

The impact of district heat electrification on electricity market scarcity situations in Finland

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Abstract— Finland is committed to reaching carbon neutrality by 2035. Due to the large amount of wind and nuclear power, Finland’s electricity production is 95% carbon neutral. It is essential to electrify also transport, industry and heating. District heating is a vital part of Finland’s energy system, designed to provide reliable heating also in extreme winter temperatures. However, in cities it still relies largely on fossil fuels. This contribution analyses the outlook of district heat electrification and whether the growing electricity demand and retirement of combined heat and power plants will threaten electricity supply security. Analysis is done with PLEXOS electricity market model, considering the expected development of demand, generation and transmission capacities in the whole Nordic and Baltic region, and modelling 35 different weather years from the ENTSO-E ERAA 2022 data. The study shows that retirement of combined heat and power plants aggravates challenging winter situations and deficit may occur.

Index Terms—Combined heat and power, District heating, Load shedding

I. INTRODUCTION

Finland has committed to reaching carbon neutrality by 2035 [1], which is significantly earlier than the EU commitment to carbon neutrality by 2050 specified in the European climate law [2]. Finland’s electricity production is already almost carbon neutral with 4300 MW of nuclear power since the start of Olkiluoto 3 commercial operation in 2023 and 8400 MW of wind power, together with hydro power and biomass use in combined heat and power (CHP) plants of forest industry and in cities [3]. Wind and solar power are being installed in Finland on market basis, *i.e.*, without economic subsidies. This development of the electricity sector provides a good basis for CO₂ emission reductions via electrification in other sectors, primarily transport, industry, and heating.

The Finnish power sector is undergoing significant changes by 2030. Very significant amounts of wind and solar PV construction are expected. Simultaneously, the decarbonization of district heating is advancing rapidly, and it is expected to lead to Combined Heat and Power (CHP) capacity retirements. This may be a very significant loss of controllable generation capacity from the system. Combined Heat and Power

production has been a very valuable resource in Finland’s energy system, as it provides both heat and electricity during the cold seasons. The current electricity generation capacity of CHP plants in Finland totals at 4540 MW. Currently, district heat (DH) companies are replacing CHP heat production with large-scale heat pumps (HP) and electric boilers (EB), thus amplifying the negative impact on wintertime electricity generation sufficiency. The amount of EBs in Finland’s DH systems is currently about 800 MW and expected to increase rapidly. Investment decisions for 2.4 GW of EBs by 2030 are already made [4], [5].

Russia’s attack to Ukraine and the related European energy crisis of 2022 has increased the importance of energy security in every European country. Pollitt has analyzed the crisis at European level and shows that the shock to both European gas and electricity prices was unprecedented [6]. He also noted that the growing reliance on wind and solar power and sector coupling will result in more exposure to weather related occasionally high energy prices. The ENTSO-E Winter Outlook 2024-2025 found that only two mainland European countries, Finland and Poland, currently have a notable risk level concerning the security of supply [7]. Already at present, Finland is very import dependent during cold winter periods and during periods when there is no wind. In such situations, import connections are often in full use. Thus, it is essential that the domestic firm capacity would not decrease.

Electrification of district heating in the Nordic countries has been studied widely and proposed as one important solution for both reaching carbon neutrality and for balancing variable renewable electricity with sector coupling and large heat storages. Lindroos found based on several case studies that electrification of DH systems is likely to continue, benefiting from the periods of low electricity prices and also providing balancing to the electricity system via power-to-heat technologies [8]. Gudmundsson et al. concluded that in the Danish energy system, which has a high penetration of renewables, the optimum storage solution for excess renewable energy production lies in power-to-heat (P2H) sector-coupling with electrified heat production and large thermal energy storages [9]. Sihvonen et al. concluded that electric heat plants are not only able to provide balancing services for the grid but

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benefit from or even require attendance at reserve markets with a complementing heat storage to ensure financial feasibility [10]. Trotter et al. found that total electrification of district heating systems in the Nordics results in significantly increased inter-annual and seasonal variations in power demand and thus, an increased weather risk in the Nordic power system [11]. However, most of these studies did not analyze in detail the wintertime security of supply.

This contribution reviews the current plans of Finnish DH companies and based on them, analyses the expected security of supply on Finland's electricity market with three alternative levels of CHP retirement. The analysis focuses on winter months, and the vulnerability of the system is additionally analyzed by assuming also an unexpected outage in the largest power plant unit of the system.

II. METHODS

This paper analyses the expected security of supply on Finland's electricity market by the year 2030 by considering three levels of CHP retirement. In the optimistic no-retirement scenario, no CHP retirement would occur, and the 2024 CHP capacity for Finland is used. This scenario is referred to as the CHPAll – scenario. The Base case scenario assumes the currently decided and expected retirements to take place, *i.e.*, 390 MW of CHP capacity would be retired compared to 2024 capacity levels. In the high retirement scenario 780 MW of CHP capacity is retired, and this scenario is referred to as the HighEB – scenario, and there is 4.2 GW of EBs in DH networks as opposed to 2.4 GW in Base case. These figures have been retrieved by examining the current CHP fleet and company plans in Finland.

A. Overview of the model

This paper presents the results of a Nordic power system model implemented in PLEXOS version 9.2. The model contains all the Nordic and Baltic power market areas. Finland has additionally district heating modelled as a single node. The model used in this paper is documented in detail in [12]. The security of supply is investigated by examining realistic electricity demand, generation and transmission capacity scenarios for the Nordic and Baltic areas in 2030. Security of supply in Finland is then investigated through 35 different weather years 1982-2016 available from the ERAA 2022 data set of ENTSO-E with the different CHP capacity levels [13].

PLEXOS is an energy market simulation platform developed by Energy Exemplar Ltd [14]. PLEXOS seeks to minimize the overall system cost by optimizing dispatch of resources. Additionally, the solution must adhere to different balance constraints, such as electricity balance constraints, heat balance constraints, hydro constraints, storage constraints and transmission constraints. While it is possible to also optimize investment allocation, in this work capacities were predetermined by the user.

PLEXOS contains multiple different solution schedules to decrease the computational complexity of the models. In this modelling, especially medium-term (MT) and short-term (ST) schedules were utilized. The MT schedule first solves the model for the entire year using simplified data, by simulating the year

in daily load duration curves split into blocks. In this simulation, three blocks are used for each day of the year. This simplified optimization is then sent to the ST schedule, which is then a mixed-integer programming based chronological unit commitment and economic dispatch model. The model was set to contain 73 5-day ST periods within each year, meaning that after the MT schedule finished the solution, the ST-schedule then solves it in 73 different calculations.

Each scenario was run through all different weather years, meaning that for each scenario, the capacity mix was identical within the scenarios, with only the parameters covering the weather years being different. Weather years impact renewable generation profile, the electricity demand profiles and hydro inflow profiles.

In this modelling, district heat HPs and EBs are running based on electricity spot prices. Thus, during periods of high electricity prices, they are not operating. In every DH network in Finland, there is also a large capacity of heat-only boilers. The DH network has very high flexibility, due to the aggregated nature of the DH network, which ensures that all heat could be produced with heat-only boilers and CHP capacity.

In addition, the security of supply with the different generation capacity scenarios is further examined by simulating a possible fault in Olkiluoto 3 nuclear power plant, which is the largest power generation unit (1600 MW) in the entire Nordic and Baltic power system. This case is chosen as an indicator, as it is the largest unit in the Nordic power system, and in 2023-2024 there were several events leading to unexpected outages. On the other hand, no other faults are assumed in the system. Therefore, if OL3 is operational, all other components of the power system are running in ideal condition, with only scheduled maintenances taking place. OL3 faults are modelled as one month long forced outages, which take place in either January, February, November or December.

This contribution presents the modelling results in terms of residual loads and deficit margin.

B. Input Parameters

The input parameters used in this model are presented in Tables I, II and III. The Finnish power system has the following capacities which are presented in Table I. Electricity transmission capacities with the neighboring regions are presented in Table II. Connections with Sweden are available with the northernmost bidding zone of Sweden SE1 and with the Stockholm bidding zone SE3. In addition, Finland has two HVDC connections with Estonia. The transmission values in Table II presents the expected situation in 2030, when new connections with both SE1 and Estonia are scheduled to be in operation. The used fuel prices are presented in Table III. The EU-ETS CO₂ price was set at 78 €/tonCO₂ at the beginning of 2030, with the ETS price increasing to 82.5 €/tonCO₂ by the end of the year.

TABLE I. ELECTRICITY PRODUCTION CAPACITIES IN FINLAND USED IN THE MODEL.

Technology	Capacity MW
Wind	25992
PV	10695
Hydro	3200
CHP (HighEB/Base/CHPAll)	3760 / 4150 / 4540
Nuclear	4394
Demand-side management	1689
Electricity demand, (incl. EB & HP)	105.8 TWh (118.6 TWh)

TABLE II. INTERNATIONAL ELECTRICITY TRANSMISSION CONNECTIONS IN FINLAND IN 2030.

Finnish electricity trading	Import /Export Capacity MW
SE1-FI	2300/2000
SE3-FI	1200/1200
EE-FI	2016/2016

TABLE III. FUEL PRICES IN THE MODEL FOR 2030. EU-ETS PRICE INCREASES DURING THE MODELLING LINEARLY FROM 78 TO 82.5 €/TONCO₂.

Fuel	Price €/MWh
Biomass	31
Coal	7.09
Natural gas	14.65
Oil	36
Oil Shale	8.28
Peat	16
Uranium	1.69
Waste and other	1
EU-ETS Price	78-82.5 €/tonCO ₂

The study assumes that the Finnish power system includes a maximum demand response corresponding to 10% of the average yearly peak load, *i.e.*, 1689 MW, activated in five steps based on the electricity market price. The other Nordic and Baltic market areas have also various response capacities, based on their average maximum yearly power demand. Generation scarcity situations are modelled via the existing market ceiling price. This is represented as a price of 3999 €/MWh in the

modelling and reaching it in the model runs means that the system has run out of reserve margin in that specific market zone or is coupled with a market zone that has ran out of reserve margin.

C. Indicators: Residual load and reserve margin

Residual load is the main indicator for the state of the power system. Residual load is the remaining load after any wind and solar PV generation has been subtracted from it. Reserve margin in this work means the amount of generation that is still left to be dispatched. A negative value here means that the system has run out of power, and this kind of situation would incur rolling blackouts or other similar measures.

III. RESULTS

The main results are shown in Table IV. This table presents the number of ceiling price hours in Finland within the model, where the maximum modelled price of 3999 €/MWh is reached. This price indicates that Finland or the coupled regions in the model have run out of reserve margin. The table below shows ten most difficult weather years, having the highest amount of these deficit situations occurring. They are sorted in descending order with regard to the Base scenario result with the OL3 power plant being unavailable. Each scenario has two variants. In the ideal scenario, all power plants and other components are working ideally, with no faults. In the OL3 scenario, OL3 nuclear power plant is offline for one month, in either January, February, November or December. In each of these results, the plant is offline for one month, and the worst month out of the four is displayed here.

TABLE IV. NUMBER OF CEILING PRICE (3999 €/MWh) HOURS IN FINLAND. THE TABLE CONTAINS TEN WEATHER YEARS HAVING THE LARGEST NUMBER OF HIGH PRICE HOURS IN CASE OF AN OL3 FAULT IN THE BASE SCENARIO. THE NUMBER OF HOURS IS SHOWN FIRST IN THE CASE OF IDEAL SITUATION (NO FAILURES IN ANY POWER PLANT OR TRANSMISSION CONNECTION), AND THEN WITH THE FAILURE, IN BASE, CHPALL AND HIGH EB SCENARIO.

Weather year	Number of hours where the ceiling price is met					
	Base		CHPAll		HighEB	
	Ideal	OL3	Ideal	OL3	Ideal	OL3
1985	0	68	0	46	2	84
2016	17	58	12	50	22	70
1987	21	35	11	19	37	52
2007	7	34	4	26	9	43
2011	9	26	2	18	17	40
1986	0	23	0	19	3	27
2003	0	23	0	14	0	30
2010	1	20	0	15	5	24
1999	3	19	3	19	6	23
2005	5	15	4	7	8	21
Average h/a	2.1	9.2	1.2	6.3	3.7	12.5

From Table IV it can be seen, first, that if the 1600 MW OL3 plant is unavailable, it increases the number of high price hours significantly. Indeed, assuming the severe weather year of 1985 there would not be any ceiling price hours at all if the system were working nominally. Yet, if Olkiluoto 3 were unavailable, there would be the highest number of ceiling price hours. The main interest is the difference between the scenarios with different CHP retirement levels.

By comparing the results, the scenarios show that even a few hundred-megawatt changes in the expected capacity levels can have a large impact on the power scarcity events, especially if there is a fault already occurring within the system. In the nominal case, either increasing or decreasing the available CHP capacity can approximately either half or double the average amount of ceiling price hours during a year. During an OL3 fault, these effects are less pronounced but can result in more extreme cases if the system is already under stress.

The CHP capacity retirement can in these cases significantly exacerbate power deficits during a low-wind cold spell occurring in many weather years. Therefore, CHP capacity retirements should be carefully considered or otherwise mitigated to avoid significant threats to power adequacy.

Currently, the national standard for Loss of Load Expected (LOLE) in Finland is 2.1 h/a, and Expected Energy Not Served (EENS) is 1.1 GWh/a [15]. These standards cannot directly be compared to our results presented in Table IV, as the scenarios

of this contribution have not been conducted with the standardized ERAA methodology that contains also randomized faults and forced outages with a certain probability. Yet, these results are concerning, as the LOLE threshold is almost breached in the base scenario. Even in the ideal case without any power plant or transmission outages there are many weather years when deficit situations would occur.

Figure 1. (a) shows the most severe deficit event, which occurs during the weather year of 2015. This month had the largest sum of missing generation, and most of this occurred within five days. In the figure, the orange line shows the electricity deficit in the base case, the blue line shows the scenario with retained CHP capacity and the green line shows the scenario with increased CHP retirement due to stronger electrification of DH systems. The power deficits are expectedly the worst in the case with the strongest electrification and smallest in the scenario where all CHP capacity would be available. In Figure 1. (b) similar trends can be seen. The patterns are similar. In this case, however, the power deficits are not as serious, but more numerous. January in the weather year of 1985 had the largest number of scarcity hours, *i.e.*, hours when the ceiling price is reached. Interestingly, if the system were working in ideal conditions, there would be no scarcity hours at all, except in the HighEB – scenario.

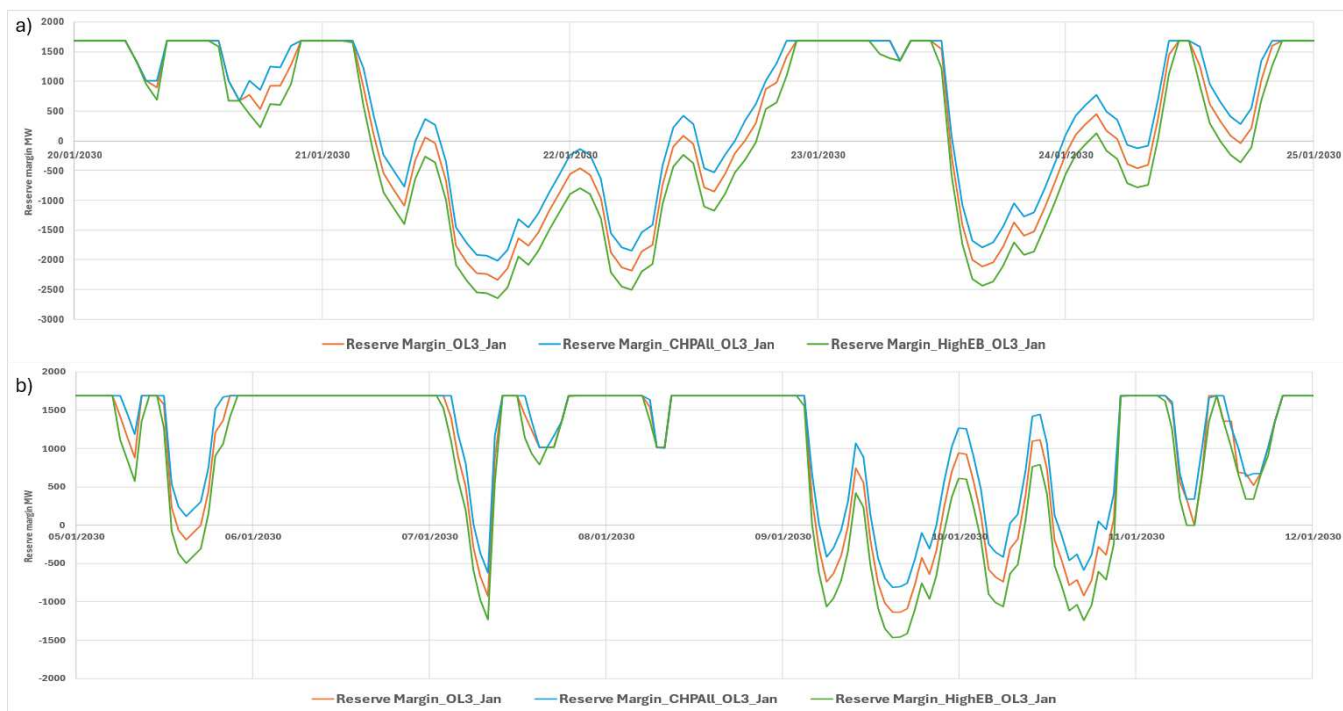


Figure 1. The most severe weather years presented here are (a) 2015 and (b) 1985 in the case that Olkiluoto 3 would be out of production in January. January in 2015 had the largest sum of missing generation while January in 1985 had the largest number of hours with power deficit. Most of this occurs during the one week period presented in figure (a) and five day period presented in (b). This presents the remaining reserve margin. A negative value means that a power deficit is occurring.

IV. DISCUSSION AND CONCLUSIONS

The retirement of CHP capacity impacts negatively the security of supply. This is due to the lost electricity generation capacity and the corresponding increase in electrical heat supply technologies. As the average spot electricity prices in Finland are currently among the lowest in Europe, it is very likely that the retirement of CHP capacity and replacement with large heat pumps and electric boilers will continue. The European energy crisis of 2022 and the extremely high energy prices experienced showed that societies in Europe are not willing to tolerate very high electricity market prices or the threat of rotating outages. Thus, in Finland measures to ensure sufficient capacity also in severe winter conditions are needed. The whole energy system should be prepared to withstand several weeks long episodes of extremely cold weather and low winds, such as was experienced in Finland in early January 2024, when temperature in Helsinki region was around -20°C and even -40°C in Lapland.

However, as scarcity situations are still rather rare and average electricity market prices rather low, it is very unlikely that investments in flexible capacity would be made on a market basis. Thus, mechanisms of ensuring adequate capacity are needed. For instance, a capacity mechanism covering the most difficult situations could be considered, resulting in a publicly upheld strategic capacity reserve, which could be used especially in case of a larger malfunction within the system when the power balance is seen to be challenging by the transmission system operator, for instance. Alternatively, there could be actions of support for flexible capacity or agreed guarantee prices. The Finnish Government is currently preparing a non-fossil flexible support scheme in accordance with the EU guidelines on electricity market design [16]. It is essential that measures to ensure demand management of all electricity consuming sectors are also promoted. Recent experience has shown that without considerable further action, DSM beyond the assumed maximum 10% of load would not be likely even with extreme market prices [17].

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Modelled results data for Finland for the weather years 1985 and 2015 (Figure 1) is available at Zenodo, <https://doi.org/10.5281/zenodo.15118983>.

CONFLICT OF INTEREST

Tero Koivunen has main affiliation at Helen Ltd. This is a purely academic contribution and does not reflect the views of any organization.

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