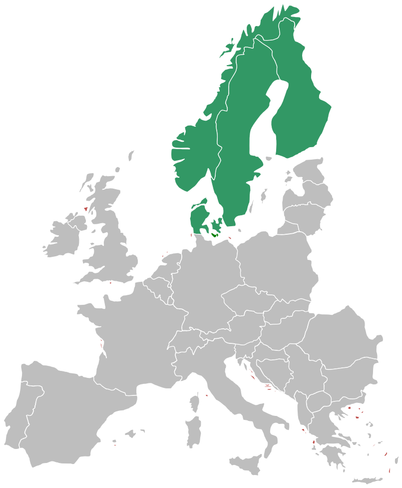

Nordic Capacity Calculation Methodology Project (Nordic CCM)

Nordic CCM – Phenomena report

11 April 2023

ENERGINET SVENSKA KRAFTNÄT FINGRID Statnett

Abstract

This paper introduces the development and implementation of the flow-based capacity calculation method for the day-ahead market and explains recurrent phenomena that have been observed during the parallel run phase of the Nordic Capacity Calculation Methodology project. The idea behind this document is that it will support the market reports with detailed explanations of those recurring phenomena, and that it is to be continuously updated with new phenomena.

The chapter Introduction to CCM, introduces the work on developing and implementing a common Nordic Capacity Calculation Methodology where the NTC methodology is replaced by the FB methodology.

The chapter Disclaimers, addresses the issue of data quality and the simplifications of the FB simulations as disclaimers that could potentially influence the simulation results.

The chapter Phenomena, addresses and elaborates on the initial identified phenomenon on non-intuitive flow

Abbreviations

Abbreviation	Description
CCC	Coordinated Capacity Calculator
CCM	Capacity Calculation Methodology
CCR	Capacity Calculation Region
CGM	Common Grid Model
CNE	Critical Network Element
CNEC	Critical Network Element with Contingency
EPR	External parallel run
FB	Flow-based
Fmax	Maximum allowed flow for the CNEC/maximum power flow on a CNE/Operational security limits of the CNE
(F)RM	(Flow) Reliability Margin
IGM	Individual Grid Model
JAO	Joint Allocation Office
LHF	Last Hour Flow
MTU	Market Time Unit
NEMO	Nominated Electricity Market Operator (i.e. power exchanges)
NP	Net Position (supply minus demand)
NRCC/RCC	The Nordic Regional Coordination Centre (replaced the earlier Nordic Regional Security Coordinator, RSC)
NTC	Net Transfer Capacity
PTDF	Power Transfer Distribution Factor
RAM	Remaining Available Margin (margin of a CNEC available for cross-zonal trade within a CCR)
SW WG	Simulation & Analysis Working Group, part of the Nordic CCM project
SDAC	Single Day-Ahead Coupling
SEW	Socio-economic Welfare
SF	Simulation Facility
TRM	Transmission Reliability Margin

Content

Introduction to CCM

The four Nordic TSOs work together in order to develop and implement a common Nordic Capacity Calculation Methodology (CCM). This common methodology is in line with the Commission Regulation (EU) 2015/1222 of 24 July 2015 establishing a guideline on capacity allocation and congestion management (CACM). The flow-based (FB) methodology is being implemented by the Nordic Regional Coordination Centre (NRCC). Before going live with the new capacity calculation methodology for the day-ahead market, a few phases are foreseen along the implementation timeline, such as the internal and external parallel runs.

During the parallel runs the market outcome, based on the NTC methodology, is compared with a market simulation result using the FB methodology. The comparison is presented in the market reports written by the CCM project. The analysis presented in the market reports will focus on the socio-economic welfare (SEW) outcome of the Nordic power systems.

Capacity allocation in the Nordic CCM parallel runs

The new capacity calculation methodology (i.e. FB) differs in many ways from today's NTC methodology. However, the capacity allocation in SDAC still have the aim to maximize the socio-economic welfare. Both in the NTC and the FB methodology, the network capacities are submitted to the NEMOs. The NEMOs utilize the Euphemia algorithm to maximize the socio-economic welfare in the market, while respecting the network constraints of the TSOs (being NTC or FB), which results in traded volumes and prices.

Where each TSO determines its NTC capacities, in the FB methodology it is a more coordinated, formalized, and automated process. The input datasets provided by the TSO to the NRCC - that acts as a coordinated capacity calculator (CCC) – include critical network elements with associated contingencies (CNECs), power transfer corridors (PTCs) and the operational limits for these elements (Fmax). Those are sent for each market time unit (MTU), for each day, and are used by the CCC to calculate –based on an hourly common grid model (CGM) - the Remaining Available Margin (RAM) and Power Transfer Distribution Factors (PTDFs): the FB parameters that are sent to the NEMOs, after the TSOs have validated them.

When TSOs today calculate NTC capacities, they do this individually by looking at mostly its own grid constraints and critical network elements and by translating these into a capacity on the borders, subject to the market allocation. With FB the

TSOs provide the critical network elements as is to the market as a simplified grid model –instead of pre-calculating resulting capacities on the border in the form of a MW-value.

When the TSOs give capacity in the form of NTC values, all border capacities are available at the same time to the market for allocation, at least conceptually. One of the advantages with FB is that each TSO does not have to make a distribution of the capacity between different bidding zone borders before the capacity is sent to the NEMOs. Instead, the maximum available capacity is given to the market through submission of the FB domain. The capacity is then allocated to the energy transactions that provide the most socio-economic welfare, when prices and flows are calculated by the NEMOs.

Socio-economic welfare

Socio-economic welfare (SEW) is calculated as the sum of consumer surplus, producer surplus and congestion income for each hour. SEW is used as the main optimization parameter and the Euphemia coupling algorithm tries to maximize the overall SEW gain among all bidding zones participating in Single Day -Ahead Coupling (SDAC).

Consumer and producer surplus are calculated by Euphemia and used as is without any further calculations.

Congestion incomes are calculated per border, based on the flows and price differences. Flows are calculated based on border PTDF's and the net positions and prices are calculated by Euphemia. Congestion incomes are distributed among all borders based on the Congestion Income Distribution methodology[1].

Bidding zone prices

Prices for each bidding zone are calculated by Euphemia.

[1] ACER Decision 07-2017 on CIDM.pdf (europa.eu)

Net positions

Net positions of actual bidding zones are calculated by Euphemia and used as is. Euphemia does not calculate net positions for virtual bidding zones (which are used for modelling HVDC links) but it calculates the flows on these links. Net positions of virtual bidding zones are calculated based on these flows.

Border flow calculation

Border flows are calculated by summing the products of each bidding zone PTDFs and corresponding bidding zone net positions to the F_0-flow.

Flow for FB is calculated using the border CNEC PTDF's and net positions from FB market coupling and flow for NTC is calculated using the same border CNEC PTDF's but taking the net positions from NTC market coupling instead. The results from these calculations are not the same as scheduled exchanges which are currently used as commercial border flows.

The flows presented here are the physical flows, calculated by:

$$\text{Physical flow}_k = \mathrm{F}_{0,k} + \sum_{\forall i \in BZ} \mathrm{PTDF}_{i,k} \times \mathrm{NP}_i$$

Where $F_{0,k}$ is the F_0-flow and is defined as the reference flow on a certain CNEC when the NP is on border k. $\mathrm{PTDF}_{i,k}$ parameter corresponds to the PTDF value on border k for bidding zone i. BZ are all real and virtual bidding zones related to the Nordic CCR.

Business process during parallel run

During the internal parallel run, the Nordic CCM project's Simulation and Analysis working group (SA WG) took the responsibilities off running the market simulations. In the external parallel run (ERP) the market simulations are performed by the NRCC together with the NEMOs. The daily process, illustrated in Figure I, starts with each TSO creating and sending their IGMs, CNEs and CNECs (input data) to the NRCC. The NRCC merges the IGMs to one CGM and performs FB calculations based on the TSOs' input data. The NRCC, together with the NEMOs, then run FB simulations on a TSO validated FB domain (RAM and PTDF).

The FB domains are accumulated for a one-week period before running the simulations. However, the grace period is currently set to two (2) weeks after the energy delivery date. The production of the market report will need to comply with the grace period.

The NRCC provide the Nordic CCM (SA WG) with the FB market results from simulations. The market algorithm Euphemia provide prices, net positions, consumer and producer surplus for all bidding zones. The SEW is calculated by summing up consumer surplus, producer surplus and congestion income. The calculated FB SEW is then compared to the NTC SEW, hour-by-hour, to evaluate the impact of the new capacity calculation and allocation.

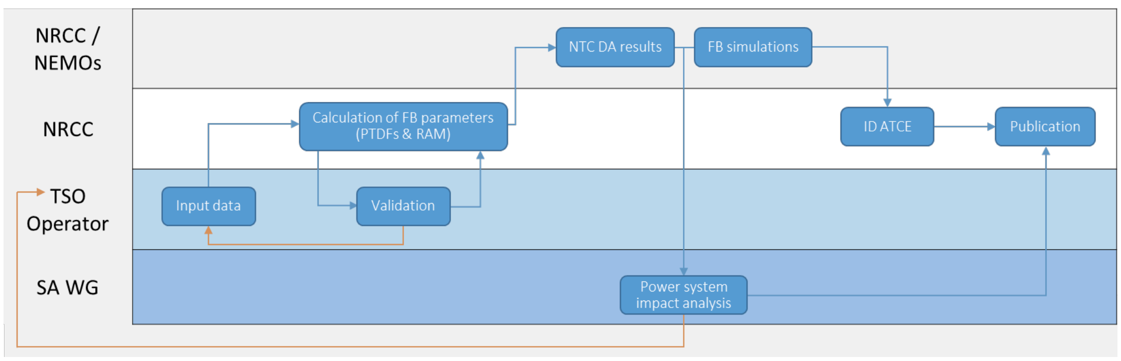

Figure 1. The high-level business process illustrating the roles, responsibilities and interactions among the NRCC, TSO operators and the Nordic CCM (SA WG) during the external parallel run.

Simulated market results

Before the summer of 2022, the simulations were calculated by Simulation Facility (SF). Both NTC and FB market results were simulated in this period. However, SF has been unavailable since June 2022 due to failed updates in the system. Consequently, since this period, it has not been possible to produce simulations and, therefore market reports.

From December 2022, the Euphemia test environment at the NEMOs has been used to simulate the FB simulations. The NTC market results are taken directly from the production system of Euphemia.

Both the test environments at the NEMOs and SF use the same market coupling algorithm that is used for day-ahead market coupling.

Nordic CCM remarks

The EPR market reports show the SEW comparison between the current NTC methodology and the FB methodology approved for CCR Nordic. Besides the congestion income generated for the bidding zone borders included in CCR Nordic, the figures in the reports also include the SEW of the Nordic bidding zone borders connected to CCR Hansa (NO2-NL, N02-DE/LU, DK1-NL, DK1-DE/LU, DK2-DE/LU) and to CCR Baltic (SE4-LT, FI-EE) to have a full picture of the effect on the entire Nordic SEW.

In simulations some HVDC cables are modelled to include the power transfer losses, and some are not.

- Norned, Nordlink, Skagerak, Baltic cable consider losses.
- Cobra cable, Storebelt, Kontiskan, Swepol, Nordbalt, Fennoskan, Estlink and Kontek do not consider losses.

Disclaimers

Disclaimers for data publication at JAO during external parallel run

Data quality

The capacity calculation tool and the data used for the capacity calculation is continuously being improved, and TSO operators are improving their processes by using the domain validation tool in daily operations. The outcome of the FB calculations is considered valid for comparison with NTC even with some known disclaimers that are being continuously evaluated and improved by the TSOs.

Domain validation process

The TSO operators are in the 'learning-by-doing' phase in the parallel run process. The validation tool that is supporting the domain validation activities is still under active development.

Disclaimers related to market analysis report (Nordic CCM)

The market analysis reporting is under development by the Nordic CCM project. Stakeholder inputs is gathered, and improvements are being implemented. During the external parallel run weekly reports will be published along with supplementary data and in-depth additional documents.

The Nordic TSOs welcome comments and questions from the stakeholders. Please send an email to ccm@nordic-rcc.net.

NTC order books being used in the FB market simulations

The market simulations of the FB methodology use the NTC order books, due to the unavailable dedicated FB order books. This means that the bids (and also final market solution) of the FB calculations are based on the order books of the actual NTC-based electricity market.

Typically, a FB simulation results in a less-constrained power market and more production in areas with cheaper power production. This often means more hydro power production in the northern bidding zones in the FB simulations compared to the NTC. This leads to a phenomena where "cheap hydro" is over utilised. This is evaluated in the section Market impact from high structural export from the Northern Nordic area.

Last hour flow

The last hour flow (LHF) is relevant for the ramping restrictions from one day to the next. For the FB simulations, the LHF will be taken from the last hour of the previous FB simulation results. Additionally, when there is a (few) missing day(s) in the simulations, the LHFs of FB are set to zero as default. Consequently, the simulated market results may not be strictly comparable to the NTC market results, since NTC results comes directly from the production environment. The NTC does therefore always have LHF included.

Simulation set up – Lineset ramping

A new FB topology had to be created in order to incorporate the previously missing South-West link and the newly formed bidding zone NO2A. NO2A was created in order to limit the total ramping on Norned and Nordlink. In the new topology, this is managed by introducing a lineset ramping – a ramping limitation for multiple line segments.

When performing the initial simulations with the new topology, an error occurred. The simulations failed applying both the individual line ramping and the lineset ramping. The reason why the simulations fails when applying both individual line ramping and lineset ramping is still under investigation. In the meantime, in order to produce any simulation results, the lineset ramping was removed from both FB and NTC. This means that the total ramping for Norned and Nordlink can exceed 900 MW as long as the individual ramping restrictions are respected.

Congestion income computation as post-processing of the market data

Market results require post-processing to create a readable format of the results and to calculate generated congestion incomes. Currently, congestion incomes are calculated by Nordic TSOs in accordance with the congestion income distribution methodology. Later this will be calculated by JAO with production-grade tools. FB and NTC congestion income methodologies are the same but the distribution of negative congestion incomes is different[2].

SEW comparison in the operational security perspective

Fair comparison between FB- and NTC-market results requires same level of operational security as a basis for the two methodologies. In other words, it is not fair to compare SEWs if FB respects the operational security and yields smaller SEW outcome, whereas NTC breaches the operational security and yields larger SEW outcome. Additionally, the remedial actions and the associated costs to solve the operational security issues in 'real-time' are not known to make a fair comparison.

Checks have been made comparing the NTC market outcome and the security domain. The TSOs recommend viewing the SEW comparison outcome both from a socio-economic and an operational security perspective.

Reliability Margin (RM) compared to Transmission Reliability Margin (TRM)

As part of the common Nordic Capacity Calculation Methodology (CCM), a methodology is included for determining Reliability margin. This shall be used such that:

$$RAM_{bv} = F_{max} + F_{RA} - F_{RM} - F_0 - F_{AC}$$

Until the RM has been determined, as defined in the methodology, RM has been defined such that F_{RM} shall be equal to 5 % of F_{max} for each CNE/CNEC. TRM is used in NTC and is are generally a fixed value set per bidding zone border. TRM values are set per connection and agreed upon by TSOs in specific System Operation Agreements. Therefore, there may be some differences when comparing FB and NTC. For example: F_{RM} for the limiting CNE/CNEC for the SE4-DK2 border may have a higher F_{RM} than the TRM in NTC, but SE1-FI may have a higher TRM compared to the F_{RM} of the limiting CNE/CNEC for that border. Another example of a difference is that capacity reservations are applied for the aFRR-market in FB, but these are considered as part of TRM for the internal Swedish bidding zone borders and no additional reductions are currently applied in NTC.

[2] Annex I - Congestion income distribution methodology

Uncertainties related to topology or topological remedial actions

FB results are derived from the CGM, in which TSOs provide their best prognosis of the expected situation for the day of delivery. As the FB-results are typically derived from the model provided in D-2, the flows are optimized for the network topology in the D-2 models. As specific models are not always used in NTC, operators can consider various topologies and provide the highest secure capacity for all topologies considered in D-1, including topological remedial actions which may not be included in the CGM for FB. This may result in cases where more capacity is provided in NTC compared to FB, but is expected to improve along with TSOs' ability to provide the best prognosis of the expected topology and model the topological remedial actions in FB-parameters. An example of this is the series capacitors on lines included the SE2-SE3 border. In total eight lines include series compensation. Flows, as well as the limit for voltage collapse, are affected by which series compensators are in operation.

Countertrade and redispatch

There are cases where TSOs consider countertrade and redispatch in order to increase capacities in NTC and these are not always fully modelled in FB. Such cases may result in more SEW being observed in NTC compared to FB. An example of this has been applied countertrading by Svenska kraftnät during the winter period of 2022/2023[3]. It is expected that such measures will be accounted for if applied after the go-live of FB.

[3] Svenska kraftnät has an article on this on their website (in Swedish): Mothandel och omdirigering höjer kapaciteten

Phenomena

When entering external parallel run, market reports are created with a slightly changed format compared to the reports as published during the internal parallel run. The market reports from the external parallel run still contain a comparison between flow-based and NTC in terms of socio-economic welfare, but the part analysing observations in more detail has been removed. This is partly to streamline the work process to create the reports, thereby facilitating an earlier publication, and partly because over time certain phenomena tended to occur repeatedly in the results. To allow for further elaboration on the identified phenomena, this separate report is created to complement the market reports. This document is intended to be used as support to the market reports and the content might expand over time as new phenomena are likely to appear throughout the parallel run.

In addition to elaborating on observed phenomena, the report also contains a section with fundamentals of optimization using the flow-based methodology intended to support the reader in understanding the reasons behind certain phenomena. The initial phenomenon included in the report is on the non-intuitive flows; flows from a bidding zone with higher price to one with a lower price. These flows occur also with NTC but to a lesser extent than in the flow-based simulations of the market coupling.

Non-intuitive flow

Non-intuitive flows are flows resulting from the market coupling that go from a higher priced bidding zone to a bidding zone with a lower price. These flows generally occur when the loss of socioeconomic welfare resulting from the non-intuitive flow is smaller than the socioeconomic benefit of relieving a congestion. This allows for an overall market efficiency gain as the Euphemia algorithm maximizes the pan-European welfare in the market coupling.

To understand why non-intuitive flows exist and why they are more prevalent in flow-based compared to NTC, a theoretical background on welfare optimization theory is needed. The theoretical background is given to prove that the market equilibrium requires that the marginal value of a bilateral trade equals the marginal cost of transmission, see Equation 19.

Welfare optimization theory

Consumer behaviour - Utility maximization

The function $V_i(x_i^d)$ defines the consumer's benefit, in monetary value, of electricity consumption x_i^d in bidding zone *i*. By maximizing utility, we find that:

$$\text{Max } V_i(x_i^d) - p_i * x_i^d \quad \rightarrow \quad \frac{\partial V_i}{\partial x_i^d} = p_i \tag{1}$$

Further, we have that electricity consumption is a function of the electricity price p_i:

$$x_i^d = x_i^d(p_i) \rightarrow \quad \frac{\partial V_i}{\partial p_i} = \frac{\partial V_i}{\partial x_i^d} * \frac{\partial x_i^d}{\partial p_i} = p_i * \frac{\partial x_i^d}{\partial p_i} \tag{2}$$

Producer behaviour - Profit maximization

The cost of electricity production can be defined by the function $C_i(x_i^S)$, which is a function of electricity generation x_i^s. By maximizing profit for the generator, we find that:

$$\text{Max } p_i * x_i^S - C_i(x_i^S) \quad \rightarrow \quad \frac{\partial C_i}{\partial x_i^S} = p_i \tag{3}$$

Further, we have that electricity generation is a function of the electricity price p_i:

$$x_i^S = x_i^S(p_i) \quad \rightarrow \quad \frac{\partial c_i}{\partial p_i} = \frac{\partial c_i}{\partial x_i^S} * \frac{\partial x_i^S}{\partial p_i} = p_i * \frac{\partial x_i^S}{\partial p_i} \tag{4}$$

We now have the relations we need in order to address the welfare optimization problem for the NTC, and for the flow-based electricity markets. Let us at first start with the NTC approach.

Welfare maximization – NTC

In NTC, exchange capacity is provided for each border. However, the NTCs themselves, are based on capacities for actual critical grid components with their individual location in the power grid. The NTC capacities are computed by a method where these individual grid components (Critical Network Elements or CNEs) are translated to a border level.

Because the NTCs do not contain any information on how electricity actually flows in an electricity grid, it is not possible to relate the electricity exchange between two particular bidding zones to one particular CNE or border (NTC). It is however possible to relate the maximum export for any particular bidding zone to the total capacity on all NTCs from this particular bidding zone to any other bidding zones. This is also valid for the relation between the max import for any bidding zones and the total capacity from any other bidding zone to this bidding zone.

$$(x_i^s - x_i^d) \leq \textstyle\sum_j NTC_{ij} \qquad \text{Export limitation for bidding zone i} \qquad (5)$$

$$(x_i^s - x_i^d) \geq \textstyle\sum_j NTC_{ji} \qquad \text{Import limitation for bidding zone i} \qquad (6)$$

The two equations above, are the grid constraints applied in the market algorithm for the NTC approach, and we are now ready to formulate and to solve the NTC market optimization problem.

The objective of the market algorithm is to maximize the economic welfare surplus in the electricity market while ensuring that the market solution (in terms of generation and consumption) remains inside the operational security limits as expressed by the export and import limits above. The problem can formally be described as:

$$\text{Max}_{p_i} \textstyle\sum_i V_i(x_i^d) - C_i(x_i^s) \qquad \text{Subject to} \qquad \begin{array}{lll} (x_i^s - x_i^d) & \leq \sum_j NTC_{ij} & \forall^{4}\, i \\ (x_i^s - x_i^d) & \geq \sum_j NTC_{ji} & \forall\, i \\ \sum_i\left(x_i^s - x_i^d\right) & = 0 & \end{array} \qquad (7)$$

We can form the Lagrangian function for this optimization problem as[5]:

$$\begin{aligned} L(p_i, \tau_i^{exp}, \tau_i^{imp}, \lambda\ ) \quad = \quad & \textstyle\sum_i V_i(x_i^d) - C_i(x_i^s) + \tau_i^{exp} * \left[\sum_j NTC_{ij} - (x_i^s - x_i^d)\right] \\ & + \tau_i^{imp} * \left[\left(x_i^s - x_i^d\right) - \textstyle\sum_j NTC_{ij}\right] \\ & + \lambda \quad * \textstyle\sum_i\left(x_i^s - x_i^d\right) \end{aligned} \qquad (8)$$

[4] $\forall$ meaning "for all".

[5] The slack variables for the inequalities have been omitted for simplicity.

Derivation by p_i gives the first order condition for a welfare optimum:

$$\frac{\partial L}{\partial p_i} = p_i * \frac{\partial x_i^d}{\partial p_i} - p_i * \frac{\partial x_i^s}{\partial p_i} - \tau_i^{exp} * \left(\frac{\partial x_i^s}{\partial p_i} - \frac{\partial x_i^d}{\partial p_i}\right) + \tau_i^{imp} * \left(\frac{\partial x_i^s}{\partial p_i} - \frac{\partial x_i^d}{\partial p_i}\right) + \lambda * \left(\frac{\partial x_i^s}{\partial p_i} - \frac{\partial x_i^d}{\partial p_i}\right) = 0 \qquad (9)$$

Which by rearrangement gives:

$$p_i = \lambda + \tau_i^{imp} - \tau_i^{exp} \qquad (10)$$

The interpretation is as follows:

1. If a bidding zone is unconstrained in the optimum market solution, the price in that area equals the price in the slack zone, λ. If no bidding zones are constrained in the optimum market solution, all bidding zone prices are equal to λ.
2. If a bidding zone is constrained by the import limitation (deficit area), the area price will increase compared to the slack price by the shadow cost of the import constraint, τ_i^{imp}.
3. If a bidding zone is constrained by the export limitation (surplus area), the area price will decrease compared to the slack price by the shadow cost of the export constraint, τ_i^{exp}.

Welfare maximization – FB

Similar to the NTC approach, the Flow-Based approach is based on actual grid constraints (CNEs). However, unlike the NTC approach, the constraints are not transposed to the border level, rather they are directly provided to the market algorithm together with Power Transfer Distribution Factors (PTDFs). The capacity for each CNE is called the Remaining Available Margin, or RAM. The RAM has an index relating it to the actual CNE_n as RAM_n.

Each PTDF is a factor describing how much of the injection of one MW in a particular bidding zone and extracted in the "slack zone" will flow on a particular CNE. This means that each bidding zone will have one (zone to slack) PTDF for each (relevant) CNE in the system, and thus each (relevant) CNE will have one (zone to slack) PTDF for each bidding zone. This implies that a zone to slack PTDF will have two indices, one indicating which bidding zone (i), and one which CNE (n) it entails: $PTDF_i^n$.

Based on the zone to slack PTDFs, it is however straight forward to derive the zone to zone PTDFs for any pair of bidding zones (or bilateral exchanges). The zone to zone PTDFs are recognizable by a small change in the lower indices, to now indicate both from zone and to zone. The zone to zone PTDF is derived by:

$$\mathrm{PTDF}_{ij}^{n} = \mathrm{PTDF}_{i}^{n} - \mathrm{PTDF}_{j}^{n} \qquad (11)$$

By introducing PTDFs and RAMs, the FB market is receiving information on physical flows in the power system. Thus, in FB markets, there is a relation between electricity exchanges between bidding zones and the flows on CNEs and borders. This change in market design is significant as it makes it possible for the market participants themselves (through the bids) to decide how transfer capacity should be efficiently allocated between different trades based on welfare economic value.

The introduction of PTDFs does not change the objective of the market algorithm, which is to maximize the welfare economic surplus of the electricity market. The grid constraints however are changed:

$$\sum_i \mathrm{PTDF}_i^n * (x_i^s - x_i^d) \leq \mathrm{RAM}_n \qquad \forall\, n \qquad (12)$$

The FB market optimization problem can formally be described as:

$$\mathrm{Max}_{p_i} \sum_i V_i(x_i^d) - C_i(x_i^s) \quad \text{Subject to} \quad \begin{aligned} &\sum_i \mathrm{PTDF}_i^n * (x_i^s - x_i^d) \leq \mathrm{RAM}_n && \forall\, n \\ &\sum_i \left(x_i^s - x_i^d\right) = 0 && \end{aligned} \qquad (13)$$

The Lagrangian function for this optimization becomes:

$$L(p_i, \rho_n, \lambda) = \sum_i V_i(x_i^d) - C_i(x_i^s) + \sum_n \rho_n * \left[\mathrm{RAM}_n - \sum_i \mathrm{PTDF}_i^n \, (x_i^s - x_i^d)\right] + \lambda * \sum_i \left(x_i^s - x_i^d\right) \qquad (14)$$

Derivation by p_i gives the first order condition for a welfare optimum:

$$\frac{\partial L}{\partial p_i} = p_i * \frac{\partial x_i^d}{\partial p_i} - p_i * \frac{\partial x_i^s}{\partial p_i} - \sum_n \rho_n * \mathrm{PTDF}_i^n * \left(\frac{\partial x_i^s}{\partial p_i} - \frac{\partial x_i^d}{\partial p_i}\right) + \lambda * \left(\frac{\partial x_i^s}{\partial p_i} - \frac{\partial x_i^d}{\partial p_i}\right) = 0 \qquad (15)$$

Which by rearrangement gives:

$$p_i = \lambda - \sum_n \rho_n * \mathrm{PTDF}_i^n \qquad (16)$$

The interpretation is as follows:

1. If the optimum market solution is unconstrained, all shadow cost of limiting CNEs (ρ_n) are zero. In such case prices are equal in all bidding zones and equal to the price in the slack zone, λ.
2. If any CNE becomes limiting to the optimum market result, the shadow cost on that CNE becomes positive. In such situation all bidding zone prices will deviate from the price in the slack zone by its impact (PTDF) on the constraining CNE.

From the equation above, we can subtract p_j from both sides:

$$p_i - p_j = \lambda - \sum_n \rho_n * PTDF_i^n - (- \sum_n \rho_n * PTDF_j^n) \tag{17}$$

Rearranging gives us:

$$p_i - p_j = -\sum_n \rho_n * PTDF_i^n + \sum_n \rho_n * PTDF_j^n = \sum_n \rho_n *(PTDF_j^n - PTDF_i^n) \tag{18}$$

$$p_i - p_j = \sum_n \rho_n * PTDF_{ji}^n \tag{19}$$

The interpretation of this relation is that an optimal market equilibrium requires that the marginal value of a bilateral trade equals the marginal cost of transmission, where ρ_n is the marginal cost (shadow price) of congested element n and the differences in prices is the marginal value (provided that prices in each zone reflects the marginal cost of serving the marginal MWh). If a bilateral trade from j to i has a relieving effect on limiting CNEs (that is when the zone to zone PTDF is negative), the export price must be higher than the import price to reflect the benefit generated by the relieving effect, which is referred to as a non-intuitive flow.

Case study: Non-intuitive flow

In this case study we aim to show that the theory described in the previous chapter apply for the market simulations done in the parallel run. In this case study we only focus on trying to describe the non-intuitive flow going from NO3 to SE2. The same principles, as described below, apply to all other non-intuitive flows as well.

The flow-based market results and the corresponding market results using NTC constraints are shown in Figure 1 for 2022-01-18, MTU 8. The circles represent bidding zones, for which the energy prices are given in numbers, and are coloured from blue to red for increasing prices. Market flows between bidding zones are shown as arrows. The magnitude of the flows are shown as numbers and indicated by the thickness of the arrows. A red arrow indicates a flow towards a bidding zone where the energy price is lower, a so-called "non-intuitive flow". The flow-based market results show several instances of such flows. We shall examine the justification for this below.

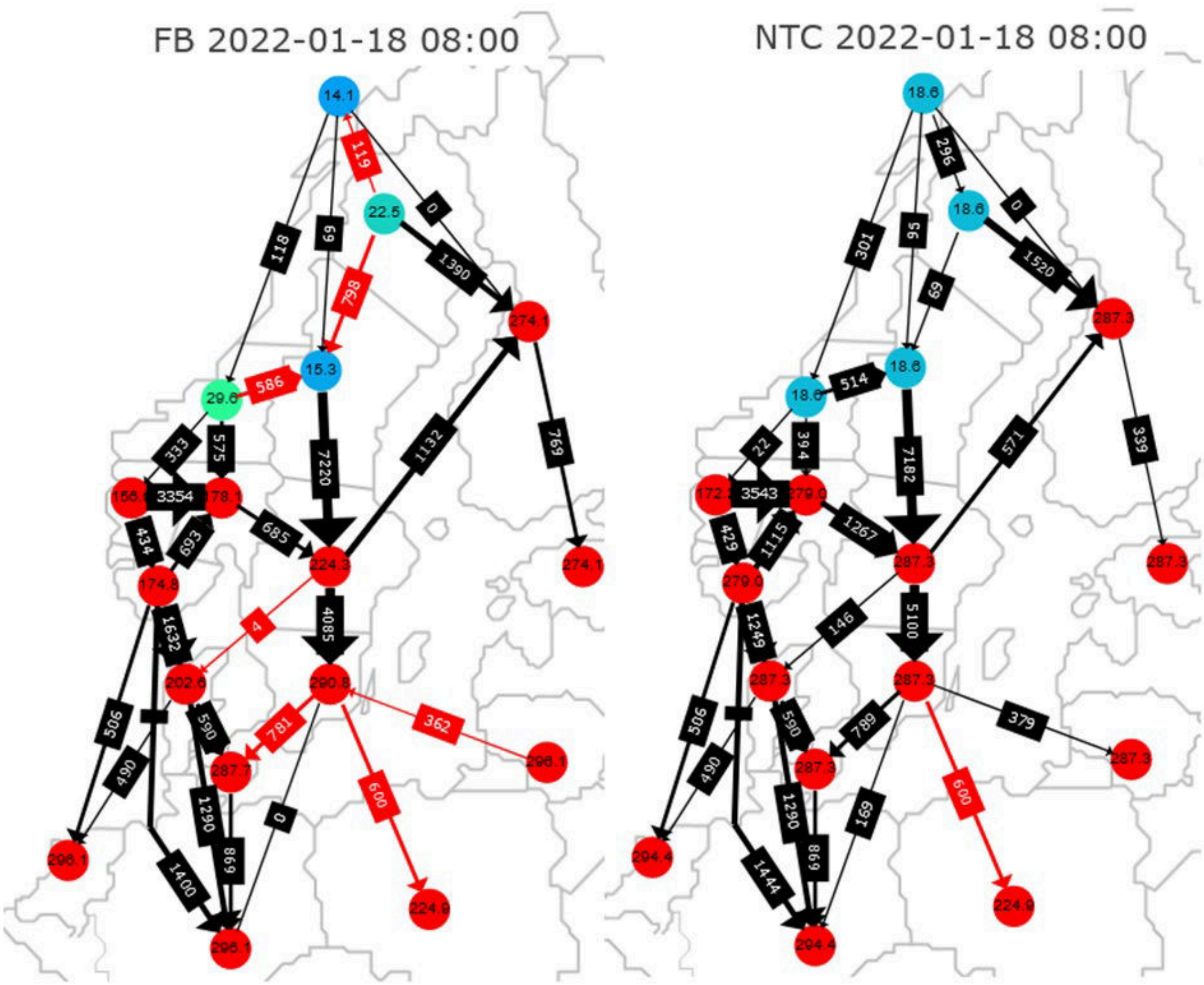

Figure 2. Nordic bidding zone prices for the FB simulation and NTC for MTU 8 on the 18 January 2022.

Some observations from the FB and NTC market illustrations:

- Both market cases show the four northern bidding zones of Norway and Sweden having lower prices than the other parts of the Nordic market.
- The flow-based market manages to export 400 MW more compared to NTC from the northern bidding zones SE1, SE2, NO4 and NO3 to the southern high-price

areas, thus contributing significantly to the increased social welfare, as this export replaces production at much higher costs in the importing bidding zones.

- Some zonal net positions have changed in the FB case, reflecting the prices differing from the NTC results: NO4 export reduced, NO3 and SE1 exports have increased, and SE2 export has decreased, see Figure 2.
- In the NTC case the four low-price areas have the same price, whereas in the FB case, the prices are all different. This is as expected in the flow-based market due to the zonal prices depending on zonal net positions and CNE shadow prices, and not on seemingly uncongested flow on zonal borders as in the NTC market.
- The prices are reduced in most of the high-priced areas, but not in all.

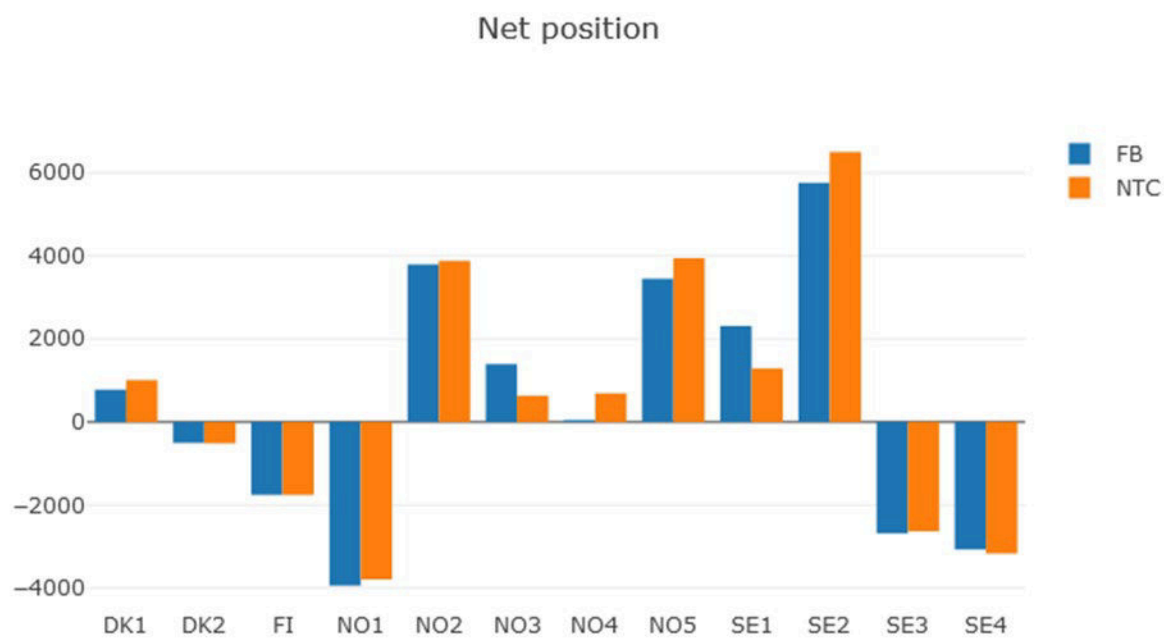

Figure 3. Net positions (NPs) in the Nordic bidding zones for MTU 8 on 18th of January 2022.

We consider the flow from NO3 to SE2, having market prices of 29,6 EUR/MWh and 15,3 EUR/MWh, respectively, and a price difference of 14,3 EUR/MWh. The relevant CNEs shadow prices and PTDF values are shown in Table 1. Table 2 shows the product of the shadow price and PTDF corresponding to the marginal value of relaxing the flow limitation (RAM) for each CNE and corresponding to the net position of each bidding zone see Equation 19.

CNE	Shadow price	PTDF Z2S NO3	PTDF Z2S SE2	PTDF Z2Z SE2-NO3	PTDF Z2Z NO3-SE2
CNE 1	303,320543	0,08128	0,14016	0,05888	-0,05888
CNE 2	251,27586	0	0	0	0
CNE 3	211,874888	0,33969	0,01319	-0,3265	0,3265
CNE 4	158,255881	0,52392	0,93882	0,4149	-0,4149
CNE 5	111,722485	0	0	0	0
CNE 6	111,281198	0	0	0	0
CNE 7	93,507099	0	0	0	0
CNE 8	93,507099	0	0	0	0
CNE 9	85,06981	0	0	0	0
CNE 10	78,483338	1	1	0	0
CNE 11	20,950474	0	0	0	0
CNE 12	8,438872	0	0	0	0
CNE 13	2,779889	0	0	0	0
CNE 14	0	0	0	0	0
CNE 15	0	-0,19894	-0,0224	0,17654	-0,17654

Table 1. CNEs with the largest shadow prices and their PTDF values for MTU 8 on the 18 January 2022.

CNE	$\rho_n * \mathrm{PTDF}_{NO3}^{n}$	$\rho_n * \mathrm{PTDF}_{SE2}^{n}$	$\rho_n * \mathrm{PTDF}_{NO3-SE2}^{n}$
CNE 1	24,65389374	42,51340731	-17,85951357
CNE 2	0	0	0
CNE 3	71,9717807	2,794629773	69,17715093
CNE 4	82,91342117	148,5737862	-65,66036503
CNE 5	0	0	0
CNE 6	0	0	0
CNE 7	0	0	0
CNE 8	0	0	0
CNE 9	0	0	0
CNE 10	78,483338	78,483338	0
CNE 11	0	0	0
CNE 12	0	0	0
CNE 13	0	0	0
CNE 14	0	0	0
CNE 15	0	0	0
Tot	258,0224336	272,3651613	-14,34272767

Table 2. Product of the shadow price and PTDF for CNE's with the highest shadow price.

The energy market price difference is consistent with the transportation costs in the power grid. In Table 2 (underlined) one can see that the marginal value of the bilateral trade equals the marginal cost of transmission.

As can be seen in Figure 1, In FB a greater portion of the south bound flow from the northern part of the Nordics are diverted to Finland compared to NTC. This increase of export from SE3 – FI is made possible by the increased net positions of SE1 and NO3 (Figure 2). The net position increase of NO3 gives rise to a larger export to SE2 and the southern parts of Norway where the prices are higher, causing the price in NO3 to increase. Instead of increasing the net position in SE2, the market algorithm identifies that the marginal cost of transmitting power from NO3 (258,02 €) is lower than the marginal cost of transmission induced by a net position increase in SE2 (272,36 €), see Table 2. Even though the flow between NO3 – SE2 is non-intuitive, the socio-economic benefit is greater than if the flow were to be the other way around (intuitive).

Conclusion

The notion of "non-intuitive flows" comes from the NTC-based market algorithm that maximizes social welfare within constraints defined by NTC limitations on bidding zone borders, or effectively on bidding zone net positions. The flow-based market algorithm takes into account that congestion may occur anywhere in the grid, not only on bidding zone borders, and more importantly, that the cross-border flow may be uncongested while there are internal congestions. The flow-based security domain captures this, and it allows market results that are not feasible according to the NTC domain. It is important to realize that the marginal social value of cross-border trade in the flow-based market coupling is equal to the aggregated marginal value of impacted CNEs, i.e. shadow price * PTDF per CNE. This is also shown in the case study.

To conclude, non-intuitive flows occur when the welfare economic cost of a non-intuitive flow is smaller than the welfare economic benefit of relieving a congestion.

Market impact from high structural export from the Northern Nordic area

As mentioned in the "Disclaimers related to market analysis report (Nordic CCM)" section, external parallel run simulations utilize NTC order books. This is done for the lack of dedicated FB order books, i.e., for the lack of better estimation by TSOs on how market participants would change their bidding behaviour when the capacity calculation is done based on flow based parameters.

It is expected that the FB domains allow for a better utilization of the power grid and transmission. When this happens, FB may allow for higher structural exports from low-priced bidding zones with large hydro reservoirs than NTC. If such flows sustain over time, the overall market outcome may become cumulatively biased in terms of over utilizing cheap hydro power. This is not reflected in the NTC order books that the simulations use. With FB capacity calculation in operation, the market participants in corresponding bidding zones would be expected to adjust their bidding behaviour accordingly, i.e., to reflect the more pressed hydro reservoir release. As a result, the prices for sell orders are expected to increase, resulting in lower net positions than the EPR simulations suggest because the market equilibrium is at a lower volume with higher price level for the supply orders. The impacts on indicators such as bidding zone prices and overall welfare are a result of a complex dynamic, leaving them beyond our estimation without any quantitative estimations on market participants' bidding behaviour changes.

It has been observed in the weekly CCM EPR market reports, and mentioned in the data quality remarks/disclaimers since the start of the EPR, that especially bidding zone NO4 has been affected by the aforementioned phenomenon. Indeed, NO4 has faced significantly higher exports and hence higher prices and producer surplus than the NTC market outcome. The outcome seems to be a combination of the NTC order book issue mentioned above and how the FB domains affecting this area are calculated and modelled. The TSOs are continuously working on the latter to ensure the comparability of the results.