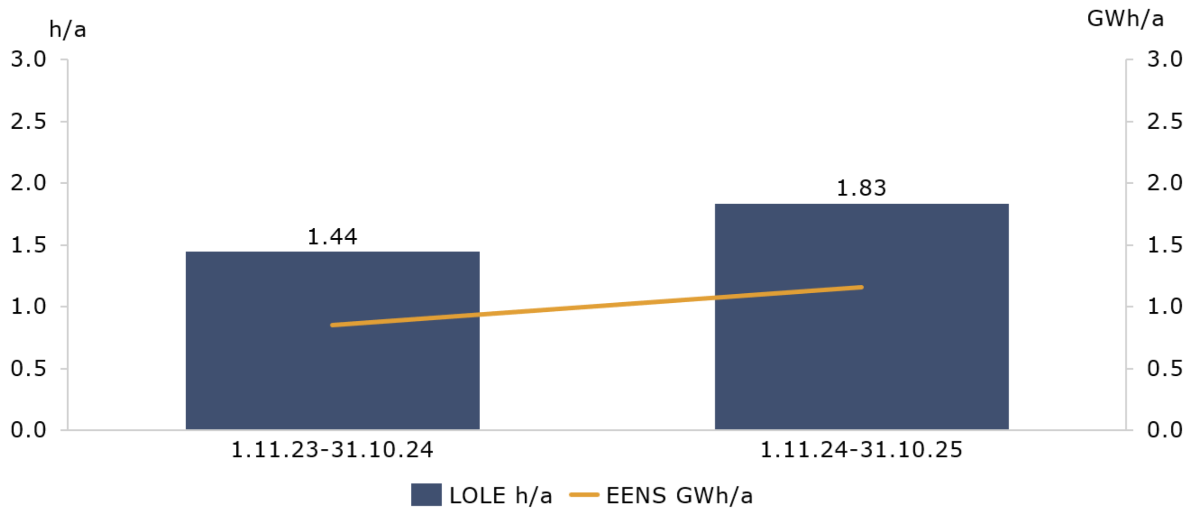
system. Increased demand combined with increasingly variable electricity production impacts resource adequacy negatively.

Table 5 - LOLE and EENS values between 2023 and 2033 in the base scenario

	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033
LOLE h/a	32.9	1.5	1.9	0.8	0.9	1.0	1.5	6.6	14.7	19.3	22.4
EENS GWh/a	32.3	0.9	1.2	0.6	0.6	0.7	1.0	6.3	15.4	21.3	25.7

The impact of Olkiluoto 3 in the 2023 results is very visible when examining the LOLE and EENS values for the reserve periods of 1.11.2023-31.10.2024 and 1.11.2024-31.10.2025. The LOLE hours are presented in Figure and they are well below maximum values set by the Finnish government. There are no adequacy issues in the Finnish electricity system in the base scenario.

Figure 7 - LOLE and EENS values for 23-24 and 24-25 reserve periods in the base scenario



5.2 Sensitivity analysis 1

In the first sensitivity, Olkiluoto 3 has a 10% outage rate during 2023-2025. As depicted in the base scenario 2023 results for LOLE and EENS, the impact of Olkiluoto 3 on the resource adequacy of the Finnish electricity system is significant and further analysis on the availability of the plant deemed necessary.

Figure and Table 6 present the resource adequacy indicators for Sensitivity 1 scenario modelling. The LOLE values are 0.7 hours higher for the 2023-2024 reserve period and 0.9 hours higher for the 2024-2025 reserve period when compared to the base scenario. Similarly to the base scenario, most of the LOLE hours occur during the first two months of each year. January and February are generally the tightest months in the Finnish electricity system because of the cold outdoor temperatures and thus, the heating demand being higher. In line with the base scenario, LOLE and EENS values are higher in 2025 than in 2024, indicating more potential resource adequacy issues during the second reserve period.

Figure 8 - LOLE and EENS values for 2023-2024 and 2024-2025 reserve periods in sensitivity 1

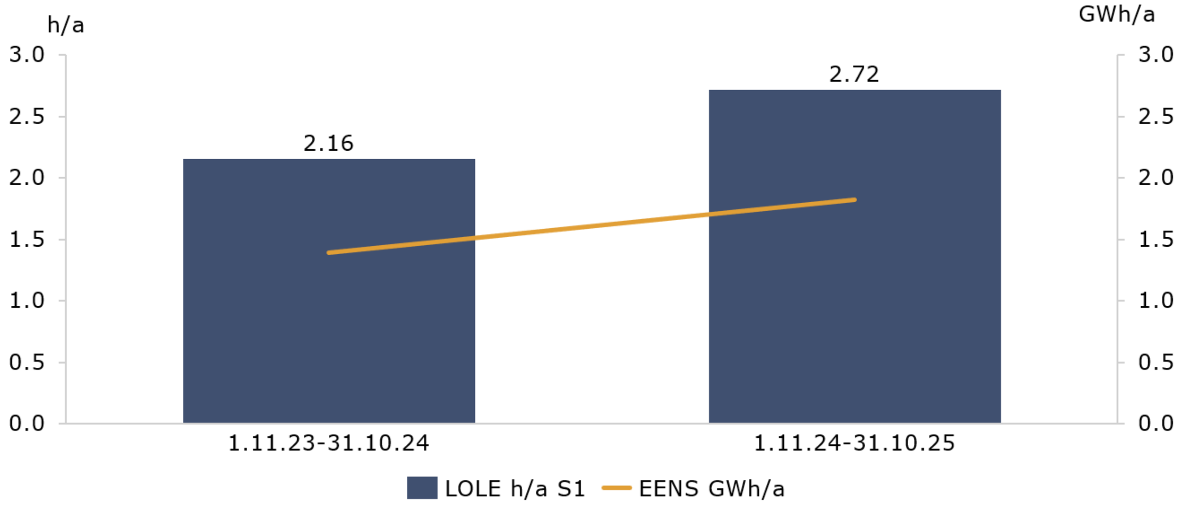


Table 6 – LOLE and EENS values for 2023-2024 and 2024-2025 reserve periods in sensitivity 1

	1.11.2023 - 31.10.2024	1.11.2024 - 31.10.2025
LOLE h/a	2.16	2.72
EENS GWh/a	1.39	1.82

5.3 Sensitivity analysis 2

In the second sensitivity, Olkiluoto 3 is not producing electricity at all during 2023-2025. While Olkiluoto 3 is expected to begin full commercial production on 17.4.2023, there have been significant delays to the timeline during the whole project as well as during the first months of 2023. Because of the importance of the power plant for the Finnish electricity system, it is necessary to observe what the worst-case scenario is in terms of resource adequacy if the plant is not in operation.

Figure presents the LOLE and EENS values as a result of the sensitivity 2 scenario modelling. Both values are significantly higher compared to the base and sensitivity 2 scenarios. If Olkiluoto 3 is not in full production, the SE1-FI interconnection capacity is 1500MW compared to 1200MW when the plant is in full production. This makes the resource adequacy slightly better even when the power plant is not producing electricity, but not sufficient enough to cover the resource shortfall.

In line with the base and sensitivity 1 scenarios, the LOLE and EENS values are higher during the 2024-2025 reserve period, indicating more resource adequacy issues compared to the 2023-2024 reserve period.

Figure 9 - LOLE and EENS values for 2023-2024 and 2024-2025 reserve periods in sensitivity 2

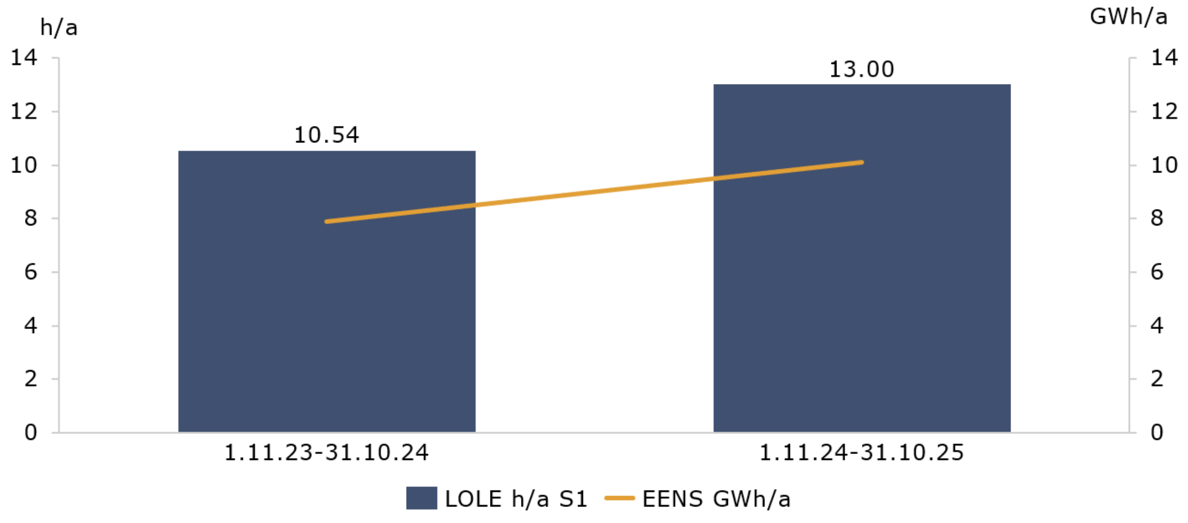


Table 7 - LOLE and EENS values for 2023-2024 and 2024-2025 reserve periods in sensitivity 2

	1.11.2023 - 31.10.2024	1.11.2024 - 31.10.2025
LOLE h/a	10.54	13.00
EENS GWh/a	7.88	10.12

5.4 Reserve capacity for sensitivity 1

Even though the base scenario does not have resource adequacy issues, sensitivity 1 scenario can be seen as possible scenario for 2023-2025. Because of the relatively high likelihood of Olkiluoto 3 having higher outage rate during the first few years of operation, it is deemed necessary to evaluate the adequate reserve capacity in sensitivity 1 scenario. Thus, the modelling of the reserve capacities is done only for the sensitivity 1 scenario.

The need for the strategic reserve capacity is done based on the Finnish government set reliability standard of 2.1 hours per year[31]. Based on the CONE value analysis and update results, the Finnish Energy Authority has evaluated that there is no need to change the current reliability standard. For the reserve capacity analysis, a gas turbine has been selected as the reserve power plant type and three different reserve capacities, 50MW, 100MW, and 150MW have been studied.

5.4.1 *100MW reserve capacity*

A 100MW gas turbine has been added as a reserve capacity and modelled to the system. The LOLE and EENS values are presented in Figure . The reserve capacity is slightly higher than necessary in for the 2023-2024 reserve period and slightly less than necessary for the 2024-2025 reserve period in terms of the national LOLE threshold of 2.1 hours.

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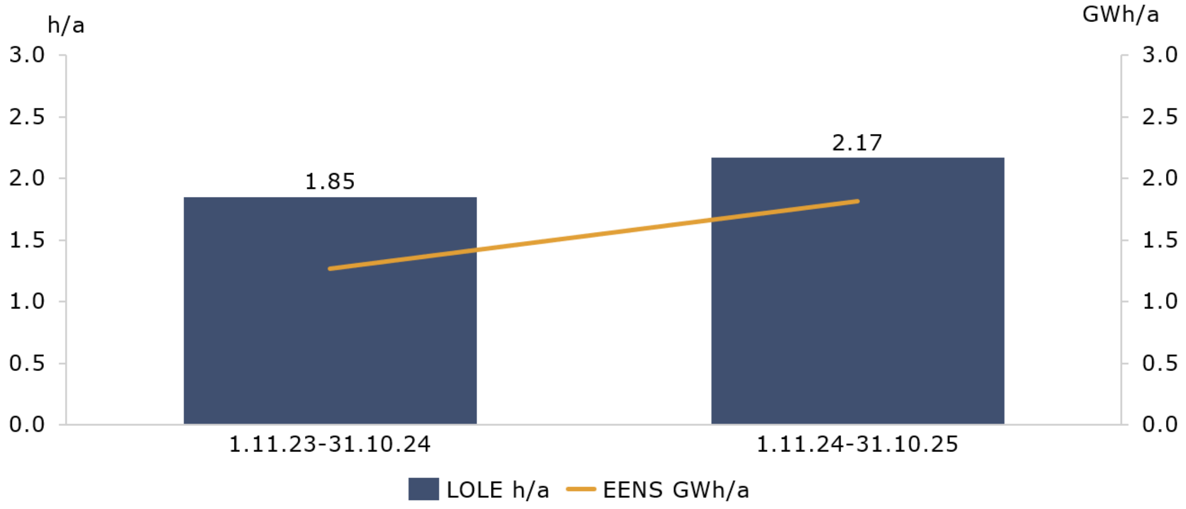
[31] https://valtioneuvosto.fi/paatokset/paatos?decisionId=0900908f807a154a

Figure 10 - LOLE and EENS values for 2023-2024 and 2024-2025 reserve periods with 100MW reserve capacity in sensitivity 1

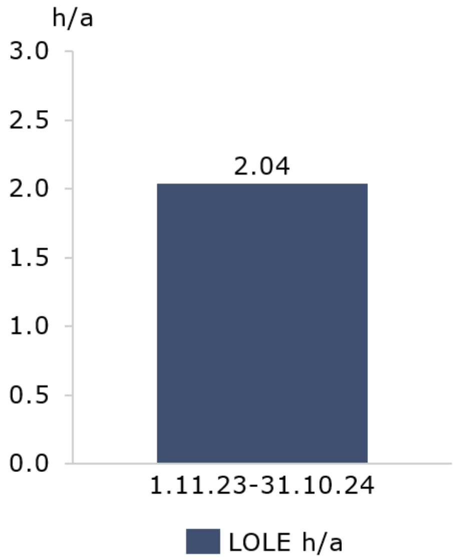


5.4.2 *50 MW reserve capacity*

Because the 100MW reserve capacity is seen as too high for the 2023-2024 reserve period, 50MW reserve capacity is studied. The 50MW reserve capacity is not modelled for the 2024-2025 reserve period, as it is known to be not sufficient to fill resource adequacy for the period based on the results shown in Figure .

Figure presents the LOLE value for the 2023-2024 reserve period in sensitivity 1 scenario with 50MW reserve capacity. The additional capacity is sufficient to fulfil the national reliability standard in terms of the LOLE by being 0.06 hours lower than the 2.1 hours limit. The EENS value for the reserve period with the 50MW reserve capacity is 1.41 GWh/a.

Figure 11 - LOLE and EENS values for 2023-2024 reserve period with 50MW reserve capacity in sensitivity 1

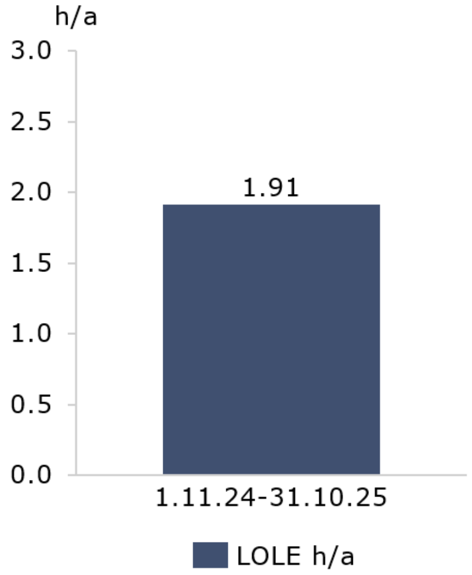


5.4.3 150MW reserve capacity

As the 100MW reserve capacity is not sufficient for the 2024-2025 reserve period, the 150MW capacity was modelled. The 150MW capacity was not modelled for the 2023-2024 period, because the 100MW was already sufficient to fulfil the reliability standard in terms of LOLE hours.

Figure shows the LOLE value with 150MW reserve capacity in sensitivity 1 for the 2024-2025 reserve period. The LOLE value is 0.2 hours lower than the national threshold of 2.1 hours and the modelled capacity is sufficient to fulfil the reliability standard. The EENS value for the period with 150MW reserve capacity is 1.65 GWh/a.

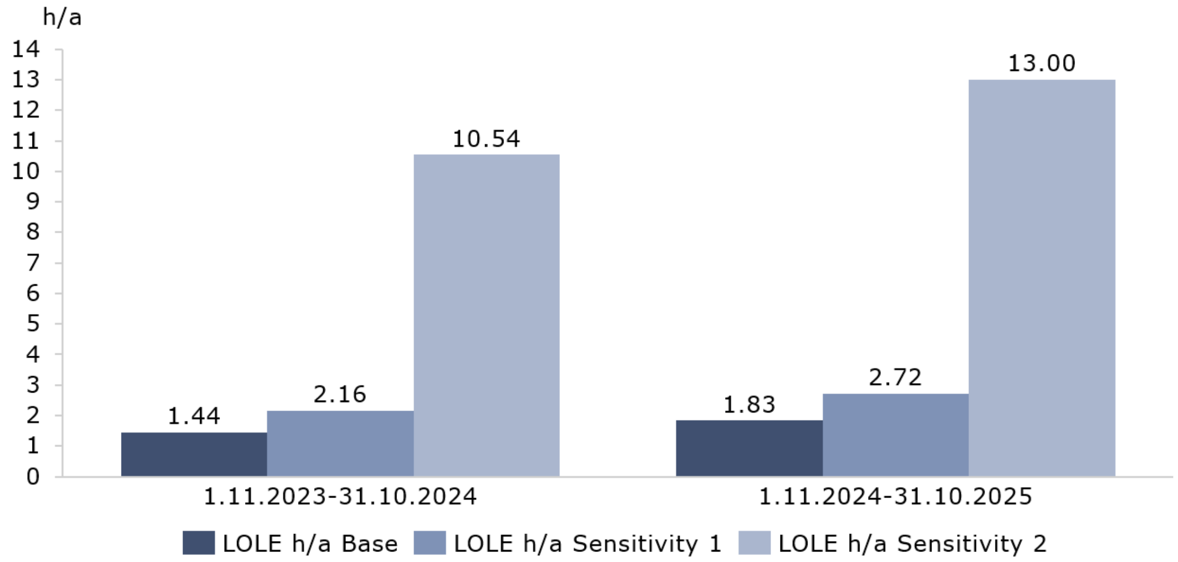
Figure 12 - LOLE and EENS values for 2024-2025 reserve period with 150MW reserve capacity in sensitivity 1



6. CONCLUSIONS

The results show that there are resource adequacy issues during many of the years within the studied timeframe. The modelled results show that the loss of load expected hours occur especially during cold months, as temperature has a major impact on the electricity demand in Finland. While the base scenario does not show loss of load expected hours that are above the national threshold occurring after 2023 until 2030, the sensitivity analysis for 2023-2025 implicate that there may be resource adequacy issues during 2023-2025. Sufficient resource adequacy is highly dependent on Olkiluoto 3. Figure shows the modelled LOLE and EENS results for all three scenarios.

Figure 13 - LOLE and EENS values for 2023-2024 and 2024-2025 reserve periods in all modelled scenarios



In the base scenario, there are no adequacy issues during the reserve periods. In the results presented in Figure , there was 33 LOLE hours for 2023, although almost all occurred during the first months of the year when Olkiluoto 3 is not in operation. The results show that challenges with resource adequacy start to increase after 2030 as industrial electrification and renewables share in the electricity mix increase. Increased demand combined with variable electricity production create electricity system that is extremely tight during some hours, creating the risk for loss of load hours and high amount of electricity not served during those hours.

In the sensitivity analysis 1 scenario, LOLE values are slightly higher compared to the base scenario, and higher than the national reliability standard. In sensitivity 2 scenario where Olkiluoto 3 is not in use at all, LOLE values are significantly higher than in either of the other scenarios. These results further highlight the importance of the nuclear power plant for the national resource adequacy.

ENTSO-E recently published a Europe wide resource adequacy assessment study, including an assessment for the Finnish resource adequacy for the year 2025[32]. Based on ENTSO-E modelling, Finland has LOLE of 3.5 hours in 2025, which slightly differs from the results of this study. The LOLE values found in this study are 1.9 hours in the base scenario and 2.8

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[32] https://www.entsoe.eu/outlooks/eraa/2022/

hours in the sensitivity 1 scenario. AFRY has found several factors contributing to this difference.

ENTSO-E has

- assumed a 3% outage rate for Finnish nuclear power, compared to AFRY 2% assumption in base scenario;
- modelled 1982-2016 weather years, which includes more extreme years compared to the AFRY 1999-2018 weather years;
- slightly higher demand than AFRY has assumed;
- 11.2% average for thermal biomass capacity forced outages compared to AFRY 7.5%.

It is found in this study, through the results of all three modelled scenarios, that the single most important factor for the Finnish national resource adequacy in short-term is the availability of Olkiluoto 3 nuclear power plant. Especially sensitivity 2 scenario results show that there could be extremely tight hours for the resource adequacy if the power plant is not in production during 2023-2025. If Olkiluoto 3 is in operation, but having high unpredictable unavailability rate during 2023-2025, which could be a plausible scenario, the LOLE and EENS values are still above the national reliability standard. If sensitivity 1 scenario realizes, 50MW of reserve capacity is needed for the 2023-2024 reserve period and slightly less than 150MW reserve capacity needed for the 2024-2025 reserve period.

ANNEX

Annex 1 – Unpredictable unavailability assumptions

Table 8 – Generation and interconnector unpredictable unavailability assumptions in base scenario

Generation type / Interconnector	Unpredictable unavailability	Average duration of unavailability
Hydropower	7.50 %	1 day
Nuclear power	2 %	7 days
CHP (biomass)	7.50 %	1 day
CHP (coal)	10 %	1 day
Gas turbines	5 %	1 day
SE1-FI	0.05 %	7 days
SE3-FI	3 %	7 days
EE-FI	3 %	7 days
NO-FI	3.50 %	7 days

Annex 2 – Base scenario generation and transmission capacity

Table 9 - Generation capacities in base scenario, MW

	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033
Battery	120	120	121	121	121	121	121	121	121	121	121
Solar PV	695	895	1195	1356	1517	1678	1839	2400	2560	2720	2880
Wind power	5656	7066	8264	8400	8537	8673	8810	9166	9696	10226	10756
CHP and condencing power	9342	8883	8494	8242	8178	8177	8122	7630	7391	7192	7083
Nuclear power	4380	4380	4380	4380	4380	4380	4380	4380	4380	4380	4380
Hydropower	3132	3132	3132	3132	3132	3132	3132	3132	3132	3132	3132

Table 10 - Interconnector capacity in base scenario, MW

	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033
EST-FI	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
SE-FI	2400	2400	2400	3200	3200	3200	3200	3200	3200	3200	3200
NO-FI					150	150	150	150	150	150	150

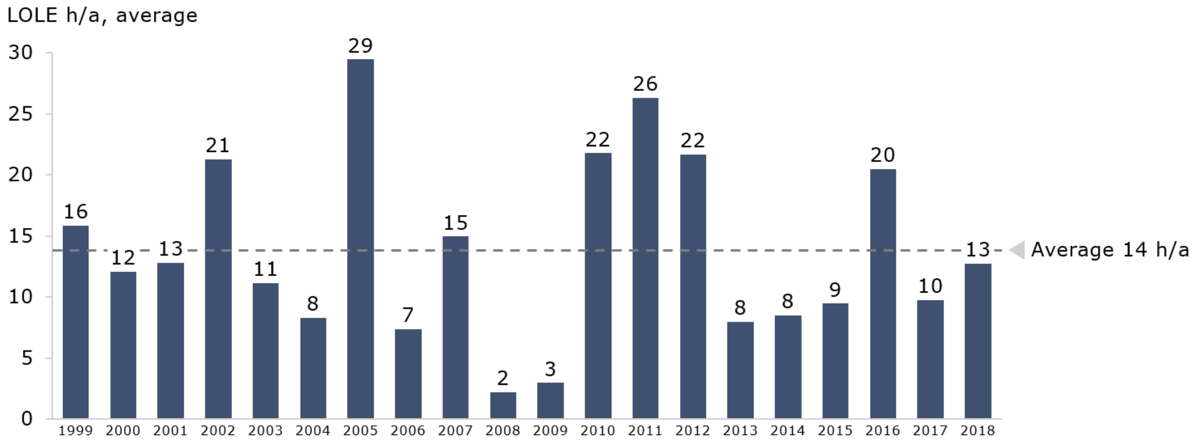
Annex 3 – Reliability of results

Table 11 - Number of Monte Carlo simulations

Scenario	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033
Base	252	252	252	252	252	252	252	252	252	252	252
Sensitivity 1	252	252	252	252	252	252	252	252	252	252	252
Sensitivity 2	252	252	252	252	252	252	252	252	252	252	252

Annex 4 – Weather year impact in base scenario

Figure 14 - Weather year impact as an average for all modelled years in base scenario



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