What is Flow-Based Market Coupling?

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Market Expert at Montel Analytics
16/01/2025

1. Market timeline and competition

2. Introduction to Market Coupling

3. Connection to the physical grid

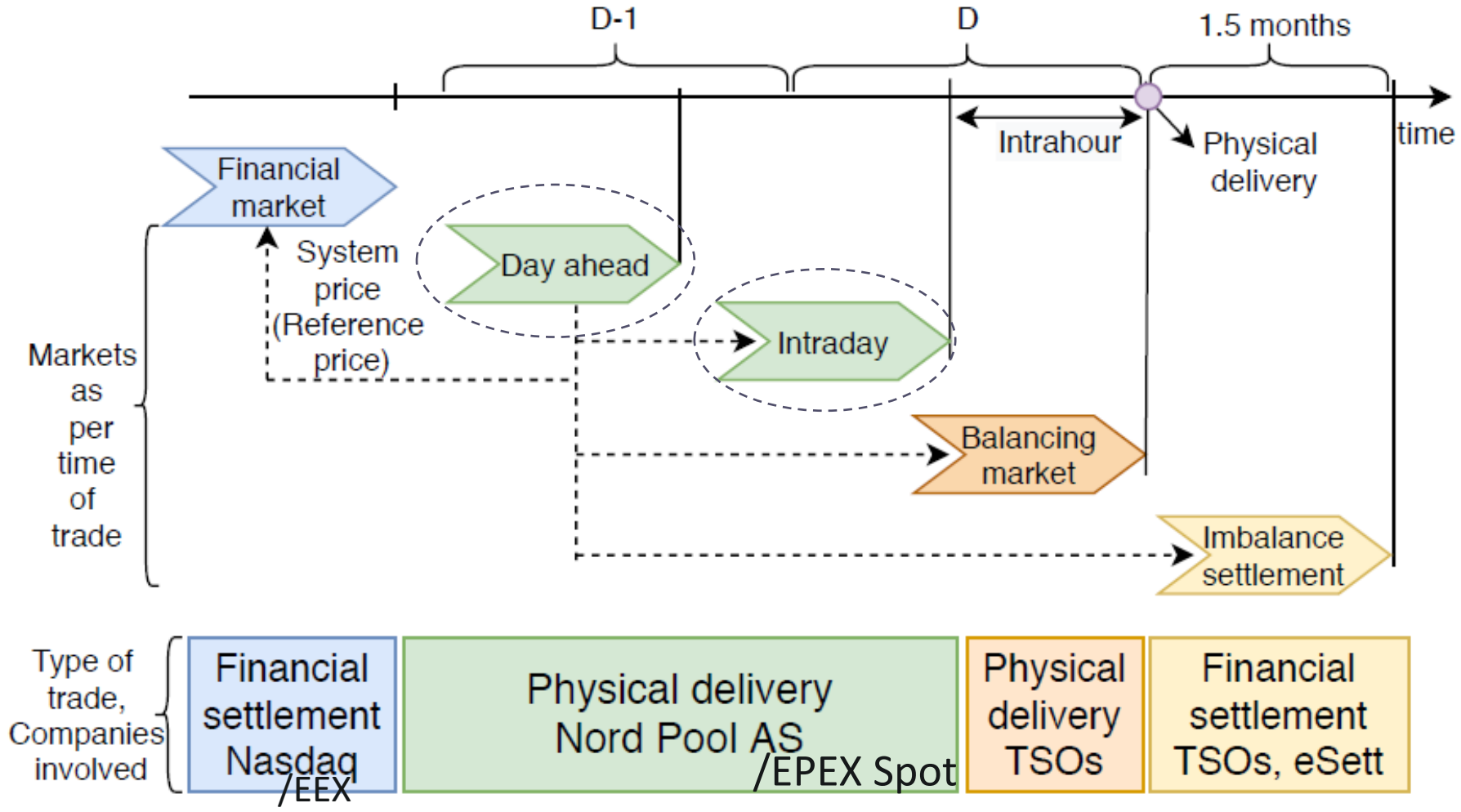
4. Market outcomes to observe after flow-based market coupling

5. Topics for further discussions

6. Conclusion

1. Market timeline and competition

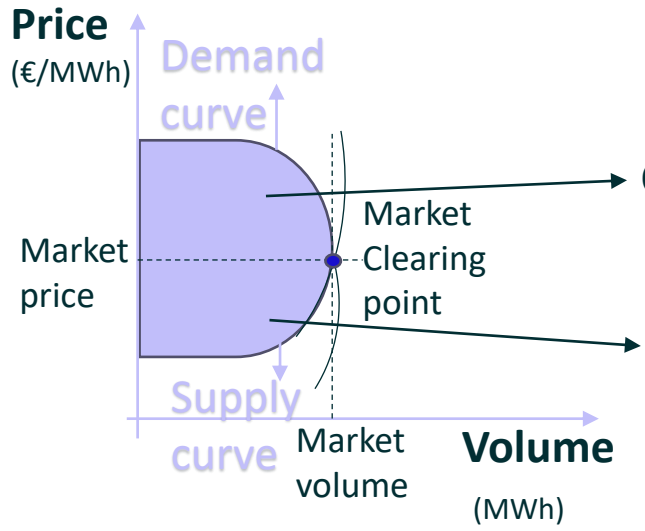
Market Timeline



Source: Khodadadi, A., Herre, L., Shinde, P., Eriksson, R., Söder, L. and Amelin, M., 2020, September. Nordic balancing markets: Overview of market rules. In *2020 17th International Conference on the European Energy Market (EEM)* (pp. 1-6). IEEE.

Competition in market

- To drive innovation, improve transparency



Consumer surplus = Area under the demand curve and up to the market price

+

Producer surplus = Area above the supply curve and up to the market price

=

Social welfare = Area between the supply and demand curve
(total of the supply and demand surplus)

Market clearing point is determined by:

Maximize Social welfare
Subject to:
Supply - demand balance (price = Lagrangian multiplier)
Supply side constraints
Demand side constraints

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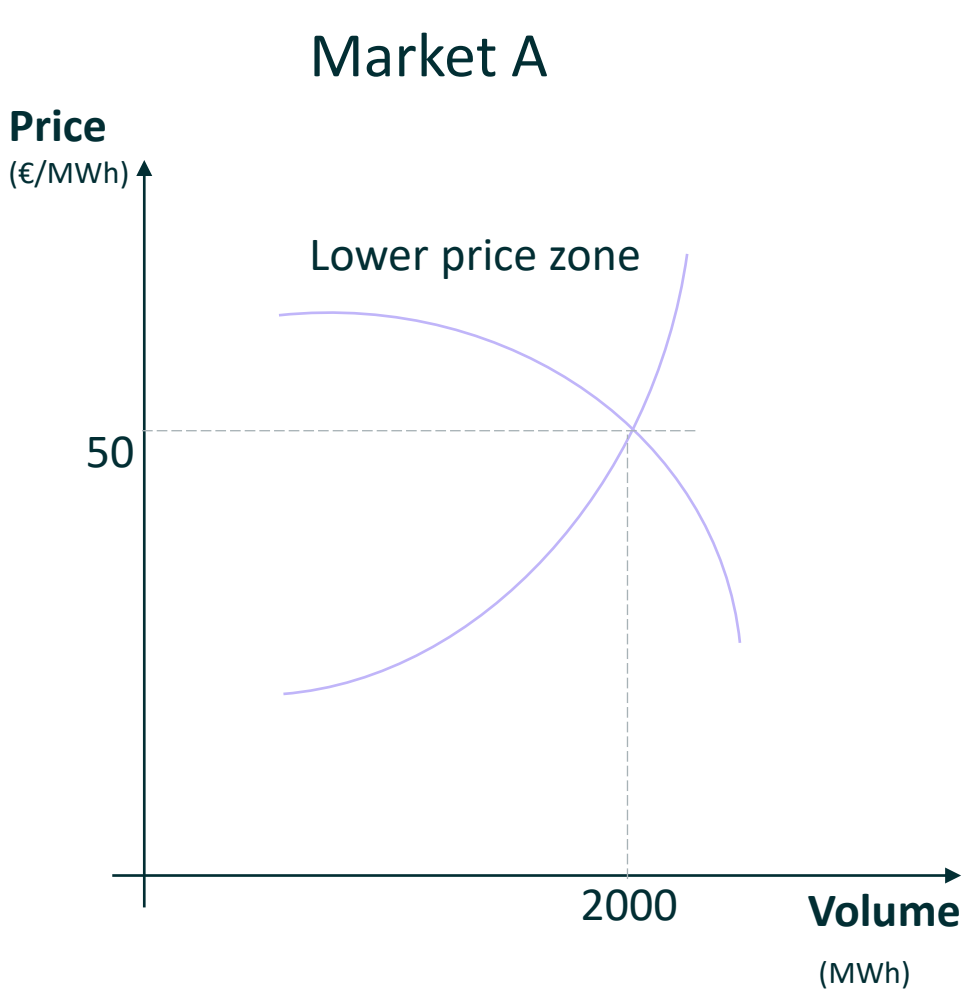
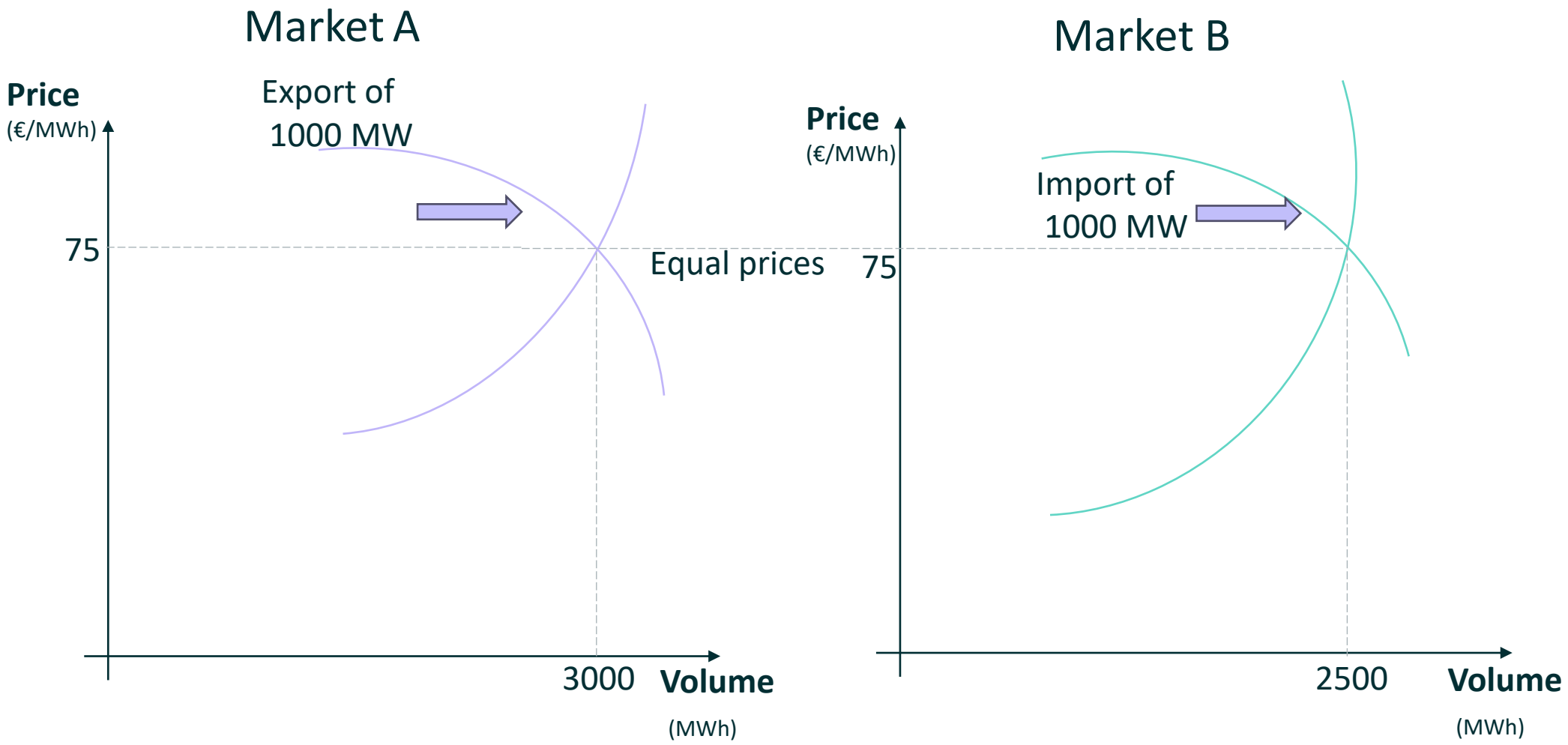
2. Introduction to Market Coupling

Case 1: Uncoupled Markets



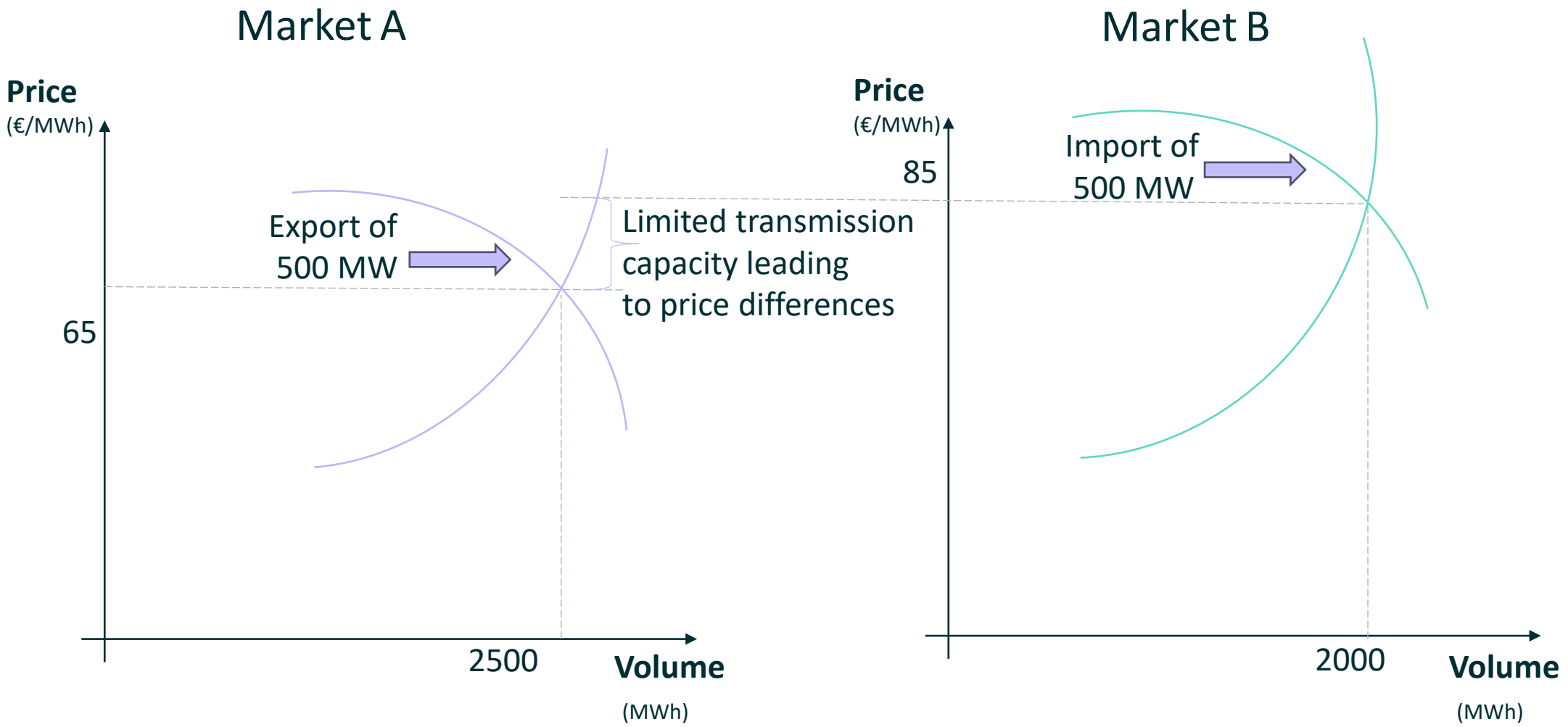
- Bidding zones A and B operate as separate markets and have their own prices due to no exchange in between them.

Case 2: Fully Coupled Markets



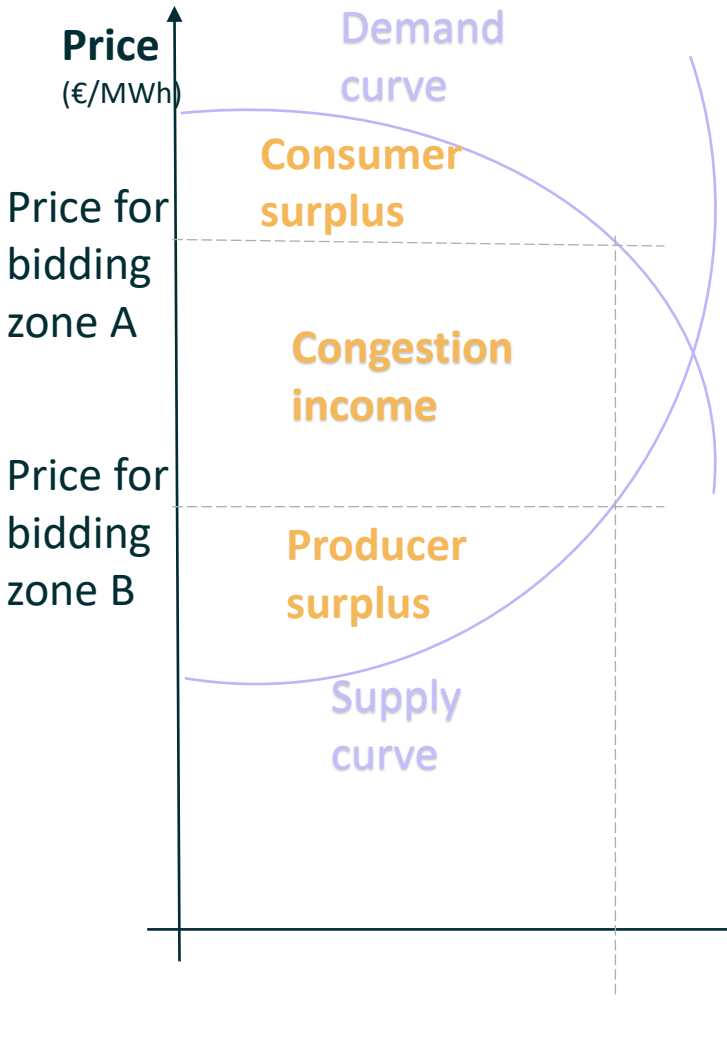
- Bidding zones A and B have enough transmission capacity to allow for exchanges such that prices are equal in both zones.
- Intuitive flows: flow from low price zone to higher price zone (improves social welfare)

Case 3: Partially Coupled Markets



- Price differences arises due to congestion in the network.
- This price difference multiplied by the exchanged volume gives the congestion income to TSOs.

Market clearing with transmission constraints



Social welfare = Producer surplus + Congestion income + Consumer surplus

Market clearing point is determined by:

Maximize Social welfare
Subject to:
Supply - demand balance (price = Lagrangian multiplier)
Transmission constraints
Supply side constraints
Demand side constraints

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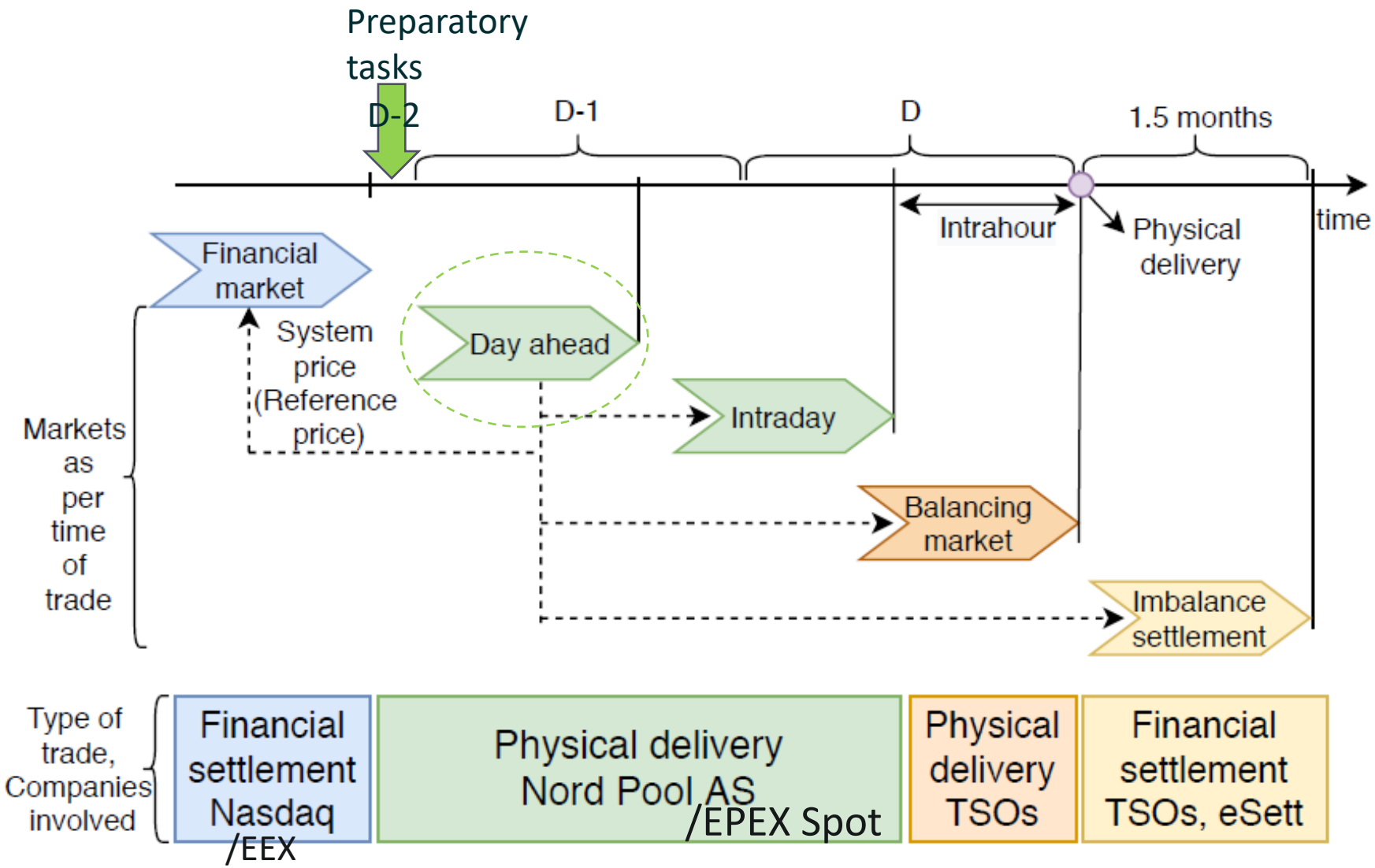
3. Connection to the physical grid

Back to the timeline



Relation of electricity market to physical grid

Physical grid

Detailed grid model

Bidding zone model

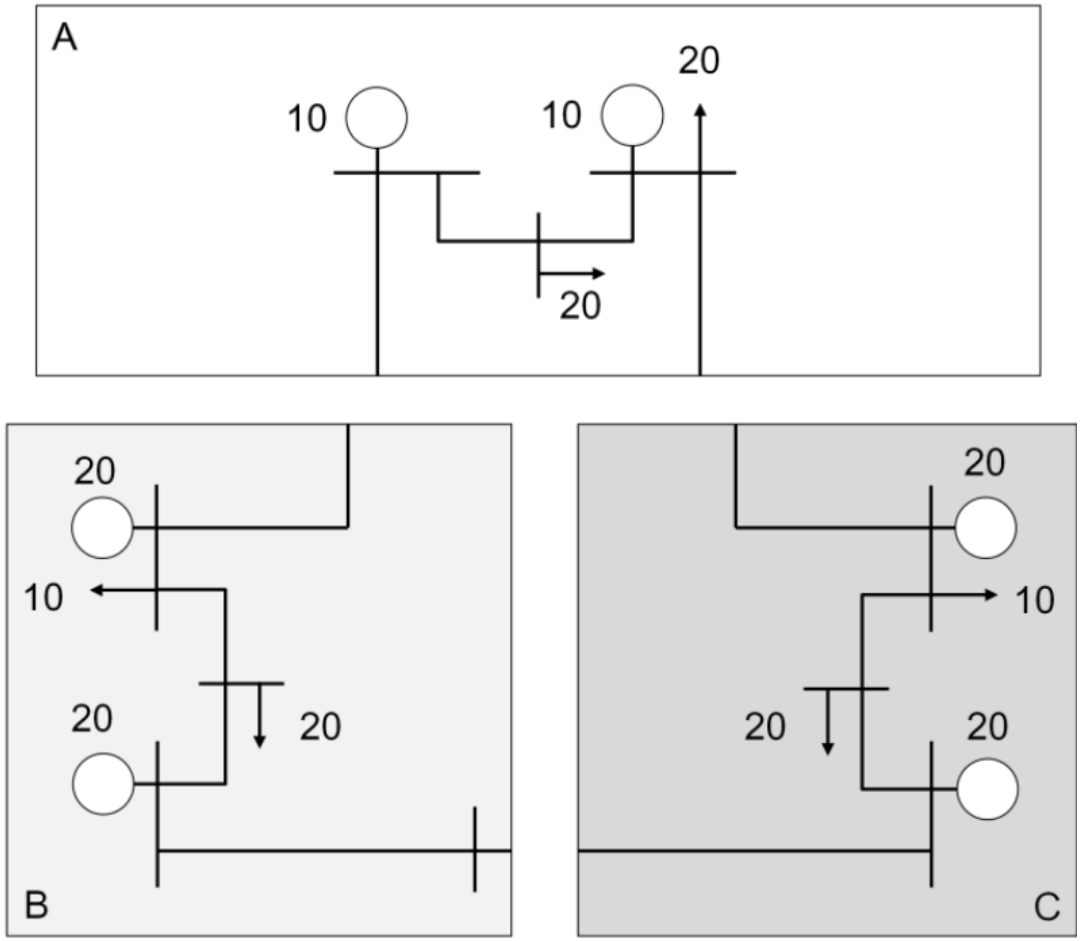
Commercial representation

Capacity calculation is done by translating the complex physical grid into a simplified form that can be utilised by the power exchange

- Zonal pricing: In a zonal market, the transmission system is divided into several zones and the wholesale price of electricity is set for each settlement period, as a separate uniform price for each zone.
- Nodal pricing: The price at each node reflects the locational value of energy (incremental cost of serving one additional MW of load at each location subject to system constraints), including the cost of the energy and the full cost of delivering it including network losses and congestion.

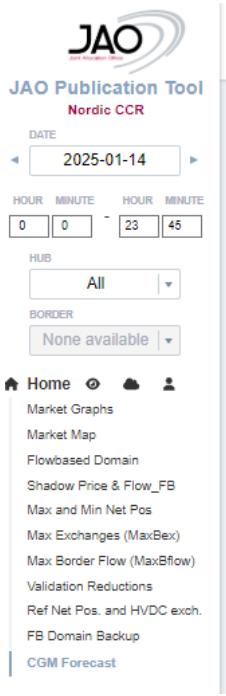
Source of figures: Swedish TSO, SVK

Two days ahead forecast from TSOs



Source: Annex 16.2 Educational example “How does flow-based capacity calculation work?”

Example of D-2 load and generation forecasts

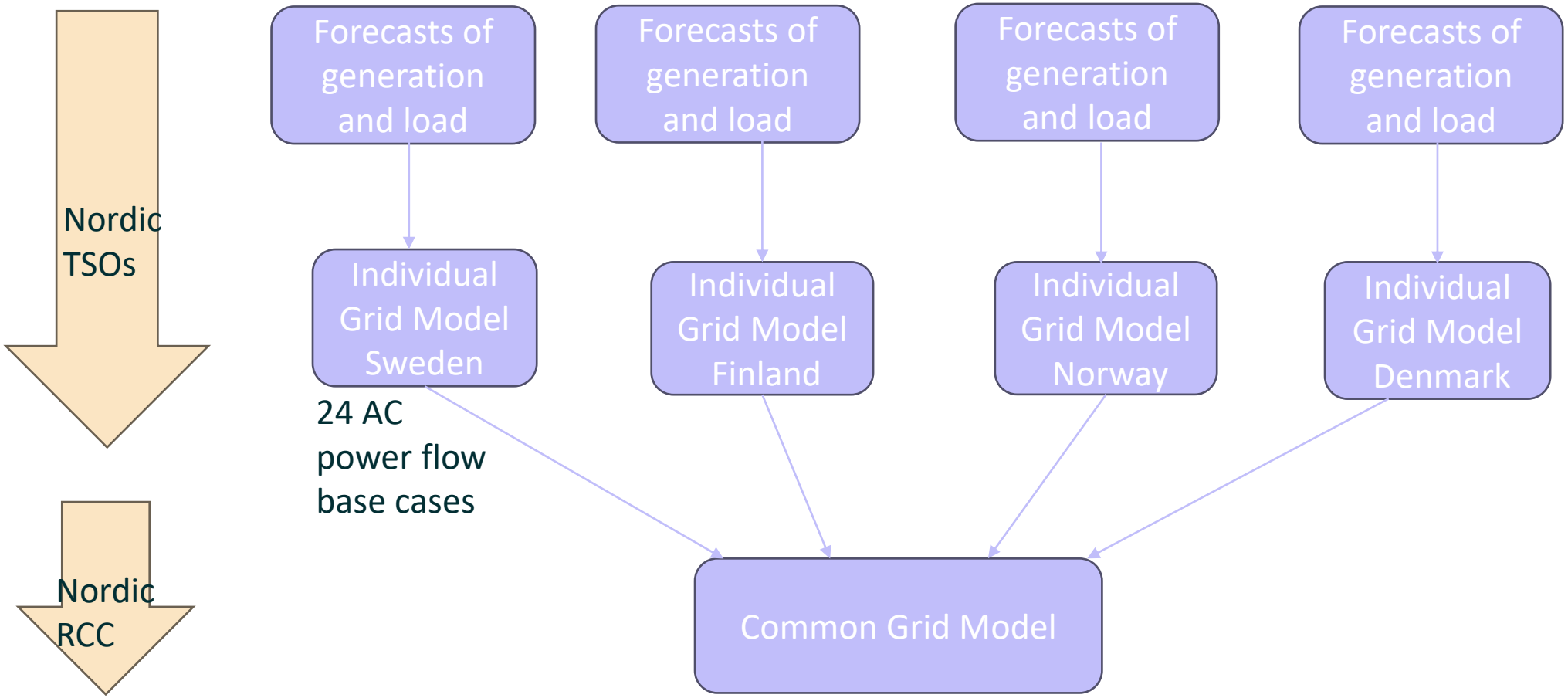


CGM Vertical Load and Generation Forecast

Download

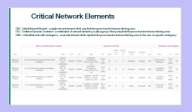
	Vertical Load												Generation											Vertical Load	Gen	Vertical Load	Gen	Vertical Load	Gen	Vertical Load	Gen
Date	DK1	DK2	FI	NO1	NO2	NO3	NO4	NO5	SE1	SE2	SE3	SE4	DK1	DK2	FI	NO1	NO2	NO3	NO4	NO5	SE1	SE2	SE3	SE4	ENERGINET		FINGRID		STATNETT		SvK	
2025-01-14 00:00:00	3485	1830	10414	4089	4549	3484	2306	2100	1337	1432	11711	2820	-3501	-2325	-11649	-2762	-7253	-2532	-2950	-4113	-3121	-7425	-9000	-1821	5315	-5826	10414	-11649	16529	-19610	17300	-21367
2025-01-14 01:00:00	3427	1825	10276	4088	4494	3487	2257	2084	1336	1283	11824	2882	-3437	-2322	-11505	-2764	-7199	-2538	-2899	-4089	-3127	-7418	-9000	-1839	5252	-5759	10276	-11505	16409	-19489	17325	-21383
2025-01-14 02:00:00	3332	1796	10195	3969	4444	3478	2224	2060	1392	1277	11727	2880	-3334	-2303	-11435	-2756	-7149	-2529	-2819	-3951	-3142	-7361	-9000	-1848	5128	-5637	10195	-11435	16176	-19204	17276	-21350
2025-01-14 03:00:00	3286	1781	10212	3848	4434	3473	2212	2048	1418	1288	11628	2843	-3287	-2298	-11469	-2755	-7139	-2523	-2806	-3817	-3139	-7264	-9000	-1829	5067	-5585	10212	-11469	16015	-19040	17177	-21232
2025-01-14 04:00:00	3221	1757	10248	3728	4431	3463	2219	2044	1345	1278	11678	2795	-3221	-2285	-11744	-2756	-7137	-2513	-2814	-3689	-3032	-7109	-9000	-1795	4978	-5506	10248	-11744	15885	-18910	17097	-20935
2025-01-14 05:00:00	3192	1619	10628	4009	4498	3197	2240	2049	1354	1306	9601	3681	-3192	-1297	-11777	-2753	-7199	-3322	-1984	-3992	-3093	-6886	-9000	-1770	4811	-4489	10628	-11777	15993	-19250	15941	-20749
2025-01-14 06:00:00	3066	1543	10871	4809	4790	3445	2325	2173	1290	1432	9996	3916	-3048	-1998	-11705	-2751	-8017	-2489	-2925	-3896	-3065	-7357	-9031	-1764	4608	-5046	10871	-11705	17542	-20077	16634	-21217
2025-01-14 07:00:00	2996	1702	10954	5126	5003	3433	2399	2221	1320	1552	10908	3521	-2906	-2161	-11961	-2737	-7921	-2475	-3002	-4369	-3331	-7681	-9000	-1746	4697	-5068	10954	-11961	18182	-20504	17300	-21758

Individual grid model to common grid model



Steps in Capacity Calculation

IGMs based on production, consumption forecasts

Critical Network Elements 

Generation and load Shift keys

Reliability Margins

Bidding zone definitions

TSOs

Merged Common Grid Model

Flow-based parameters

Nordic RCC

Critical Network Elements

CNE - Critical Network Element - a single network element which may limit the power transfer between bidding zones
CDC - Combined Dynamic Constraint - a combination of network elements (usually a group of lines) may limit the power transfer between bidding zones
CNEC - Critical Network with Contingency - a network element which may limit the power transfer between bidding zones in the case of a specific contingency

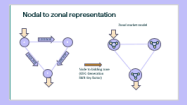
	CNEC or Combined Dynamic Constraint				Information on the CNE							Information on the Contingency		
Date	Name	mRID	Type	TSO	Name	EIC	Status	Bidding Zone From	Bidding Zone To	Substation From	Substation To	Type	Name	EIC	Status
2025-01-16 00:00:00	FI_P0_PYHANSELKA-ISOKANGAS_PIRTTIKOSKI-PIKKARALA	ca0f0dad-767a-11eb-bdca-e470b896f59a	BRANCH	FINGRID	ISOKANGAS - PYHÄNSELKÄ - Terminal: PS: IK4-PS4 1 400	44T-IS-PS-000007	OK	FI	FI	Pyhanselka	Isokangas	CNE	FI_PIRTTIKOSKI - PIKKARALA	44T-PI-PR-000004	NK
2025-01-16 00:00:00	FI_P0_PYHANSELKA-ISOKANGAS_KEMINMAA-PIKKARALA	ca0f0dae-767a-11eb-bdca-e470b896f59a	BRANCH	FINGRID	ISOKANGAS - PYHÄNSELKÄ - Terminal: PS: IK4-PS4 1 400	44T-IS-PS-000007	OK	FI	FI	Pyhanselka	Isokangas	CNE	FI_KEMINMAA - PIKKARALA	44T-KI-PR-00000R	NK
2025-01-16 00:00:00	FI_P1_ALAJARVI-PIKKARALA_J2_TUOVILA-HIRVISUO	e8a0cbaf-767a-11eb-bdca-e470b896f59a	BRANCH	FINGRID	UUSNIVALA - ALAJÄRVI ITÄINEN J2 - Terminal: : UN4ETIT-AJ4 1 400	44T-AJ-PS-00000H	OK	FI	FI	Alajarvi	Pyhanselka	CNE	FI_TUOVILA - HIRVISUO	44T-HI-TU-000003	NK
2025-01-16 00:00:00	FI_P1_ALAJARVI-PIKKARALA_J2_VUOLIJOKI-ALAPITKA	ef19b615-767a-11eb-bdca-e470b896f59a	BRANCH	FINGRID	UUSNIVALA - ALAJÄRVI ITÄINEN J2 - Terminal: : UN4ETIT-AJ4 1 400	44T-AJ-PS-00000H	OK	FI	FI	Alajarvi	Pyhanselka	CNE	FI_VUOLIJOKI - ALAPITKA	44T-VJ-AP-00000Z	NK

Steps in Capacity Calculation

IGMs based on production, consumption forecasts

Critical Network Elements

Generation and load Shift keys



Reliability Margins

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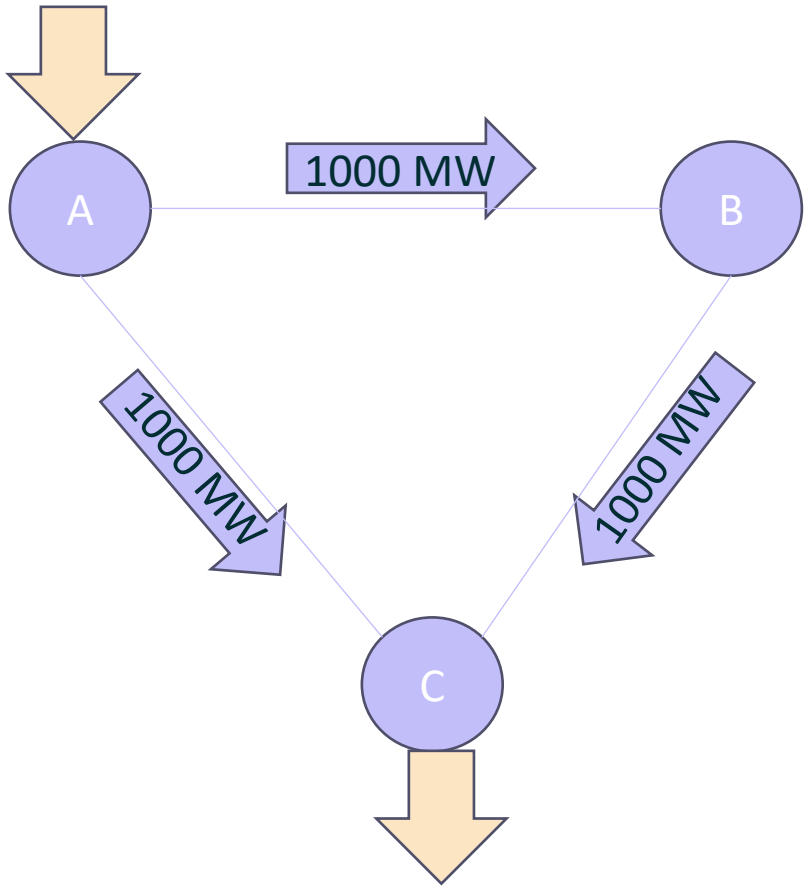
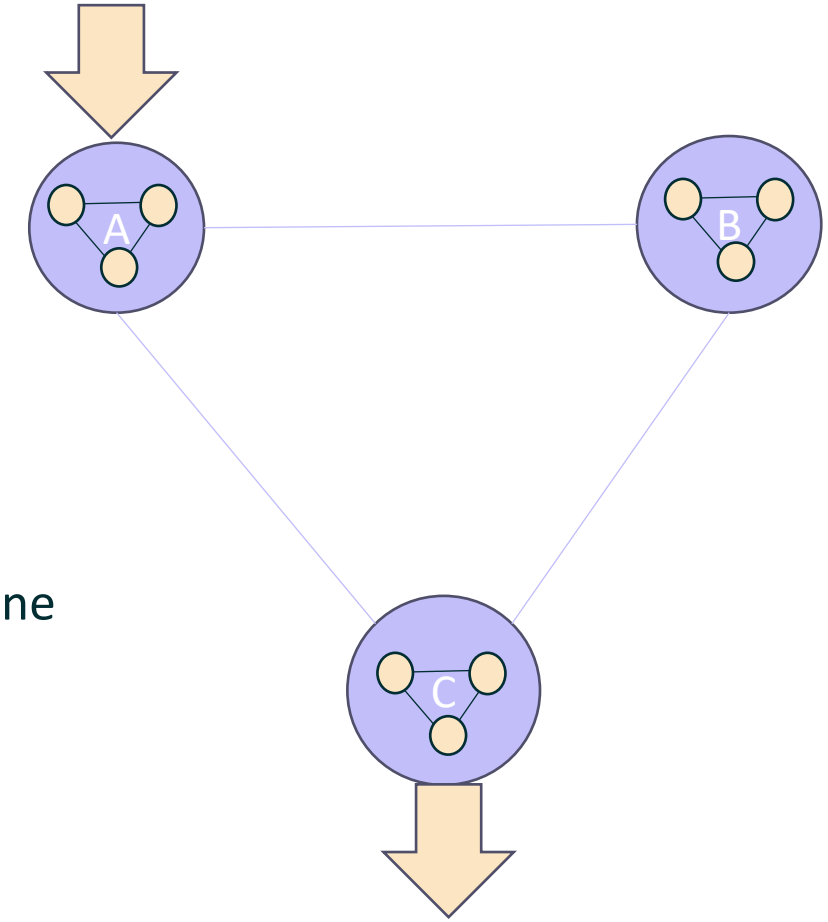
Nordic RCC

Nodal to zonal representation



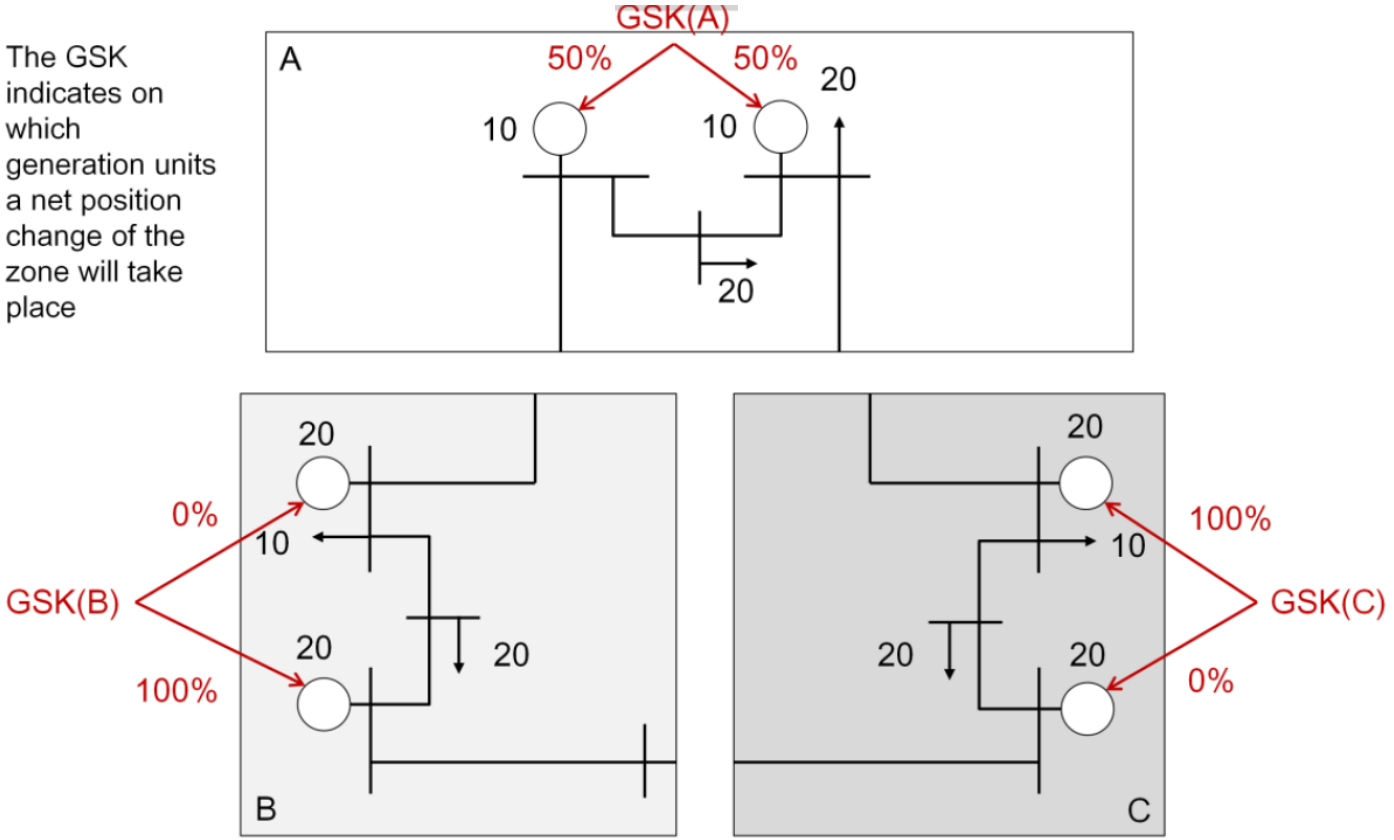
Node to bidding zone
(GSK: Generation
Shift Key factor)

Zonal market model



Generation Shift Key factor

The GSK indicates on which generation units a net position change of the zone will take place



Different GSK strategies

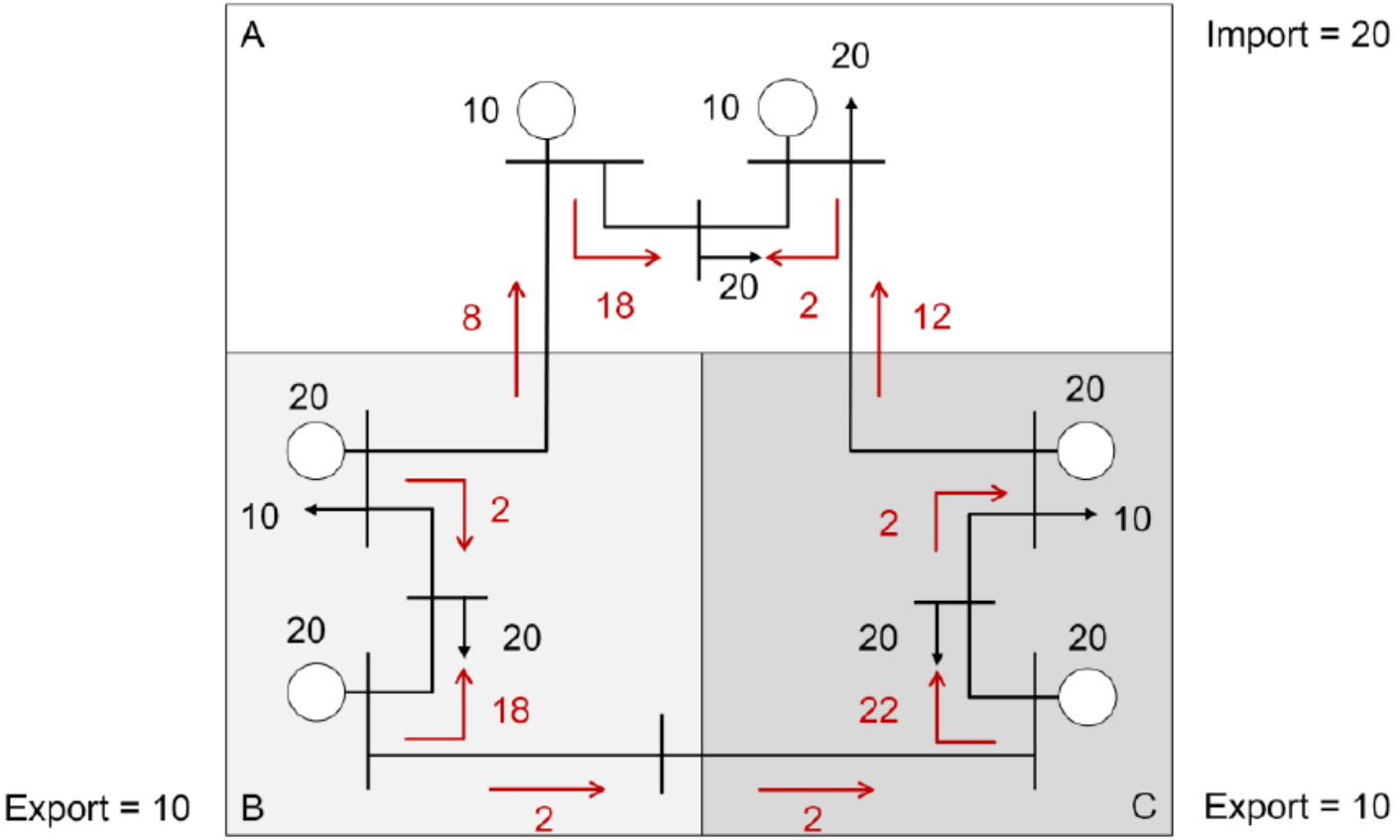
GSK number	Production	Load
1	Max(P-P_{min})	0
2	Max(P_{max}-P)	0
3	P_{max}	0
4	1	0
5	P	0
6	P	Max(0|P)
7	0	Max(0|P)
8	0	1

Generation Shift Key (GSK) defines how a change in net position is mapped to the generating units in a bidding area

Source: Annex 16.2 Educational example “How does flow-based capacity calculation work?”

Merged D2CF grid model

The reference flow (Fref) under N conditions is the physical flow computed from the common base case: it reflects the loading of the critical branches given the exchange programs of the chosen reference day.

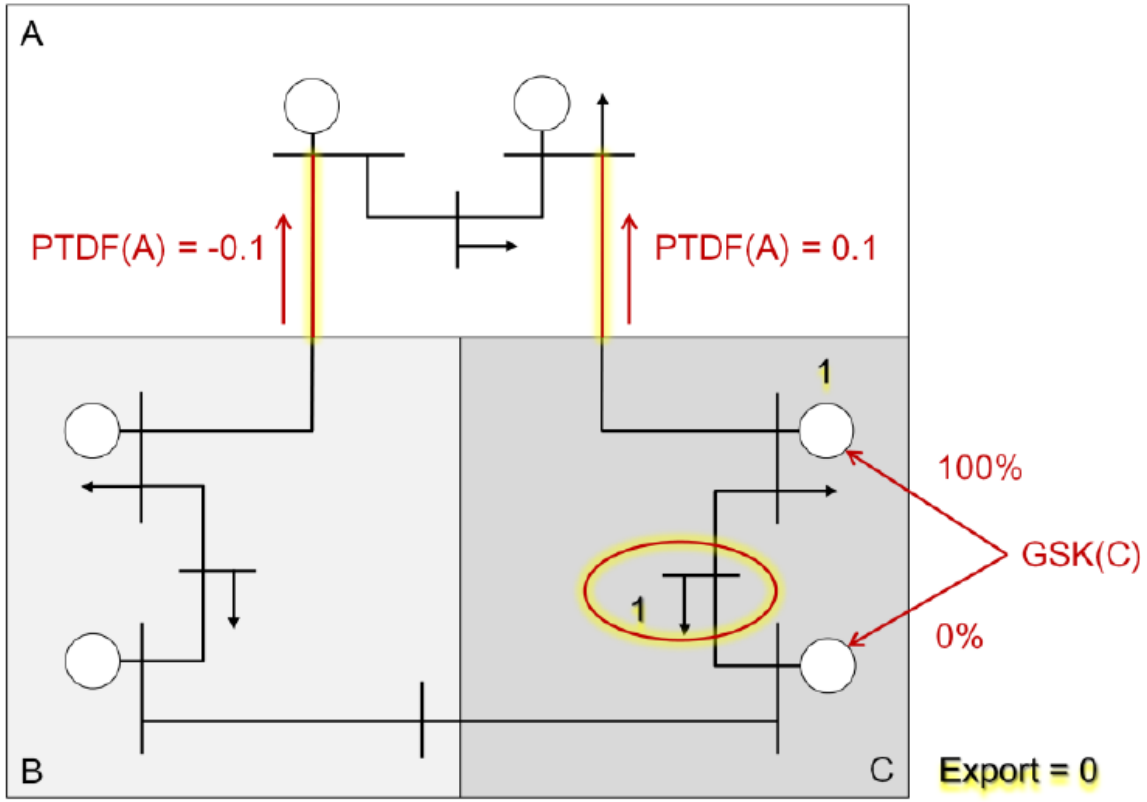


Source: Annex 16.2 Educational example “How does flow-based capacity calculation work?”

Power Transfer Distribution Factor (PTDF)

FB parameter computation: increase of generation in zone C with 1 MW
- Difference compared to the basecase -

PTDF factors resulting from the 1 MW exchange between zone C and the hub for the monitored branches in A under N conditions.



Under N-conditions, the PTDF factors of line 1 and line 2, when changing the net position of zone C, are:

For line 1, the PTDF(C), line1 = -0.1 MW.
For line 2, the PTDF(C), line2 = 0.1 MW.

Source: Annex 16.2 Educational example “How does flow-based capacity calculation work?”

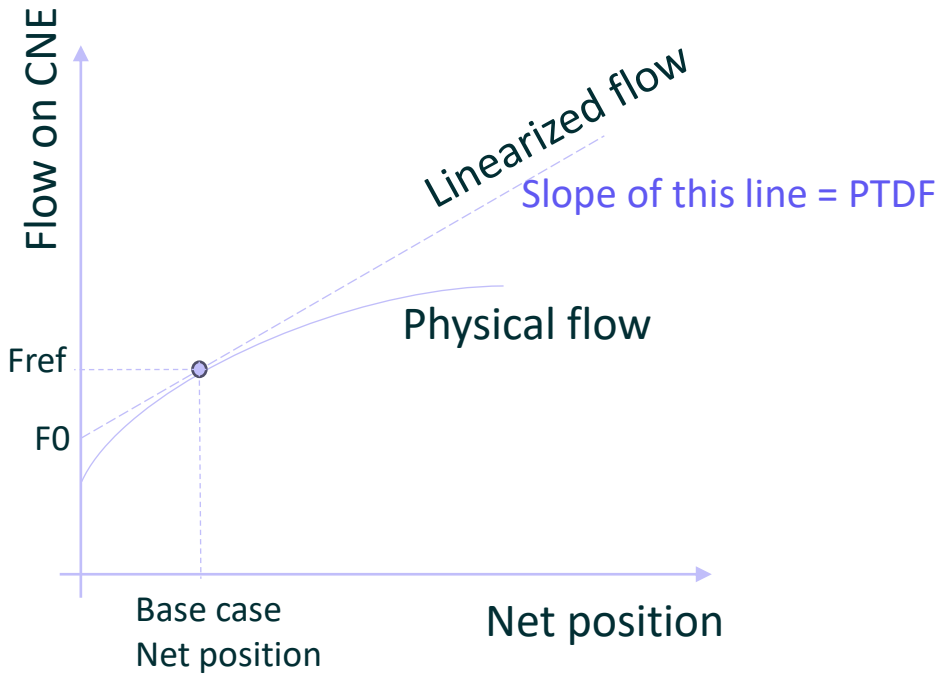
PTDFs of CNECs

	CNEC or Combined Dynamic Constraint				PTDF											
Date	Name	mRID	Type	TSO	DK1	DK2	FI	NO1	NO2	NO3	NO4	NO5	SE1	SE2	SE3	SE4
2025-01-14 00:00:00	FI_RAC_FI-SE1_PETAJASKOSKI-VUENNONKOSKI_KUKKOLANKOSKI-KEMINMAA	023e074e-767a-11eb-bdca-e470b896f59a	BRANCH	FINGRID	0	0	1	0	0	0	0	0	0	0	0	0
2025-01-14 00:00:00	FI_RAC_SE1-FI_KUKKOLANKOSKI-KEMINMAA_OLG2	4a083dd6-767a-11eb-bdca-e470b896f59a	BRANCH	FINGRID	0	0.00001	-0.52717	-0.00683	-0.00645	-0.01773	-0.05694	-0.00784	0.09403	0.00531	0.00424	0.00057
2025-01-14 00:00:00	FI_RAC_SE1-FI_KUKKOLANKOSKI-KEMINMAA_PETAJASKOSKI-VUENNONKOSKI	4a083dd7-767a-11eb-bdca-e470b896f59a	BRANCH	FINGRID	0	0	-1	0	0	0	0	0	0	0	0	0
2025-01-14 00:00:00	FI_P0_KEMINMAA-PIKKARALA_ISOKANGAS-PYHANSELKA	80643459-767a-11eb-bdca-e470b896f59a	BRANCH	FINGRID	0	0	-0.3959	-0.00133	-0.00126	-0.00345	-0.01109	-0.00153	0.01834	0.00104	0.00083	0.00011

...

- Every CNEC at a given time has a PTDF value corresponding to each bidding zone.
- Same CNEC at a different time might have a different PTDF with respect to the same bidding zone.

PTDFs and reference flows



- Physical flows are non-linear function of net positions.
- To find PTDF: DC load flow analysis
- Linearization at Base case net position

F0: Flow on the CNE in case all bidding zones are operating at zero NP.

Fref: reference flow on CNE.

$$Fref = F0 + \Sigma z\ PTDF*NPz$$

Source: Inspired by Nordic RCC presentation

CNECS with reference flows

F0 = Fref - Σz PTDF*NPz

	CNEC or Combined Dynamic Constraint					
Date	Name	mRID	Type	TSO	Fref	F0
2025-01-14 00:00:00	FI_RAC_FI-SE1_PETAJASKOSKI-VUENNONKOSKI_KUKKOLANKOSKI-KEMINMAA	023e074e-767a-11eb-bdca-e470b896f59a	BRANCH	FINGRID	503	0
2025-01-14 00:00:00	FI_RAC_SE1-FI_KUKKOLANKOSKI-KEMINMAA_OLG2	4a083dd6-767a-11eb-bdca-e470b896f59a	BRANCH	FINGRID	120	201
2025-01-14 00:00:00	FI_RAC_SE1-FI_KUKKOLANKOSKI-KEMINMAA_PETAJASKOSKI-VUENNONKOSKI	4a083dd7-767a-11eb-bdca-e470b896f59a	BRANCH	FINGRID	-503	0
2025-01-14 00:00:00	FI_P0_KEMINMAA-PIKKARALA_ISOKANGAS-PYHANSELKA	80643459-767a-11eb-bdca-e470b896f59a	BRANCH	FINGRID	-248	-124

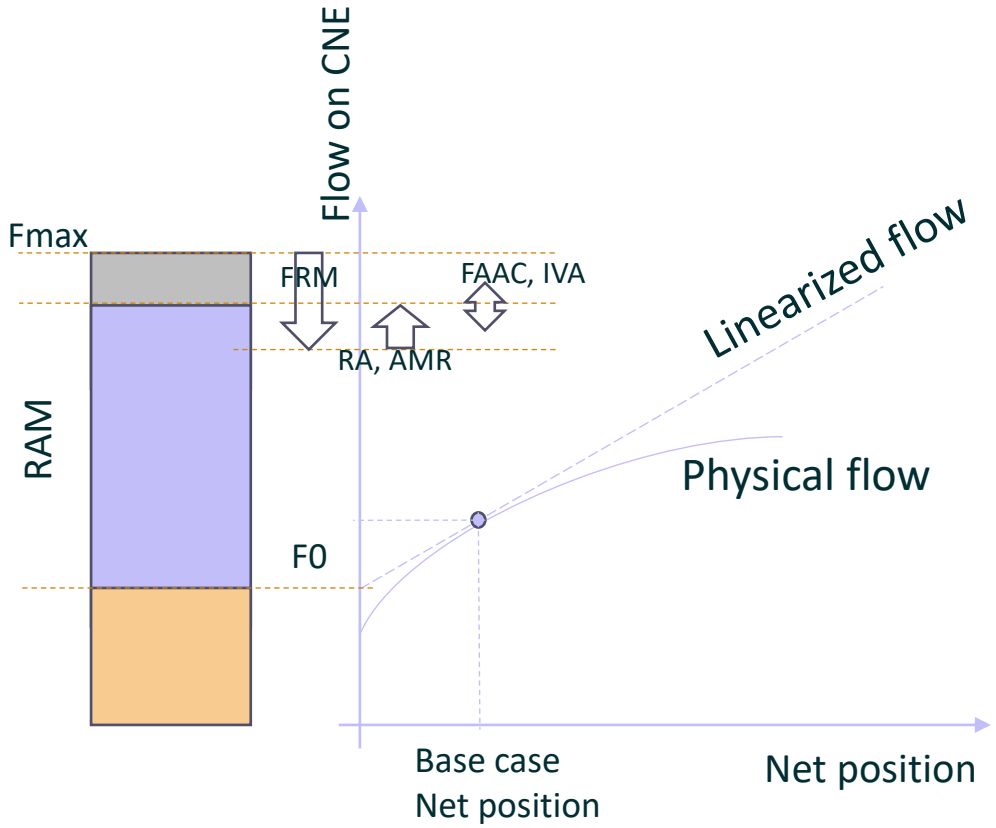
Significant and non-redundant CNECS

	CNEC or Combined Dynamic Constraint				Detailed Breakdown					
Date	Name	mRID	Type	TSO	Non-redundant	Significant	RAM	Min Flow	Max Flow	U
2025-01-14 00:00:00	FI_RAC_FI-SE1_PETAJASKOSKI-VUENNONKOSKI_KUKKOLANKOSKI-KEMINMAA	023e07…767a…eb-…bdca-e47…b896f59a	BRANCH	FINGRID	✗	✓	1457	-1196	1050	412
2025-01-14 00:00:00	FI_RAC_SE1-FI_KUKKOLANKOSKI-KEMINMAA_OLG2	4a083dd6-767a-11eb-bdca-…470b896f59a	BRANCH	FINGRID	✗	✓	1355	-866	1342	402
2025-01-14 00:00:00	FI_RAC_SE1-FI_KUKKOLANKOSKI-KEMINMAA_PETAJASKOSKI-VUENNONKOSKI	4a083dd7-767a-11eb-bdca-…70b896f59a	BRANCH	FINGRID	✗	✓	1588	-1050	1196	402
2025-01-14 00:00:00	FI_P0_KEMINMAA-PIKKARALA_ISOKANGAS-PYHANSELKA	…643459-…-11eb-…e4…	BRANCH	FINGRID	✗	✓	1654	-709	519	403

“True”: the CNEC is constraining the flow-based domain.
“FALSE”: the CNEC represents a redundant constraint

“True”: The constraint has been considered in flow-based parameters calculation. “False”: The constraint has been disregarded in the flow-based parameters calculation.

Deriving Remaining Available Margins (RAM)



- Fmax: the maximum allowed flow on a CNE/operational security limit

- This maximum flow is then altered due to:
  - Flow Reliability Margin (FRM) (accounting for uncertainties in forecasts/modelling errors)
  - Remedial Action (RA)
  - AMR (Adjustment for min RAM to ensure RAM >=0)
  - FAAC (Already allocated capacity on CNE for FRR)
  - IVA (Individual validation adjustment by TSOs during domain validation)

- The net capacity available after the alterations:
  Fmax – FRM + RA +AMR – FAAC - IVA

- The flow on CNE can be given as: F0 + Σz PTDF * NPz

- Market constraint:
  F0 + Σz PTDF*NPz <= Fmax – FRM + RA +AMR – FAAC - IVA
  Σz PTDF*NPz <= RAM

  where RAM = Fmax– FRM– F0 + RA + AMR– FAAC– IVA

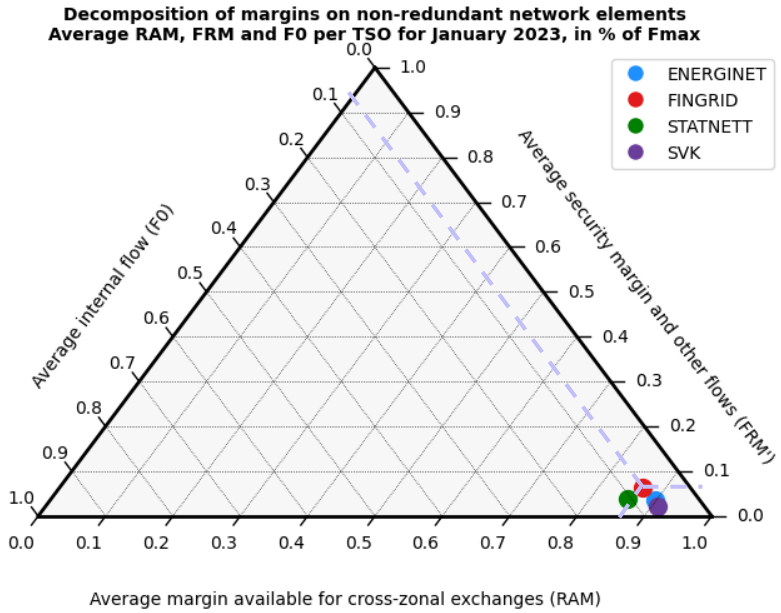
Source: Inspired by Nordic RCC presentation

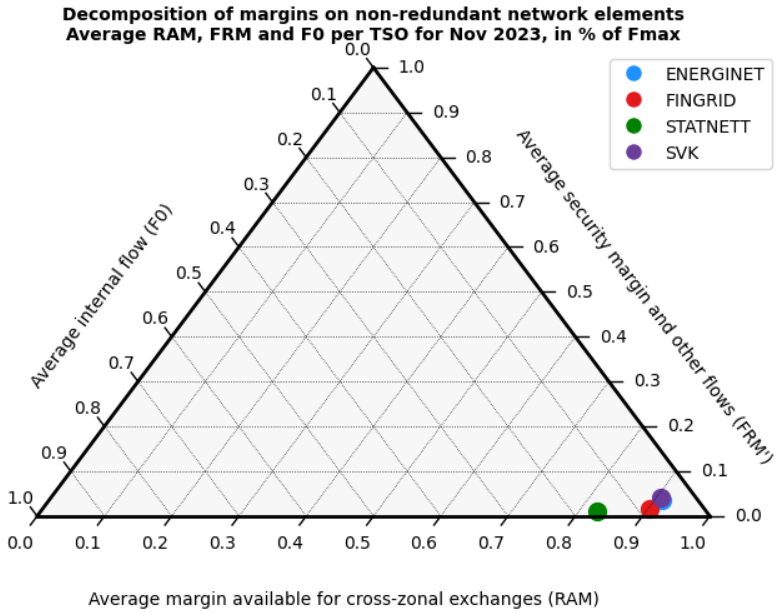
Flow parameters on CNECs

	CNEC or Combined Dynamic Constraint															
Date	Name	mRID	Type	TSO	RAM	Min Flow	Max Flow	U	Imax	Fmax	FRM	Fref	F0	FRA	AMR	FAAC	IVA
2025-01-14 00:00:00	FI_RAC_FI-SE1_PETAJASKOSKI-VUENNONKOSKI_KUKKOLANKOSKI-KEMINMAA	023e074e-767a-11eb-bdca-e470b896f59a	BRANCH	FINGRID	1681	-711	507	404	2444	1625	81	-16	-143	0	0	6	0
2025-01-14 00:00:00	FI_RAC_SE1-FI_KUKKOLANKOSKI-KEMINMAA_OLG2	4a083dd6-767a-11eb-bdca-e470b896f59a	BRANCH	FINGRID	1658	-673	507	404	2444	1625	81	8	-121	0	0	7	0
2025-01-14 00:00:00	FI_RAC_SE1-FI_KUKKOLANKOSKI-KEMINMAA_PETAJASKOSKI-VUENNONKOSKI	4a083dd7-767a-11eb-bdca-e470b896f59a	BRANCH	FINGRID	1472	-459	653	404	2444	1625	81	191	63	0	0	9	0
2025-01-14 00:00:00	FI_P0_KEMINMAA-PIKKARALA_ISOKANGAS-PYHANSELKA	80643459-767a-11eb-bdca-e470b896f59a	BRANCH	FINGRID	1179	-240	328	412	1870	1267	63	56	25	0	0	0	0

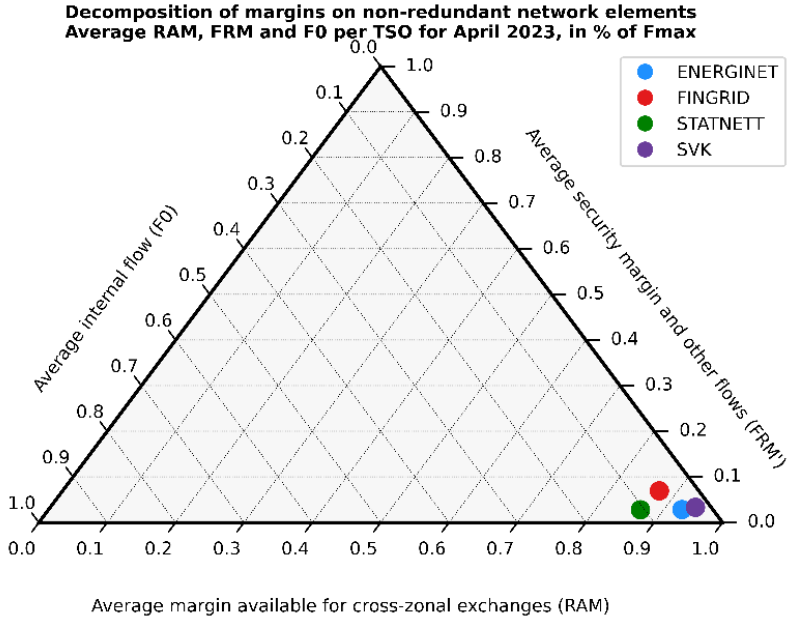
Ternary plots for decomposition of margins in the Nordics

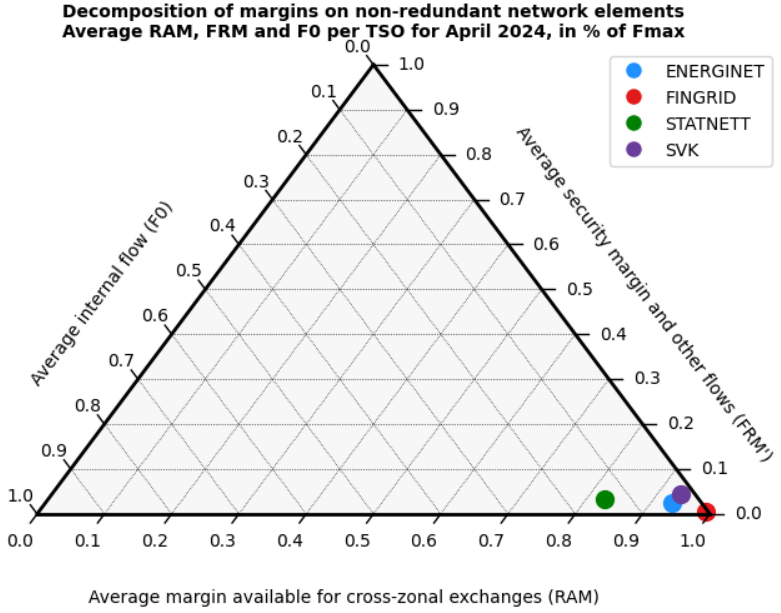
RAM
= Fmax – FRM – F0 – AAC + RA + AMR - IVA



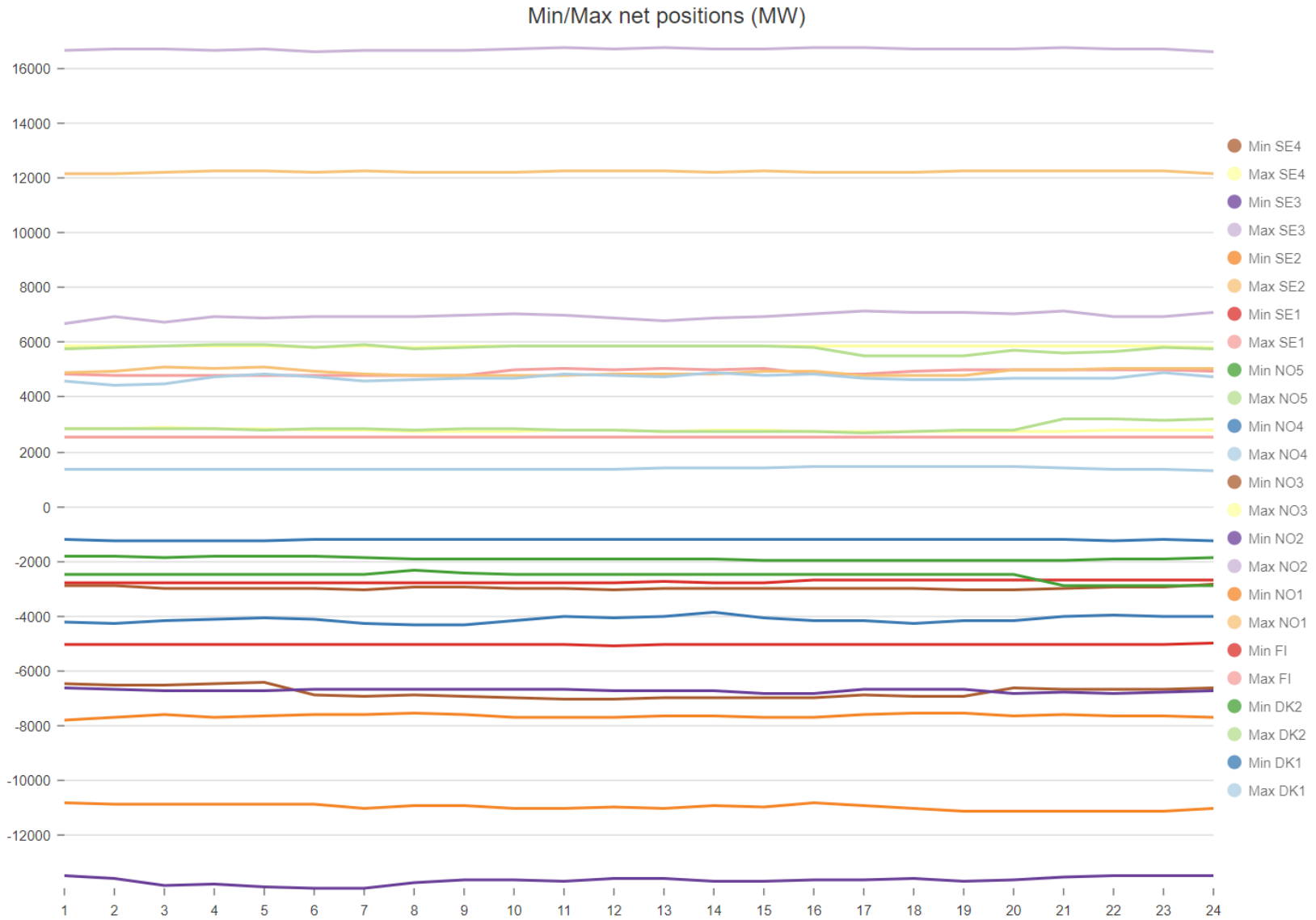


FRM'
= FRM – RA – AMR + AAC + IVA





Bounds on net positions



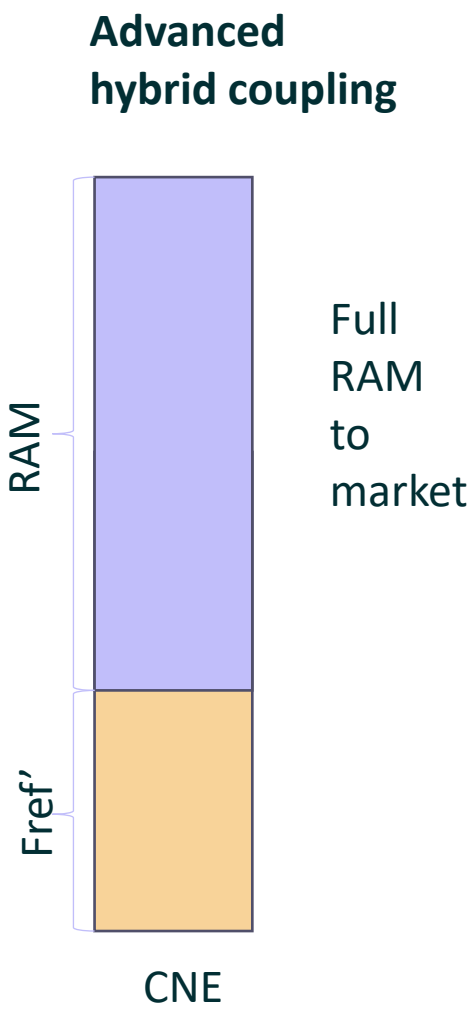
- In the presence of Long-term Allocation (LTA), it would also need to be considered along with FB domain by taking convex hull of both to determine the bounds.

Bounds on net positions

Min and Max Net Positions

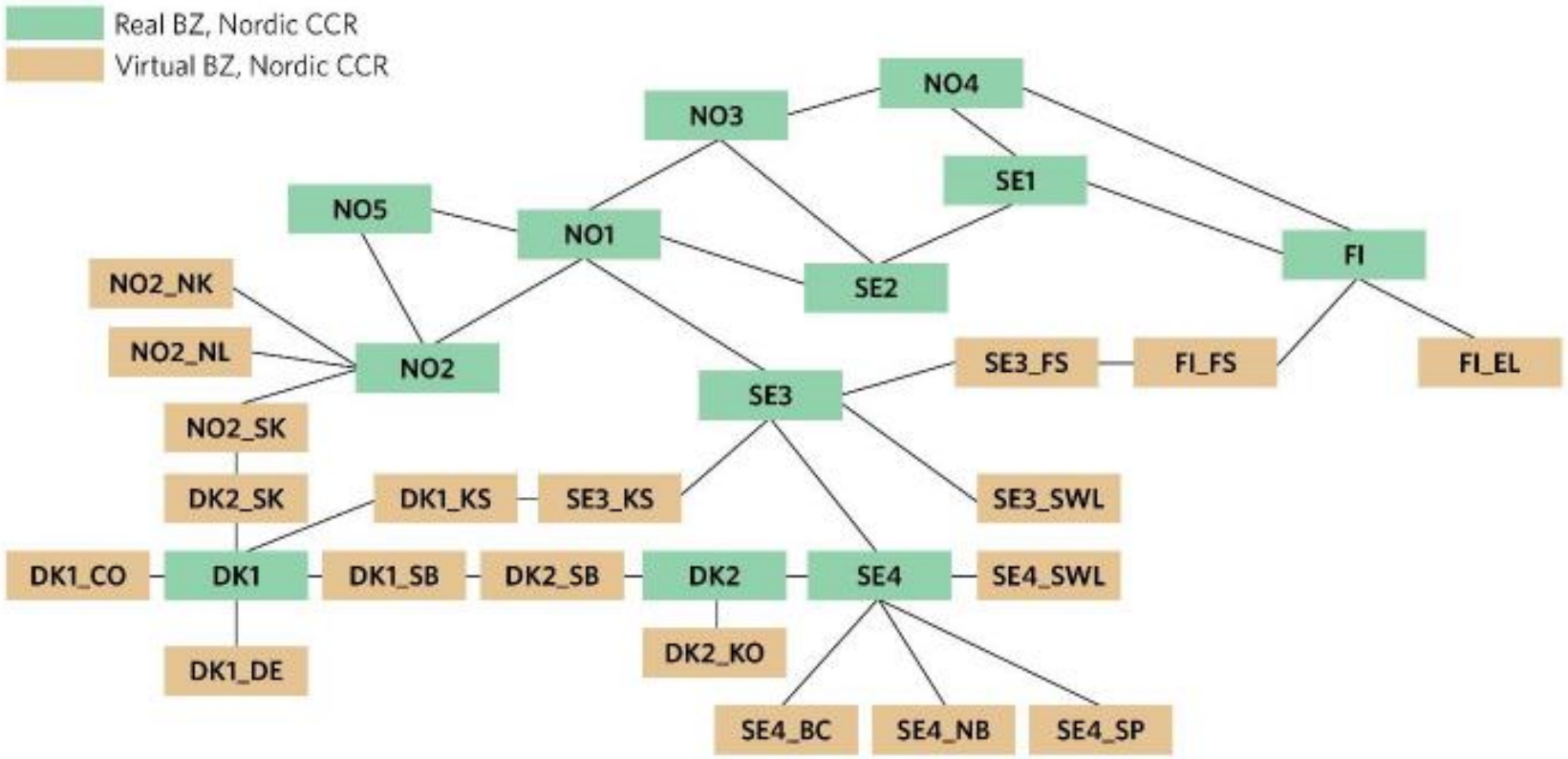
Date	lin _FS	Min SE3_KS	Min SE3_SWL	Min SE4	Min SE4_BC	Min SE4_NB	Min SE4_SP	Min SE4_SWL	Max DK1	Max DK1_CO	Max DK1_DE	Max DK1_KS	Max DK1_SB
2025-01-16 00:00:00	200	-715	-1200	-6477	-615	-700	-600	0	4577	700	2500	715	600
2025-01-16 01:00:00	200	-715	-1200	-6515	-615	-700	-600	0	4442	700	2500	715	600
2025-01-16 02:00:00	200	-715	-1200	-6505	-615	-700	-600	0	4458	700	2500	715	600
2025-01-16 03:00:00	200	-715	-1200	-6444	-615	-700	-600	0	4750	700	2500	715	600
2025-01-16 04:00:00	200	-715	-1200	-6421	-615	-700	-600	0	4840	700	2500	715	600

HVDC lines as virtual bidding zones



- Flow on HVDC lines and radial AC lines are controllable by operators (unlike AC lines in a meshed network).
- For HVDC lines, market can schedule a flow and operator can realize it.
- Advanced hybrid coupling is a method popularly used for managing HVDC and AC lines in the same network.
- PTDFs of the transformer station at HVDC lines used for calculating flows due to HVDC lines on AC lines.

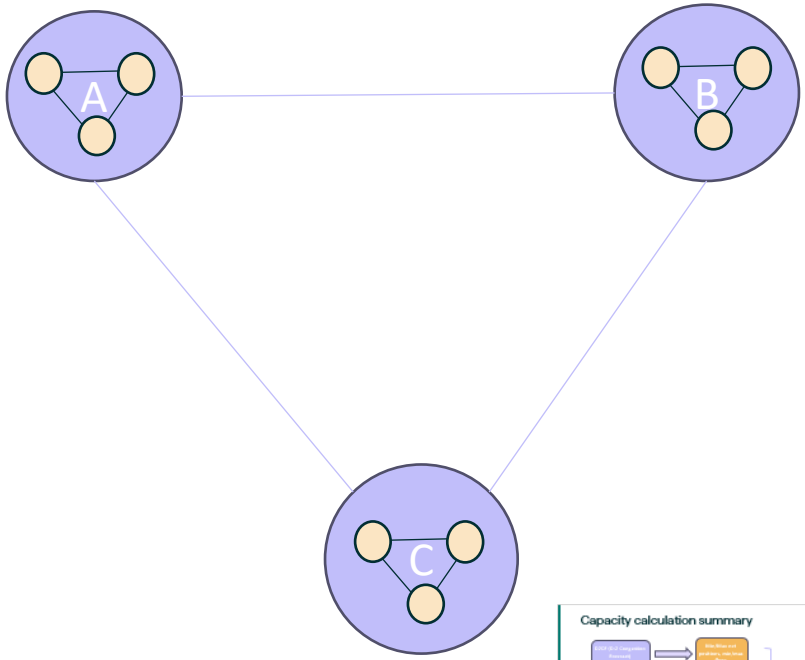
Nordic Capacity Calculation Region (CCR) topology

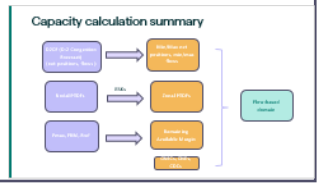


- 12 real bidding zones in the Nordics
- HVDC links are also modelled as bidding zones in the flow-based methodology
- 19 HVDC links lead to 19 virtual bidding zones
- Total bidding zones: 31

Process of market coupling

Capacity Calculation





TSOs and Nordic RCC

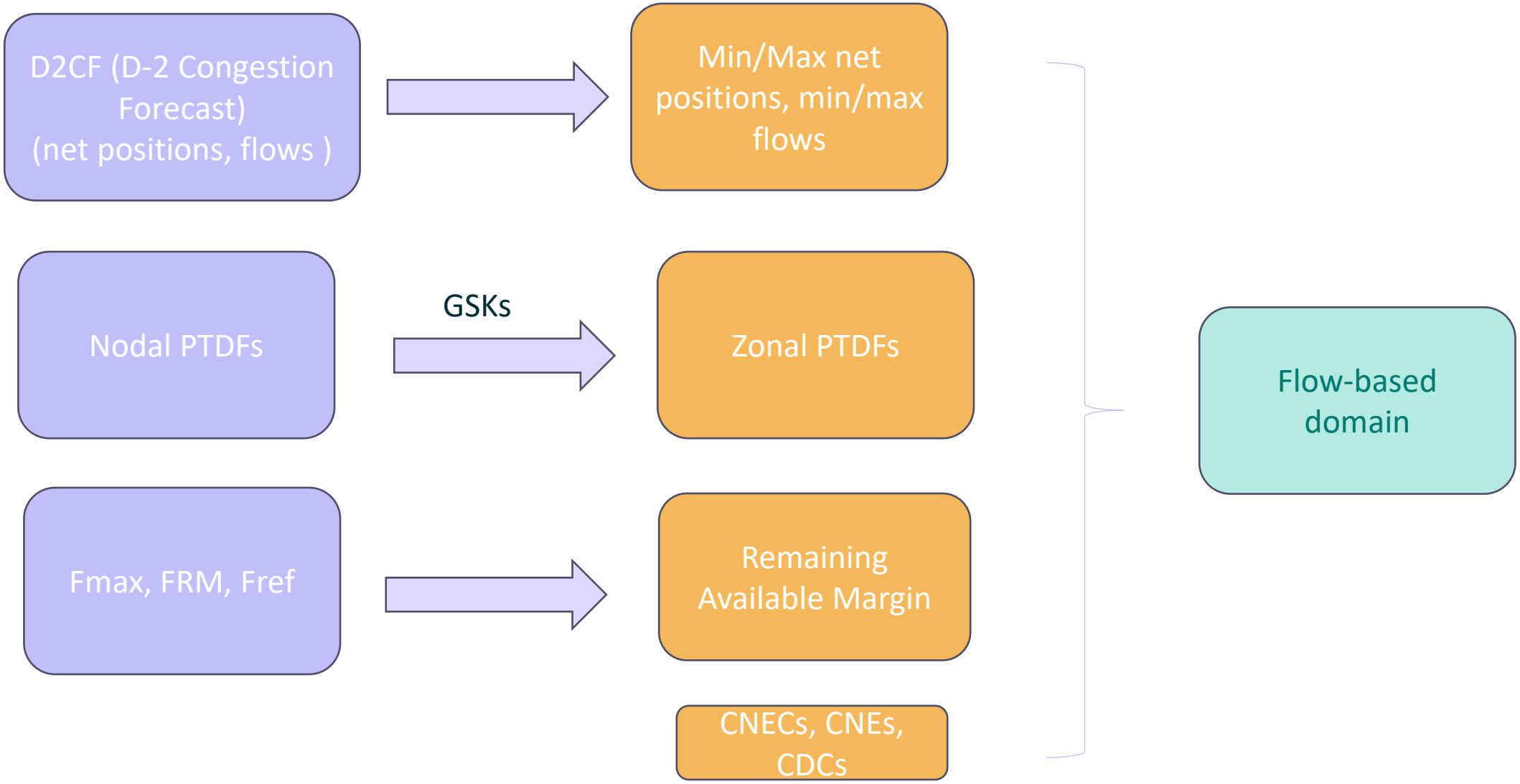
Capacity allocation

Maximize Social welfare
Subject to:
Supply - demand balance
(price = Lagrangian multiplier)
Transmission constraints
Supply side constraints
Demand side constraints

NEMOs

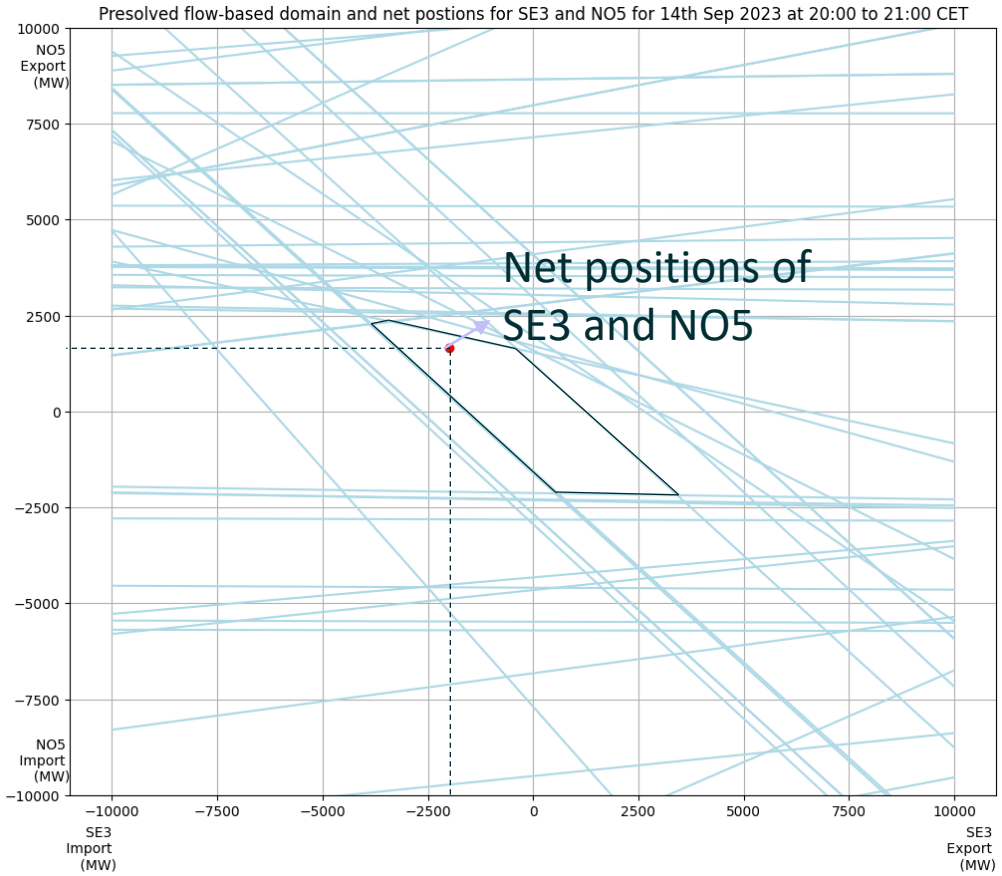
time

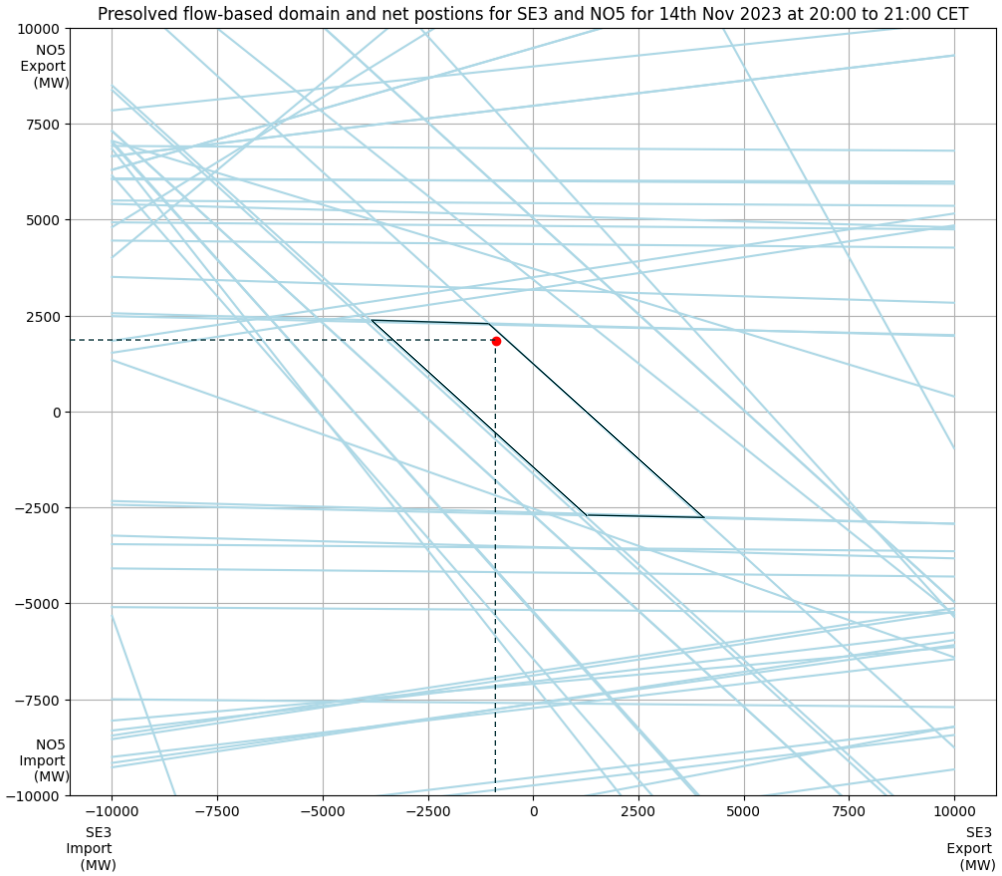
Capacity calculation summary



1. Visualizing flow-based domains

Presolved flow-based domain and net positions for SE3 and NO5

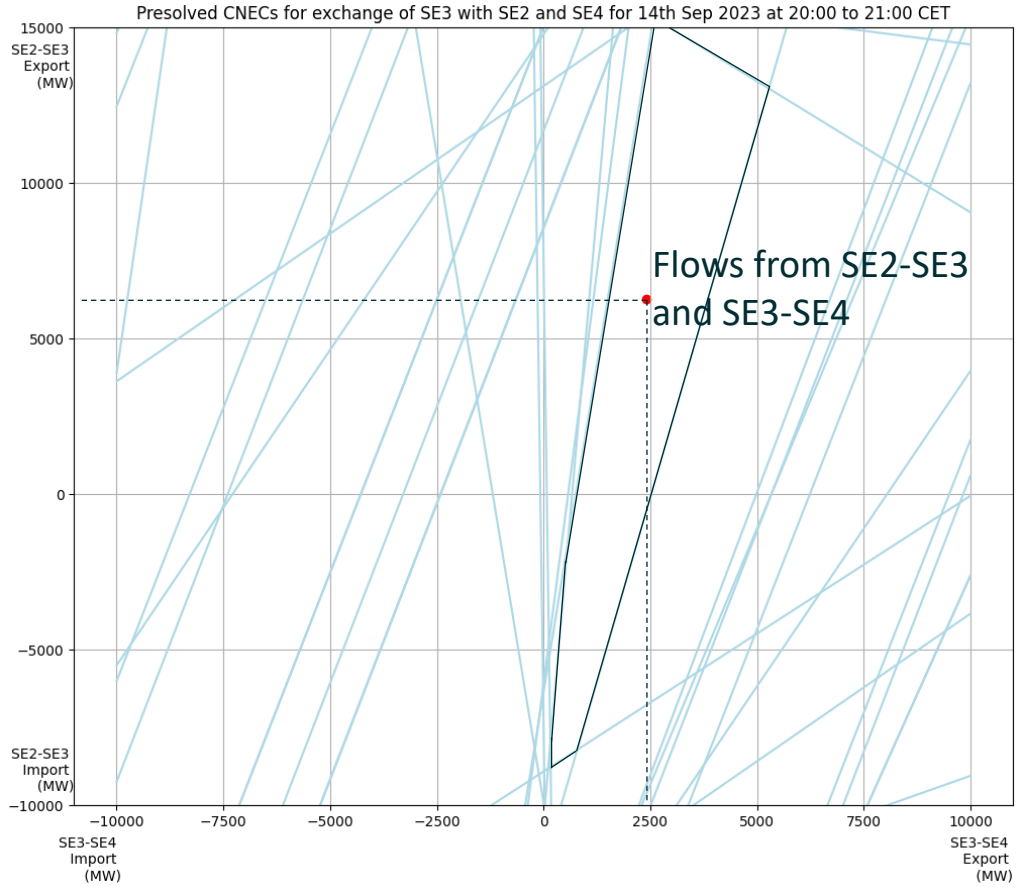


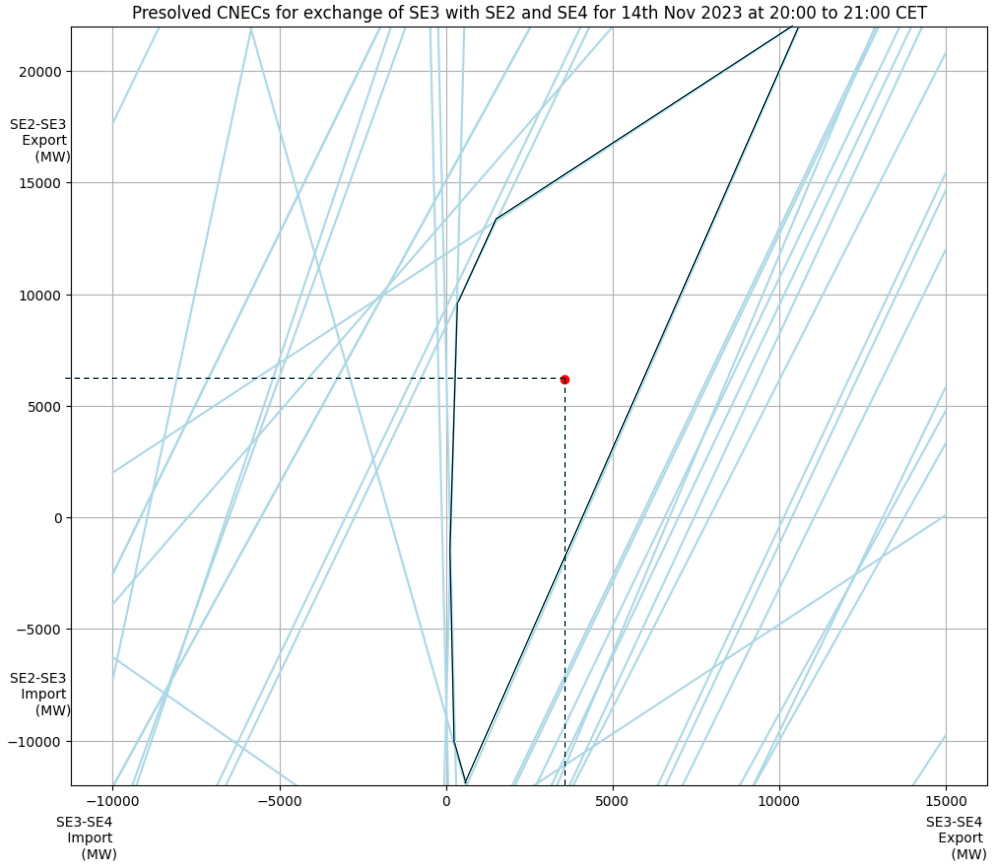


- PTDFs of SE3 and NO5 and RAMs published for each non-redundant presolved CNEC is used to obtain the above flow-based domains.
- It is one of the 930 (n*(n-1)) combinations possible for this hour
- The net positions of SE3 and NO5 are indicative of the market outcome from parallel runs.

2. Visualizing flow-based domains

Presolved flow-based domain and scheduled exchanges between SE2-SE3 and SE3-SE4.

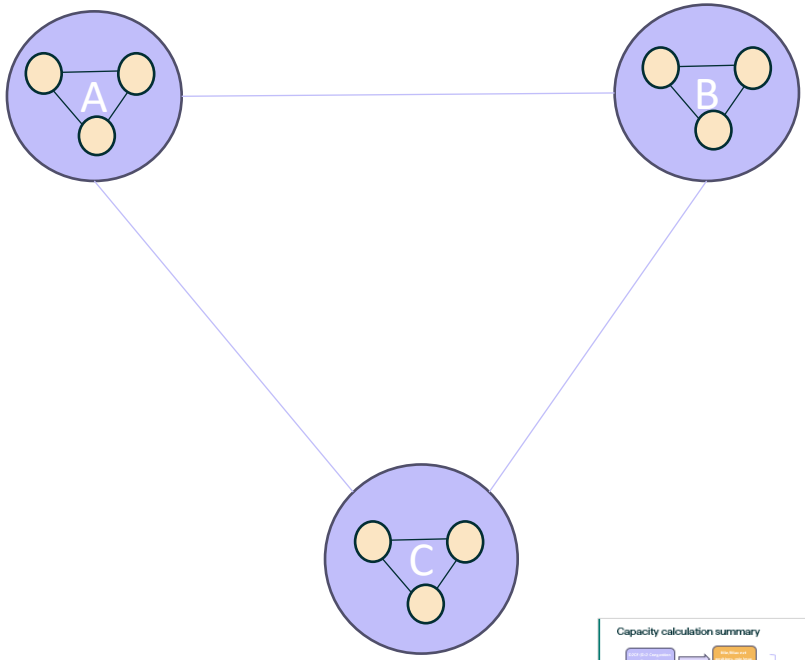


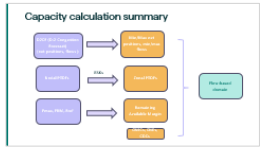


- The zone-to-zone PTDFs are useful in creating the flow-based domain for set of borders which gives the bilateral scheduled exchanges.
- The total number of cross-border lines would be 37. Therefore, it results in a 37-dimensional space for visualising the flow-based method for exchanges.

Process of market coupling

Capacity Calculation





TSOs and Nordic RCC

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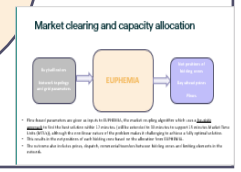
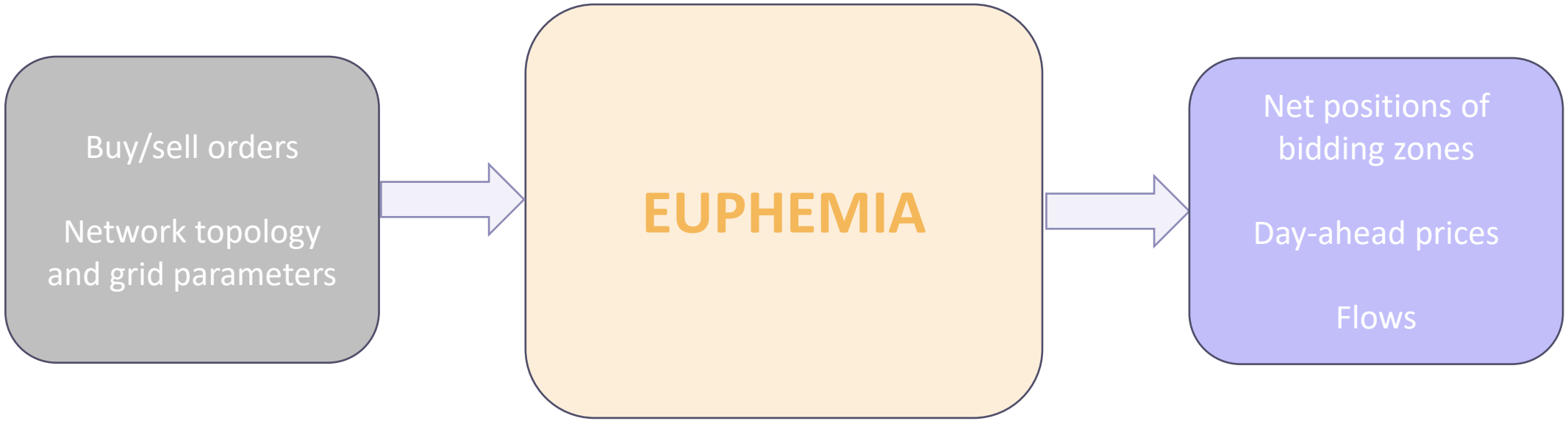


NEMOs

time

Market clearing and capacity allocation



- Flow-based parameters are given as inputs to EUPHEMIA, the market coupling algorithm which uses a heuristic approach to find the best solution within 17 minutes. (will be extended to 30 minutes to support 15 minutes Market Time Units (MTUs)), although the non-linear nature of the problem makes it challenging to achieve a fully optimal solution.
- This results in the net positions of each bidding zone based on the allocation from EUPHEMIA.
- The outcome also includes prices, dispatch, commercial transfers between bidding zones and limiting elements in the network.

1. Market timeline and competition

2. Introduction to Market Coupling

3. Connection to the physical grid

4. Market outcomes to observe after flow-based market coupling

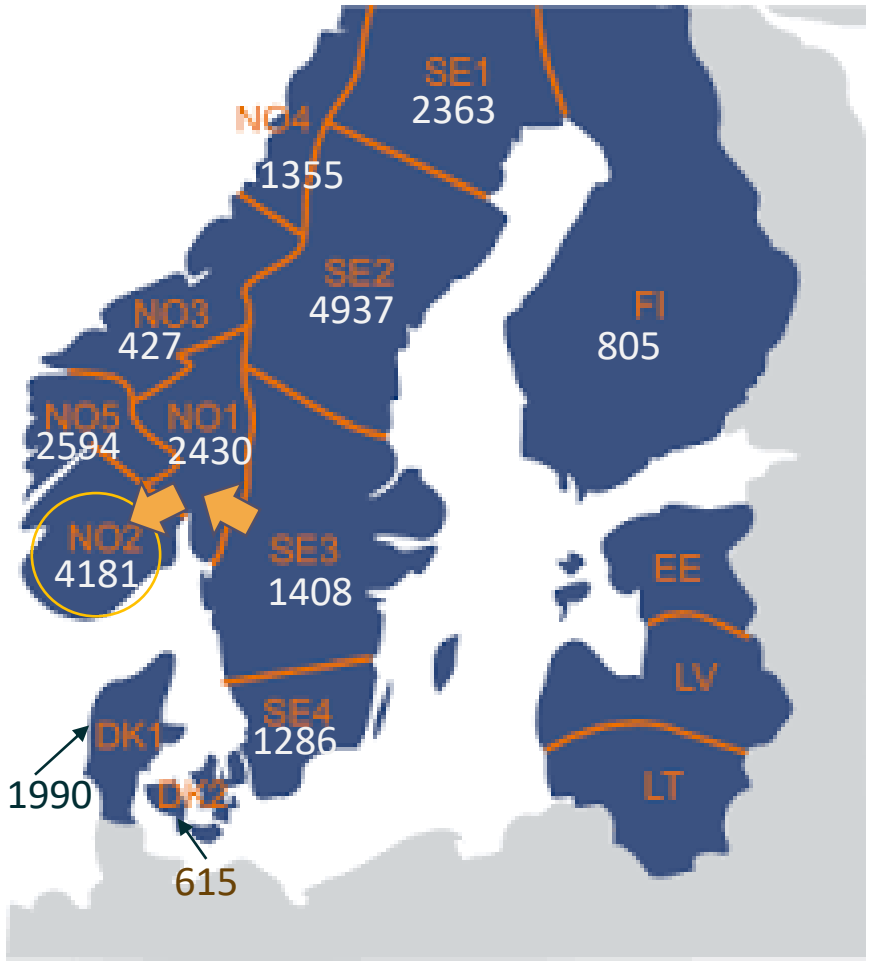
5. Topics for further discussions

6. Conclusion

4. Market outcomes to observe after flow-based market coupling

Comparison of Average net positions

Average Net positions of 18th Nov'24: FBMC



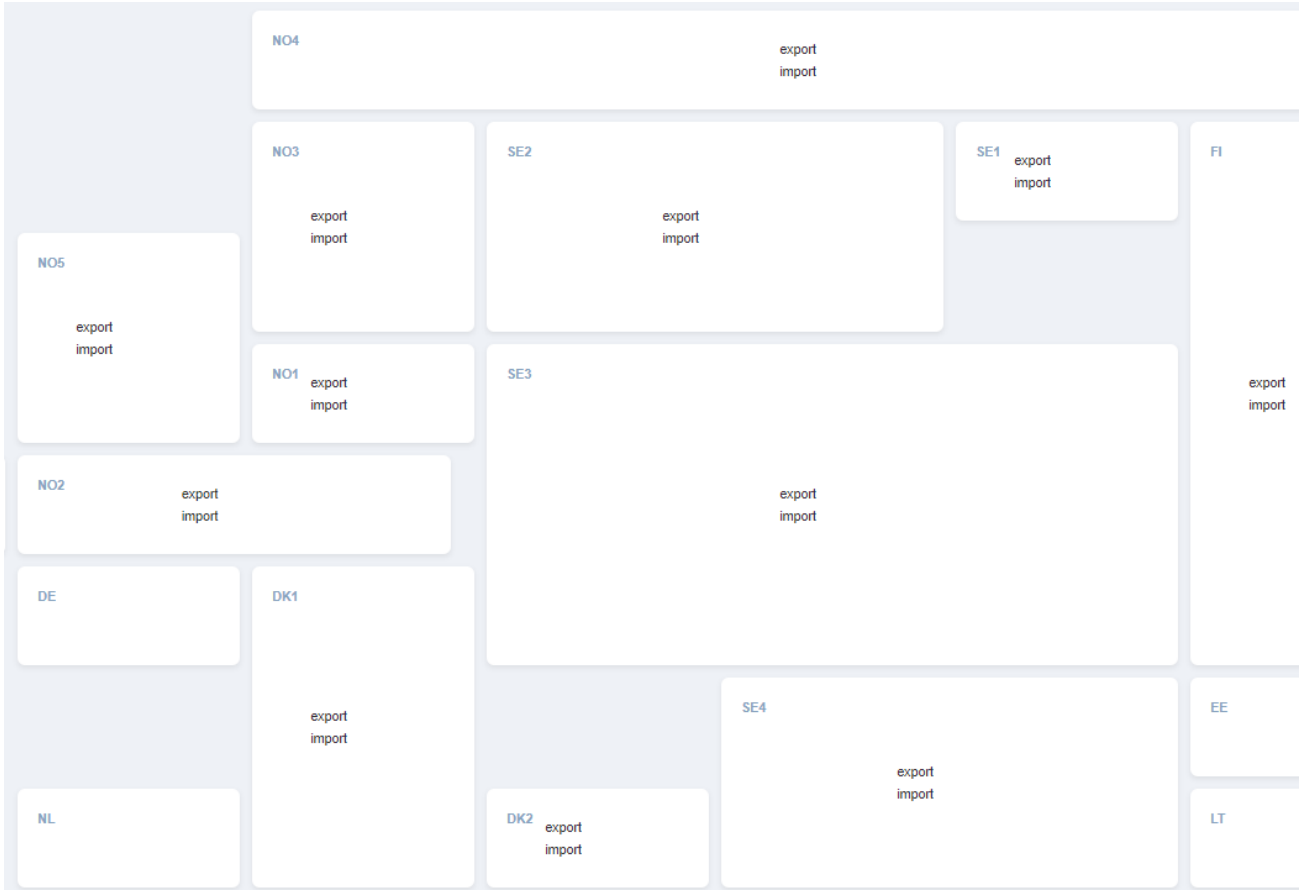
Average Net positions of 18th Oct'24: ATC

Increase in net positions means increase in export (production)/decrease in import (consumption).

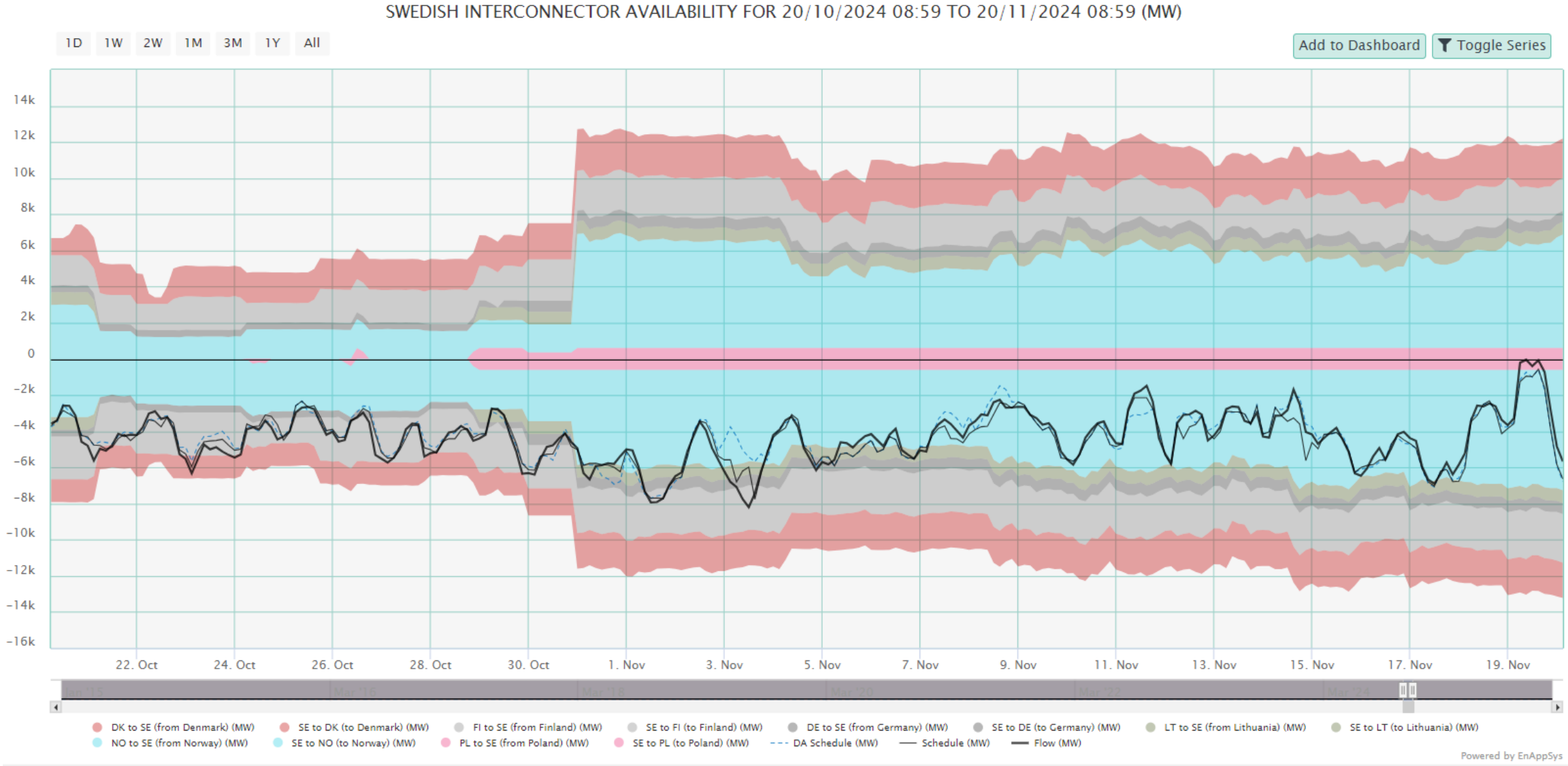
How to interpret capacities between bidding zones now?

- MaxBex calculates the maximum possible exchange between two zones taking into account all paths.

- For example, NO1-SE3 would have a Max Bex not only through NO1-SE3 but all other possible paths.



Interconnector availability assessed on max exchanges



Different flows to consider

$$Flow\_FB(c) \leftarrow PTDF(c,n) \cdot NP(n) + f_0(c)$$

The grid is operated based on the Additional Aggregated Flow (AAF), which is calculated by RCC.
AAF is also the foundation for the settlement of congestion rents.

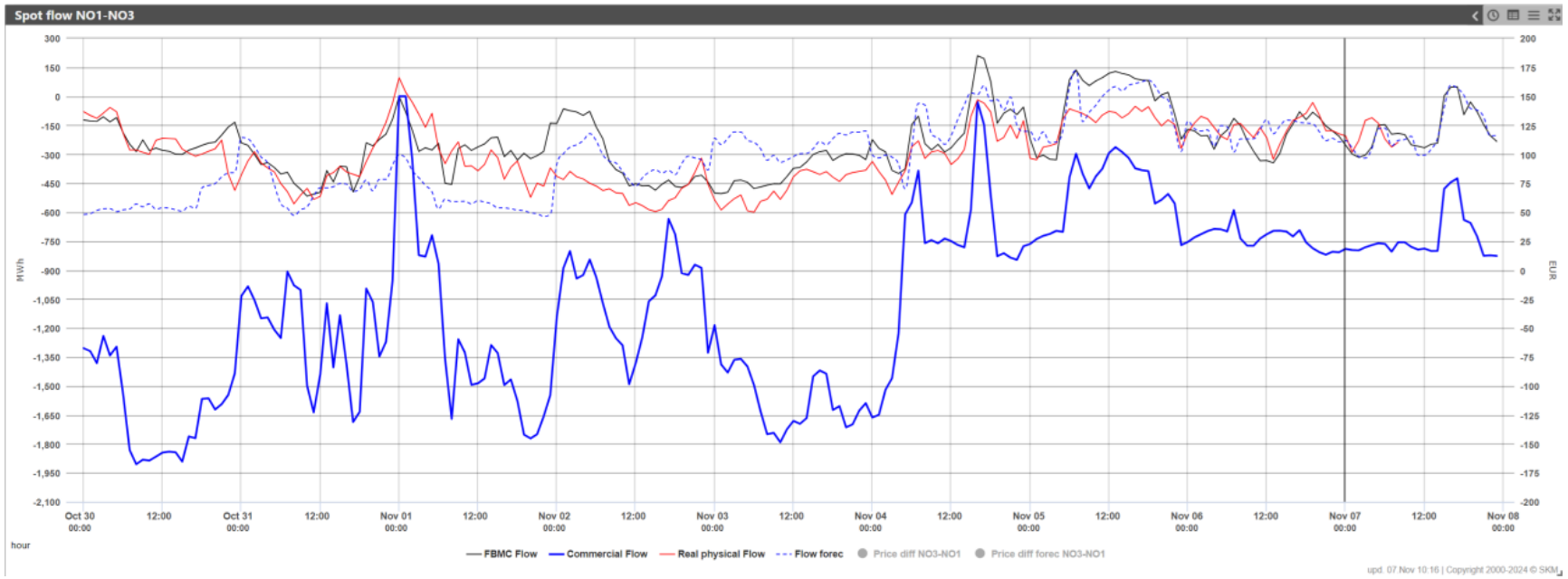
AAF = Flow_FB - f0 = NP*PTDF

Shadow Price & Flow_FB
Test data. Full Disclaimer

SEARCH

Detailed Breakdown

Date	Imax method	Non-redundant	Significant	RAM	Min Flow	Max Flow	U	Flow_FB	Imax	Fmax	FRM	Fref	F0	FRA	AMR	FAAC	IVA	Shadow Price
00:00:00																		
2024-08-30 00:00:00		✓	✓	985	-1000	985	0	348	0	985	0	645	0	0	0	0	0	0
2024-08-30 00:00:00		×	✓	1624	-451	505	0	-451	0	1750	88	-1258	0	0	0	38	0	
2024-08-30 00:00:00		✓	✓	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1603.4726641718



Source of eq. : publicationtool.jao.eu/PublicationHandbook/Nordic_PublicationTool_Handbook_v1.1.pdf

Source of second fig: Montel Syspower

Are shadow and DA market prices the same?

- Shadow Price of an element: in the Market coupling optimization can be interpreted as “a value of a potential increase of welfare in a case an extra 1 MW of exchange would be possible on given element.” Elements with non-zero shadow prices are those, which are effectively limiting the cross-zonal exchanges.
- It is the Lagrange multiplier of the CNEC with respect to a bidding zone in the RAM equation.

- Day-Ahead market price is the Lagrange multiplier of supply-demand balance equation.

Market equilibrium and price relation in FBMC

1. First order condition for global welfare optimum gives the market price for bidding zone i:

$$P^i = \lambda - \sum_n \rho_n \, PTDF_n^i$$

- P^i: Bidding zone i price
- λ: Slack node price
- ρ_n: Shadow price of CNE n
- $PTDF_n^i$: Zone-to-slack PTDF for zone i on CNE n

2. Marginal value of flow between bidding zones i and j is given by:

$$\left(P^j - P^i\right) = \sum_n \rho_n \, * \, PTDF_n^{ij}$$

- $\left(P^j - P^i\right)$: Price differences between bidding zones i and j
- $PTDF_n^{ij}$: Zone-to-zone PTDF for zone i - zone j on CNE n

Results from 6th May to 19th May 2024 for hour 1

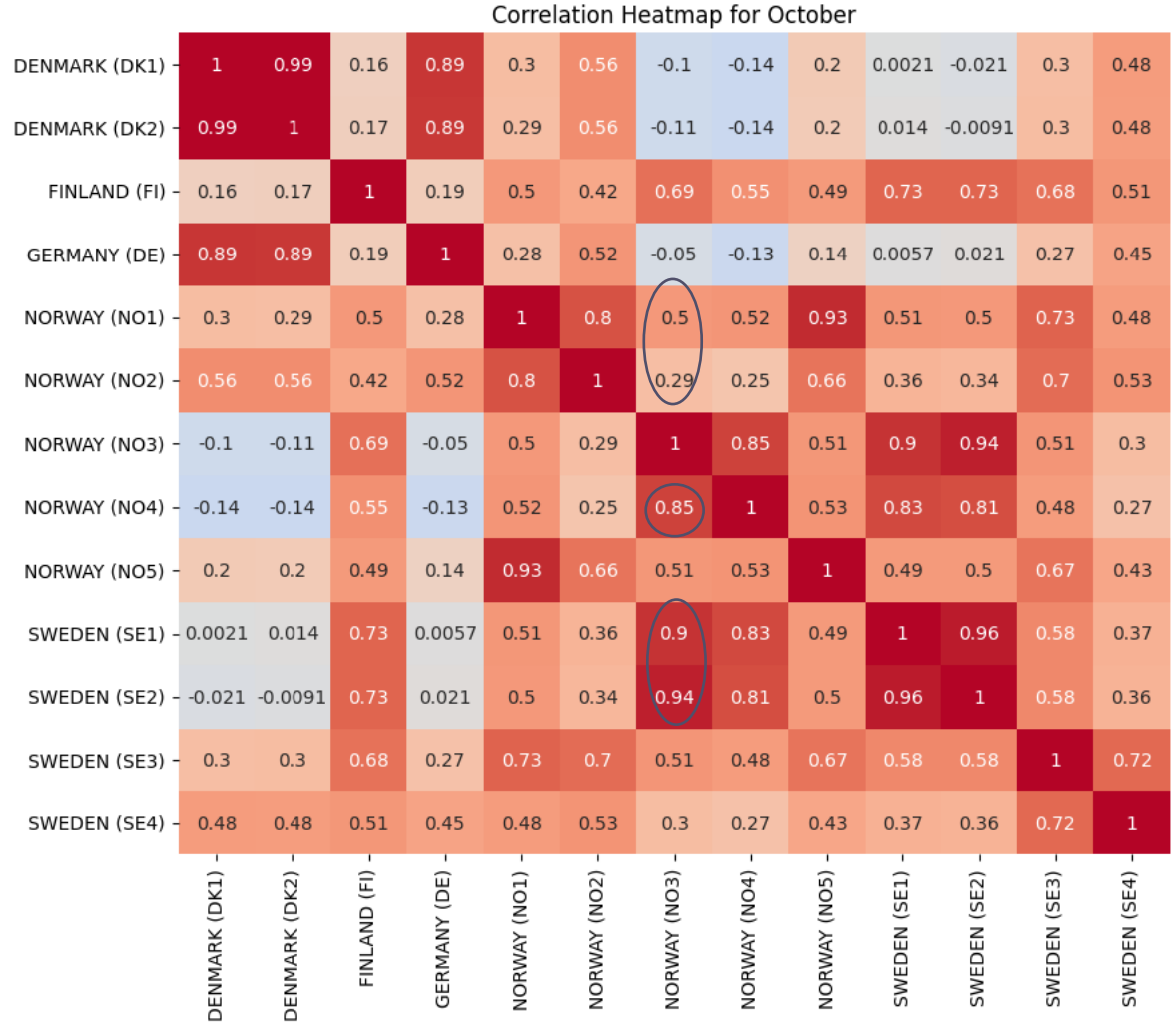
Counts of hours with shadowprice (FB)

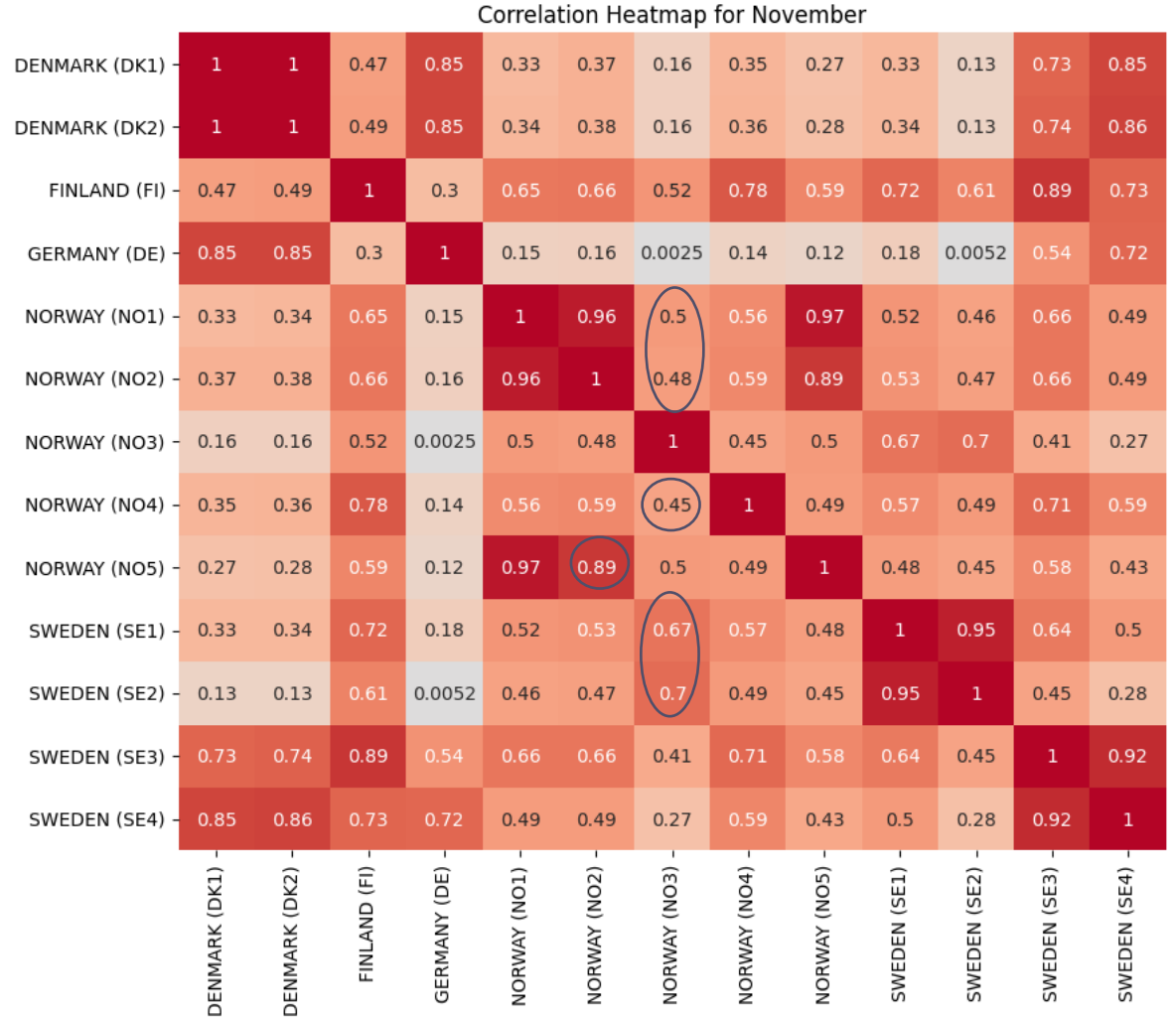
Thousands separated by comma and decimal separated by dot. Example: 1,234.56

CNEC	Count of hours	Average shadowprice	Total shadowprice
ACLineSegment ENDK DK1 E_KAE-LYK_3 1 N Terminal : N|165KV LINE E_KAE-LYK_2	33	793.08	26,171.58
AC_Minimum_SE4_SWL	184	113.92	20,960.67
AC_Minimum_SE3_SWL	101	206.73	20,879.59
FI_PTC_FI_EL_EXPORT	203	56.61	11,492.19
AC_Minimum_SE4_NB	198	51.66	10,229.19
AC_Minimum_NO2_ND	226	37.02	8,366.27
AC_Minimum_NO2_NK	235	32.73	7,692.57
ACLineSegment ENDK DK1 E_KAE-LYK_3 1 N Terminal : N|165KV LINE E_KAE-LYK_1	10	736.98	7,369.83

Data source: Nordic RCC presentation

Price correlation with FBMC and ATC methods





- For NO3, the correlation with SE1, SE2 and NO4 reduces while it improves with NO1, NO2, NO5.
- NO2 and NO5 get higher correlation.
- FI seems to get higher correlation with most Nordic bidding zones and Germany.
- DK1 and DK2 also have more correlation with the Swedish and northern Norwegian zones.

Comparison of Average DA price spreads

Borders	Oct-24	Nov-24
FI->NO4	29.2	37.9
FI->SE1	29.5	23.8
FI->SE3	20.5	-15.9
NO1->NO2	-7.8	-9.3
NO1->NO3	20.6	38.3
NO1->NO5	-0.1	6.9
NO1->SE3	13.7	-12.5
NO2->NO5	7.8	16.2
NO3->NO4	1.9	3.0
NO3->NO5	-20.6	-31.4
NO3->SE2	1.4	-4.9
NO4->SE2	-0.4	-8.0
DK1->DK2	0.4	0.5
DK1->SE3	56.5	45.7
DK2->SE4	49.9	25.7
SE1->NO4	-0.4	14.1
SE1->SE2	-0.8	6.2
SE2->SE3	-8.3	-45.9
SE3->SE4	-6.3	-19.5

Marginal value of flow between bidding zones i and j is given by:

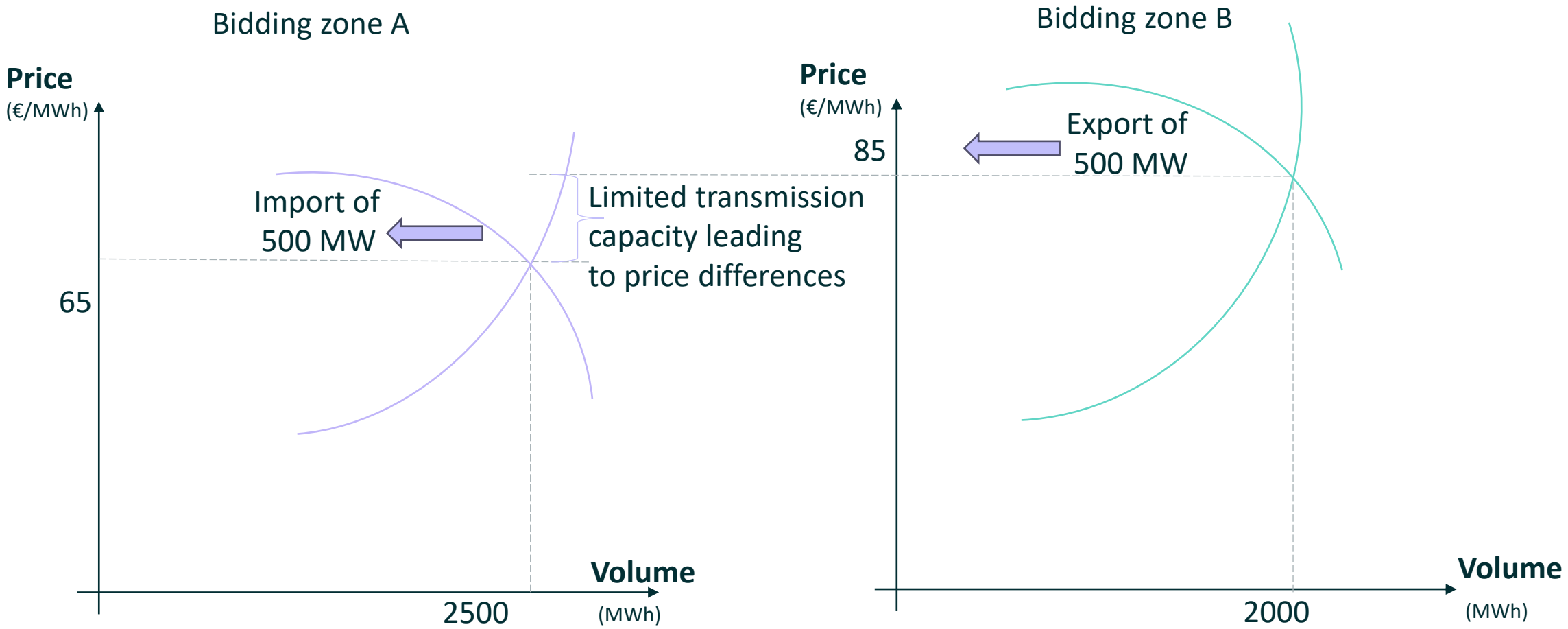
$$\left(P^{j} - P^{i}\right) = \sum_{n} \rho_{n} * PTDF_{n}^{ij}$$

Price differences between bidding zones i and j

Zone-to-zone PTDF for zone i - zone j on CNE n

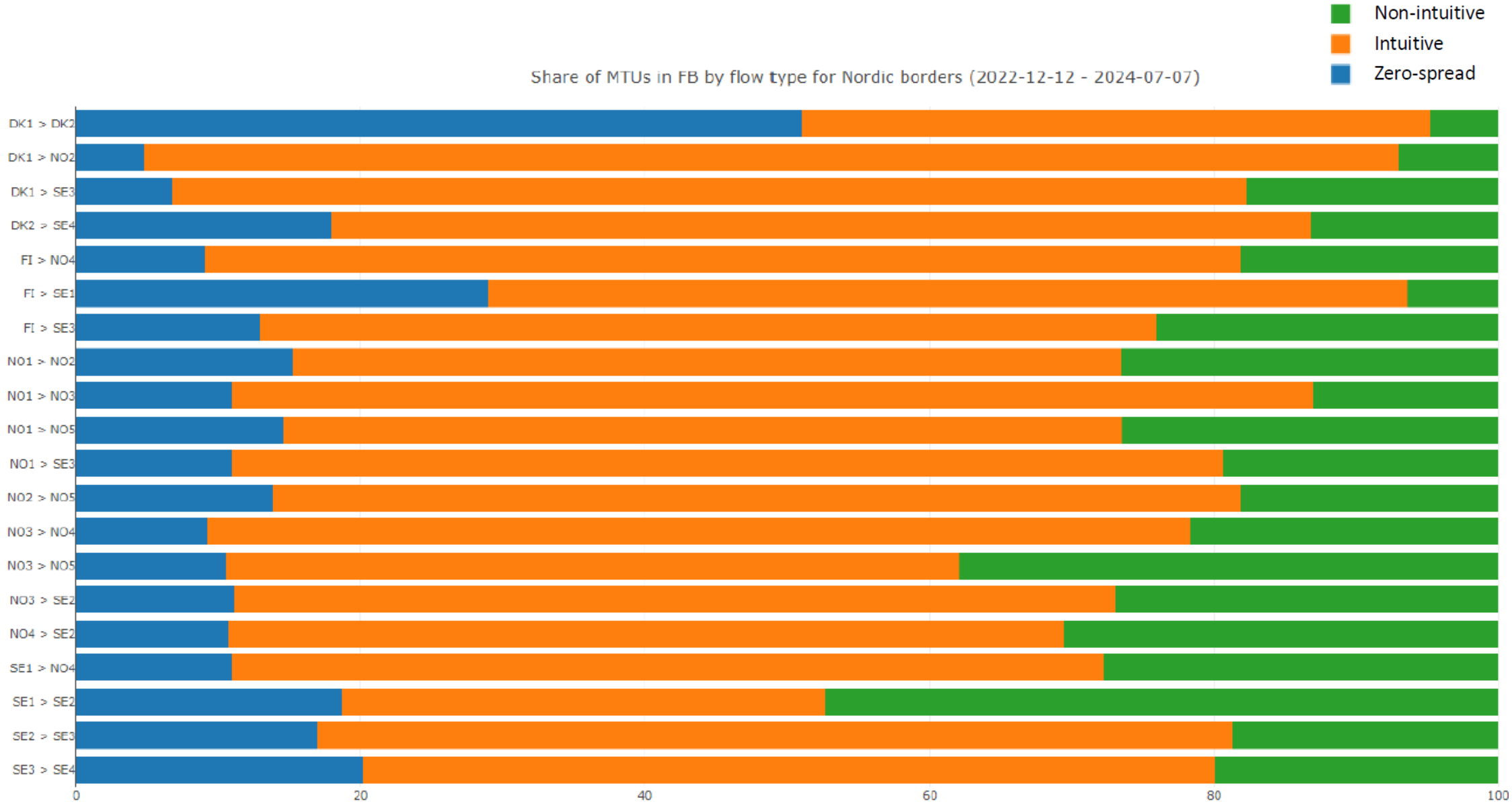
- The price differences reduce in FBMC compared to ATC on most bidding zone border combinations.
- Indicating that FBMC is more efficient in allocating capacities, compared to the ATC method, leading to more price convergence

Non-intuitive flows



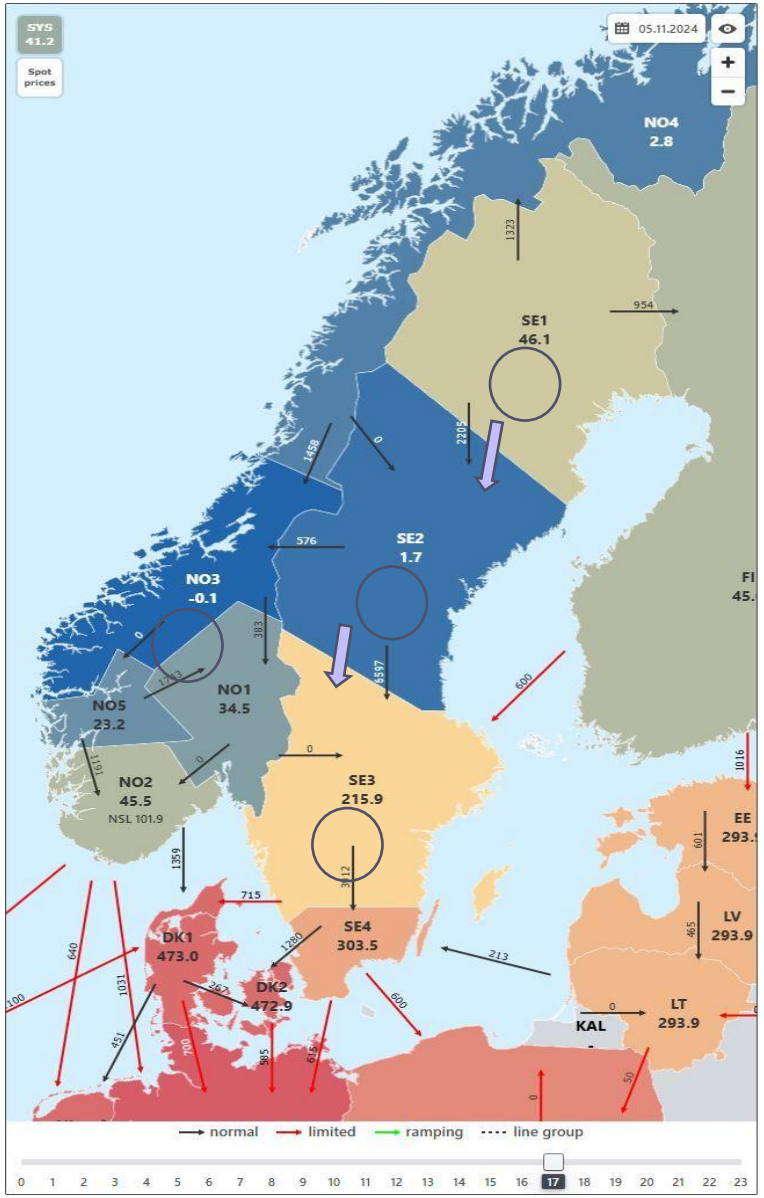
- Flow from high price to low price zone from Flow-based optimization to relieve congestion on grid elements.
- These flows can contribute to the overall social welfare by relieving more capacities in the grid.

Non-intuitive flows are a part of flow-based



Source: Nordic TSOs

The Saga of Non-intuitive flows



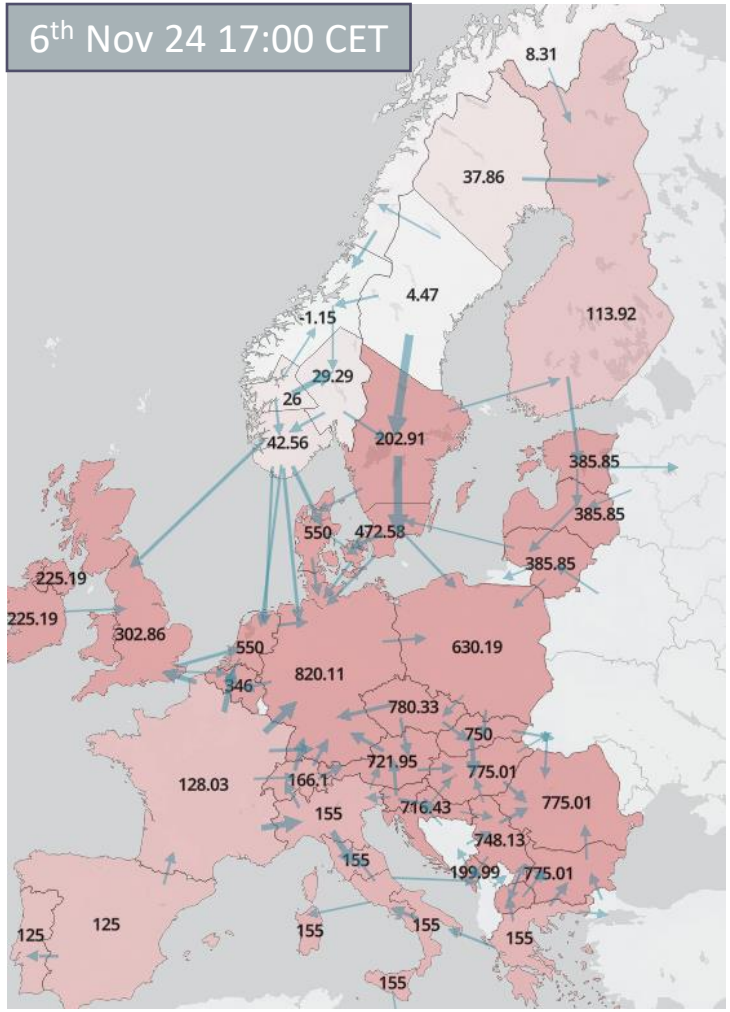
Source: Montel Syspower

- 5th Nov 2024 17:00 CET: NO3 with a negative price was a net importer despite very high water levels in the reservoirs.
- Looking at the CNE in SE2, first we can observe from the PTDF values that it loads this CNE more if we increase generation in NO3 and NO4 (green area)…
- Than if we increase generation in SE1 and SE3 (blue area),
- SE2 generation is worse than in NO4 but it is better than in NO3.
- This means that it is **more efficient** to send power to cover SE3 demand from SE1 than to generate it in NO3. It also means that we want to limit how much we generate in SE2 as this loads heavily on the SE2 CNE.

CnecName	FI_PTC_FI_	FI_PTC_FI_	fc07bbd89	9dbcc00cf	5cfe582b9	f0d648b65	3314a958a	30bf19ea5	DK2_VE_E	DK2_SV_IN	NO2->DK1	15326_11	L15827_10	5b7c88142	AC_Minimu
CnecType	BRANCH	BRANCH	BRANCH	BRANCH	BRANCH	BRANCH	BRANCH	BRANCH	BRANCH	BRANCH	BRANCH	BRANCH	BRANCH	BRANCH	ALLOCATIO
Tso	FINGRID	FINGRID	SVK	SVK	SVK	SVK	SVK	SVK	ENERGINE	ENERGINE	STATNETT	STATNETT	STATNETT	STATNETT	SVK
CneName	FI_PTC_FI_	FI_PTC_FI_	6fcbf6d56	946174fc0	11e05af81	38eb2b112	9b1e5bf35	f5930918b	AREA EAST	AREA EAST	NO2->NO_	300VERDA	300HUSNE	0c43220c5	0e642fdbb6
CneEic															
CneStatus	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
BiddingZoneFrom	FI	FI	SE2	SE2	SE2	SE4	SE4	SE3	DK2	SE4	NO2	NO4	NO2	NO3	SE3_KS
BiddingZoneTo	FI_EL	FI_FS	SE2	SE2	SE2	SE4_SP	SE4_BC	SE3	DK2_KO	DK2	NO2_SK	NO4	NO2	NO3	SE3_KS
CneType	PTC	PTC	CNE	CNE	CNE	PTC	PTC	CNE	PTC	PTC	PTC	CNE	CNE	CNE	
ShadowPrice	249	107	1049	105	34	202	189	1707	32	166	412	56	76	49	115
Ptdf_FI	0	0	0,14916	0,13446	0,25069	0	0	0,04815	0	1	0	0,05794	0,00169	-0,05071	0
Ptdf_FI_EL	-1	0	0,14914	0,13445	0,25067	0	0	0,04815	0	1	0	0,05792	0,00169	-0,05069	0
Ptdf_FI_FS	0	-1	0,14914	0,13445	0,25067	0	0	0,04815	0	1	0	0,05792	0,00169	-0,05069	0
Ptdf_NO1	0	0	0,15511	-0,14379	-0,13803	0	0	0,09023	0	1	0	-0,04037	0,02549	-0,49022	0
Ptdf_NO2	0	0	0,15213	-0,15921	-0,13934	0	0	0,09138	0	1	0	-0,03376	-0,08709	-0,49031	0
Ptdf_NO2_ND	0	0	0,15187	-0,1601	-0,13936	0	0	0,09149	0	1	0	-0,03332	-0,11776	-0,48974	0
Ptdf_NO2_SK	0	0	0,15175	-0,16051	-0,13937	0	0	0,09153	0	1	-1	-0,03313	-0,10749	-0,48948	0
Ptdf_NO2_NK	0	0	0,1519	-0,16001	-0,13936	0	0	0,09147	0	1	0	-0,03337	-0,12019	-0,4898	0
Ptdf_NO3	0	0	0,21938	0,07528	-0,12694	0	0	0,06351	0	1	0	-0,11754	0,01007	-0,59563	0
Ptdf_NO4	0	0	0,18552	0,11992	0,11416	0	0	0,05382	0	1	0	0,26227	0,00422	-0,27927	0
Ptdf_NO5	0	0	0,15476	-0,15023	-0,13916	0	0	0,09032	0	1	0	-0,03808	0,18801	-0,49601	0
Ptdf_SE1	0	0	0,14834	0,13417	0,24694	0	0	0,04811	0	1	0	0,05954	0,00171	-0,05255	0
Ptdf_SE2	0	0	0,19039	0,15671	0,11975	0	0	0,04945	0	1	0	0,00848	0,0012	0,00661	0
Ptdf_SE3	0	0	0,02294	0,04477	0,05627	0	0	0,03535	0	1	0	0,00433	0,00035	0,00024	0

Source: https://www.linkedin.com/posts/morten-pindstrup-28aa004_flowbased-sdac-euphemia-activity-7259675808955285505-EFq_?utm_source=share&utm_medium=member_desktop

Explaining the price differences during non-intuitive flows



Source: Montel EnAppSys

In Flow-based, price differences between bidding zones can be verified by computing the sum of shadow prices on all congested physical network elements multiplied by the PTDFs of those bidding zones.

CnecName	BiddingZo	Bidding Zo	PTDF SE1	PTDF SE2	Shadow prices	Calculation
FI_PTC_RAC_SE1-FI	SE1	FI	0	0	76.03326771	0
d19712a4aa1742b5ae7de49fda56c8ce	SE2	SE2	0.1338	0.15929	1018.50843	25.96177988
c31c155925524403b4e3b198defd2843	SE2	SE2	0.25966	0.12651	20.84939646	-2.776097139
5d09ffcdec2441e887359c59a50bdc34	SE4	SE4_SP	0	0	356.3484675	0
52e6fce885e14075b6724e23c1bbcfa9	SE4	SE4_BC	0	0	312.9749613	0
ece2ac65b00e496ca11f8af3d2ea36ed	SE3	SE3	0.23095	0.2387	1512.504705	11.72191146
DK2_VE_EXP	DK2	DK2_KO	0	0	270.1056895	0
DK2_SV_IMP	SE4	DK2	1	1	19.34782211	0
DK1_EO_EXP	DK1	DK1_DE	0	0	270.1056895	0
15326_11 60% 420 Namsos-Ogndal + 30	NO4	NO4	0.06017	0.00901	29.34270044	-1.501172554
13792_457 300 Mauranger-Blåfalli	NO5	NO5	0.00125	0.00087	53.22469588	-0.020225384
AC_Minimum_FI_EL	FI_EL	FI_EL	0	0	271.9211054	0
AC_Minimum_NO2_SK	NO2_SK	NO2_SK	0	0	492.5963919	0
				Price difference SE1 - SE2		33.38619627

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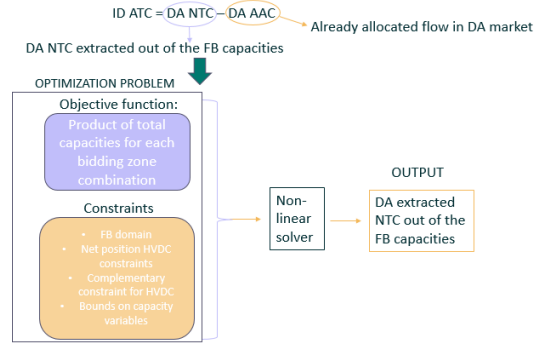

Flow-based impact on balancing

nordic balancing Model

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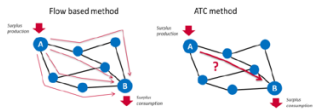

Figure 4 Difference in calculated power flows between bidding areas using the FB and CNTC methods

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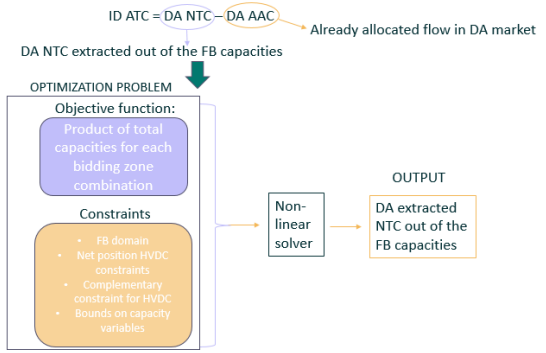

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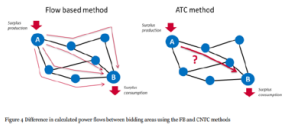

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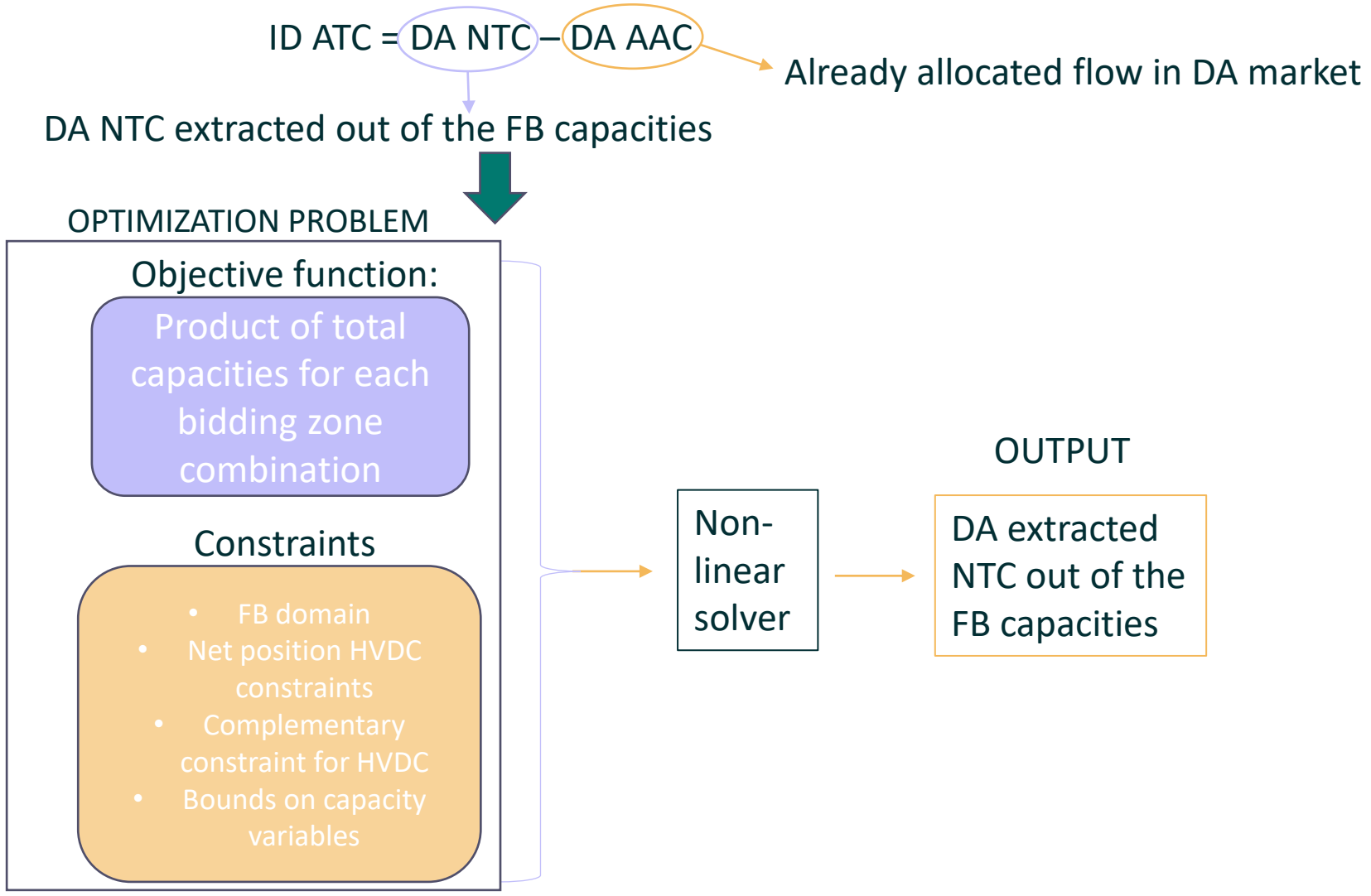
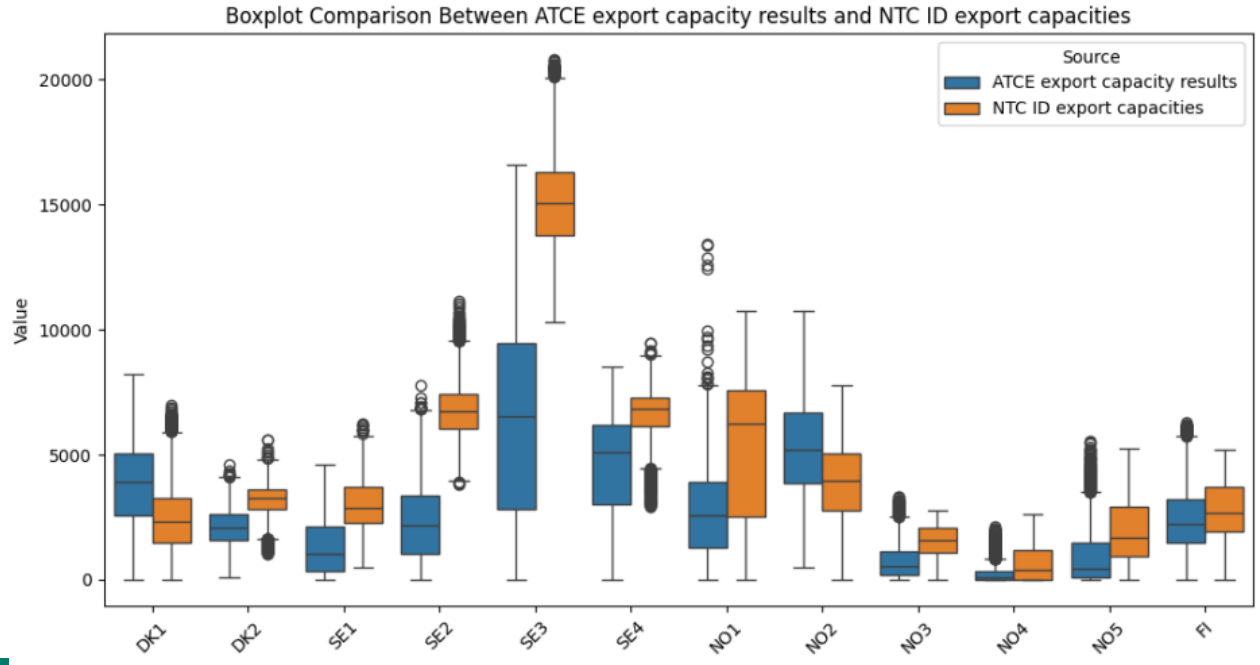
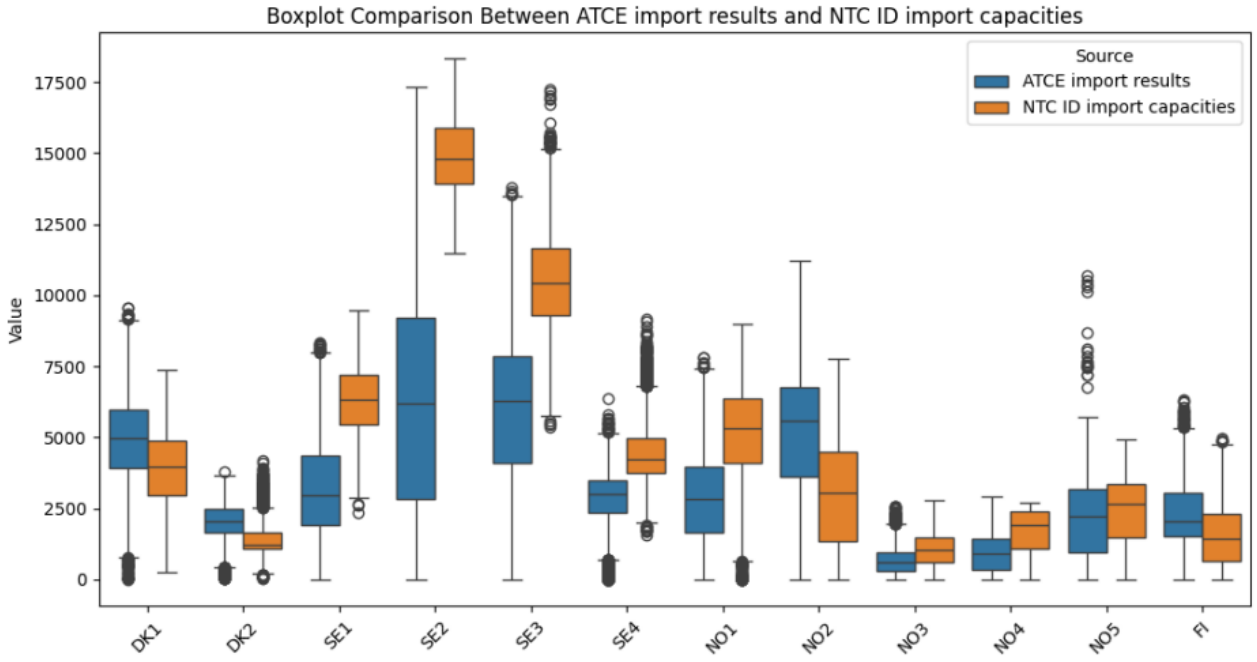


Intraday capacities after FB go-live in DA

Comparison based on ATCE results from week 26 2023 until week 13 2024

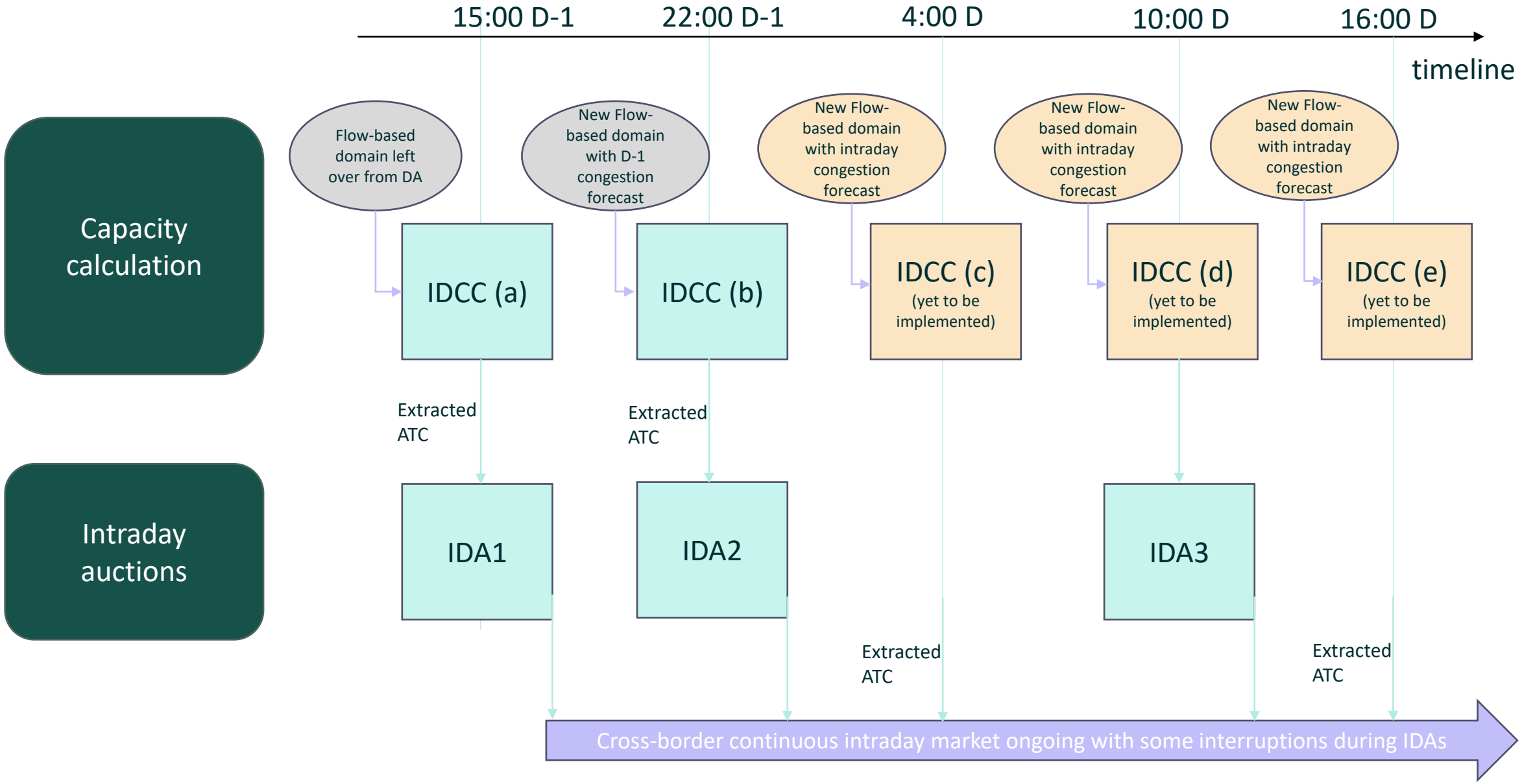




- ID capacities in some countries are much higher today than the ATCE results, for example, in Sweden.
- Large intraday capacities allocated without physical consideration could lead to overloads which need to be resolved by TSOs (could be more expensive).
- ATCE takes these situations into account.

Figures source: Nordic RCC presentation

Intraday Capacity Calculation in Core region



Note: Boxes with color ▭ are yet to be implemented

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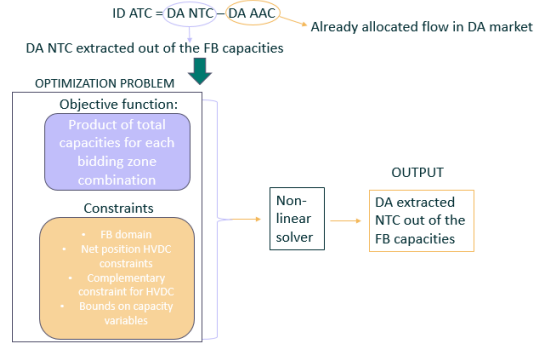

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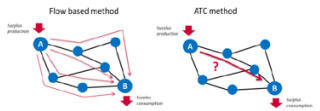

Figure 4 Difference in calculated power flows between bidding areas using the FB and CNTC methods

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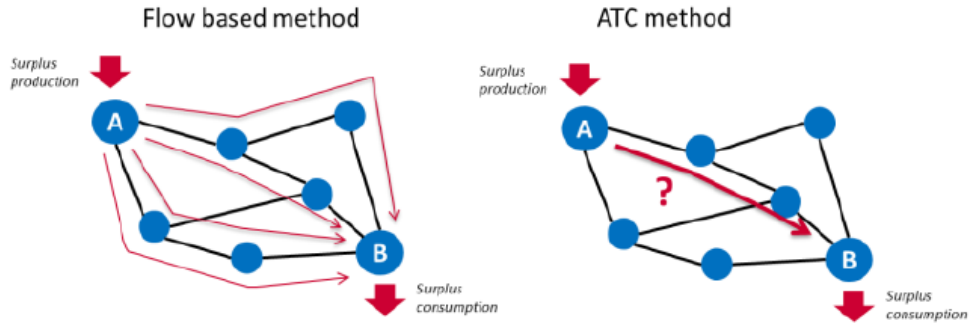

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Developments in Nordic aFRR and mFRR capacity markets

- Swedish TSO has started a new mFRR capacity market in October 2023 and has been increasing the procured volumes every quarter.
- **Joint mFRR capacity market** with Sweden, Denmark, Finland launched on 19th November 2024.
- **Nordic aFRR capacity market** (excluding DK1) has been in operation since December 2022.
- New aFRR capacity market was launched in DK1 on 1st October 2024. The aFRR down capacity market saw price spike of €1055/MW on 7th October even though volume required was just 100 MW.
- Several price spikes in aFRR down capacity market in the Nordics in the week of 22nd Oct'24. Further reinstating the importance of cross-border capacities and flexibility in the system.

Topics for future work

- How can market actors better forecast the flow-based domains?
- GSKs strategies and estimation.

- 15 min MTUs shift making flow-based domains even more computationally intensive to compute and process, can this be done faster?

- Savings on redispatch/countertrading as a result of flow based is a useful analysis … collecting real data..

- Long-term market point of view: how does flow-based impact long-term outlook of the energy system and forward markets.

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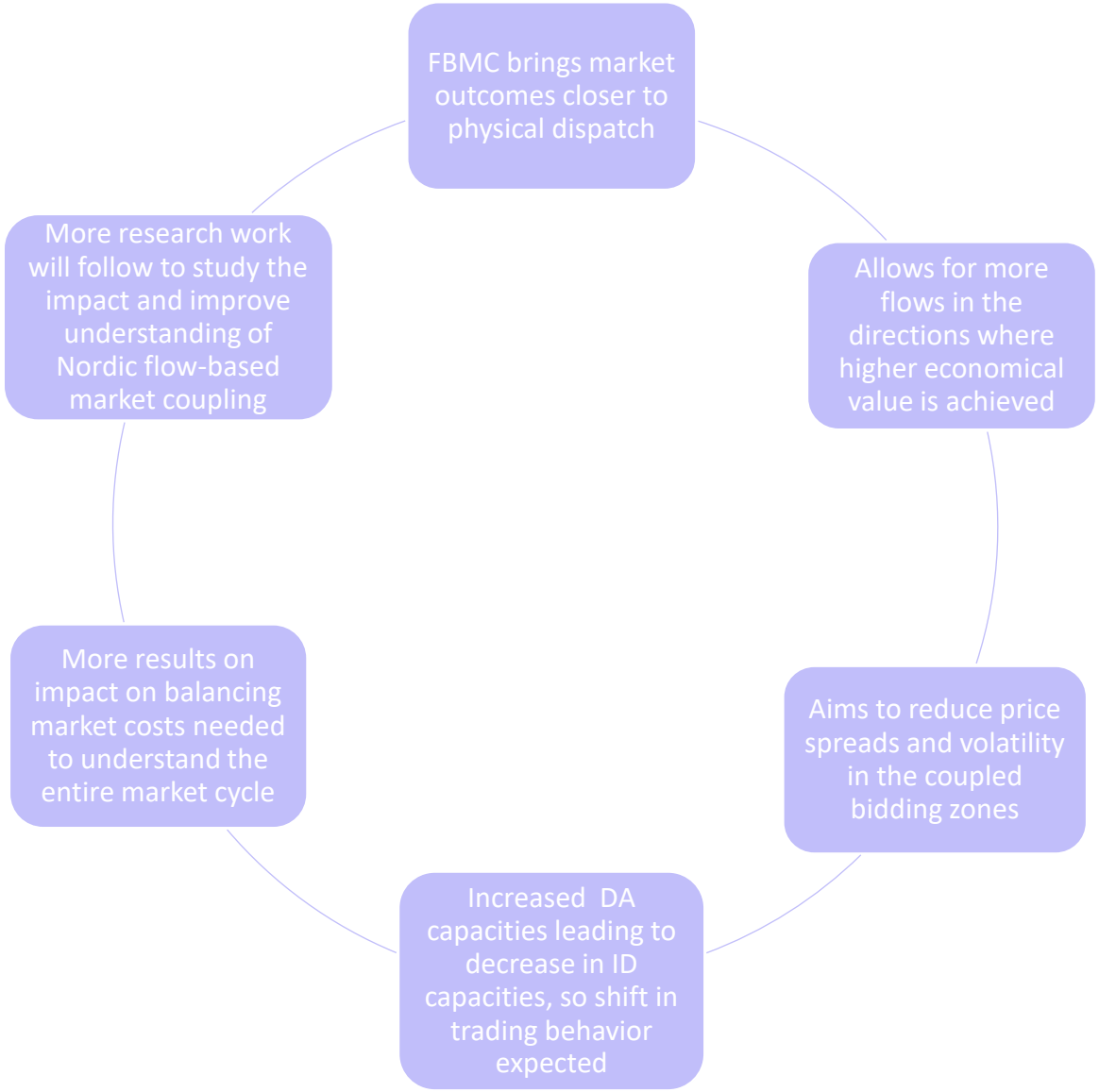

FBMC brings market outcomes closer to physical dispatch
Allows for more flows in the directions where higher economical value is achieved
Aims to reduce price spreads and volatility in the coupled bidding zones
Increased DA capacities leading to decrease in ID capacities, so shift in trading behavior expected
More results on impact on balancing market costs needed to understand the entire market cycle
More research work will follow to study the impact and improve understanding of Nordic flow-based market coupling

Who are we?

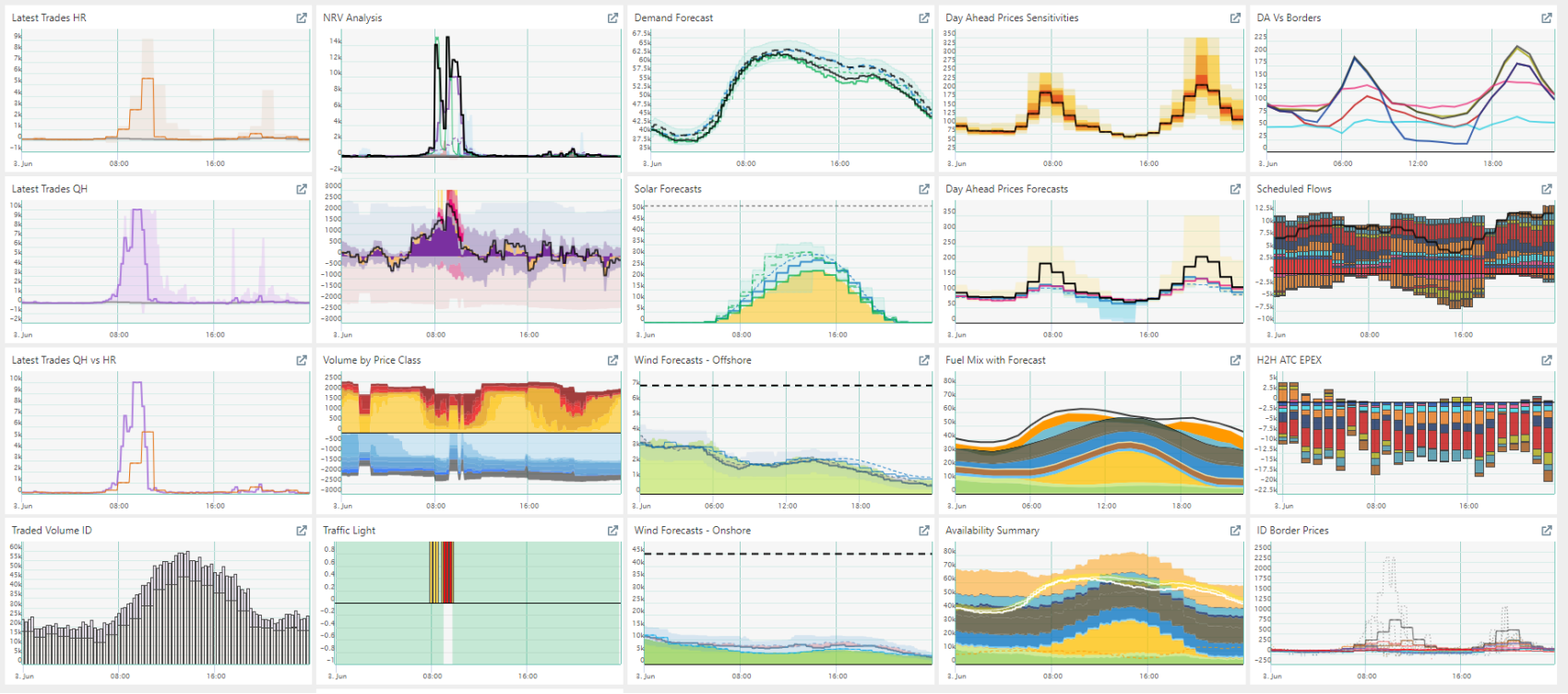
MONTEL

Helping you make sense:

How Montel Analytics Products help you make sense of Day Ahead Prices and their impacts on markets from intraday to short-term, to energy buying, to PPA's and Long-Term Investment

Another line of offering: Montel News and Energy days/conferences

Intraday, real-time, balancing, day-ahead



- Your real-time cockpit view of the market
- Real-time decision support
- Short-term trading
- Balancing markets
- Ancillary Services
- Sensitivities
- Volatility indicators
- Price and generation forecasts for trading

Day Ahead, Week Ahead, Energy Purchasing (to 45 days ahead)

- Your daily dose of energy market data.
- Weather forecasts, hydrology
- Fundamentals
- Price forecasts
- Carbon intensity
- Market Commentary

Thank You

For more details on Flow-based market coupling data and products:
Feel free to contact us:

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Priyanka.shinde@montel.energy
www.montel.energy