The impact of Flow-Based Market Coupling on the Nordic region

Andreas Hovde Bø*, Vegard Viken Kallset*, Irina Oleinikova*, Hossein Farahmand* and Karl Ludvig Refsnæs†
*Norwegian University of Science and Technology, Dept. of Electric Power Engineering
†Senior Production Planner, TrønderEnergi Kraft AS
Trondheim Norway

***Abstract*—The primary objective of capacity calculation is to reflect physical transmission limits in the power grid into limits on commercial trades at the electricity markets. The Nordic capacity calculation methodology is currently based on a Coordinated Net Transmission Capacity (CNTC) approach. This paper investigates a structural change of the power supply, in conjunction with the introduction of Flow-Based Market Coupling (FBMC) in the Nordic region. Overall, the results indicate that total welfare increases and differences between average prices are smaller when using FBMC instead of CNTC, especially on a power system with increased wind power capacity.**

***Index Terms*—Capacity Calculation, Coordinated NTC, Flow-Based Market Coupling.**

Nomenclature

Sets and indices

e ∈ E	Set of critical network elements
h ∈ H	Set of hours
p ∈ P_z	Set of power plants in zone z
z,zz ∈ Z	Set of price zones

Parameters

$C^{prod}_{p,h}$	Production cost for power plant p in hour h
$D_{z,h}$	Demand in zone z for hour h
K^{CNE}_{e}	Max capacity on critical network element e
$K^{NTC}_{z,zz}$	Flow restriction from zone z to zone zz
$ptdf_{z,e}$	Power transfer distribution factor of zone z on critical network element e

Variables

$g_{p,h}$	Generation from power plant p in hour h
$np_{z,h}$	Net position of zone z in hour h
$t_{z,zz,h}$	Transmission from zone z to zone zz in hour h

I. Introduction

In 2017, Transmission System Operators (TSO) of the Nordic Capacity Calculation Region (CCR) submitted a proposal for using a new Capacity Calculation Methodology (CCM) [1]. Capacity calculation translates physical transmission limits in the power system to commercial trade limits based on market design and operational security [2]. The capacity calculation in the Nordic CCR is currently based on a CNTC approach [3]. In CNTC, the electricity grid is described as a set of lines connecting bidding zones. Since electricity flows in the grid follows the laws of physics, the assumption that power can be transferred directly from one zone to another is not valid in a meshed grid [4]. The new proposed CCM is instead based on FBMC. FBMC considers a linearized contribution from each bidding zone on each critical line in the system [5]. By using FBMC instead of CNTC, the available grid should be utilized to a higher degree, which should lead to more frequent price convergence between zones and higher total social surplus [1, 6, 5, 7]. The proposed change will, at the earliest, be implemented in 2021 and will be preceded by a period of running FBMC in parallel so that actors in the market have time to adjust.

The Nordic Regional Security Centre (RSC) is responsible for making the capacity calculations for the Nordic region, using local input from the TSOs [8]. As a part of the preparation for using a CCM based on FBMC, Nordic RSC performed a test to compare FB methodology with the current CNTC methodology [9]. The simulations examine 12 weeks in 2017 and compare socioeconomic welfare, prices, overloads, total available capacity, and the total amount of trade between zones. The results show that total welfare increases, price convergence is more frequent, and structural congestions are handled more efficiently.

TrønderEnergi[1] has, along with other power market players invested substantially in wind power in the price areas NO3 and NO4 [10]. Especially until 2022, the production portfolio in the NO3 price area is expected to change significantly, with a share of intermittent production (wind and run-of-river production) close to 40%.

The contribution of this article is to improve the understanding of how a structural change in the supply side, along with the introduction of FBMC, will impact the Nordic region.

II. Methodology

Two optimization models were created to compare the FBMC and the CNTC approaches. The optimization models were implemented using the python package Pyomo and solved with Gurobi as a solver. The models are

[1]https://tronderenergi.no/ Power company based in Trondheim, Norway, that operates hydro power plants and wind farms.

deterministic and span one year at a time. **The objective is to meet the demand in all areas with the lowest production cost.** The optimization models are similar; the differences lie in how they handle power flow between the different bidding zones. In order to compare the approaches, the models have been tested on three scenarios with different installed wind power capacity levels.

The models also include much of western Europe, but this research is focused on the Nordic region. The areas bordering the Nordic region are modeled using the CNTC approach. Therefore, all areas outside of the Nordics are modeled the same way in both models.

A. The mathematical formulation of optimization model

A mathematical formulation used for the two models is provided in equations (1)-(8). The objective function and the first constraints are the same for both models, but the last two are different.

Constraints CNTC

$$min \sum_{z}^{z\in Z} \sum_{p}^{p\in P_z} \sum_{h}^{h\in H} g_{p,h} * C_{p,h}^{prod} \tag{1}$$

$$np_{z,h} = \sum_{p}^{p\in P_z} g_{p,h} - D_{z,h}, \quad \forall h \in H, \forall z \in Z \tag{2}$$

$$np_{z,h} = \sum_{zz}^{zz\in Z} t_{z,zz,h} - \sum_{zz}^{zz\in Z} t_{zz,z,h}, \quad \forall h \in H, \forall z \in Z \tag{3}$$

$$0 \leq t_{z,zz,h} \leq K_{z,zz}^{NTC}, \quad \forall z \in Z, \forall zz \in Z, \forall h \in H \tag{4}$$

Constraints FBMC

$$min \sum_{z}^{z\in Z} \sum_{p}^{p\in P_z} \sum_{h}^{h\in H} g_{p,h} * C_{p,h}^{prod} \tag{5}$$

$$np_{z,h} = \sum_{p}^{p\in P_z} g_{p,h} - D_{z,h}, \quad \forall h \in H, \forall z \in Z \tag{6}$$

$$\sum_{z}^{z\in Z} np_{z,h} = 0, \quad \forall h \in H \tag{7}$$

$$\sum_{z}^{z\in Z} ptdf_{z,e} * np_{z,h} \leq K_e^{CNE}, \quad \forall e \in E, \forall h \in H \tag{8}$$

The objective functions of the formulations, equation (1) and (5), sums all the costs associated with satisfying the demand in all zones. These costs are mostly made up of the production costs for all the power plants in the system. The models also include a mechanism for reducing the demand if it should be necessary. The price for doing so is very high and represents the value of the lost load.

Equation (2) in the CNTC model and equation (6) in the FBMC model ensures that the net position variable of each zone is equal to the difference between generation and demand in that zone.

In the CNTC model, equation (3) says that any surplus in power must be exported to neighboring zones or that a deficit must be made up for by import. Equation (4) ensures that there are no overloads in the system.

In the FBMC model, the system energy balance is enforced by equation (7), while equation (8) restricts the flow on all critical network elements. The transmission capacities provided to the market come together with information on the physical flows on all Critical Network Elements (CNE) in FBMC.

The full mathematical formulation can be found in the master's thesis [11] and includes several parts that are not included here. Among them are:

- Maximum and minimum constraints for power plants
- Constraints for hydropower
- Start/stop costs
- DC-lines
- Batteries

B. Input data sources

TrønderEnergi provided most of the data used as input for the models. This data includes an estimation of fuel prices, production capacities for each production type in each area, demand in each area, and inflow to the hydropower reservoirs for each hour of the year.

Nordic RSC has run simulations where the two capacity calculation methodologies are compared. The simulations are spanned over 12 weeks in 2017, and the used and produced data is available on their webpage [9]. This data includes one set of PTDFs and Remaining Available Margin values for the Nordic system for every hour in the simulation period. In this research, the set from 2017-01-08 10:00-11:00 is used. Using only one set of grid constraints for the entire year implies a simplification that the grid is static throughout the year.

It is necessary to use PTDFs and NTC-values from the same hour to get a fair comparison between the two different capacity calculation methodologies. The NTC values used are retrieved from Nordpool [12] and can also be found in the appendix of the master's thesis [11].

C. Simulation scenarios

To see how the Nordic area is affected by increased wind-power levels, the models were run with three scenarios:

1) **Base case 2020**
2) **Base case 2022**
3) **Increased wind 2022**

Two of the scenarios, base case 2020 and base case 2022, use the projected data for those years. The third scenario uses the data for 2022, but with 20% increased wind power in Mid-Norway (NO3), Northern Norway (NO4), Northern Sweden (SE1), and Mid-Sweden (SE2). Fig. 1 shows the installed wind capacity in those four zones for all three scenarios.

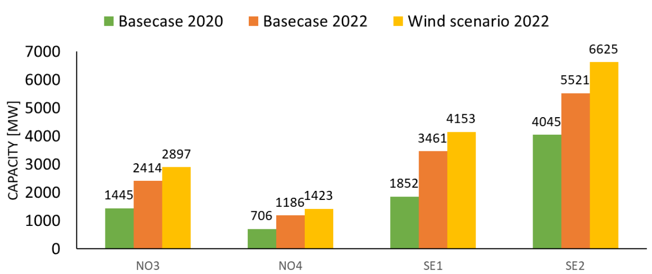

Fig. 1: Wind capacity in NO3, NO4, SE1 and SE2 for all scenarios

The years 2020 and 2022 were chosen for the base case scenarios because most of the near future planned expansions in wind power will happen between those two years. In the scenario with increased wind power, NO3, NO4, SE1 and SE2 were chosen as the zones to increase wind power, because most future developments are expected to happen there, according to Statnett's long term market analysis in these bidding zones [13].

III. Results and discussion

A. Changes in average prices

The annual average prices for all scenarios are summarized in table I. Two trends are evident by examining the table. The first is that the prices decrease as more wind power is added to the system. This is a consequence of wind power replacing other, more expensive types of production.

TABLE I: Simulated area prices [EUR/MWh] for both CNTC and FBMC in the Nordics and parts of Europe.

Zones	2020 Base case		2022 Base case		2022 Wind	
	CNTC	FB	CNTC	FB	CNTC	FB
NO1	37.13	36.94	33.61	33.51	24.51	22.67
NO2	36.80	36.89	33.14	33.45	23.77	22.56
NO3	36.49	36.58	32.23	32.96	**12.36**	21.66
NO4	36.49	36.58	32.67	32.96	**12.52**	21.57
NO5	36.53	36.80	32.82	33.29	23.18	22.22
SE1	36.38	36.47	32.42	32.84	22.27	21.74
SE2	36.41	36.49	32.45	32.86	22.30	21.77
SE3	37.06	36.85	33.66	33.52	24.89	23.34
SE4	38.38	38.06	35.12	35.05	27.52	26.39
DK1	36.54	36.43	33.74	33.77	26.38	25.38
DK2	38.15	38.26	35.61	35.62	28.83	27.64
FIN	37.27	37.12	33.95	33.96	25.78	24.55

The other trend can be seen by comparing the capacity calculation approaches. Price differences in FBMC are generally smaller than in CNTC; the high prices are lower, and the low prices are higher. This effect indicates better utilization of the grid, since the electricity market is to some extent aligned with the physical electricity flows. The converging of the prices is most apparent when looking at the scenario with the most constrained grid, that is, the scenario with increased wind capacity. With CNTC, prices in NO3 and NO4 drop down to 12-13 euros, while in FBMC, they stay close to the other areas at 21-22 euros, since the electricity grid in the neighboring bidding zones are physically interconnected.

B. Relative weights on binding CNEs determine relative prices

The prices of the FBMC model in week 52 are shown in Fig. 2. They take on a hammock-shape that does not occur in the CNTC model. The prices are partially dependent on the grid constraints of the system, and since the grid constraints are different in the two models, the relationships between the prices are expected to be different.

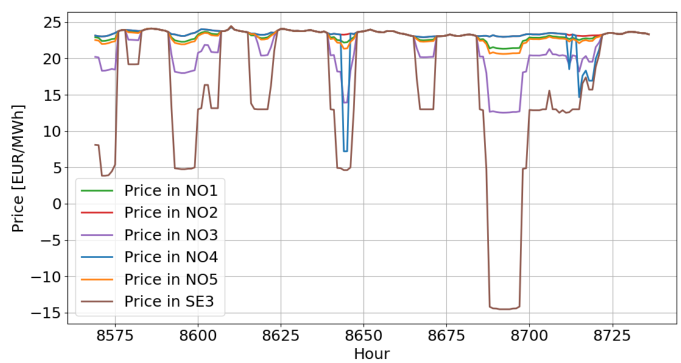

Fig. 2: Hourly FBMC prices in week 52. The other Nordic prices roughly follows the price of SE3

For the FBMC model, the relative zonal prices in the system are dependent on the relative weights of the zones on the binding CNEs. In table II, the prices of the Nordic zones in hour 8600 are given along with their PTDF-values on the two binding CNEs for that hour. The relative prices in Norway mostly correspond with the relative PTDFs on CNE 1. The zone with the lowest PTDF, NO2, also has the highest price. NO4 deviates from this pattern, but that can be explained by it having the lowest PTDF on CNE 2.

TABLE II: PTDF values on binding CNEs in hour 8600

	Prices	CNE 1 scaled	CNE 2 scaled
NO1	23,29	-3,6 %	-0,7 %
NO2	23,76	-3,8 %	-0,6 %
NO3	20,77	-1,9 %	-1,8 %
NO4	23,76	-0,6 %	-5,8 %
NO5	23,09	-3,4 %	-0,8 %
SE1	13,02	-0,1 %	0,2 %
SE2	13,02	-0,1 %	0,2 %
SE3	13	0,1 %	-0,1 %
SE4	12,86	0,2 %	-0,2 %
DK2	12,84	0,2 %	-0,2 %
FIN	13,14	-0,1 %	0,2 %

C. Increased wind power capacity and the FBMC approach leads to higher export from Nordic region

The combined net position (total generation minus total demand) of NO3, NO4, SE1, and SE2, is increased by about 21,2 TWh in the 2022 wind scenario relative to the 2020 base case scenario. All this increased power is exported out of that region to load centers located in the southern bidding zones. About 16 TWh, goes from SE2 to SE3. On the other connections out of that region, NO3-NO1, NO3-NO5, and SE1-FIN, the transfer is increased by about 1-2 TWh, due to the fact that the direct interconnection between SE2 and SE3 is congested. Figs. 6 and 7 in the Appendix presents the total yearly flow and average prices for 2022 increased wind capacity scenario for FBMC and CNTC, respectively.

The Nordic region's net export increases from 24,9 TWh to 38,5 TWh in the FBMC model and from 24,7 TWh to 37,8 TWh in the CNTC model, in comparison with base case 2020. In other words, the FBMC model exports slightly more power from the Nordic region than the CNTC model. Additionally, the difference between the two models increases with increased grid congestion. In the scenario with the least congestion, the FBMC model exports 0,8% more than the CNTC model, but in the scenario with the most congestion, the difference increases to 2,6%. Since the prices are generally lower in the Nordics, exporting power to continental Europe leads to a higher social surplus.

D. Changes in production patterns in FBMC

When using FBMC, the solution domain is larger than when using CNTC. Since the objective function in the models is just a summation of the total production costs, total production costs should decrease with FBMC relative to CNTC. In other words, cheaper production sources can be utilized more with FBMC. In Fig.3 this effect is most visible in SE3 and FIN, because the production in these zones is sensitive to price changes. The total production in a zone dominated by reservoir hydropower and windpower is mostly unaffected because the marginal cost on these energy sources is low.

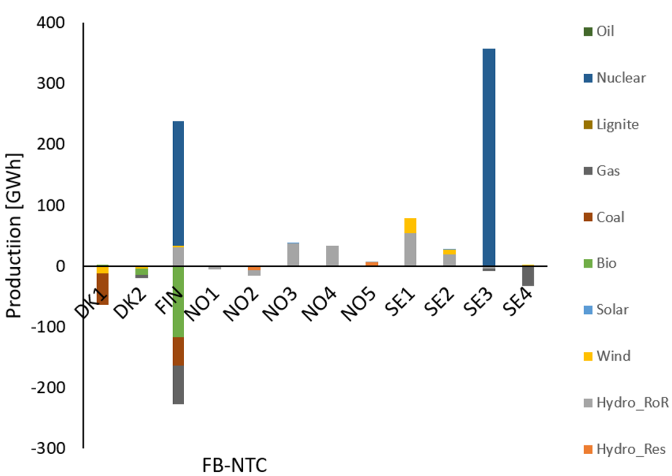

Fig. 3: Changes in production between FBMC and CNTC in 2022 wind scenario

There are two main reasons there are differences in production in the FBMC model compared with the CNTC model. The first comes as a direct consequence of higher export capability. During some hours, when surplus wind power is available, the FBMC model performs better because more transmission capacity is exposed to the market.

The second change in production is more indirect through the changed prices and is most visible in SE3 and FIN. Fig. 4 shows the prices in FIN for both CNTC and FBMC. The CNTC model has both more hours with a price of over 30 EUR/MWh and more hours with a price lower than 13 EUR/MWh. The marginal cost of Nuclear power in the models is 13 EUR/MWh; when the price is lower than that, production from nuclear power will be at the minimum level.

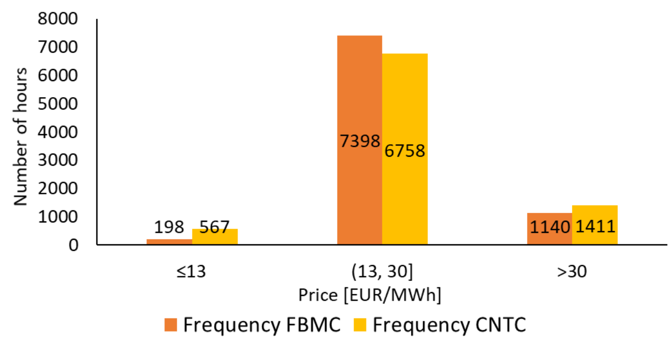

Fig. 4: Distribution of prices in FIN, 2022 increased wind capacity scenario

The marginal costs of the cheapest coal, gas, and biopower plants in FIN are 39 EUR/MWh, 46 EUR/MWh, and 30 EUR/MWh, respectively. Since high prices are rarer in the FBMC model, these power plants are not profitable as often and therefore produce less power.

E. Increased social welfare with FBMC

An interesting aspect of the shift from CNTC to FBMC for stakeholders in the Nordic system is how it will affect the social surplus. The sum of consumer surplus, producer surplus, and congestion rent is usually used to measure the social welfare. In total, the social welfare increases in the FBMC model in comparison with the CNTC model for all scenarios. However, the distributional effect, representing the redistribution of the final gains and costs for market participants, is different. In Fig. 5, the changes on each component for the 2022 wind scenario is shown.

Congestion rent is reduced in most cases because of the lower price differences between the zones. The exception is when increased flow offsets the reduced price differences. Consumer surplus and producer surplus are mostly dependent on price. If the price of a zone goes up, producer surplus increases if the price of a zone goes down, consumer surplus increases.

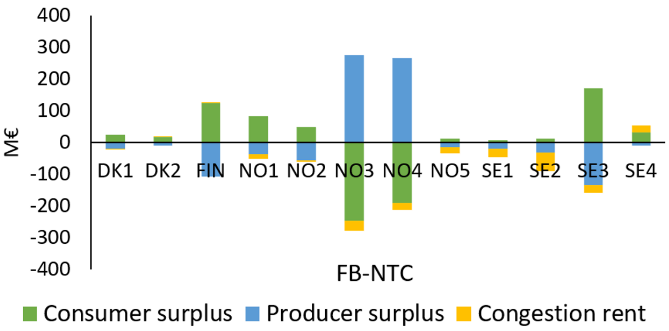

Fig. 5: Changes in Nordic socio-economic welfare per area with FBMC relative to CNTC

IV. Conclusion

In this study, deterministic optimization models based both on the CNTC, and the FBMC approaches to capacity calculation was developed. The objective was to analyze how the transition to FBMC will impact the Nordic power market.

For the prices, the results show smaller differences between bidding areas when using FBMC, compared to CNTC. This contrast is particularly clear in the scenario with 20% increased wind power. Additionally, the general price level decreases as more wind is added to the system.

When comparing the power flow of the FBMC and the CNTC models, an approximation of the physical flow, calculated using PTDFs and the net positions of the respective solutions of the models, is used. The export from the Nordic areas to other European areas is increased in FBMC relative to CNTC in all scenarios. Comparing the scenarios, about two-thirds of the added wind power is exported to other European areas.

The most significant differences in production patterns between CNTC and FBMC happens in FIN and SE3. There are fewer hours with very high prices in FBMC, so production from expensive energy sources like bio, coal, and gas is decreased. There are also fewer hours with very low prices in FBMC, so production from Nuclear power remains at its maximum a higher portion of the time. Another difference happens with production from intermittent energy sources, as, in some hours, the production from wind and run-of-river hydro is so high that it is impossible to use all the available power. Since the FBMC model handles most bottlenecks in a better way than the CNTC model, it can use more of the wind and run-of-river energy.

Total social welfare increases when using FMBC compared to CNTC, even though not all stakeholders benefit. The direction of change in producer surplus and consumer surplus in each zone is mostly determined by whether the price goes up or down in that zone. Share of congestion rent mostly decreases in all zones, except for when reduced-price differences between zones are weighed up for by increased power flow.

Although the method in this analysis contains some assumptions and simplifications, the observed effects will likely show in the real world to some degree.

The main limitations of the method in this research are that the grid is frozen on a 2017-level and that the same grid restrictions are used for each hour of the year. By generating grid-restrictions more dynamically, the comparison between CNTC and FBMC can be made more accurate. By taking future developments of the grid into account, the models can better represent the future Nordic power market. A study with a more long-term perspective, incorporating these changes, would be of great interest.

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V. Appendix

A. FBMC 2022 increased wind

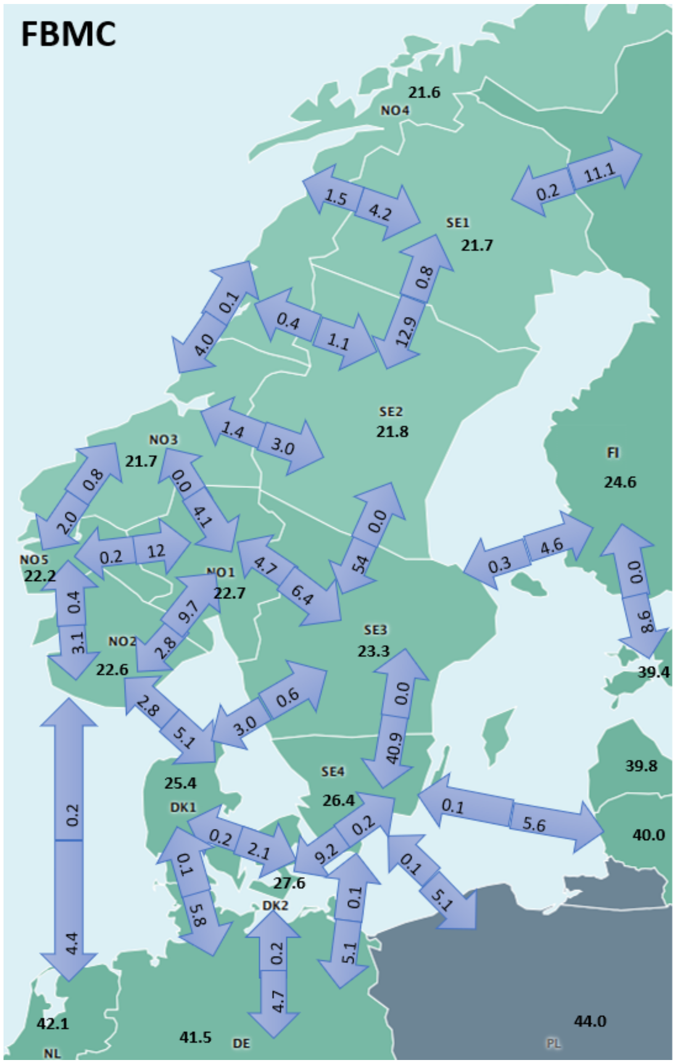

Fig. 6: Zonal prices [EUR/MWh] and approximated physical power flow [TWh] with FBMC in the Nordic zones in 2022 increased wind

B. CNTC 2022 increased wind

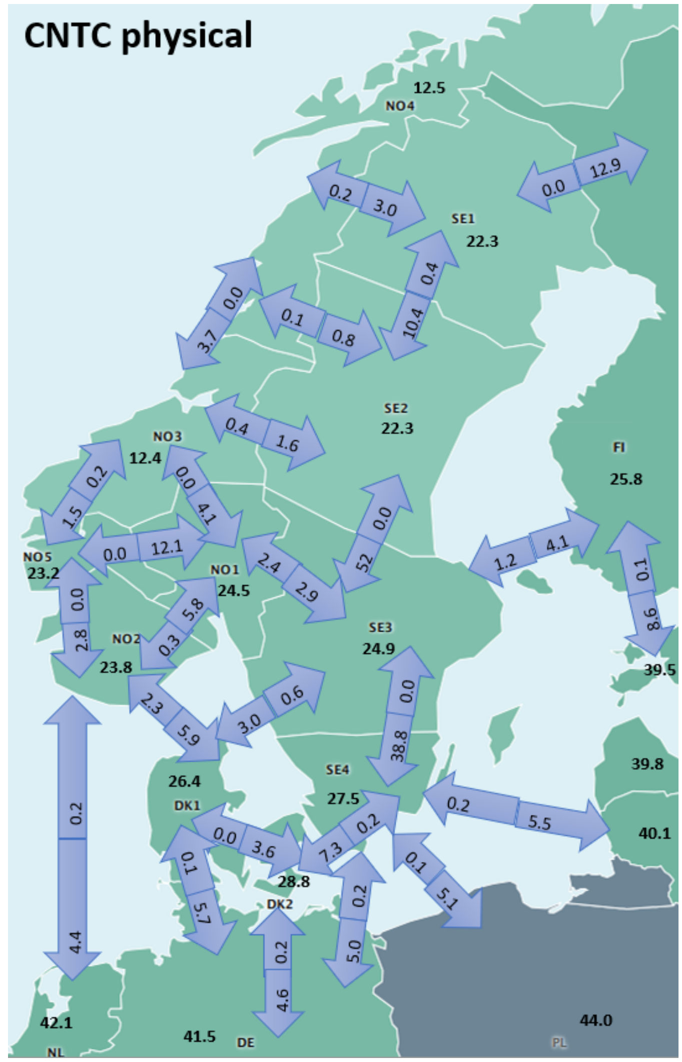

Fig. 7: Zonal prices [EUR/MWh] and approximated physical power flow [TWh] with CNTC in the Nordic zones in 2022 increased wind