

Lessons learnt from two crisis situations on the Finnish electricity market

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Abstract—This paper investigates two exceptional situations experienced on the Finnish electricity market in 2023 and 2024. Both situations are linked with price extremes and significant changes in electricity demand due to the day-ahead price signal. The role of private consumers was crucial in these situations, as currently over 30% of Finnish consumers have spot-priced electricity contracts. The severity of these situations was assessed by assuming slightly different weather conditions or an unexpected fault of one transmission connection. The main observations are that with colder or less windy weather in November 2023, the spot-priced consumers could have endangered the system adequacy with increased consumption, whereas in January 2024 they saved the situation by consuming significantly less due to the spot signal. This case study therefore provides important information for other European electricity markets about the flexibility of consumers with spot-priced electricity contracts.

Index Terms—Consumer behavior, demand response, power system security, resilience

I. INTRODUCTION

Finland has set an ambitious target of reaching carbon neutrality by 2035 [1]. Key steps in achieving this target include increasing renewable electricity and heat production, maintaining a high share of nuclear power, electrifying heating, transport and industry, and improving energy efficiency [1]. Furthermore, the European energy crisis in 2022 has accelerated the energy transition in Finland and other European countries. As M. Pollitt [2] states, the crisis in both electricity and natural gas prices was unprecedented. Before the crisis, Russia accounted for nearly one third of Finland's total energy supply, but Finland has now cut the ties with Russian energy nearly completely: electricity, wood-based fuels and pipeline natural gas import ended by May 2022 [1]. Ending the reliance on Russian energy was aided by major increases in domestic power production capacity in 2023 with the commissioning of 1600 MW Olkiluoto 3 nuclear reactor and a steep increase in installed wind power capacity [3].

The Finnish electricity system is characterized with high seasonal variation in electricity consumption and a diverse electricity generation mix. The Finnish electricity production

and share of total consumption by generation type in 2023 is presented in Table I [4].

TABLE I. Finnish electricity production and share of total consumption by type in 2023.

Production type	Production [TWh]	Share of total consumption [%]
Hydro power	15.0	18.8
Wind power	14.5	18.1
Solar power	0.72	0.9
Nuclear power	32.8	41.0
Combined heat and power (CHP)	13.5	16.9
Conventional condensing power	1.8	2.3
Net import	1.7	2.2

The share of electricity net import in the past decade has been around 20% of annual electricity consumption, but as seen from Table I, the share decreased to 2 % in 2023 [4]. The main interconnectors between Finland and neighboring countries are to Estonia (EE) and Sweden (SE1 and SE3 electricity market regions). The maximum net transfer capacities (NTC) of these connections are presented in Table II [5].

TABLE II. Maximum net transfer capacities between Finland and Sweden and Finland and Estonia.

Connection	FI-EE	EE-FI	FI-SE1	SE1-FI	FI-SE3	SE3-FI
Maximum net transfer capacity [MW]	1016	1016	1100	1200 (1500) ^a	1200	1200

a. When Olkiluoto 3 is producing over 1000 MW, transmission capacity from SE1 is reduced to 1200 MW.

Electricity consumption peaks take place during winter and are most affected by outdoor temperature and the length of the cold periods [1]. This paper presents a case of an extremely cold week with temperatures ranging down to -25°C in Helsinki region and -40°C in Lapland. The hourly demand peak for winter season 2023-2024 was estimated to be 14 300 MW, and of the total installed capacity of 23 700 MW, only 12 800 MW was estimated to be available during the peak [3]. Therefore, although the annual net import greatly decreased in 2023, Finland remains dependent on electricity imports during winter peak load hours [1]. According to the

ENTSO-E Winter Outlook 2024-2025 [6], the mainland European countries which have an elevated risk for electricity supply adequacy are Finland and Poland. High electricity price volatility has been experienced on the Finnish electricity market during the past few years, and price fluctuations are estimated to increase in the future due to the wider integration to European electricity markets [1] and increasing share of weather-dependent renewable generation [7]. The increasing share of renewable generation requires flexibility in the power system, including demand response, flexible power generation, and storages.

After the European energy crisis in 2022, Finnish private consumers are increasingly aware of the electricity day-ahead price fluctuations. This is implied by the increased share of spot-priced electricity retail contracts, which was 31 % at the end of 2023 [8]. Recently, typical for the Finnish and Baltic market has been that during very high prices, even about 50 MW demand increase can result in prices multiplying [9]. However, many studies, e.g. [10] and [11], have estimated significant demand response potential in Finland, including heating loads in the residential sector. Electricity is commonly used in space heating in Finland, and in 2023 it accounted for approximately 25 % of heating energy of residential buildings [12].

The diverse electricity portfolio with high shares of wind and nuclear power, large electricity day-ahead price fluctuations, and high self-sufficiency apart from the elevated risk for supply adequacy during cold and windless winter periods make Finland an interesting case study for investigating demand response. The role of consumers was emphasized during two exceptional electricity market situations experienced on the Finnish electricity market in November 2023 and January 2024. Both situations were characterized by electricity price extremes and resulting significant change in electricity demand. The consumption of spot-priced consumers in these situations were recently analyzed by [13] and [14] based on actual consumption data of over thousand private customers in [13] and 571 customers in [14]. Both studies found that of all consumers, spot-priced consumers were the most flexible during the extreme prices, but changes in consumption are insignificant when prices are low. Private consumers with spot-priced electricity contracts could have potentially threatened the power system stability in November 2023, but on the other hand, they had a crucial role in balancing the system in the tight power situation in January 2024. The extreme electricity prices also had a notable impact on the private consumers' electricity bills. This paper investigates the impact of spot-priced consumers on electricity supply of security based on data on power system and electricity prices, and this study aims to answer the following questions:

- How critical was the state of the power system in these two situations and what was the role of demand change due to the spot price signal?
- What could the system adequacy have been, had the weather been colder or less windy, or had there been different cross-border transmission capacities available?

- What was the role of spot-priced consumers in the outcomes of these exceptional situations?

II. MATERIALS AND METHODS

A. Description of the situations

On Friday, November 24th, 2023, the Finnish electricity day-ahead price dropped to minimum price limit of -500 €/MWh for ten consecutive hours between hours 15 to 24 [15]. The record-low price was a result of a false bid placed on the Nordic electricity market by a Norwegian company Kinect Energy who offered an excessive but nonexistent amount of 5787 MWh/h of power supply to Finland, leaving many higher-bidding Finnish power producers out from the market [15], [16]. The day-ahead market solution based on the incorrect bid supposed that Finland had enough generation to meet domestic consumption and additionally to export to Sweden and Estonia with full capacity, whereas in reality, the Finnish power system was facing a risk of a power deficit [15], [16]. However, no power shortages were experienced due to active trading on the intraday market [15]. The hourly electricity demand during the negative price hours increased on average by 1000 MW from the forecasted demand [15]. As the demand grew significantly, a colder or less windy weather would have exacerbated the situation, as will be shown in the next section.

The first week of 2024 was exceptionally cold, and the temperatures reached -25°C in Southern Finland and down to -40°C in Lapland [17], [18]. The cold weather increased electricity consumption across the country, and an all-time weekly level demand record was broken [18]. Hourly electricity demand peaked at 14 993 MWh/h on January 3rd of 2024, exceeding the estimated 14 300 MW peak [18]. Electricity was imported from Sweden, Norway, and Estonia with nearly maximum capacity and domestic production plants were running with full power, except for faulted generation units [19]. As much as 1500 MW of power generation capacity was unavailable due to both planned maintenances and unexpected faults due to the cold weather [19]. Towards the end of the week, the increased demand together with limitations in power supply drove the electricity prices up to a record peak of 1896 €/MWh at hour 19 on Friday, January 5th, 2024 [18]. With VAT of 24 %, this meant a price of over 2300 €/MWh for consumers. As a result, hourly electricity demand during Friday afternoon and evening decreased by 1000 MW at most from the forecast made in the previous day [19]. Electricity retailers were not prepared for the change in consumption and faced financial setbacks, as they had to sell the unconsumed electricity at much lower prices on the intraday market.

On January 26th, 2024, a failure in one of the two electricity transmission cables connecting Finland and Estonia, Estlink 2, was detected [20]. The connection was out of use for over half the year and returned in operation in early September, decreasing the maximum transmission capacity between Finland and Estonia by 650 MW [20]. If Estlink 2 had faulted only a couple of weeks earlier at the beginning of the year, the situation on the first week would have been

significantly more critical in terms of power sufficiency, as Finland was importing from Estonia in early January 2024.

B. Data sources

The data for Finnish electricity generation by type, electricity demand and demand forecast, net imports and exports, and day-ahead transmission capacities are retrieved from Fingrid Open Data service [21]. Electricity day-ahead price and cross-border physical flow data are from ENTSO-E Transparency Platform [22]. Data for day-ahead bid curves is from Nord Pool [23]. The bid curves for Friday, November 24th, 2023, at hour 18 is shown in Figure 1. Outside temperature data is from the Finnish Meteorological Institute (FMI) [17]. Helsinki-Vantaa airport is chosen as the measuring point based on Finnish population density and is thus estimated to represent the geographical distribution of electricity consumption accurately enough, slightly underestimating the increase in electricity consumption due to the colder temperatures. Additionally, data for the hourly electricity consumption of a Finnish detached house with direct electric heating and an annual consumption of approximately 14 MWh is from a study by Hyvönen et al. [24] to estimate the cost of electricity for a private consumer.

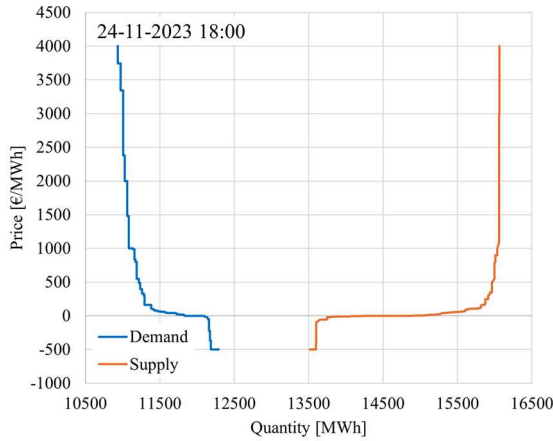


Figure 1. Bid curves for Friday, 24th November 2023, at hour 18 in the Finnish bidding zone [23].

C. Methodology

The impact of different temperature and wind conditions on power sufficiency on 24th November 2023 is assessed based on two scenarios, A and B. In scenario A, the impact of colder weather on electricity demand is assessed by replacing the temperature profile of Friday 24th with the one of the colder next day. The outdoor temperature is estimated to increase electricity consumption by 100 MW until -15°C and further by 150 MW per one degree [25]. As temperature stays above -15°C on both days, the hourly demand values based on a new temperature profile are then calculated as in (1).

$$\text{When } T_t^2 < T_t^1 \text{ and } -15^\circ\text{C} < T_t^2 < 0 : \\ D_t^{Temp} = \begin{cases} D_t + (|0 - T_t^2|) \cdot 100, & T_t^1 \geq 0 \\ D_t + (|T_t^1 - T_t^2|) \cdot 100, & T_t^1 < 0 \end{cases} \quad (1)$$

where D_t is the original demand, D_t^{Temp} is the new temperature-adjusted demand, T_t^1 is the original temperature and T_t^2 is the new temperature. The resulting hourly power deficit in scenario A, $P_t^{Deficit,A}$, is defined as the difference of the temperature adjusted demand, total hourly power generation P_t^{total} and net import $P_t^{net import}$, as in (2). Total power generation P_t^{total} is defined as the sum of generation from nuclear, wind, hydro, solar, industrial and district heating CHP, and small scale and reserve power plants.

$$P_t^{Deficit,A} = D_t^{Temp} - P_t^{total} - P_t^{net import} \quad (2)$$

In scenario B, the impact of lower wind production is estimated based on hourly day-ahead bid curve data from Nord Pool. All wind power producers are assumed to bid their generation at -500 €/MWh, as they do in reality (Fig. 1). Thus, the maximum amount of wind power generation that could have been reduced from the supply curve during Friday 24th without raising the electricity price is calculated as the difference between the minimum supply bid and maximum demand bid quantity (see Fig. 1) for each hour between 15 to 24. This amount, $P_t^{\Delta wind}$, is then reduced from the hourly total production P_t^{total} during those negative price hours, and the resulting hourly power deficit in scenario B $P_t^{Deficit,B}$ is defined as the difference between demand, total power generation and net import, as in (3).

$$P_t^{Deficit,B} = D_t - P_t^{total} - P_t^{\Delta wind} - P_t^{net import} \quad (3)$$

Hourly available transmission capacity (ATC) on a connection between two bidding zones, ATC_t , is calculated in general as in (4) based on the hourly physical flows f_t and the maximum net transfer capacities NTC^{max} presented in Table II.

$$ATC_t = \begin{cases} NTC^{max} - f_t, & 0 < f_t < NTC^{max} \\ 0, & \text{otherwise} \end{cases} \quad (4)$$

Thus, ATC values indicate how much import capacity was still available in addition to the realized transmissions. The ATCs are calculated here for EE-FI, SE1-FI, and SE3-FI connections. The total ATC is the sum of available transmission capacities on all these three connections. The ATC between EE-FI without Estlink 2 on the first week of 2024 is determined by limiting the maximum NTC between Finland and Estonia to the capacity of Estlink 1, 358 MW. The ATC for EE-FI is then calculated as in (5).

$$ATC_t^{EE-FI} = \begin{cases} 358 - f_t^{EE-FI}, & 0 < f_t^{EE-FI} < 358 \\ 0, & \text{otherwise} \end{cases} \quad (5)$$

The cost of electricity paid by private consumers with spot-priced electricity contracts is estimated for a consumer living in a detached house with direct electric heating based on consumption data from [24] and electricity day-ahead prices c_t^{spot} . Hourly consumption values based on accurate outside temperatures E_t^{new} are derived from original consumption data with linear regression. The cost of electricity is calculated for normal consumption C_{normal} as in (6) or for extreme consumption C_{extra} as in (7). P_t^{extra} is for example the power of an electric sauna stove. A 24 % VAT is included in the c_t^{spot} price, excluding negative values.

$$C_{normal} = \sum_1^t E_t^{new} * c_t^{spot} \quad (6)$$

$$C_{extra} = \sum_1^t (E_t^{new} + P_t^{extra}) * c_t^{spot} \quad (7)$$

The cost estimations here do not include distribution fees, electricity taxes, or any retailer and contract-specific costs, and thus the electricity bills are likely higher.

III. RESULTS AND DISCUSSION

A. 24th November 2023

The electricity generation profile, forecasted and actual electricity demand, and electricity day-ahead prices for week 47, 2023, are depicted in Figure 2. On Wednesday with very high wind production, Finland was a net exporter.

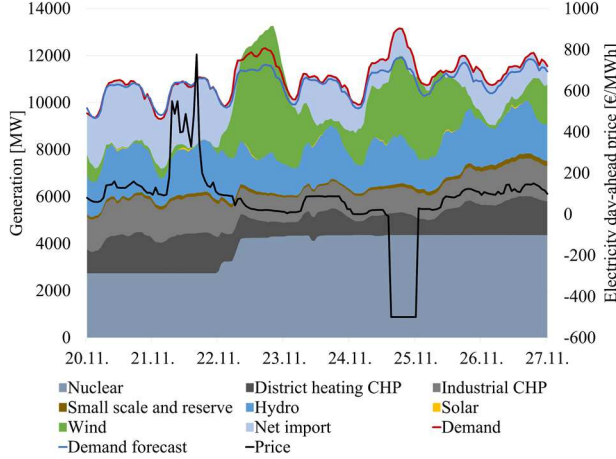


Figure 2. The electricity generation profile, forecasted and actual electricity demand, and electricity spot prices in Finland during week 47, 2023.

Fig. 2 shows how significantly the actual demand exceeded the demand forecast on Friday 24th during the negative price hours. Electricity demand peaked at hour 18 and the difference between the forecasted and actual demand was also at the highest, nearly 1300 MW. According to [13] and [14], of all private electricity consumers, spot-priced consumers increased their consumption the most during the negative prices. The demand increase accounted for roughly 10 % of total domestic power generation and was mainly met with import. Fig. 2 also shows the strong variation in wind conditions over the course of just one week: the wind power output happened to be abundant on Friday, whereas for example the previous day Thursday was not nearly as windy. Additionally, the average temperature in Southern Finland was -2°C, but the next day Saturday, the average temperature dropped to -10°C [17]. The impact of temperature conditions on power sufficiency during the Friday price pit is assessed by replacing Friday's temperature profile with that of Saturday's in scenario A. The impact of reduced wind power output is estimated from hourly bid curves as the maximum amount of production bid at -500 €/MWh that could be reduced from the total power output on hours 15-24 without affecting the electricity price. The results for the peak demand hour 18 are categorized for the original situation and two scenarios A and B in Table III.

TABLE III. The values for the original situation and results for the two scenarios for hour 18 on Friday, November 24th, 2023.

Scenario	Demand [GW]	Forecasted demand [GW]	Net import [GW]	Total generation [GW]	Deficit [GW]
Original	13.2	11.9	1.2	12.0	-
A	14.0	12.7	1.2	12.0	0.8
B	13.2	11.9	1.2	10.8	1.2

The results show that the increased demand due to colder weather in scenario A would have caused a power deficit of 0.8 GW. During hour 18, nearly 300 MW free transmission capacity was available from Sweden. Therefore, the gap in generation could have been covered with import from Sweden and possibly with CHP generation, albeit CHP plants have usually rather slow response times. If the demand had followed the forecast, colder weather in scenario A would not have caused problems. However, lower wind power output in scenario B would have raised more serious issues, as the deficit was 1.2 GW at hour 18. Thus, 900 MW domestic production would have been needed, assuming that all available transmission capacity from Sweden could have been utilized. As nuclear and hydro were already generating at maximum capacity, the gap would have been very difficult to fill. It is important to note that according to both day-ahead and actual physical flows, Finland was exporting to Estonia during the day, which makes estimating the total available transmission capacities challenging.

The estimated cost of electricity for a spot-based private consumer with normal consumption on 24th November 2023 was approximately -10 €. With extreme consumption, here defined as keeping a 9 kW sauna stove on for 10 hours during the negative prices, the consumer could have saved 55 € in their electricity bill. The cost of electricity for the entire November 2023 would have been roughly 120 €. Therefore, savings during Friday 24th were notable, and spot-based consumers had a possibility to even earn money by consuming more electricity. These figures do not include distribution fees and taxes, and therefore the realized savings would have likely been a little smaller. However, in reality, many consumers increased their consumption more than this sauna example.

B. The first week of 2024

The electricity generation profile with actual and forecasted demand and electricity day-ahead prices for week 1 in 2024 are depicted in Figure 3. Due to the extremely cold temperatures, demand was near or above the estimated winter peak demand since New Year's afternoon. Fig. 3 shows how the actual demand continuously exceeded the forecast on average by 600 MW from Monday to Thursday, even though spot prices were rather high, from about 100 to 400 €/MWh. Nuclear and CHP were producing at maximum capacity, and wind power output was moderate throughout the week. Due to the prolonged extreme temperatures and announced faults in several power plants, the electricity spot prices peaked on Friday the 5th to more than five times higher levels than during the previous days.

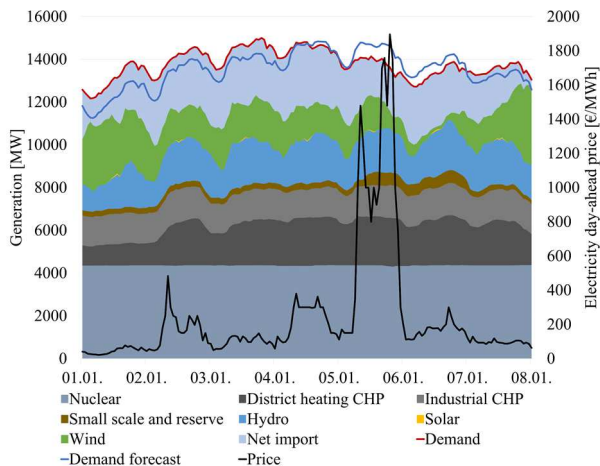


Figure 3. The electricity generation profile, forecasted and actual electricity demand, and electricity spot prices in Finland during week 1, 2024.

The unprecedented price levels sparked very significant demand reduction: demand decreased at most by over 1000 MW from the forecasted at hour 20 despite the extremely cold weather. [14] found that spot-priced consumers decreased their consumption the most (up to 38 %) during the high price hours. During the week, Finland imported electricity from both Sweden and Estonia. The theoretical available transmission capacities for connections between Finland and SE1, SE3 and EE were determined in this study for both the actual situation and a situation where Estlink 2 would be out of use. The demand, forecasted demand, net import, total domestic generation and the total ATC in the original situation and if Estlink 2 had been out of use on hour 20 are shown in Table IV. The ATCs are calculated based on physical flows and maximum NTCs.

TABLE IV. The actual and forecasted demand, net import, total generation and ATCs for hour 20 on Friday, January 5th, 2024.

Demand	Forecasted demand [GW]	Net import [GW]	Total generation [GW]	ATC [GW]	ATC without Estlink 2 [GW]
13.4	14.4	2.1	11.3	1.3	1.0

Table IV shows that there would have been just enough available transmission capacity on hour 20 to cover even the forecasted demand, even if Estlink 2 was out of use. In the latter situation, the full capacity of Estlink 1 would already have been in use, so additional transmission capacity would have been available only on the Swedish interconnectors. However, the data for the entire week reveals that the faulting of Estlink 2 would have increased the need for Swedish import and caused even momentarily power deficits during the week even with the realized demand.

The estimated cost of electricity for Friday, January 5th with normal consumption was approximately 77 € for the example detached house consumer, accounting for roughly 30 % of the total January's cost 260 €. For comparison, the cost of electricity with January 2023 prices and January 2024 temperatures would have been 170 €. Although the estimated electricity cost for one day is already very high, taking distribution fee and taxes into account, the realized electricity

bills would have been even higher. It is also likely that many consumers with direct electric heating ended up paying more for their electricity consumption on that specific Friday due to the extremely cold temperatures, unless they had the possibility to heat significantly with a wood stove.

IV. CONCLUSIONS

The main observation from both situations analyzed in this contribution is that private consumers with spot-priced contracts had a strong reaction to the electricity price signals, as these signals implied significant monetary amounts especially for electrically heated houses. In the exceptional market situation in November 2023, lower wind power production would have caused serious problems for the Finnish power system. In the second case analyzed, the power situation during the first week of 2024 was tight, but according to the results, there would have been sufficient available transmission capacity from Estonia and Sweden to cover even the forecasted demand on Friday, January 5th. However, in case Estlink 2 had faulted already at the beginning of the year, the power supply situation would have been very critical and vulnerable for any other unexpected faults in generation or transmission capacity. The results for the first week of 2024 confirm the previous estimations that Finland is highly dependent on electricity imports during lengthened cold winter periods.

The share of demand response in both these exceptional situations was approximately 10 % of total domestic power generation, and the share of spot-priced electricity contracts for private consumers was about 30 %. Especially Friday, January 5th in 2024, was a very expensive day for private consumers: the cost of electricity for the day was estimated to be roughly 80 € for an electrically heated house, which is a considerable sum for particularly low-income households. Many consumers likely ended up paying even more for their electricity consumption. Respectively, the strongly negative prices on Friday, November 24th in 2023, enticed private consumers to consume more electricity in the hope of significant savings. In both these exceptional situations, the very strong day-ahead price signals were effective in steering electricity consumption, and the spot-priced consumers had a crucial role in the outcome of the situations. The main lesson to be learnt from these situations is that spot-priced electricity contracts provide a significant demand response potential and are therefore essential for ensuring security of supply in crisis situations, but the price signals needed for all the potential to realize are apparently very strong. For both better resilience and for flexibility needed with large amounts of variable renewable electricity generation, spot-based contracts should be made possible to private consumers everywhere in Europe. However, providing transparent information about the risks for sometimes higher bills is also essential. It is important that consumers can choose the type of contract that is best suited for their needs.

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