Nordic CCM – Phenomena report

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Abstract

This document 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 document is divided into two parts. In the first part, an introduction is given to why this document is needed and how it is connected to the project. In the second part a deep dive into the phenomena is given.

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1 Introduction

During the parallel run phase of the flow-based methodology in the Nordic capacity calculation region, results from the market coupling simulations based on flow-based parameters are compared to results obtained with the NTC methodology. The comparisons are focused on socioeconomic welfare generated in the market coupling using the two methodologies and the results are presented in market reports which are available at the Nordic RSC's website[1].

When entering external parallel run, market reports are created on a weekly basis and 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 analyzing 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.

[1] Nordic RSC, simulation results: https://nordic-rsc.net/flow-based/simulation-results/.

2 Phenomena

2.1 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.

2.1.1 Welfare optimization theory

2.1.1.1 Consumer behavior - 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:

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

The interpretation of (1) is that in optimum consumers will adjust their consumption so that the benefit of the marginal kWh will be equal to the price paid.

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

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

2.1.1.2 Producer behavior - 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:

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

The interpretation of (3) is that in optimum producers will adjust their generation so that the short run variable marginal cost of the marginal kWh produced will be equal to the price received.

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

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

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.

2.1.1.3 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.

$(x_i^s - x_i^d) \leq \sum_j NTC_{ij}$ *Export limitation for bidding zone I (5)*

$(x_i^s - x_i^d) \geq \sum_j NTC_{ji}$ *Import limitation for bidding zone I (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:

$$Max_{p_i} \sum_i V_i(x_i^d) - C_i(x_i^s) \text{ Subject to } \quad (x_i^s - x_i^d) \leq \sum_j NTC_{ij} \quad \forall^2 i \quad (7)$$

$$(x_i^s - x_i^d) \geq \sum_j NTC_{ji} \quad \forall \text{ i}$$

$$\sum_i (x_i^s - x_i^d) = 0$$

We can form the Lagrangian function for this optimization problem as[3]:

$$L(p_i, \tau_i^{exp}, \tau_i^{imp}, \lambda) = \sum_i V_i(x_i^d) - C_i(x_i^s) + \tau_i^{exp} * [\sum_j NTC_{ij} - (x_i^s - x_i^d)] \quad (8)$$

$$+ \tau_i^{imp} * [(x_i^s - x_i^d) - \sum_j NTC_{ij}]$$

$$+ \lambda \quad * \sum_i (x_i^s - x_i^d)$$

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

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

Which by rearrangement gives:

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

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}.

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2 ∀ meaning "for all".
3 The slack variables for the inequalities have been omitted for simplicity.

2.1.1.4 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:

$$PTDF_{ij}^n = PTDF_i^n - PTDF_j^n \quad (11)$$

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:

$$\sum_i PTDF_i^n * (x_i^s - x_i^d) \le RAM_n \qquad \forall n \qquad (12)$$

The FB market optimization problem can formally be described as:

$$Max_{p_i} \sum_i V_i(x_i^d) - C_i(x_i^s) \ \ \text{Subject to} \qquad \sum_i PTDF_i^n * (x_i^s - x_i^d) \le RAM_n \qquad \forall n \qquad (13)$$

$$\sum_i (x_i^s - x_i^d) \qquad = 0$$

The Lagrangian function for this optimization becomes:

$$L(p_i, \rho_n, \lambda\ ) = \sum_i V_i(x_i^d) - C_i(x_i^s) + \sum_n \rho_n \quad * \left[RAM_n - \sum_i PTDF_i^n * (x_i^s - x_i^d)\right] \qquad (14)$$

$$+ \lambda \quad * \sum_i \left(x_i^s - x_i^d\right)$$

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

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

Which by rearrangement gives:

$$p_i = \lambda - \sum_n \rho_n * PTDF_i^n \quad (16)$$

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 it's impact (PTDF) on the constraining CNE.

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

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

Rearranging gives us:

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

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

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.

2.1.2 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 I for 2022-01-18, MTU 8. The circles represent bidding zones, for which the energy prices are given in numbers, and are colored 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.

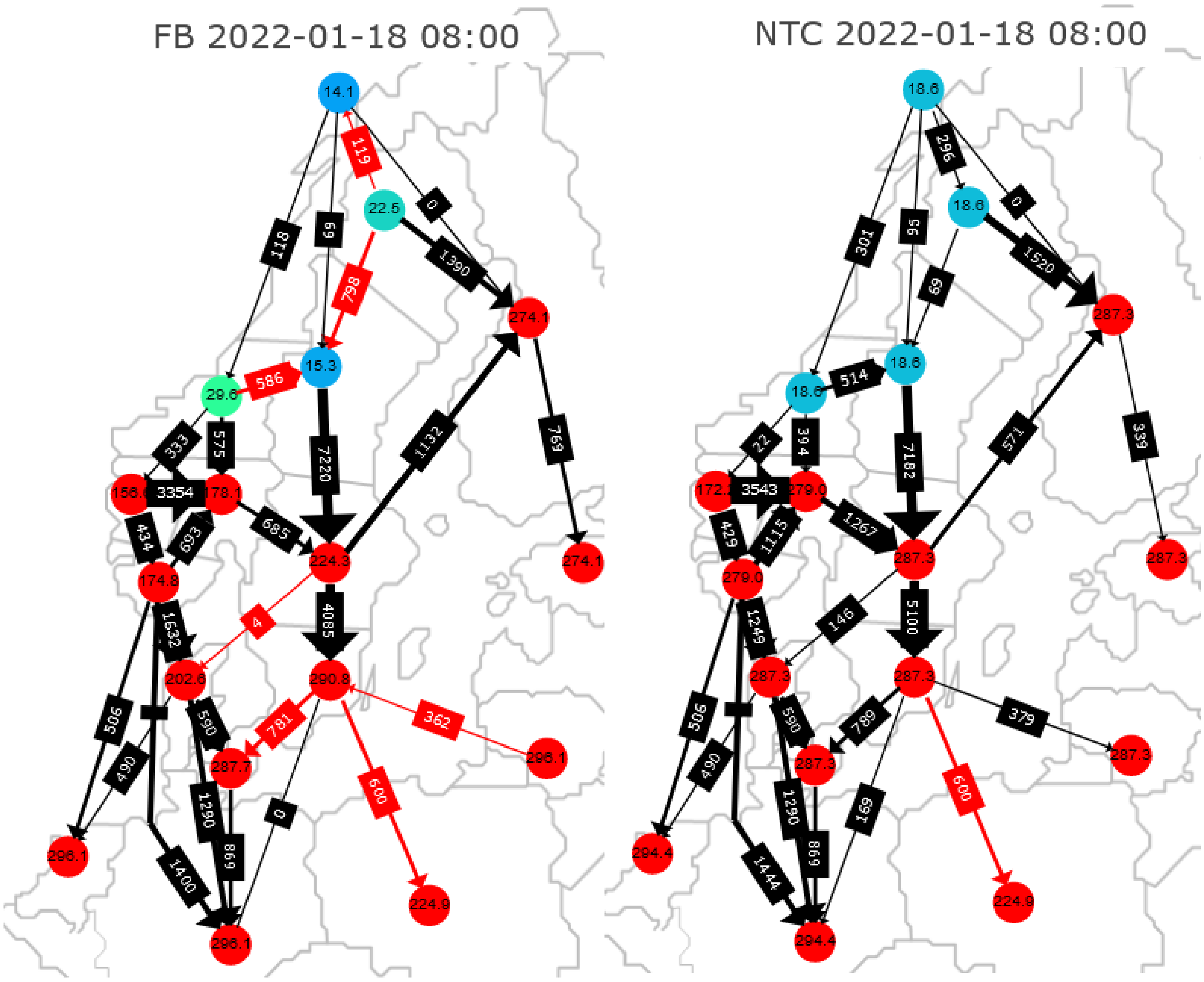

Figure I. Nordic bidding zone prices for the FB and NTC simulations for MTU 8 on the 18th of January 2022.

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 areas: 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 II.
- 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.

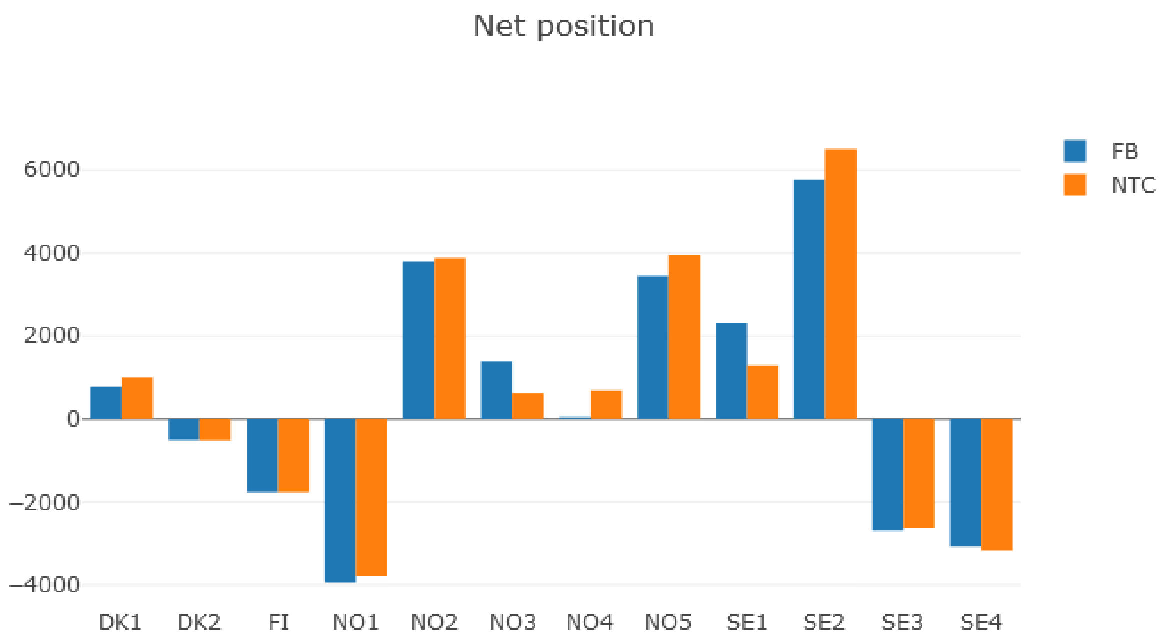

Figure II. Net positions (NPs) in the Nordic bidding zones for MTU 8 on 18th of January 2022

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 (cf. Equation 19).

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

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

CNE	$\rho_n * PTDF_{NO3}^{n}$	$\rho_n * PTDF_{SE2}^{n}$	$\rho_n * PTDF_{NO3-SE2}^{n}$
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

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

As can be seen in Figure I, 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 (see Figure II). 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).

2.1.3 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.