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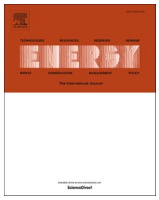

Capacity adequacy in the electrifying Nordic and Baltic region

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ABSTRACT

The energy systems in northern Europe are rapidly electrifying due to increasing electric vehicle (EV) deployment, electrifying industrial processes, and use of electricity in heating. The Nordic and Baltic electricity markets are facing new challenges stemming from higher shares of variable renewable energy, mainly from wind and solar, and the resulting volatility of electricity prices. Furthermore, multiple energy security threats have been posed on energy infrastructure of the Baltic Sea during the past few years. This contribution analyses the expected capacity adequacy in northern European power systems in early 2030s using a multi-regional electricity market model. The study utilizes 35 years of weather data and the current prospects for generation capacity and demand. Electrification of transport is analyzed by modeling two EV deployment pathways with different shares of flexible charging for each modelled area, and hydrogen production is assumed in northern Sweden and Finland. Resilience of the power system is tested by simulating outages of the two largest nuclear power plants in the region located in Finland and Sweden, and one of the two interconnectors between Finland and Estonia. The results show that power adequacy challenges will emerge particularly with increasing inflexible demand from electric vehicles. Finland has the most severe capacity adequacy challenges of all modelled areas with 2.6 - 9.1 h of annual scarcity, on average, depending on EV flexibility, and additional outages would manifold the problems. The results imply that the estimated generation capacity will not be sufficient to meet the increasing demand by 2030.

1. Introduction

European Union's (EU) targets to reach climate neutrality by 2050 and to become independent from Russian energy are pushing an accelerated decarbonization of the European power systems [1], [2]. The climate neutrality goal defined by the European Green Deal, including a sub-target of at least 50% emission reductions by 2030, is legally binding for all EU member states [1]. Low carbon electricity generation is already a prominent feature of the energy systems in the Nordic countries. Norway and northern Sweden are known for their significant hydro power resources, whereas wind power is abundant particularly in Denmark, northern Sweden, and Finland. Nuclear power generation in northern Europe is concentrated in Finland and central Sweden. Electricity generation in Estonia relies more on thermal power based on fossil fuels and biofuels, but weather-dependent generation from wind and solar photovoltaic (PV) is expected to increase in the near future in both the Nordic and the Baltic region. As electricity generation is becoming emission-free, the need to decarbonize end-use sectors is driving a rapid electrification of transport, industry, and heating. Electrification is a strong trend especially in the transport sector in Europe, as the share of electric vehicles (EV) of new car sales in EU-27 has quickly increased from 2.9% in 2019 to 21% in 2024 [3]. Electrification of transport is strongest in northern Europe, as Norway is currently leading the EV deployment in Europe with nearly all newly registered cars being either battery electric vehicles (BEV) or plug-in hybrid electric vehicles (PHEV), and Sweden, Iceland, Finland, and Denmark are closely following [4].

The heating sector in Finland, including both individual buildings and district heating (DH) systems, is also quickly electrifying. DH systems in Finland have relied on combined heat and power (CHP) production, but due to current electricity market conditions, CHP profitability is declining, which is leading to retirement of power plants. In 2024, 48% of district heating was produced with biomass, 6% with peat, 7% with natural gas, 9% with coal and oil, and 20% with electricity, heat pumps and waste heat [5]. Heat pumps and electric boilers are becoming more attractive technology solutions in DH [5] as the rapid increase in installed wind power capacity and abundant low-carbon electricity has lowered the electricity prices in Finland

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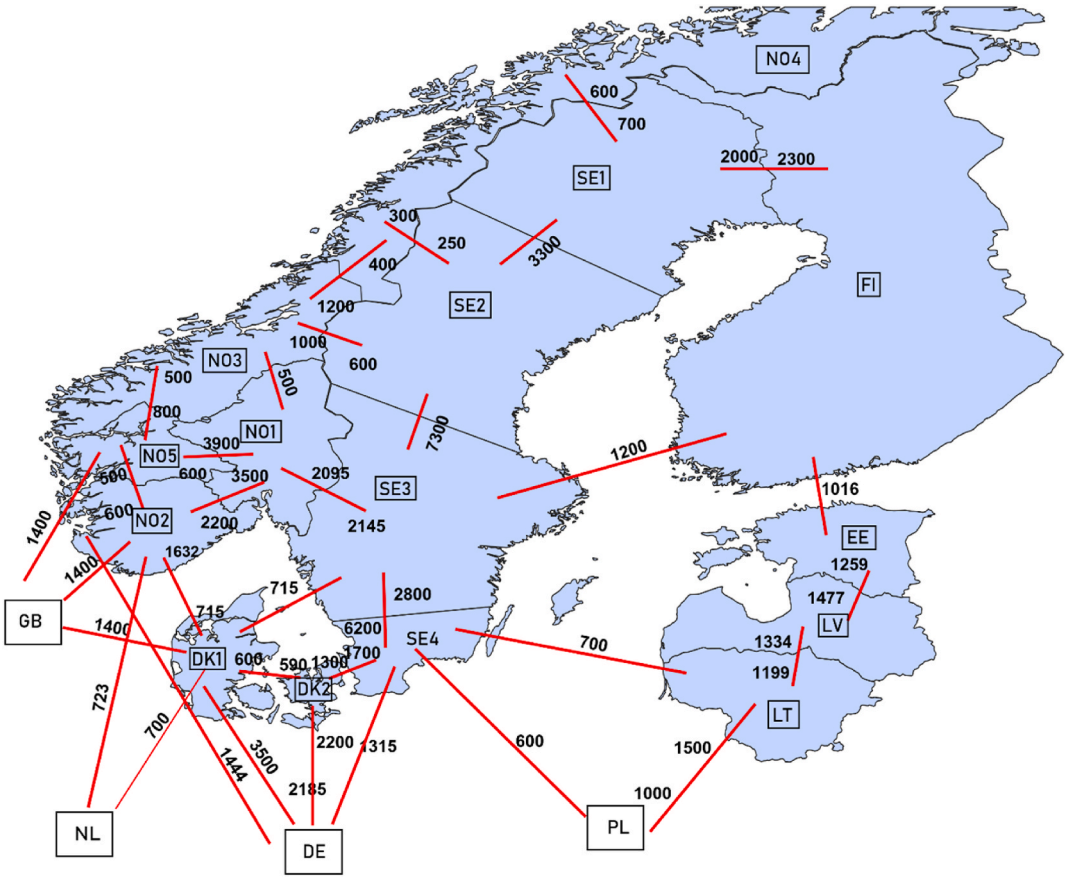

Fig. 1. Map of the modelled region and transmission connections assumed to be available 2030.

Table 1
Modelled power generation capacities and demand in 2030 in MW. Fossil category includes natural gas, oil, oil shale, and coal power plants [15], [40], [47].

Country	FI	EE	LV	LT	SE	NO	DK
Wind, Onshore	13000	1000	1760	3780	22199	5681	5600
Wind, Offshore	-	-	-	630	540	-	4080
PV	3000	1570	1450	6700	8637	4000	14267
Hydro (PHS)	3200	-	1400	110 (900)	13080	28900	-
CHP	4150	270	1160	500	4428	-	4377
Nuclear	4554	-	-	-	7008	-	-
Fossil	-	1655	1026	445	568	147	787
DSM	1689	109	157	274	2677	2652	889
Demand (TWh/a)	115	9	11	18	162	170	55

Table 2
Fuel and EU ETS prices in 2030 in €/MWh.

Fuel	Price [€/MWh]
Biomass	31
Coal	15
Natural gas	45
Natural gas (SE, FI)	50
Fossil oil	70
Oil shale	8
Peat	16
Uranium	3
Waste and other	−5
CO_2	100 [€/t]

Table 3
The number of EVs in 2024 and in 2030 in each country in both Low and High deployment scenarios.

Area	2024	2030, Low deployment scenario	2030, High deployment scenario
FI	290,000	580,000	925,000
EE	6500	13,000	30,000
LV	7900	15,800	30,000
LT	26,000	52,000	230,000
DK	548,000	1,096,000	1,600,000
NO	789,000	1,500,000	1,500,000
SE	690,000	1,380,000	3,000,000

Table 4
The assumed EV properties.

Battery capacity	70	kWh
Max charge rate	11	kW
Charging efficiency	70	%
Efficiency	0.221	kWh/km
Daily distance	50	km
Initial SoC	40	%
Min SoC	10	%
Max SoC	80	%

during the past couple of years [6]. In 2024, Finland had the third lowest electricity market prices in Europe, and the number of negative or zero price hours has steeply increased [6]. For a long time, low electricity prices have been a defining feature of electricity markets in Sweden and Norway. The low prices are, however, threatening nuclear power profitability in Sweden, as 2.8 GW of nuclear capacity was decommissioned

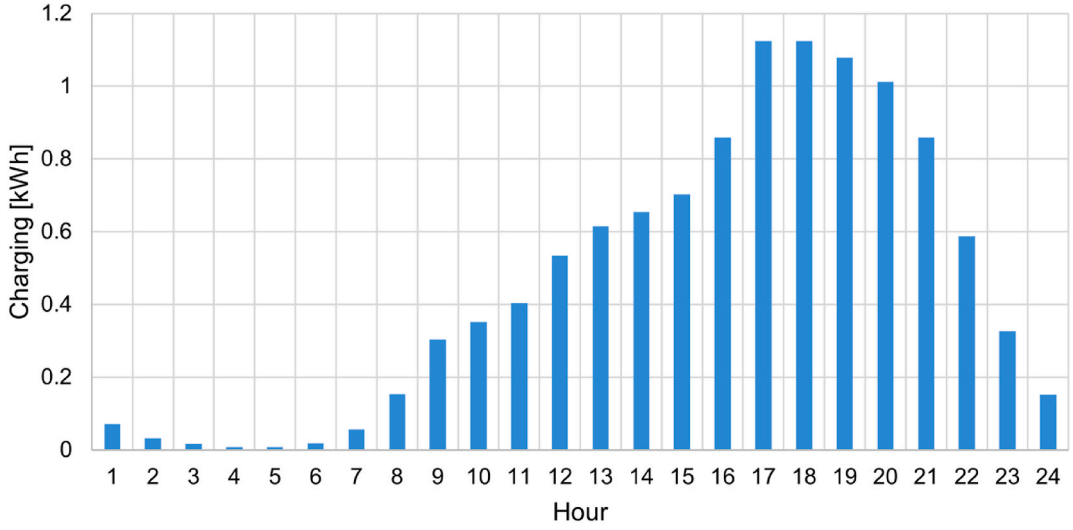

Fig. 2. The fixed daily charging profile of the "fixed" EVs for each day of the year.

Table 5
Simulated outage sub-scenarios.

Sub-scenario	Unavailable capacity	Outage months
Base case	-	-
OL3	1600	Nov, Dec, Jan, Feb
EL2	658	Jan, Feb
OL3+EL2	2258	Jan, Feb
O3	1400	Nov, Dec, Jan, Feb
OL3+O3	3000	Jan, Feb

*When OL3 is producing under 1000 MW, the import capacity from SE1 to FI is raised by 300 MW [64]. Abbreviations: OL3 = Olkiluoto 3 nuclear power plant, EL2 = Estlink 2 transmission cable, O3 = Oskarshamn 3 nuclear power plant.

between 2010 and 2020 due to adverse market conditions [7].

As the end-use sectors become electrified, the overall electricity demand is expected to grow considerably in the coming years. The use of fossil fuels in electricity production, mainly coal and natural gas, has been continuously decreasing during the past decade [8]. The use of coal in energy production in Finland ended already in 2025, four years before legal ban to take place in 2029 [9]. Coal-powered power plants that have ceased operations during the past couple of years include for example Hanasaari, Naantali, Salmisaari, and Martinlaakso power plants [10–13]. Phase-out of flexible thermal power plants together with increasing electricity consumption raise concerns about capacity adequacy during hours with low output from renewable energy sources (RES). For instance, the Finnish Energy Authority estimated that of the total installed generation capacity of 25 GW in Finland, only 11.8 GW was available for the winter period 2024-2025 during windless weather [14]. This capacity is not sufficient to meet the estimated winter peak load of 15 GW, making Finland dependent on electricity import from neighboring countries Sweden and Estonia during calm and cold days [14]. In a wider pan-European context, power system resources and adequacy risks due to electricity market developments in the near future are analyzed in the European Resource Adequacy Assessment (ERAA) by the European Network of Transmission System Operators for Electricity (ENTSO-E) [15]. One of the main findings of the assessment is that rising electricity demand together with decommissioning of thermal capacity due to economic unviability can lead to significant adequacy challenges in many European countries. In ENTSO-E Winter Outlook for 2024-2025 [16], Finland and Poland were identified as mainland countries with the highest risk for insufficient capacity during calm and cold weather and unexpected outages.

Energy security became a prominent issue in Europe during the energy crisis in 2022. The supply of energy products, including coal, oil,

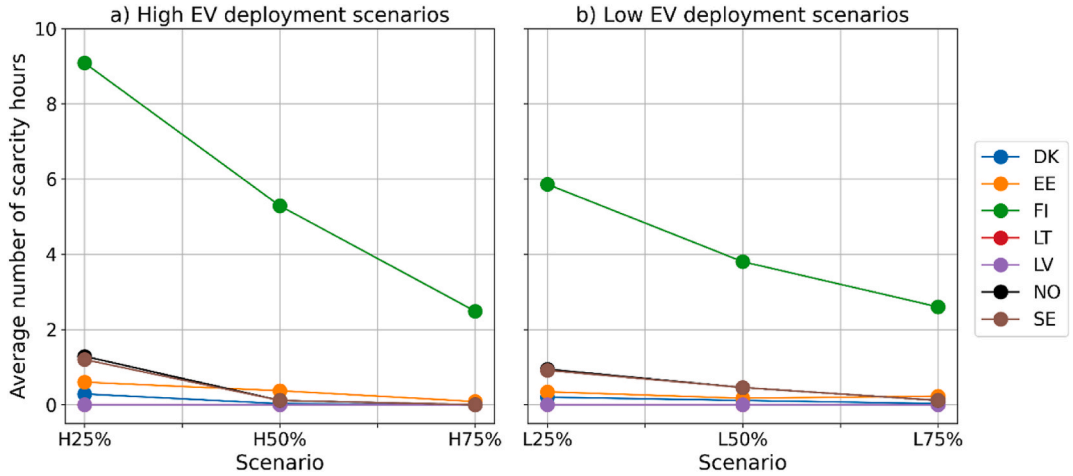

Fig. 3. The average number of scarcity hours in 2030 in modelled countries. The values are average values across all weather years in the Base case scenario in the main scenarios (H25%-L75%), in (a) High EV deployment scenarios and (b) Low EV deployment scenarios. The results for the last 24 h of the modelled horizon on 12/31/2030, for the final weather year 2016 are disregarded due to data time shift in hydro power modeling.

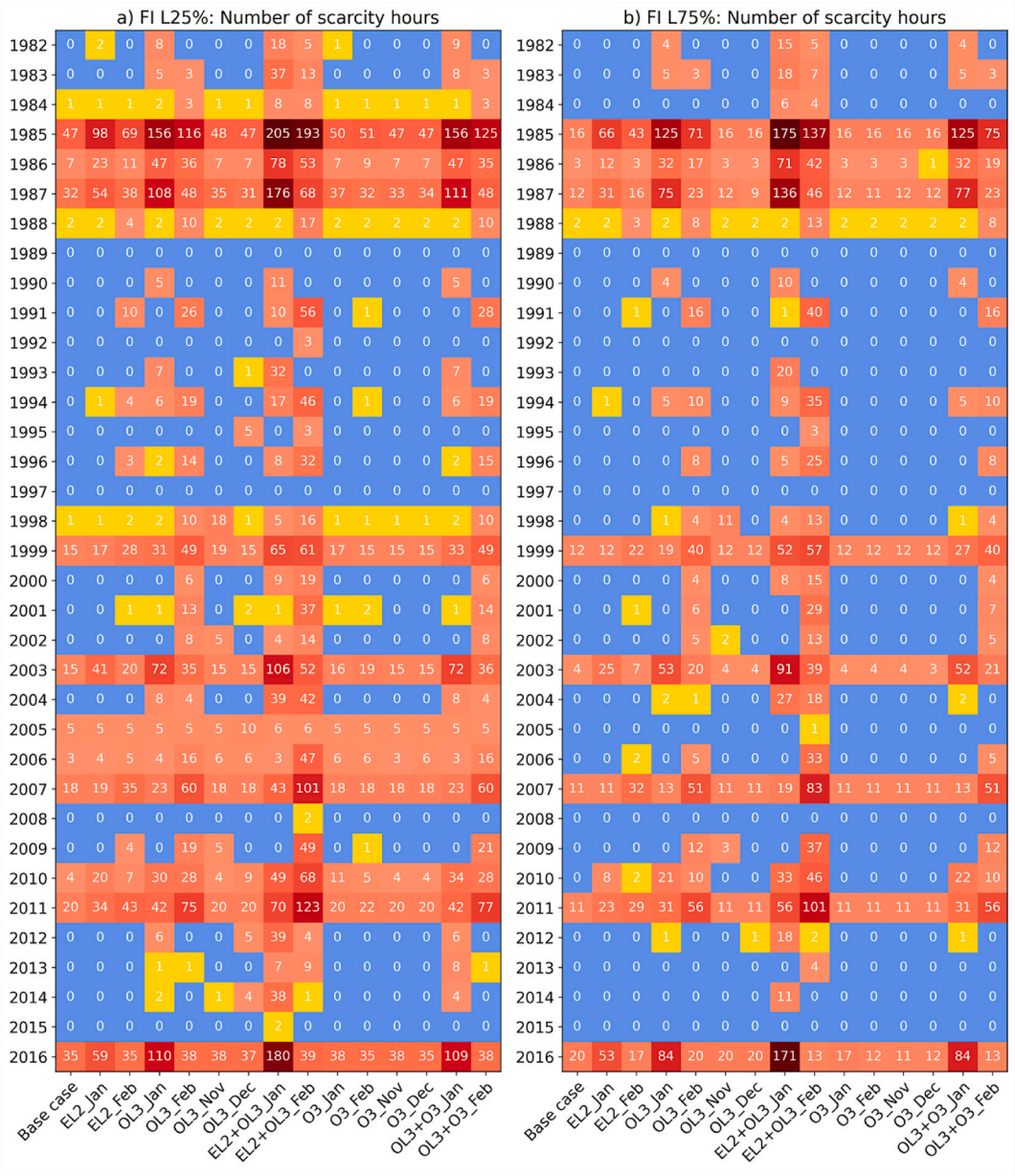

Fig. 4. Number of scarcity hours in Finland in (a) L25% scenario and (b) L75% scenario throughout all weather (y-axis) and outage scenarios (x-axis). The last 24 h of the modelled horizon on12/31/2030 for the final weather year 2016 are disregarded due to data time shift in hydro power modeling.

and natural gas, decreased abruptly in 2022 from Russia to the EU, leading to unprecedented surge of gas and electricity prices. The ending of oil and coal imports were a result of multiple EU sanctions targeted towards Russia, and as a response to the sanctions, Russian pipeline natural gas supply to Europe was widely suspended [17]. Electricity, natural gas, biomass and coal imports from Russia and Belarus to the Nordic and Baltic region were terminated in spring 2022 [18], [19]. Finland terminated electricity supply of 1300 MW (about 10% of Finland's winter peak demand) from St. Petersburg region in May 2022 [20]. The European Commission implemented the REPowerEU plan aiming at ending reliance on Russian energy imports [2].

Energy security in Northern Europe has been threatened by several energy infrastructure damages on the Baltic Sea in recent years. In October 2023, the natural gas pipeline between Finland and Estonia was damaged by a ship anchor and remained out of operation for half a year [18]. In January 2024, the larger of the two electricity transmission cables between Finland and Estonia, Estlink 2 with 650 MW capacity, disconnected from the power grid due to a technical fault [21]. The cable returned to operation in September but was damaged by a ship anchor in December 2024 and became again unusable for approximately six months [22]. The disruption in the Estlink 2 transmission connection reduced electricity supply security during cold and calm winter days [23].

Nuclear power plants have also suffered from unexpected outages and extended maintenances in Finland and Sweden during the past years. In spring 2024, the annual maintenance of one of the largest nuclear power units in Europe, Finnish Olkiluoto 3 with a capacity of 1600 MW, was prolonged from the planned 37 days to 74 days due to various technical issues [24]. Since March 2025, the largest nuclear unit in Sweden, 1450 MW Oskarshamn 3, has been out of operation due to an extended maintenance for over half a year [25]. The outage period overlapped with the annual maintenance of Ringhals nuclear power plant, weakening nuclear power supply in Sweden during the summer [26]. Outages of major nuclear power units in a certain price area impact also the power supply and electricity prices in the neighboring areas. For example, a sudden shutdown of Forsmark 1 and 2 in April 2023 doubled

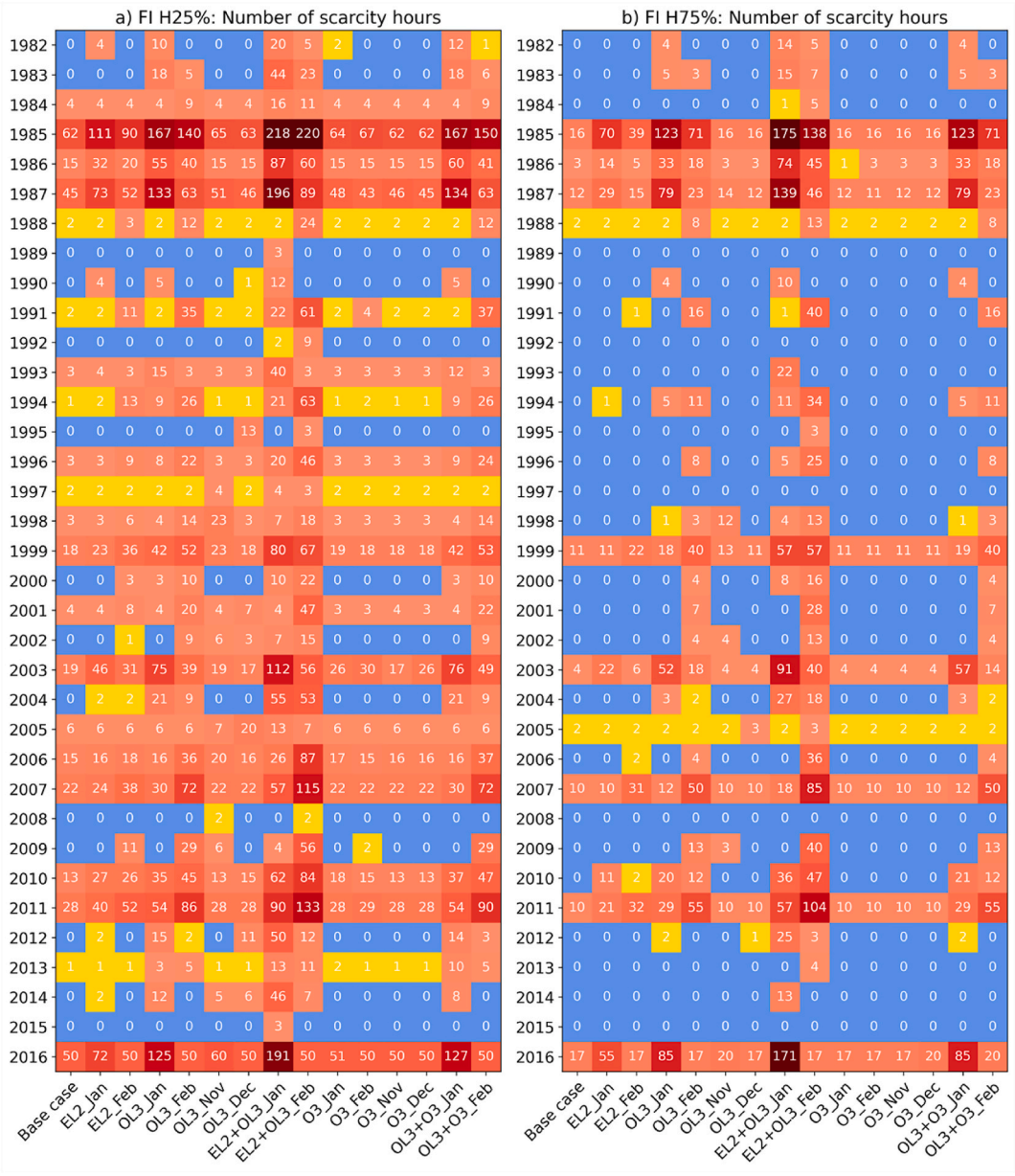

Fig. 5. Number of scarcity hours in Finland in (a) H25% scenario and (b) H75% scenario throughout all weather years (y-axis) and outage scenarios (x-axis), excluding 12/31/2030 of weather year 2016.

electricity spot prices in Finland [27].

Outages in other power generating facilities together with high electricity demand can have severe consequences on the power system. This was seen in Finland in early January 2024, when the electricity spot price reached nearly 2000 €/MWh. The price hike was a result of an extraordinarily cold week and consequent high electricity demand and simultaneous outages of multiple power plants, as a total of 1500 MW of conventional generation capacity was unavailable [28]. Study [29] assessed a scenario where Estlink 2 would have been out of use during the same week and found that the situation would have been exacerbated and the system would have been extremely vulnerable to any other disruptions in power plants or interconnections.

1.1. *Review of previous studies*

Energy security and different energy system decarbonization scenarios have been widely studied in academic literature. Muhammad et al. [30] assessed the impacts of energy security on EU consumer electricity prices over the range of 2007 to 2022. They found that although diversifying energy sources and decreasing dependency on foreign energy suppliers enhances resilience towards geopolitical shocks, the investments in new technologies and infrastructure may increase electricity prices, therefore creating a need to balance between affordability and energy security. Mišik [31] suggests that although the pressure for the clean energy transition in the EU increased after the energy crisis, fossil fuels will still be needed in the transition period until 2050 to balance the variable RES supply and demand.

In an editorial piece, Stavrakas [32] summarizes a variety of research articles based on energy system and integrated assessment models regarding the clean transition of European energy systems and finds that the need for climate neutrality and the phase out of fossil fuels is obvious but the pathways to reach these goals remain unclear. Zappa et al. [33] modelled a fully renewable European power system by 2050 with seven scenarios based on 37 weather years using PLEXOS energy system model. They found that a 100% RES-based power system without other low-carbon technologies, like nuclear power, could provide the same

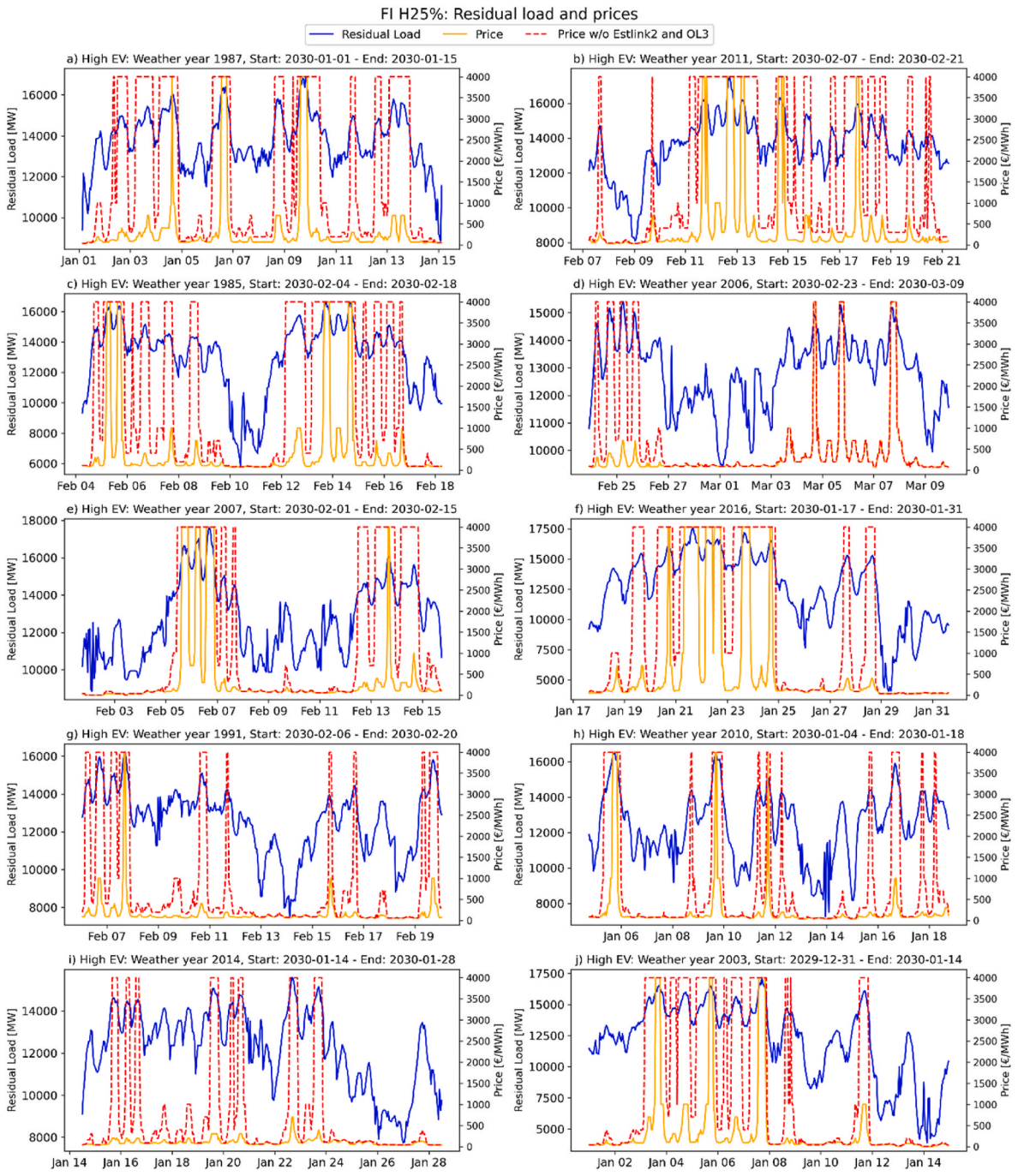

Fig. 6. The residual loads for Finland H25% scenario in 2030 in the top 10 worst Dunkelflaute events across all weather years, defined as the highest sum of residual load over a two-week period from (a) the highest to (j) the 10th highest period. The blue line is the residual load in the Base case scenario, the yellow line is the Base case scenario price, and the dashed red line represents the price in the EL2+OL3 scenario in either January or February.

system adequacy as currently, however, requiring significant expansion of generation and cross-border transmission capacities and substantial flexible firm capacity to balance the intermittent renewable generation. Mathisen et al. [34] modelled decarbonization scenarios in the Nordic countries until 2050 using five different energy system models and found that electricity export from the Nordic region can support the rest of Europe to reach energy independence from Russia, leading to increased investments in wind power in the Nordic countries. Both [33] and [34] highlight the need for generation and transmission capacity expansion to achieve a fully renewable energy system.

Much of the academic literature also focuses on flexibility and demand-side solutions in power system decarbonization. Kirkerud et al. [35] analyzed the economic potential of demand response (DR) in Northern Europe using BALMOREL energy system model and found that household space and water heating in the Nordic countries hold great technical and economical DR potential. Söder et al. [36] assessed the technical flexible capacity potential in different end-use sectors in the Nordic and Baltic countries by reviewing various studies. They recognized the largest DR potentials in Sweden, Finland and Norway due to their energy-intensive industry and the high share of electrical heating. In Finland, the technical DR potential was estimated to be 4500 MW, or 30% of the peak demand, consisting of flexible loads on service sector, like grocery stores and warehouses, industrial processes, and electrical heating and appliance loads in households [36]. However, evidence

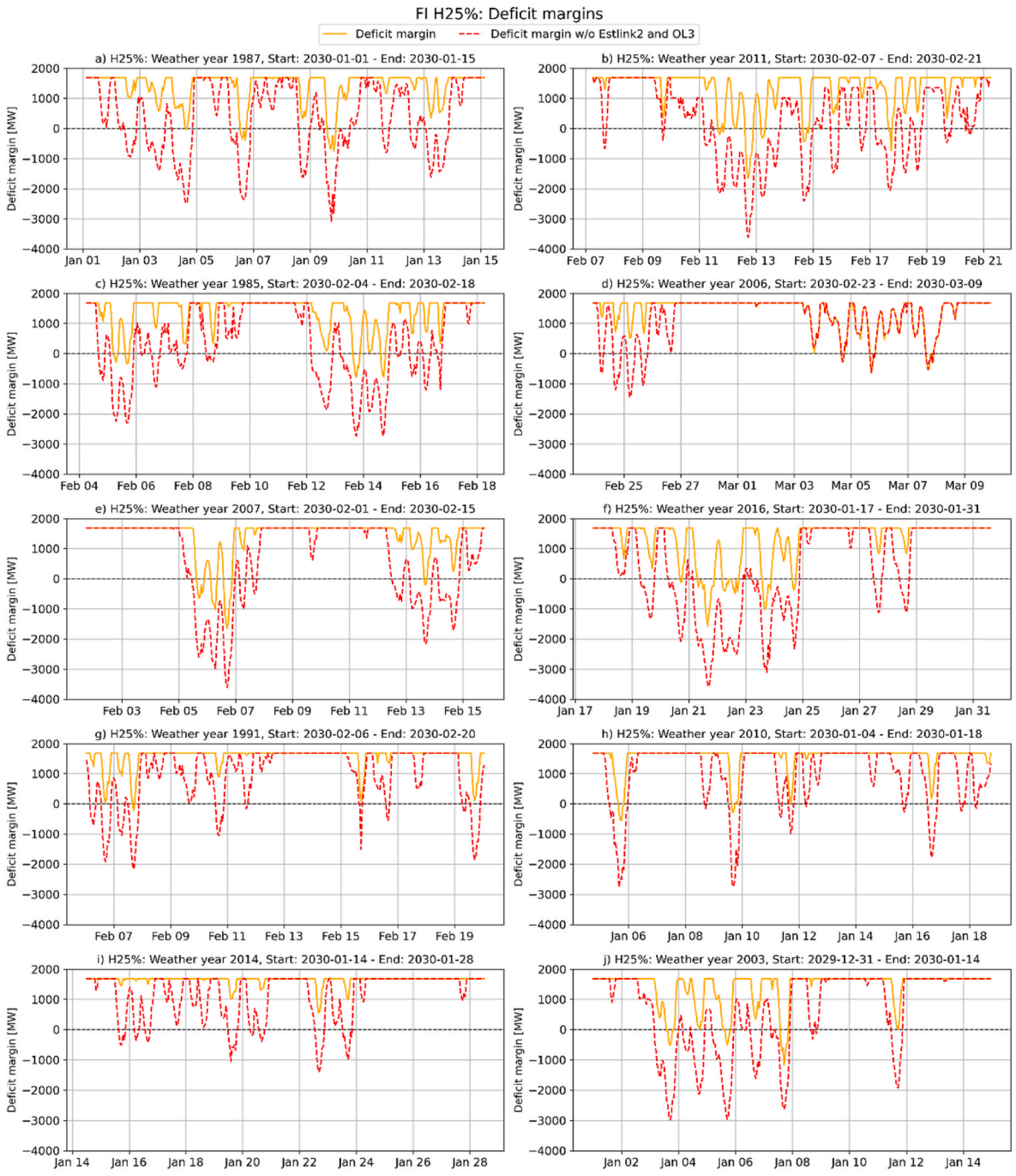

Fig. 7. The deficit margins for Finland H25% scenario in 2030 in the top 10 worst Dunkelflaute events across all weather years, defined as the highest sum of residual load over a two-week period from (a) the highest to(j) the 10th highest period. The yellow line represents the deficit margin in the Base case scenario, and the dashed red line is the deficit margin in the EL2+OL3 scenario in either January or February. Negative values represent the power deficit, i.e., the amount of load not met.

from recent two exceptional electricity market situations in 2023 and 2024 indicates that the realized amount of available flexible DR would be much lower even with extreme prices at least in the case of Finland. These situations – a record-low price of −500 €/MWh in November 2023 and a record-high price of nearly 2000 €/MWh in January 2024 – were analyzed in Ref. [29] and by Haakana et al. [37]. Both studies found that the amount of hourly DR was approximately 1000 MW in these situations, corresponding to nearly 10% of 15 GW peak demand. The realized DR originated mainly from small-scale consumers with spot-priced electricity contracts who reacted to the prices by shifting their electricity consumption during the price peaks [37].

Both [35] and [36] found that direct electrical space and water heating in households provide the largest potential for flexibility, however, neither of the studies included EVs in their DR assessment. Göke et al. [38] implemented a linear optimization model to research flexible electrification and its potential to reduce the need for thermal backup power plants and storage in a 100% renewable European energy system. They found that flexible demand from particularly electrolyzers, DH, and charging of electric vehicles can have considerable impacts on reducing the residual load, whereas flexible space and process heating has only a minor impact.

Kiviluoma et al. [39] assessed the flexibility potential, technologies, and challenges of electrifying end-use sectors including transport, heating, industry, and hydrogen and P2X. As Göke et al. [38], they

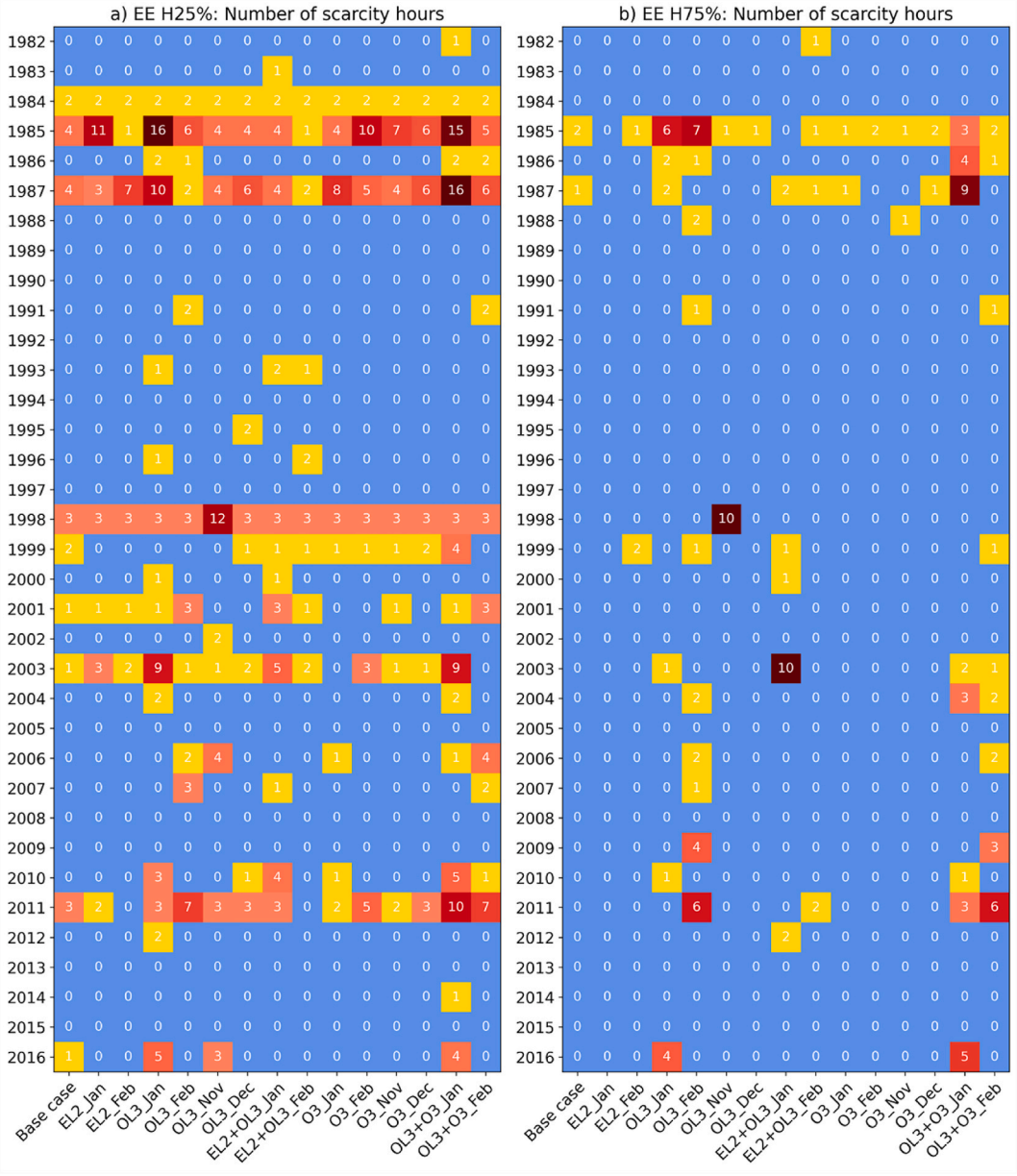

Fig. 8. The number of scarcity hours in Estonia in (a) H25% scenario and (b) H75% scenario throughout all weather years (y-axis) and outage scenarios (x-axis), excluding 12/31/2030 of weather year 2016.

suggest that direct electrification provides largest potential for flexibility, although indirect electrification can provide additional flexibility due to easier storage and better suitability in for example high-temperature industrial processes. The rapid deployment rate of passenger electric vehicles is acknowledged by Refs. [37] and [39] with a remark that without flexible charging, large EV fleets may create notable demand peaks. Kiviluoma et al. [39] also note that the monetary benefits for single consumers charging their electric vehicles are rather insignificant, not incentivizing sufficient flexibility. Göke et al. [38] did not implement EV discharging, so-called vehicle-to-grid (V2G) modeling, in their work due to the need for additional charging infrastructure, and Kiviluoma et al. [39] found that flexible discharging is less beneficial on the system level compared to flexible charging.

Many scientific articles focus on modeling the required future capacity expansion or estimating the flexibility potential of end-use sectors. However, market analyses modelling the future electricity markets at an hourly level regarding also the most challenging weather conditions are scarce. ENTSO-E ERAA [15] provides a probabilistic multi-region market analysis regarding adequacy risks in the near-future pan-European energy systems. The assessment shows that of northern European countries, power adequacy risks increase until 2035 at least in Finland and Sweden. ENTSO-E Ten-year network development plan (TYNDP) [40] assesses the long-term energy system development 10 to 30 years ahead mainly from the perspective of transmission infrastructure requirements [15]. TYNDP defines a stressful adequacy situation called Dunkelflaute as a cold two-week period with low wind and solar power production. The weather conditions during Dunkelflaute events are considered the most challenging regarding energy supply, and their impacts on generation adequacy are recently studied in academic literature. Li et al. [41] presented a climatological study on Dunkelflaute events in eleven countries around the Baltic Sea and found that these events of over one day are usually experienced during winter months in November, December, and January. Beck-Bang et al. [42] modelled energy systems in eleven European countries in 2035 with three different electricity mix scenarios, focusing on capacity adequacy on two-week Dunkelflaute periods. They found that adequacy issues are

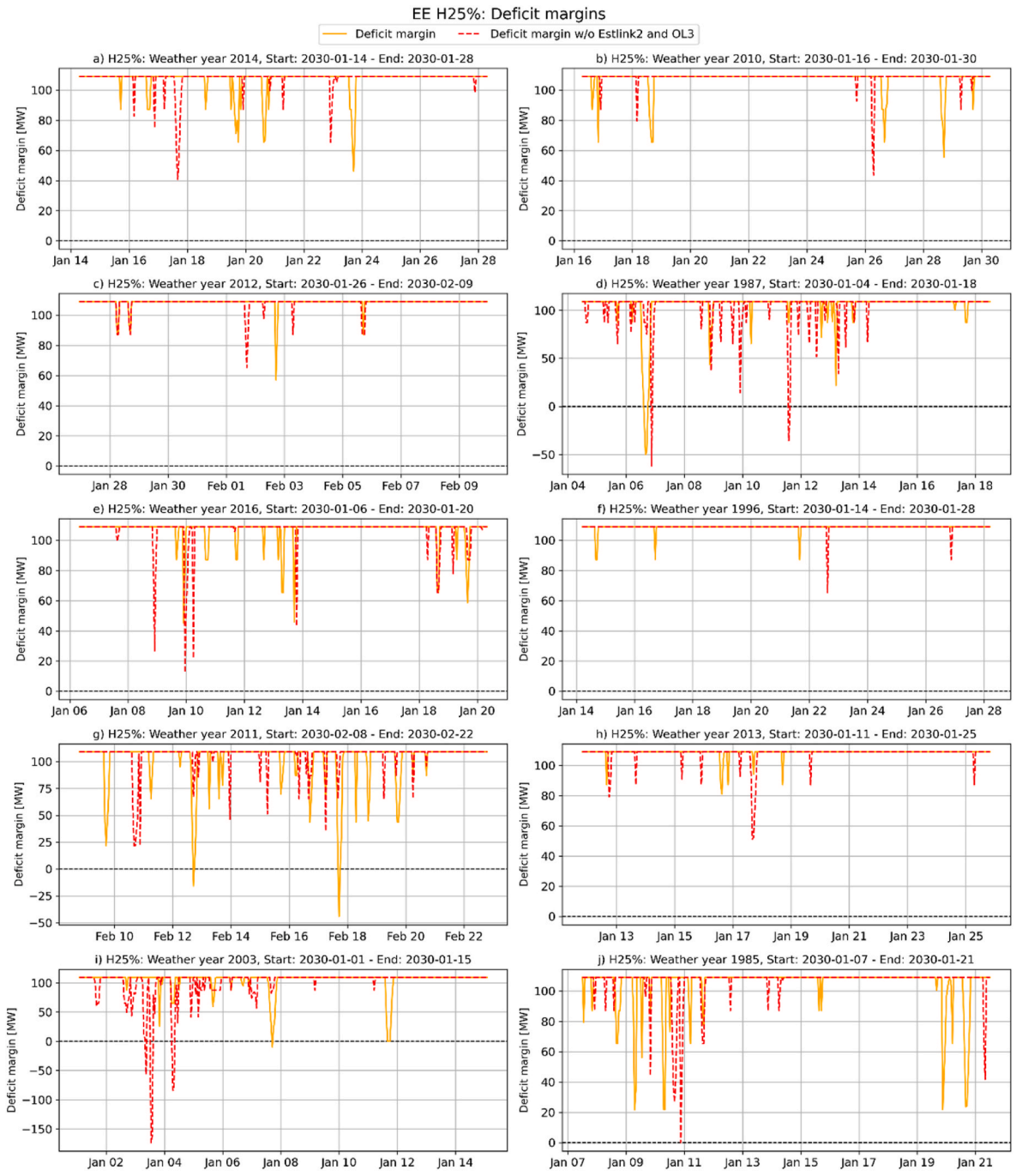

Fig. 9. The deficit margins for Estonia H25% scenario in 2030 in the top 10 worst Dunkelflaute events across all weather years, defined as the highest sum of residual load over a two-week period from (a) the highest to (j) the 10th highest period. Note the different scales on y-axis.

experienced during Dunkelflaute events in all examined countries as energy not served (ENS), depending on the generation capacity expansion and demand prospects in three modelled scenarios. The results highlight that the adequacy problems in 2035 will be more severe if only the current plans for generation capacity expansion are realized.

Furthermore, adequacy risks in Finland are explored in more detail by Jääskeläinen et al. [43] and Koivunen and Syri [44]. In Ref. [43], the Finnish power system was analyzed during a demand peak record in January 2016 by simulating forced outages of major interconnectors and power plants using EnergyPLAN energy system model. They found that although these outages are unlikely, they would have led to activation of frequency and peak power reserves and even rolling blackouts, depending on the scenario. In Ref. [44], the Nordic and Baltic power systems were modelled for years 2024 and 2030 using PLEXOS energy system model and utilizing 35 years of weather data. The main finding in Ref. [44] is that the severity and frequency of scarcity events, defined as periods of electricity supply not meeting demand, increase towards 2030 even with an assumption of unrealistically large wind and solar power expansion.

Other electricity market analyses and research on capacity adequacy in the near future with current market prospects in northern European region are lacking. Moreover, more research on the impacts of potential energy security threats, such as the realized outages of major power plants and interconnectors in the past few years, is needed.

This paper aims to fill this gap in research by providing a multi-regional analysis of northern European power systems with the

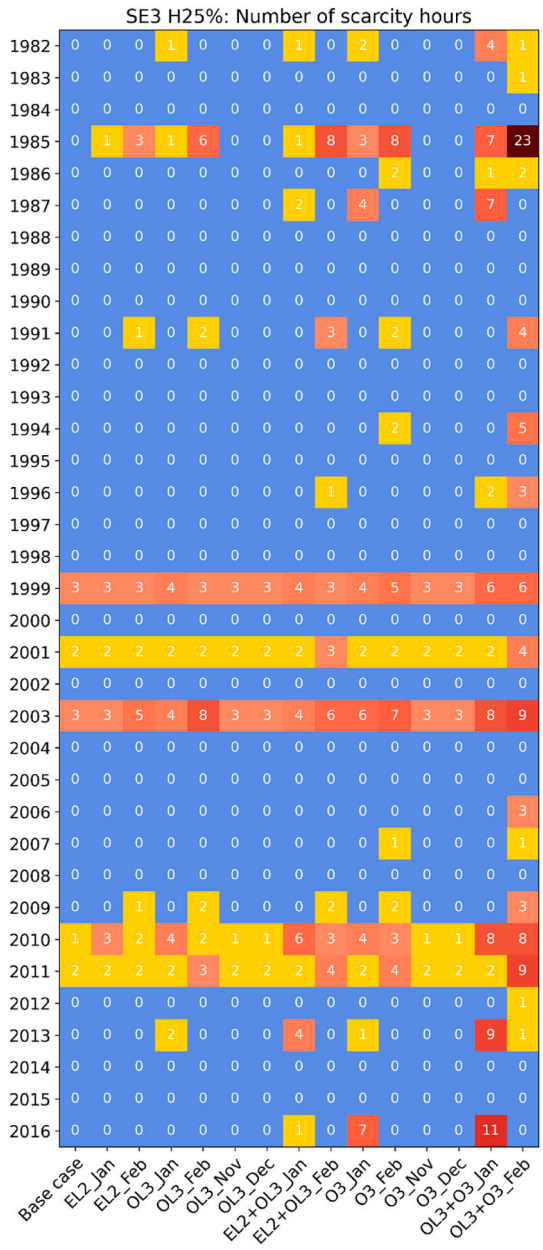

Fig. 10. The number of scarcity hours in SE3 in H25% scenario throughout all weather years and outage scenarios, excluding 12/31/2030 of weather year 2016.

expected realistic capacity and electrification prospects in the early 2030s. This work builds on the work by Koivunen and Syri [44] with multiple novel distinctions. First, more moderate future wind and solar PV capacities are assumed in all Nordic and Baltic countries. Second, detailed modelling of EVs and so-called green hydrogen (H_2) production via electrolysis are included in the model as potentially flexible loads. Finally, power system resilience is analyzed based on multiple outage scenarios in the most vulnerable regions Finland, Estonia and the Stockholm region in Sweden. This contribution thus answers the following questions.

- In the light of the current market prospects, including wind and solar PV capacities and electrification, how severe scarcity situations can be expected in early 2030s?
- What is the impact of partly flexible load from electric vehicles?
- How would unexpected outages in the largest power plants or a transmission line impact these situations?

2. Materials and methods

This section presents the overview of the energy system model and describes the data and assumptions used in the simulation.

2.1. Overview of the energy system model

This work builds on a model applied by Koivunen and Syri [44]. The modelled region in 2030 including bidding zones and transmission connections is shown in Fig. 1. Bidding zones are divided according to Nord Pool day-ahead markets: four zones in Sweden (SE1−SE4), five in Norway (NO1-NO5), two in Denmark (DK1 and DK2), and Finland, Estonia, Latvia and Lithuania each consist of a single bidding zone. External markets (Poland, Germany, Netherlands, and Great Britain) are not modelled but they are included in the model with static price profiles to model external electricity transmission. All cross-border transmission connections or capacity expansions expected to be operational by 2030 are included in the model. Future investments in capacity expansion are not modelled, as the aim of this study is to research the adequacy risks with the current market prospects. In February 2025, the power systems in Estonia, Latvia, and Lithuania were desynchronized from the Russian and Belarussian system and are now fully integrated in the EU electricity network [45].

The model is built using a commercial PLEXOS energy market simulation tool, version 11.0, developed by Energy Exemplar [46]. PLEXOS enables energy market optimization and simulation in multiple levels of detail with long-term (LT) planning, Projected Assessment of System Adequacy (PASA), and medium-term (MT) and short-term (ST) scheduling. LT planning is not used in this study. PASA schedules optimal power plant maintenances, MT schedule simulates the modeling horizon in a simplified temporal resolution to reduce computation time, and ST schedule solves the unit commitment and economic dispatch (UCED) problem based on mixed-integer programming [46]. The objective function in ST schedule is to minimize generation costs, also known as the short-term marginal costs (SRMC), and it is subject to multiple generation, storage, and transmission constraints. A simplified objective function and constraints are presented in equation (1), where $c_{elec.SRMC,t}$ is the hourly SRMC of electricity production, $c_{heatSRMC,t}$ is the hourly SRMC of heat production, and T is the total number of hours (8760) in a year.

$$min \sum_{t=1}^{T} c_{elec.SRMC,t} + c_{heatSRMC,t} \quad (1)$$

st.

electricity balance constraints

heat balance constraints

hydro power and storage constraints

transmission constraints

SRMCs of electricity and heat production are impacted by fuel and CO_2 costs, heat rate, start-up and shut-down costs, and variable operation and maintenance costs of different production plants. Electricity and heat balance constraints ensure that the hourly electricity and heat supply meets the demand. Heat production and demand is modelled in detail for Finland, including heat storage and electrified heating with heat pumps (HP) and electric boilers (EB). For other regions, electrified heating is included in the total electricity demand. Hydro power and storage constraints include constraints on inflow, dispatch, and hydro reservoir volumes. Hydro reservoir and heat storage is recycled in the

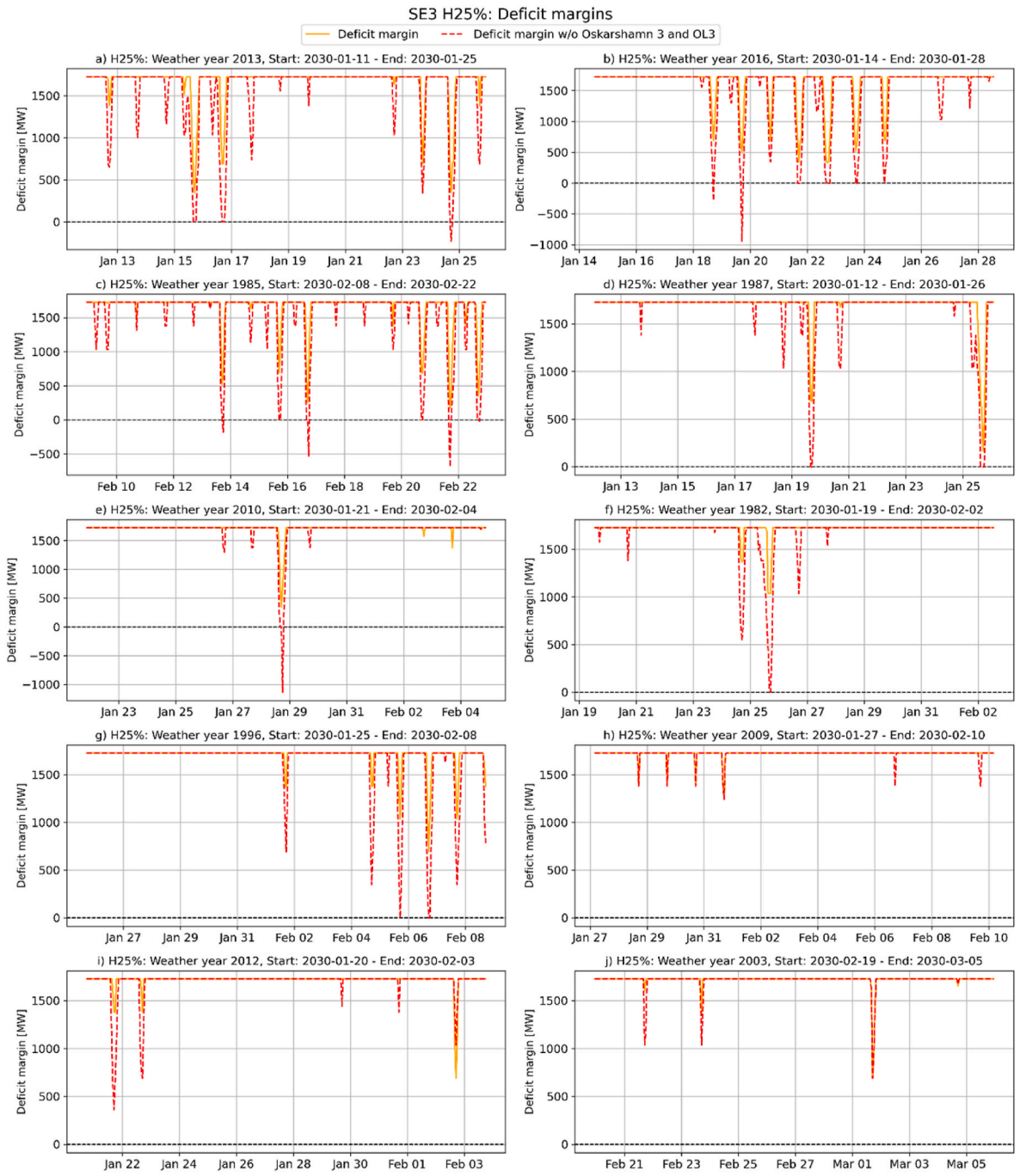

Fig. 11. The deficit margins for SE3 H25% scenario in 2030 in the top 10 worst Dunkelflaute events across all weather years, defined as the highest sum of residual load over a two-week period from (a) the highest to (j) the 10th highest period. Note the different scales on y-axis.

model, meaning that the storage levels at the end of the year must match the levels at the beginning of the year. Transmission constraints limit the transmission of electricity between bidding zones based on net transfer capacities. The model runs the year 2030 35 times through 35 weather year samples (years 1982 – 2016).

2.2. Data and assumptions

Generation capacities and electricity demand for each country in the modelled region in 2030 are shown in Table 1. The values are estimations based on ENTSO-E TYNDP [40], ENTSO-E ERAA 2024 [15], WindEurope [47], and utility and national authority websites.

Demand values are average target values for total annual electricity demand across all weather years, including demand of EVs, H_2 production in Finland, SE1, and SE2, HPs and EBs in Finland, and pumped hydro storage (PHS) load in Lithuania. All demand, except for the demand from EVs, H_2 production, HPs and EBs, and PHS load, is aggregated into baseload demand, which consists of hourly demand profiles for each area and weather year, derived from the Pan-European Climate Database PECD, which are then scaled to the total annual demand in TWh for each area in 2030. Due to the variation in the weather year data, the total annual demand varies across the weather years. Peak load values showing the absolute highest hourly demand values of all weather years and EV scenarios are shown in Table A.1 in Appendix A.

Hydro reservoir storage is modelled in Finland, Sweden and Norway, with maximum volumes of 4600 GWh, 31,600 GWh, and 84,400 GWh,

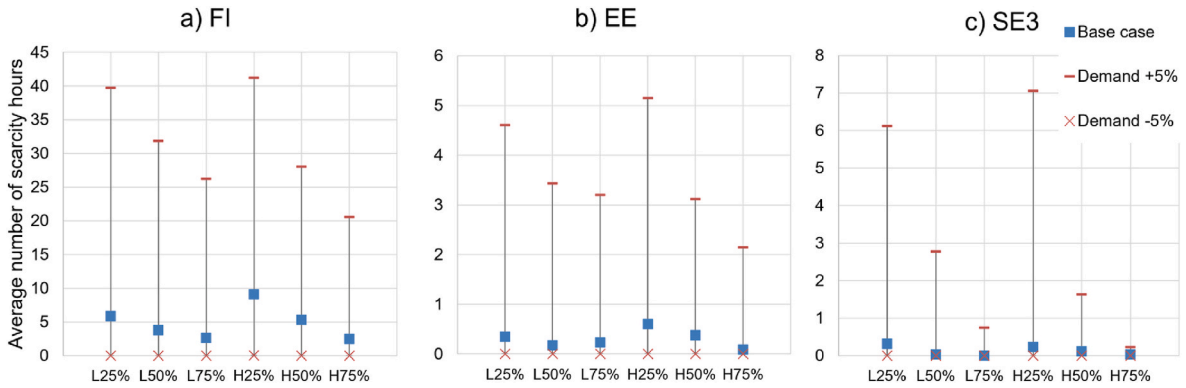

Fig. 12. Results from the sensitivity analysis for FI (a), EE (b) and SE3 (c).

respectively. The maximum pumped hydro storage volume in Lithuania is assumed to be 6 GWh, and the heat capacity for the district heat storage in Finland is 150 GWh. Fossil capacities include all power plants fueled with natural gas, fossil oil, oil shale, and coal, except for CHP plants. CHP plants are aggregated into one generator for each bidding zone. Demand response is modelled with demand-side management (DSM) "generator", which is defined as approximately 10% of the average annual peak load for each bidding zone. The DSM "generator" is divided into five sections according to electricity price steps: first 20% of the "generator" activates when the electricity price reaches 200 €/MWh, then 300 €/MWh, 400 €/MWh, 700 €/MWh, and finally at 1000 €/MWh the last 20% is activated. If DSM is not sufficient to meet the demand, the resulting power deficit in each price area is modelled with an artificial generator to ensure that the supply-demand balance is maintained in the simulation. This generator is activated at 3999 €/MWh, representing the current Nord Pool day-ahead maximum price limit of 4000 €/MWh. The maximum price indicates a situation where the market-based electricity supply is unable to match the demand. Therefore, the hourly generation of this artificial generator represents the hourly generation deficit. It is important to note that these generators do not represent the actual strategic power reserves, as they are not included in the electricity market, but they represent the generation deficit.

Fuel and the EU CO_2 Emission Trading System (ETS) prices for 2030 are shown in Table 2. These prices are assumed to stay constant during the entire year. The prices are approximations based on ENTSO-E TYNDP work and Statistics Finland [40], [48].

Weather conditions have essential impacts on the power system, including demand, wind and solar generation, and operation of thermal power plants. Especially in northern Europe, electricity demand is strongly affected by cold temperatures and the increased need for heating during winter, and hydro power generation depends on the annual rainfall. Therefore, the model is run with 35 years of weather data from 1982 to 2016 to have a comprehensive understanding of the influence of different weather conditions through extensive historical data. The model is run separately through each weather year. Hourly demand profiles for the 35 different weather years are from ENTSO-E ERAA 2022, and onshore and offshore wind and solar PV generation profiles are from Pan-European Climate Database (PECD), published together with ERAA 2022 [49]. Hydro data is retrieved from Zenodo [50].

Electric vehicles are modelled with two scenarios, "High deployment" and "Low deployment", depending on the EV adoption rate until 2030. The number of EVs in both scenarios in each modelled country in 2030 are shown in Table 3. The numbers include BEVs and PHEVs. In the Low deployment scenario, the number of EVs in 2030 is expected to double from 2024. The numbers of EVs in 2024 and in 2030 in the High deployment scenario are based on multiple national projections and targets [18,51–62].

The aim of the EV modeling is to represent a situation where a part of the EV fleet optimizes their charging according to electricity spot prices and the rest charge according to a typical, fixed charging profile. The EV properties are presented in Table 4.

The values for efficiency, daily distance, and battery state-of-charge (SoC) are not defined for the fixed profile EVs, as their hourly operation is given as a daily charging profile in the model. Discharging, or so-called vehicle-to-grid (V2G), is not modelled, as it is not seen viable at least already by the early 2030s based on the current situation and literature [38], [39]. The charging profile of the fixed part of the EV fleet is shown in Fig. 2. The charging profile is based on recent real-world data on charging events in Finnish households and shopping malls [63]. The profiles are the same across the bidding areas, and time zone differences are considered.

Hydrogen (H_2) production, or power-to-hydrogen, is modelled for Finland and the northern parts of Sweden (SE1 and SE2), as these are the regions where significant hydrogen production is planned due to the abundance of wind power and possible construction of a hydrogen pipeline. The annual load for H_2 production is 500 MW in Finland and 250 MW for both SE1 and SE2. H_2 plants are assumed to produce at a minimum of 70% efficiency.

2.3. Methods and scenarios

To assess the impact of partly inflexible charging on electricity demand, different shares of flexible EVs (25%, 50%, and 75%) are incorporated into the two main EV deployment scenarios introduced earlier. Therefore, the model is run with six main scenarios: H25%, H50%, H75%, L25%, L50%, and L75%, where H or L refers to High or Low deployment scenario, and the percentage is the share of flexible EVs. Power system resilience in each of the main scenarios is assessed with different outage scenarios of a major power plant, an interconnector cable, or both. These outages are modelled for one month at a time during the winter period, focusing particularly on January and February, as electricity demand peaks are experienced usually during those months. Table 5 shows the details of the outage scenarios. The reference scenario Base case has no modelled outages.

Scarcity events are analyzed based on residual load $P_{residual,t}$, which is defined as in equation (2).

$$P_{residual,t} = P_{load,t} - P_{wind,t} - P_{solar,t} \quad (2)$$

Where $P_{load,t}$ is the hourly total load, $P_{wind,t}$ is hourly generation from onshore and offshore wind, and $P_{solar,t}$ is the hourly solar PV generation.

Deficit margin $P_{deficit_margin,t}$ is defined as in equation (3).

$$P_{deficit_margin,t} = C_{DSM,max} - P_{DSM,t} - P_{deficit,t} \quad (3)$$

Where $C_{DSM,max}$ is the maximum capacity of the DSM "generator" in the model, $P_{DSM,t}$ is the hourly generation of the DSM "generator", and $P_{deficit,t}$ is the hourly generation of the artificial "generator" representing

the power deficit.

3. Results

This section describes the results of all the main six modelled scenarios and sub-scenarios. Section 3.1 presents an overview of the entire region, and sections 3.2, 3.3 and 3.4 provide more detailed analysis of three areas of focus: Finland, Estonia, and the Stockholm region SE3 in Sweden.

3.1. Overview of the modelled region

Scarcity situations are defined as hours when the electricity supply is not enough to meet the demand. In practice, scarcity hours are indicated by the electricity price of 3999 €/MWh in the model. Fig. 3 shows the average number of scarcity hours in 2030 in the main scenarios in the modelled countries in the Base case scenario across all 35 weather years.

Fig. 3 shows that the number of scarcity hours decreases with an increasing share of flexible EVs in both High and Low EV deployment scenarios. The scenario with the largest number of EVs and the lowest flexibility, H25%, is the most problematic when comparing the total number of scarcity hours in modelled areas, whereas H75% and L75% show very few to no scarcity events in almost all areas. Finland makes an exception, as it stands out from the other countries with the largest average number of scarcity hours in all six main scenarios, even in those with the larger share of flexible charging. The distinct results for Finland are likely explained by the low generation and particularly low firm generation capacity in relation to the high electricity demand assumption for 2030. For instance, Sweden and Norway both have high total demand, but both possess significant hydro power resources, and the onshore wind power capacity in Sweden is assumed to be even twice than that of Finland. The results imply that the generation capacity in Finland together with import capacity is more often not sufficient to cover the highest demand peaks, leading to scarcity prices. The average number of scarcity hours is less than two for all other areas in the worst main scenario. Areas directly connected to external markets, such as LT, SE4, DK1, DK2 and NO2, are exposed to additional uncertainties in the modeling results related to the limited modeling of the external markets and are therefore of lesser focus in this work.

3.2. Analysis of scarcity situations in Finland

Fig. 4 shows the Low EV deployment scenarios with the lowest (25%) and largest (75%) shares of flexibility, and Fig. 5 shows the same flexibility shares in the High EV deployment scenarios. The lowest and highest shares of flexibility are chosen to best capture the variability of results.

Finland has a national reliability standard for 2.1 h of Loss of Load Expectation (LOLE) [18]. In Figs. 4 and 5, the yellow color represents weather years in which the number of scarcity hours is within the limits of this standard, i.e., 1 or 2. The weather years in which the number of scarcity hours exceeds the reliability standard are colored with shades of red. The scarcity situations occur during more weather years in the High EV deployment scenarios (Fig. 5) than in the respective Low EV deployment scenarios (Fig. 4). The number of scarcity situations is higher with 25% share of flexible EVs compared to 75% share: in scenario H25%, there are problems in 21 weather years, whereas in H75% scenario there are problems only in ten weather years. However, certain weather years and outage scenarios are highlighted as the most challenging regardless of the EV deployment rate or flexibility in both Figs. 4 and 5.

To assess the worst-case scarcity situations, the most challenging main scenario, H25%, is put under scrutiny. This scenario is particularly problematic, as most of the 925,000 EVs in Finland in 2030 are assumed to charge rigidly regardless of the electricity spot prices. The total annual demand of EVs is 5.3 TWh in the High EV deployment scenario. The worst ten scarcity situations in H25% scenario are identified by calculating the highest sum of residual load over a two-week period in each weather year, representing the most challenging Dunkelflaute periods. A simultaneous outage of Estlink 2 and Olkiluoto 3 in January or February creates the most scarcity hours in Finland in H25% scenario (Fig. 5) and is therefore chosen as the worst-case reference sub-scenario. The residual loads and prices for these top ten worst two-week periods are shown in Fig. 6, and the deficit margins are shown in Fig. 7. Both figures show that the worst Dunkelflaute periods take place at the beginning of the year in January or February.

Fig. 6 shows that the electricity price reaches the scarcity limit for several consecutive hours or even days during the worst Dunkelflaute periods, and the highest prices coincide with the highest residual load. This implies that there is a severe shortage of generation capacity especially during periods with low wind and solar production. In Fig. 7, values between 0 and 1689 represent the available demand response (DSR) capacity. The negative values indicate power deficit, which is the amount of load that could not be met with any available market resources, including generation, import, or DR. In the Base case scenario, the hourly power deficit is approximately 1500 MW at most. In case of a simultaneous outage of both Olkiluoto 3 and Estlink 2, the hourly power deficit would reach nearly 4000 MW in the worst cases, for example with weather years 2007 and 2011 (Fig. 7(e) and (b)). The charging peak of the fixed EVs each day is 1115 MWh/h in H25% scenario. Therefore, shifting the load from fixed EVs during the worst periods could help decrease the residual load and possibly avoid power deficit.

3.3. Analysis of scarcity situations in Estonia

As most scarcity events in Estonia are experienced in the High EV deployment scenario, the scarcity hours across all weather years and outage scenarios in Estonia in 2030 in H25% and H75% scenarios are shown in Fig. 8. Fig. 9 shows the deficit margins in scenario H25% for the worst 10 Dunkelflaute events using simultaneous outage of Estlink 2 and Olkiluoto 3 as a reference scenario.

Fig. 8 shows a similar trend in Estonia as Fig. 5 for Finland: scarcity hours are experienced more in H25% scenario than in H75% scenario, and problems tend to cluster in the most challenging weather years. However, the scarcity situations are not nearly as long or severe compared to Finland: there are problems in approximately nine weather years in the Base case in H25% scenario and only two in H75% in Estonia. Interestingly, an outage of Olkiluoto 3 alone or together with Estlink 2 or Oskarshamn 3 seems to cause more scarcity events compared to an outage of Estlink 2 alone. Estonia is a net electricity importer from Finland. In Fig. 9, the deficit margin gets negative values in three weather years, implying that even a high residual load does not necessarily lead to scarcity prices in Estonia. This can be explained with the large share of thermal power capacity in generation mix.

3.4. Analysis of scarcity situations in SE3, Sweden

The scarcity hours across all weather years and outage scenarios in the capital area SE3 in Sweden in 2030 in H25% scenario is shown in Fig. 10. Fig. 11 shows the deficit margins in the worst ten Dunkelflaute periods in H25% scenario. A simultaneous outage of Oskarshamn 3 and OL3 is chosen as the reference scenario, as it seems to cause most problems in H25% scenario in SE3.

A notable difference between SE3, Finland, and Estonia is that SE3 has scarcity hours only in five weather years in H25% Base case scenario, and no scarcity hours in any weather years or sub-scenarios in H75% scenario. Fig. 11 shows that a power deficit is not necessarily experienced during the highest residual loads, and at worst it would reach over 1000 MWh/h in the case of a simultaneous outage of Oskarshamn 3 and OL3. The explanation might be the great hydro power resources in both Sweden and Norway. A scrutiny of the results for rest of the simulated areas shows that the same weather years are

highlighted as the most problematic for also the other bidding areas in Sweden, Norway and Denmark in H25% scenario. This implies that during the most challenging periods, problems in power adequacy in one area may be extended to the neighboring areas due to the interconnections and the resulting electricity trade.

3.5. Sensitivity analysis

A sensitivity analysis assessing the impact of total electricity demand on the most challenging periods is conducted by simulating the main six scenarios, H25%, H50%, H75%, L25%, L50%, and L75%, with a 5% increase and a 5% decrease of the average annual demand values (see Table 1). The annual demand of EVs and H_2 production is the same regardless of total demand change. Fig. 12 shows the average number of scarcity hours across 35 weather years in the original and sensitivity scenarios in three areas of focus: Finland, Estonia, and SE3.

The sensitivity analysis shows that the results are highly sensitive to the total electricity demand. A 5% increase in total demand can increase the number of scarcity hours by even tenfold in the focus areas, whereas a 5% decrease results in practically no scarcity issues (0.06 scarcity hours in Finland in H25%) with no additional outages. As the worst scarcity events are often experienced together with a high residual load, the sensitivity analysis suggests that a small percentual change in the total demand can have pronounced impacts on hourly-scale residual load as well. Fingrid has estimated that electricity consumption in Finland could be between 103 and 123 TWh in 2030, depending on the scenario [65]. The results from the sensitivity analysis imply great variation in scarcity events in Finland in this range of total demand, providing that the other assumptions regarding demand and production remain unchanged. However, the 2030 assumption of 13 GW of onshore wind seems optimistic given the current stagnation of wind power investments in Finland. Therefore, if wind power capacity expansion is not realized, adequacy issues could be possible even with a 5% decrease in total demand.

4. Discussion and limitations

The main finding of the results is that power adequacy challenges in northern Europe may arise with the current capacity prospects for early 2030s, and scarcity situations are exacerbated with a higher EV adoption rate together with large shares of inflexible charging. The average number of scarcity hours across 35 weather years in 2030 is between 2.6 and 9.1 in Finland depending on the EV deployment scenario, exceeding the national reliability standard. The corresponding numbers are 0.1 – 0.6 for Estonia, and 0 – 0.3 for SE3. Additional outage scenarios often increase the number of scarcity hours in certain weather years. ERAA 2024 [15] estimates scarcity risks based on LOLE values, which in 2030 are 6.5 h/a for Finland, 7.4 h/a for SE3, and 6.6 h/a for Estonia. The results of this paper are not directly comparable to ERAA LOLE values, as modeling is not conducted with the standardized ERAA methodology. However, the main difference is that ERAA estimates higher adequacy risks for Estonia and SE3. Koivunen and Syri [44], who assumed significantly higher renewable capacities in Finland in 2030 without including separate EV or H_2 modeling, estimated an average number of 2.09 scarcity hours in Finland 2030. The results of this paper therefore show that separate modeling of particularly EVs brings large variability in the results, underscoring the impacts of flexible and inflexible EV charging on severity of scarcity situations.

The sensitivity analysis shows that the results are very sensitive to changes in total annual demand, as a small percentual change in demand inputs can lead to the number of scarcity situations manifolding or dropping to zero. Overall, forecasting the development of demand and expansion of wind and solar capacities in the future involves notable uncertainty: electrification is expected to be driven by increasing renewable generation, whereas renewable generation requires increasing demand to ensure profitability. Risks related to economic viability of renewables and particularly solar PV in Finland are researched in for example [66]. Currently, wind power construction in Finland has almost stopped with a total capacity of 9000 MW. The EV modeling includes uncertainties related to both the rate of EV deployment until early 2030s and the temporality of the charging behavior, as comprehensive data on the actual charging patterns of private consumers is not available. Furthermore, discharging of the EVs back to grid, or so-called vehicle-to-grid, is not included in this work, as it is so far almost non-existent compared to the scale of the national power systems. Other sources of uncertainty in the modelling work presented in this paper include the assumptions for fuel prices, realization of green hydrogen projects, and the DSM configuration and estimation of available flexibility. Furthermore, the modeling of electrified district heating also for other areas in the Nordic and Baltic region is an area of further development of the model, together with more detailed modeling of green hydrogen production and flexible demand. However, the results of this contribution imply that with these near-future demand and capacity prospects, power adequacy problems will emerge in northern Europe and particularly in Finland.

5. Conclusions

This contribution models the power systems in the Nordic and Baltic region in early 2030s based on 35 years of weather data by assuming current prospects for renewable capacity expansion and by including hydrogen production and EV modeling with partially flexible charging. The impacts of the deployment rate and charging behavior of EVs are assessed by simulating two EV deployment pathways with varying share of flexible charging in a total of six main scenarios. Additionally, outages of major power plants (Olkiluoto 3 and Oskarshamn 3) and a transmission cable (Estlink 2) were simulated to analyze the resilience of power systems.

Societies in northern Europe are electrifying and shifting towards a system increasingly based on variable supply. The results show that inflexible charging of EVs indicated by the current charging data causes most scarcity situations in majority of the modelled countries, particularly in the High EV deployment scenario. The results therefore underscore how a substantial increase in inflexible demand from electric vehicles can have severe impacts on power adequacy during the most challenging weather conditions. Additional outages can exacerbate scarcity situations in certain areas during the worst weather years. Thus, information campaigns for EV owners would be important. In addition, enabling and encouraging for the use of vehicle-to-grid could be a cost-effective measure to secure capacity adequacy in future.

The hourly-level impacts were further examined by determining the worst ten Dunkelflaute periods for three areas of focus: Finland, Estonia, and SE3. Finland was found to have the most severe power adequacy challenges in early 2030s: in the most challenging EV deployment scenario, H25%, missing supply could reach 1500 MWh/h in the Base case and even 4000 MWh/h during a simultaneous outage of Olkiluoto 3 and Estlink 2. The results imply that the market-based capacity in Finland in early 2030s is severely insufficient to meet the increasing demand from particularly inflexible EVs.

These findings demonstrate how applying this kind of multi-regional electricity market model, particularly with the current market prospects, can reveal the resource adequacy challenges in the near future. Electricity markets do not operate within national borders only, thus simulating the systems as parts of a larger region is essential to correctly capture and analyze market phenomena and the critical issues. Also, weather data has a key role, as it causes significant variation in renewable energy production and allows the identification of the most challenging weather conditions and their frequency from the power system's perspective. Hourly level simulation allows a detailed analysis for risk mitigation planning, targeting of political measures, and steering consumer behavior, as currently a third of Finnish private consumers have spot-priced electricity contracts. If incentives or obligations are not

immediately planned, the inflexibility of electric vehicles can significantly worsen the underlying capacity adequacy issues caused by weather phenomena and retiring capacity.

Forecasting future development in electricity demand and generation capacity expansion involves uncertainty. However, the results of this contribution give important implications for near-future adequacy challenges in the Nordic and Baltic region with the presented market prospects.

CRediT authorship contribution statement

Ilona Malmipuro: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sanna Syri:** Writing – review & editing, Project administration, Funding acquisition, Conceptualization. **Tero Koivunen:** Writing – review & editing, Methodology. **Dilshika Heenatigala Kankanamge:** Writing – review & editing, Methodology.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

Table A.1
Highest peak load values for each modelled country in 2030 across all weather years and EV flexibility scenarios in the Base case sub-scenario. All values are from the H75% scenario, and the values for Sweden, Norway and Denmark are determined based on the timing of the highest peak demand in one of the constituent bidding zones. The peak loads are impacted by the flexible electric vehicle charging at low prices.

Area	Peak load (MW)	Date and time	Weather year
FI	23900	Jan 9th 03:00	1983
EE	2000	Feb 5th 12:00	2006
LV	2100	Feb 8th 09:00	1986
LT	6000	Feb 9th 11:00	1994
SE	39200	March 2nd 12:00	1996
NO	33000	Feb 9th 20:00	1985
DK	20400	Feb 5th 12:00	2000

Data availability

Research data supporting the findings of this contribution are available at Zenodo: https://doi.org/10.5281/zenodo.18833560. More data will be made available on request.

References

[1] The European green deal - European commission n.d. https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en (accessed February 17, 2026)...
[2] REPowerEU - European commission n.d. https://commission.europa.eu/topics/energy/repowereu_en (accessed July 31, 2025)...
[3] Global EV data explorer – data tools - IEA n.d. https://www.iea.org/data-and-statistics/data-tools/global-ev-data-explorer (accessed July 30, 2025)..
[4] New registrations of electric vehicles in Europe | European environment agency n.d. https://www.eea.europa.eu/en/analysis/indicators/new-registrations-of-electric-vehicles (accessed July 30, 2025)...
[5] Kaukolämpötilastot (district heating statistics) - finnish energy n.d. https://energia.fi/tilastot/kaukolampotilastot/(accessed July 30, 2025)..
[6] Sähkön hintatilasto (electricity price statistics) - finnish energy n.d. https://energia.fi/tilastot/sahkotilastot/sahkon-hintatilasto/(accessed July 30, 2025)..
[7] Nuclear power in Sweden - world nuclear association n.d. https://world-nuclear.org/information-library/country-profiles/countries-o-s/sweden (accessed July 30, 2025)...
[8] International Energy Agency (IEA). Finland - Countries & regions n.d. https://www.iea.org/countries/finland/electricity (accessed February 17, 2026)..
[9] Kivihiilen energiakäyttö Suomessa päättyy kevään aikana (The energy use of coal in Finland ends in spring) - finnish government n.d. https://valtioneuvosto.fi/-/1410877/kivihiilen-energiakaytto-suomessa-paattyy-kevaan-aikana (accessed February 17, 2026)..
[10] Jäähyväiset hanasaaren voimalaitokselle (farewell to hanasaari power plant) - helen n.d. https://www.helen.fi/uutiset/2023/jaahyvaiset-hanasaaren-voimalaitokselle (accessed February 17, 2026)..
[11] Helenin viimeinen kivihiilivoimala sammuu salmisaaressa päättäen hiilen aikakauden (Helen's last coal power plant turning off in salmisaari) - helen n.d. https://www.helen.fi/uutiset/2025/helenin-viimeinen-kivihiilivoimala-sammuu-salmisaaressa-paattaen-hiilen-aikakauden (accessed February 17, 2026)..
[12] TSE sulkee Naantalin voimalaitoksen kivihiilikäyttöisen kolmosyksikön (TSE closes the coal-powered unit of Naantali power plant) - STT n.d. https://www.sttinfo.fi/tiedote/70343194/tse-sulkee-naantalin-voimalaitoksen-kivihiilikayttoisen-kolmosyksikon?publisherId=69817834&lang=fi (accessed February 17, 2026)..
[13] Vantaan energia lopettaa kivihiilen käytön toukokuussa – martinlaakson kaasuturbiinilaitos poistuu käytöstä (vantaan energia ending coal use in may – martinlaakso gas turbine plant retiring) n.d. https://yle.fi/a/74-20150759 (accessed February 17, 2026)...
[14] Energy Authority. National report on the state of electricity and gas markets in Finland 2024. 2025. https://energiavirasto.fi/documents/11120570/13026619/National%20Report%20on%20electricity%20and%20gas%20markets%20in%202024%20in%20Finland.pdf. [Accessed 20 August 2025].
[15] ERAA 2024 downloads n.d. https://www.entsoe.eu/eraa/2024/downloads/(accessed October 10, 2025)...
[16] ENTSO-E. Winter outlook 2024-2025. 2024. https://eepublicdownloads.entsoe.eu/clean-documents/sdc-documents/seasonal/WOR2024/Winter%20Outlook%202024-2025_Report.pdf. [Accessed 25 February 2025].
[17] Urbasos I. The future of Russian gas in the EU. 2024. https://media.realinstitutoelcano.org/wp-content/uploads/2024/03/policy-paper-the-future-of-russian-gas-in-the-eu.pdf. [Accessed 18 September 2024].
[18] Ministry of Economic Affairs and Employment of Finland. Finland's integrated national energy and climate plan update. 2024. https://commission.europa.eu/document/download/069886e9-7a50-4df1-b523-9eb7bf7308c3_en?filename=FI_FINAL%20UPDATED%20NECP%202021-2030%20%28English%29.pdf. [Accessed 4 August 2025].
[19] ENTSO-E. Nordic and Baltic sea winter power balance 2022-2023 2022. https://eepublicdownloads.entsoe.eu/clean-documents/SOC%20documents/Nordic

/2022/Nordic_and_Baltic_Sea_Winter_Power_Balance_2022-2023_report.pdf. [Accessed 28 August 2025].
[20] Pitkä yhteistyö on tullut tiensä päähän (long cooperation has come to an end) - fingrid-lehti n.d. https://www.fingridlehti.fi/pitka-yhteistyo-on-tullut-tiensa-paahan/(accessed August 4, 2025)..
[21] Suomen ja viron välinen EstLink 2 -sähkönsiirtoyhteys palaa kaupalliseen käyttöön (transmission cable between Finland and Estonia, Estlink 2, back in use) - fingrid n.d. https://www.fingrid.fi/ajankohtaista/tiedotteet/2024/suomen-ja-viron-valinen-estlink-2–sahkonsiirtoyhteys-palaa-kaupalliseen-kayttoon/(accessed August 4, 2025)..
[22] Fingrid: estlink 2 -kaapeli takaisin käyttöön heinäkuussa (Fingrid: estlink 2 cable back in use in July) | Yle. https://yle.fi/a/74-20156558. [Accessed 4 August 2025].
[23] Fingrid on päivittänyt arviotaan sähkön riittävyydestä kuluvan talven ajalle: estlink 2 -yhteyden vikaantuminen heikentää sähkön riittävyyttä erittäin kylmänä ja tyynenä talvipäivänä (fingrid updated the estimation of power adequacy for the coming winter: faulting of estlink 2 decreases power availability on a very cold and calm winter day) - fingrid n.d. https://www.fingrid.fi/ajankohtaista/tiedotteet/2025/fingrid-on-paivittanyt-arviotaan-sahkon-riittavyydesta-kuluvan-talven-ajalle-estlink-2–yhteyden-vikaantuminen-heikentaa-sahkon-riittavyytta-erittain-kylmana-ja-tyynena-talvipaivana/(accessed August 4, 2025)..
[24] TVO - Olkiluoto 3:n vuosihuolto on valmis (olkiluoto 3 annual maintenance is done) n.d. https://www.tvo.fi/ajankohtaista/tiedotteetporssitiedotteet/2024/4824553.html (accessed August 14, 2025)..
[25] OKG extends 1.4 GW Oskarshamn 3 outage to end of October | montel news - English n.d. https://montelnews.com/news/d0e2c009-8c65-46db-88ae-062bc99c8bee (accessed October 10, 2025).
[26] Swedish reactor outages to cut domestic capacity flows – TSO | montel news - English n.d. https://montelnews.com/news/149c8259-e40a-4834-9abe-218b1518fd70 (accessed August 14, 2025).
[27] Swedish reactor shutdowns nearly double Finland's electricity price overnight | Yle n.d. https://yle.fi/a/74-20029194 (accessed August 14, 2025).
[28] Fingrid. Sähköjärjestelmän toiminta talvella talvella 2023–2024 (electricity system operation during winter 2023-2024) - fingrid n.d. https://www.fingrid.fi/ajankohtaista/tiedotteet/2024/yhteenveto-sahkojarjestelman-toiminnasta-talvella-20232024/(accessed August 29, 2025)..
[29] Malmipuro I, Syri S, Koivunen T. Lessons learnt from two crisis situations on the Finnish electricity market. International Conference on the European Energy Market, EEM 2025. https://doi.org/10.1109/EEM64765.2025.11050160.
[30] Muhammad S, Hoffmann C, Müsgens F. Assessing energy security risks: implications for household electricity prices in the EU. Energy 2025;327:136201. https://doi.org/10.1016/J.ENERGY.2025.136201.
[31] Mišík M. The EU needs to improve its external energy security. Energy Policy 2022;165:112930. https://doi.org/10.1016/J.ENPOL.2022.112930.
[32] Stavrakas V. Modelling in support of the European energy transition: pathways towards the 2030 targets and the vision of climate neutrality by 2050. Energy 2025;327:136441. https://doi.org/10.1016/j.energy.2025.136441.
[33] Zappa W, Junginger M, van den Broek M. Is a 100% renewable European power system feasible by 2050? Appl Energy 2019;233–234:1027–50. https://doi.org/10.1016/J.APENERGY.2018.08.109.
[34] Mathisen S, Zeyringer M, Haaskjold K, Löffler K, Mata É, Sandvall A, et al. The REPowerEU policy's impact on the nordic power system. Energy Strategy Rev 2024;54:101454. https://doi.org/10.1016/J.ESR.2024.101454.
[35] Kirkerud JG, Nagel NO, Bolkesjø TF. The role of demand response in the future renewable northern European energy system. Energy 2021;235:121336. https://doi.org/10.1016/J.ENERGY.2021.121336.
[36] Söder L, Lund PD, Koduvere H, Folsland Bolkesjø T, Høyvik Rossebø G, Rosenlund-Soysal E, et al. A review of demand side flexibility potential in Northern Europe. Renew Sustain Energy Rev 2018;91:654–64. https://doi.org/10.1016/j.rser.2018.03.104.
[37] Haakana J, Haapaniemi J, Lamminpää A, Lassila J. Sähkömarkkinan hintavolatiliteetin vaikutukset sähkön kulutusjoustoon ja sähkönjakelujärjestelmään (impacts of electricity market price volatility on demand response and distribution system). 2024. https://urn.fi/URN:ISBN:978-952-412-208-5. [Accessed 8 August 2025].
[38] Göke L, Weibezahn J, Kendziorski M. How flexible electrification can integrate fluctuating renewables. Energy 2023;278:127832. https://doi.org/10.1016/J.ENERGY.2023.127832.
[39] Kiviluoma J, Helisto N, Putkonen N, Smith C, Koivisto M, Korpas M, et al. Flexibility from the electrification of energy: how heating, transport, and industries can support a 100% sustainable energy system. IEEE Power Energy Mag 2022;20:55–65. https://doi.org/10.1109/MPE.2022.3167576.
[40] Download | ENTSOs TYNDP 2024 scenarios n.d. https://2024.entsos-tyndp-scenarios.eu/download/(accessed September 1, 2025).
[41] Li B, Basu S, Watson SJ, Russchenberg HWJ. A brief climatology of dunkelflaute events over and surrounding the north and Baltic sea areas. Energies 2021;14:6508. https://doi.org/10.3390/EN14206508. 2021;14:6508.
[42] Beck-Bang AC, Overgaard SB, Keles D. Electricity supply and demand in the European market: the effect on generation adequacy in a dunkelflaute period. Energy Policy 2026;208:114910. https://doi.org/10.1016/J.ENPOL.2025.114910.
[43] Jääskeläinen J, Zakeri B, Syri S. Adequacy of power capacity during winter peaks in Finland. In: 2017 14th international conference on the European Energy Market (EEM); 2017. p. 1–6. https://doi.org/10.1109/EEM.2017.7981883.
[44] Koivunen T, Syri S. Analysis of severe scarcity situations in Finland's low carbon electricity system until 2030. Energies 2024;17:5928. https://doi.org/10.3390/EN17235928. 2024;17:5928.
[45] Baltic states join the European continental electricity grid n.d. https://ec.europa.eu/commission/presscorner/detail/en/ip_25_436 (accessed August 15, 2025).
[46] Energy Exemplar. PLEXOS 11.0 guide. https://www.energyexemplar.com. [Accessed 19 August 2025].
[47] WindEurope. Wind energy in Europe: 2024 statistics and the outlook for 2025-2030 n.d. https://windeurope.org/intelligence-platform/product/wind-energy-in-europe-2024-statistics-and-the-outlook-for-2025-2030/(accessed June 9, 2025)..
[48] Statistics Finland. Fuel prices in electricity production by month, most important fuels n.d. https://pxdata.stat.fi/PxWeb/pxweb/en/StatFin/StatFin_ehi/statfin_ehi_pxt_13p7.px/(accessed September 26, 2025)..
[49] ERAA 2022 downloads n.d. https://www.entsoe.eu/eraa/2022/downloads/(accessed August 21, 2025).
[50] De Felice M. ENTSO-E hydropower modelling data (PECD) in CSV format n.d. https://doi.org/10.5281/ZENODO.3985078..
[51] Statistics Finland. Cars by driving power n.d. https://pxdata.stat.fi/PxWeb/pxweb/en/StatFin/StatFin_mkan/statfin_mkan_pxt_11ie.px/(accessed September 1, 2025)..
[52] Energibruk til transport (use of electricity in transport) - NVE n.d. https://www.nve.no/energi/energisystem/energibruk/energibruk-til-transport/ (accessed September 1, 2025)..
[53] Denmark: BEVs take over in 2024 with 51.5% market share | European alternative fuels observatory n.d. https://alternative-fuels-observatory.ec.europa.eu/general-information/news/denmark-bevs-take-over-2024-515-market-share (accessed September 1, 2025)..
[54] Langsiktiga scenarier for introduktion av elfordon (Long-term scenarios for electric vehicle introduction) 2022. https://energiforsk.se/media/31908/langsiktiga-scenarier-for-introduktion-av-elfordon-energiforsrapport-2022-899.pdf (accessed September 1, 2025).
[55] Lithuania to start preparations for a rapid development of electromobility - Lietuvos respublikos energetikos ministerija n.d. https://enmin.lrv.lt/en/news/lithuania-to-start-preparations-for-a-rapid-development-of-electromobility/(accessed September 1, 2025).
[56] Electromobility - Latvenergo n.d. https://latvenergo.lv/en/elektromobilitate (accessed September 1, 2025).
[57] Elbilstatistikken viser nyeste tall for elbiler i Norge (electric vehicle statistic showing latest numbers in electric vehicles in Norway) – SSB n.d. https://www.ssb.no/transport-og-reiseliv/landtransport/statistikk/bilparken/artikler/nysgjerrig-pa-elbiler-i-norge-se-siste-elbilstatistikk-her (accessed September 1, 2025)..
[58] Elbiler - Den næste generation af personlig transport (electric vehicles -The next generation of transport) n.d. https://mobility.dk/elbiler/(accessed September 1, 2025)..
[59] Elbilsåret 2024 (the year of electric vehicles) - power circle n.d. https://infogram.com/elbilsaret-2024-1h1749w3pxjpl2z?live (accessed September 1, 2025)..
[60] Transportas 2024-09 - lietuvos energetikos agentūra (transport 2024-09 - lithuanian energy agency) n.d. https://www.ena.lt/transportas_2024-09/ (accessed September 1, 2025).
[61] Stock and new registrations of passenger cars by type of motor energy at the beginning of year 1996 - 2025 | official statistics of Latvia n.d. https://data.stat.gov.lv/pxweb/en/OSP_PUB/START_NOZ_TR_TRC/TRC020/ (accessed September 1, 2025).
[62] Eestisse rajatakse Euroopa Liidu toel täiendavad sõidukite elektrilaadimispunktid | kliimaministeerium (additional electric vehicle charging points will be built in Estonia with European union support | ministry of climate) n.d. https://kliimaministeerium.ee/uudised/eestisse-rajatakse-euroopa-liidu-toel-taiendavad-soidukite-elektrilaadimispunktid (accessed September 1, 2025)..
[63] Helsingin Sanomat. Ainutlaatuinen data paljastaa, miten oudolla tavalla suomalaiset lataavat sähköautojaan (unique data reveals the odd way Finnish people charge their electric cars) n.d. https://www.hs.fi/talous/art-2000009554982.html (accessed June 9, 2025)..
[64] Olkiluoto 3 kantaverkossa (olkiluoto 3 in the transmission grid) - fingrid n.d. https://www.fingrid.fi/kantaverkko/sahkonsiirto/olkiluoto-3-kantaverkkoon/ (accessed September 26, 2025)...
[65] Prospects for future electricity production and consumption Q3 2025 - Fingrid n.d. https://www.fingrid.fi/en/grid/development/prospects-for-future-electricity-production-and-consumption-q3-2024/(accessed October 6, 2025)...
[66] Heenatigala Kankanamge D, Jääskeläinen J, Jouttijärvi S, Syri S. Economic viability of large-scale solar PV implementation in the nordic power market: case Finland. Renew Energy Focus 2026;56:100750. https://doi.org/10.1016/J.REF.2025.100750.