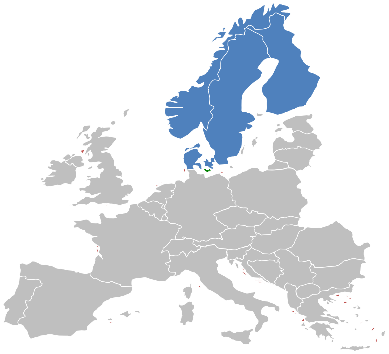

Capacity calculation methodologies explained

Flow Based market coupling (FB)
& Coordinated Net Transfer Capacity coupling (CNTC)

Explanatory slides for FB and CNTC

Nordic CCM project

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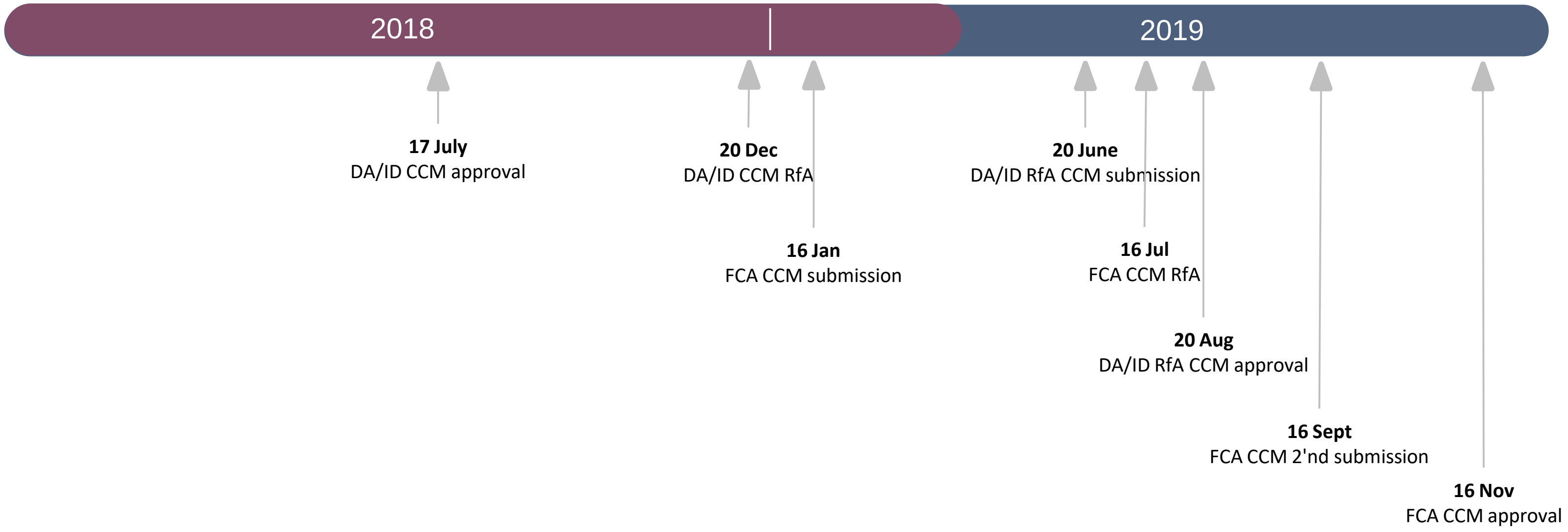
Table of content

1. Introduction

- The purpose of capacity calculation is to translate physical transmission limits in the power-grid into limits on commercial trades at par with the market design and operational security
- Capacity calculation is a legal obligation for the TSOs to be carried out in a common coordinated process within each Coordinated Capacity calculation Region (CCR)
- In the Nordics, the coordinated capacity calculation process is assigned to the Regional Security Centre (RSC) office in Copenhagen, and the TSOs are responsible to deliver the local/national input to the coordinated capacity calculation process
- The legal background for capacity calculation is provided by both national legislation, and the CACM-GL, the FCA-GL, SO-GL and the Nordic CCM

Legislative process



Motivation

- **Legal requirements:** According to the CACM, the most efficient of two different capacity calculation methodologies, and corresponding market designs, shall be introduced within each CCR:
  - ✓ Flow Based market coupling (FB)
  - ✓ Coordinated Net Transfer Capacity market coupling(CNTC)

- As opposed to the CNTC approach, which is based on the provision of ATCs, the FB approach provides capacities for commercial power exchanges by the introduction of PTDFs and RAMs

- **Efficiency considerations:** The objective of both approaches is to improve operational security and economic efficiency of the Nordic and European electricity markets by the means of regional and Europewide coordination, and significant improvements in automatization and formalisation

- **Practical requirements:** Enhancements are also necessary from a practical point of view. Many new elements increases the complexity of the current Nordic power system, making it evermore complex to maintain and support the current manual capacity calculation process
  - ✓ Higher number of HVDC interconnectors
  - ✓ New AC lines and increased capacity on AC connected borders
  - ✓ Increased generation from renewable intermittent generation (wind and photovoltaic)
  - ✓ Increased efforts within market efficiency and system integration
  - ✓ Renewed focus on flexible consumption

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2. From physical limitations to exchange capacity

Exchange capacities

- Exchange capacities provides limitations for the electricity market, in terms of linearized constraints, on cross zonal exchanges.

- The exchange capacities are derived from the physical capacity of the power-grid to provide linear MW limits for commercial power exchanges. The linearized constraints are simplifications of the complex non-linear physical limitations of the power-grid

- According to the CACM, there are two options for providing exchange capacities for the European electricity market:

  a) **FB:** The electricity market receives a linearized "security domain" described by power transfer distribution factors (**PTDF**s) on critical network elements (**CNE**s). The flow on each individual CNE is limited by a MW margin representing the secure physical capacity of the component(s), while the PTDF gives the flow on each CNE from a one MW injection in each BZ

  b) **CNTC:** The electricity market receives a MW limit on bilateral exchanges between any two bidding zones. The MW limits are derived from the "security domain" (bidding zone configuration is applied in order to capture all relevant limitations)

From complexity to simplicity

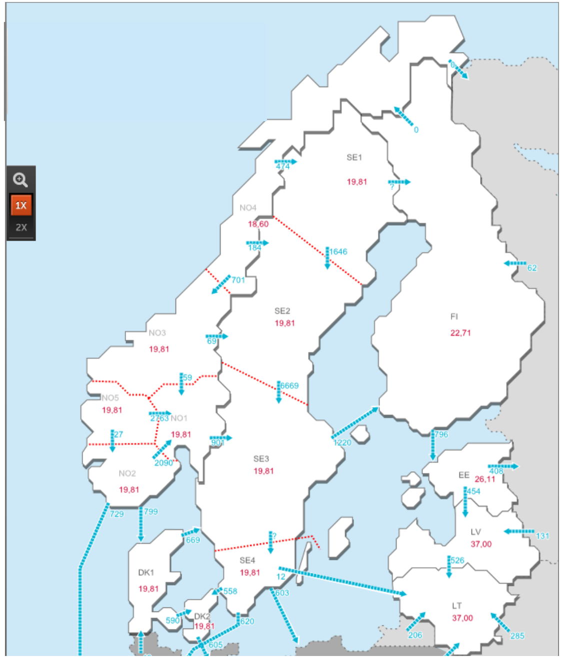
The physical world

Complexity → Simplicity

Detailed grid model → FB → CNTC

Capacity calculation is the process of translating the complex physical grid into a simplified form that can be understood and applied by the power exchange

The commercial world



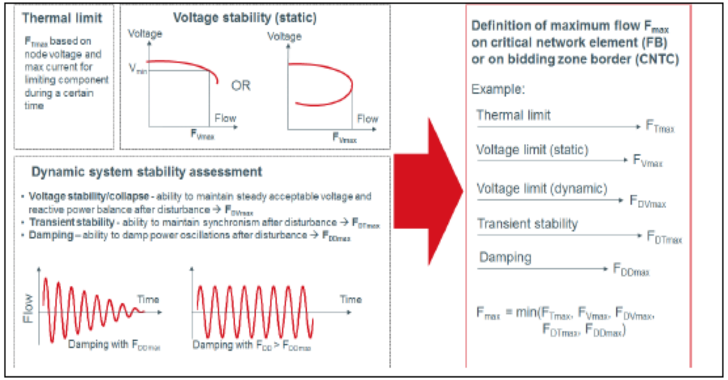
Physical grid constraints

- All physical limitations in the grid must be respected during operation and thus can either be:
  - Imposed as limits to commercial exchanges (the electricity market), or
  - Managed directly by counter trade or re-dispatch during operation
- The physical limitations are scattered around in the grid "having little regard" for actual bidding zones
  - Some physical limitations are located on, or close to, a bidding zone border
  - Other physical limitations are located inside bidding zones - internal constraints
- Bidding zone delimitation is "an attempt" to capture the limitations as efficiently as possible for the electricity market

Physical grid constraints

- The physical constraints are defined by the components of the power-grid and the state of the power system → How much power flow may be carried by the component(s) until an incident might occur
- Due to operational security and risk considerations, the "secure physical capacity" applied in operation will/may differ from the "maximum physical capacity" found in any given scenario
- Thus, the secure physical capacities of grid components will vary with grid topology, temperatures, loading and risk assessment
- **The secure physical capacity is a common base for the FB and CNTC approaches**

- The physical capacities constitute complex non-linear limitations on flows:
  - ✓ Thermal limitations for each grid element
  - ✓ Steady state and dynamic voltage limits for each grid element or group of elements
  - ✓ Dynamic stability limits for groups of grid elements
  - ✓ Short circuit limits
  - ✓ N-1 considerations



3. Principles of FB and CNTC capacity calculation

Converting physical grid constraints into linear constraints on cross border exchanges

The (linearized) security domain

The market has to respect all imposed limitations of the grid

- All possible market positions/market solutions respecting the imposed limitations from the grid constitute a secure domain in which physical overloads are prevented
- Thus the secure domain provides the boundaries for valid market positions / outcome from the market algorithm. Overloads may only occur in the market solutions due to missing, or ill-specified limitations on exchanges

The objective of capacity calculation is to calculate the security domain

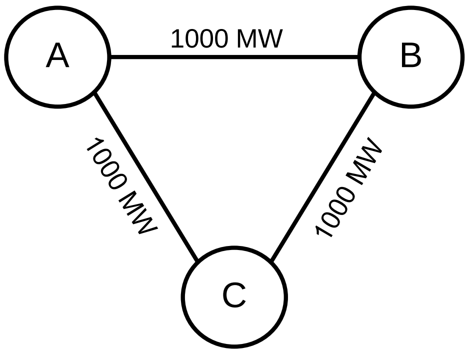
- The **full linearized security domain** is defined by the PTDFs and MW limits on CNEs applied in FB
- A "**reduced security domain"** is provided by ATCs (MW limits) applied in CNTC

Mathematically speaking, the security domain constitutes the solution space for the optimization of the objective function of the market algorithm. As such, the security domain will by definition be respected by the market optimization

Capacity calculation - Example

Example

- ✓ A power grid consisting of 3 bidding zones and three identical lines with the physical capacity of 1000 MW each
- ✓ A and B are "generation zones"
- ✓ C is a "consumption zone"



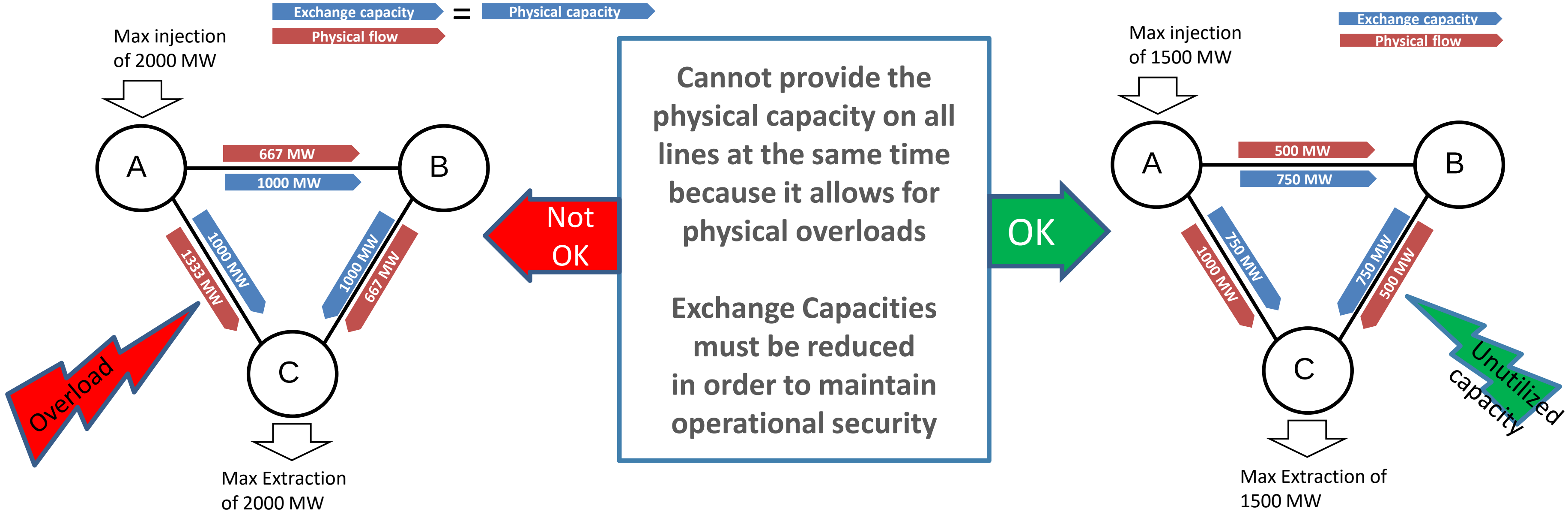
Simplifying assumptions

- ✓ No internal CNEs/grid constraints
- ✓ The only CNEs are the tie lines
- ✓ No reliability margin
- ✓ No contingencies
- ✓ No remedial actions

Objective: Calculate cross-border capacities

Capacity calculation - CNTC

- Capacity is provided as a MW limit (ATC) for bilateral exchange on each BZ border
- The market does not know real physics, and capacities are perceived as simultaneously available



Capacity calculation - CNTC

- The full set of CNTC values (ATCs) are referred to as a CNTC domain
- There is an unlimited set of potential CNTC domains available

CNTC capacities

Line	CNTC (1)	CNTC (2)	CNTC (3)	CNTC (4)	CNTC (N)
A -> B	750 MW	0 MW	200 MW	900 MW	? MW
B -> C	750 MW	1000 MW	200 MW	900 MW	? MW
A -> C	750 MW	1000 MW	1300 MW	600 MW	? MW

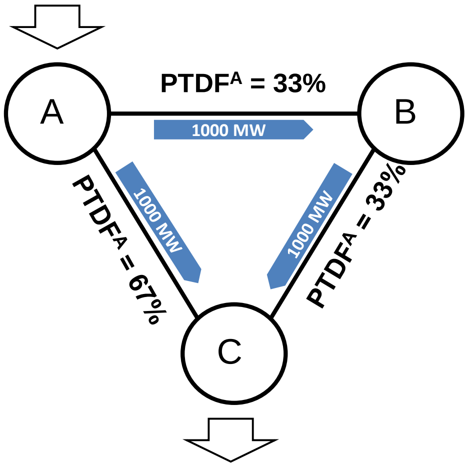
- Which ATCs to apply is based on a prognosis for the market outcome when attempting to provide capacity for the trades that are most likely to occur from a market perspective

Features of CNTC

- Priority for some bilateral trades
- Cannot fully utilize the security domain
- Complicated to manage in highly meshed grids with many BZs
- Flow determination is not a part of the market coupling (comes after), and thus there might be large differences between scheduled bilateral trades and physical flows
- The CNTC domain is not uniquely defined
- The CNTC capacities are simultaneously feasible

Capacity calculation - FB

- Capacity is provided by PTDFs, and CNEs with a MW limit/margin
- The market knows a linearized version of the real physics and understands that capacities are interdependent



- The lines (a-b), (b-c) and (a-c) are CNEs
- The full limit for each line can be provided (1000 MW)
- The PTDFs are the flows induced on each line by a net injection in A, B, and C extracted in C (slack node)
- Each BZ will have a unique PTDF on each CNE
- The PTDFs are calculated by a DC load flow process applied on a CGM (linearization)
- **The FB capacities constitute a simplified grid model to be applied by the power exchange**

Capacity calculation - FB

- The "full" security domain is provided directly as capacities to the market in the form of PTDFs and CNEs with MW margins
- The security domain is uniquely defined by the CGM

FB capacities

Line (CNE)	Max flows	PTDFs for BZ A	PTDFs for BZ B	PTDFs for BZ C (slack)
A -> B (CNE 1)	1000 MW	33 %	- 33 %	0
B -> C (CNE 2)	1000 MW	33 %	67 %	0
A -> C (CNE 3)	1000 MW	67 %	33 %	0

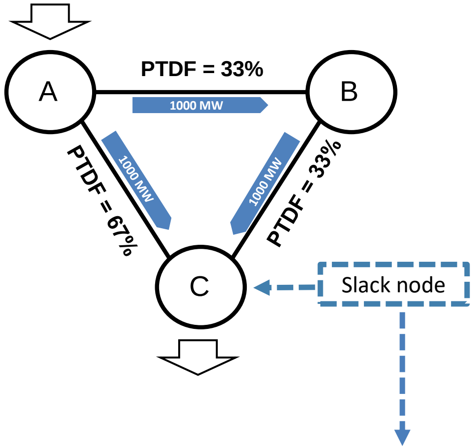
- The PTDFs are calculated by the CGM and thus depend on the impedances in the grid
- In this setting, the linearized security domain is often referred to as the FB domain

Features of FB

- Allows for price differences between uncongested areas - *increases the ability of the market to utilize all available capacity*
- The market coupling solves both net positions and flows and thus scheduled and physical flows are converging
- The FB domain is uniquely defined

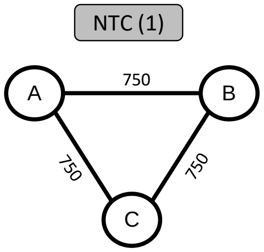
The slack node

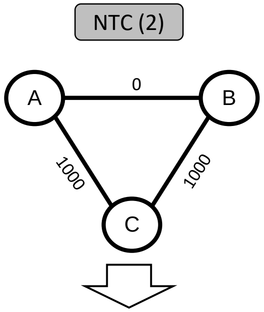
- All flows on the CNEs are being monitored by linear PTDFs by injection in a particular node and extraction in a selected slack node - "Node to slack" PTDFs
- The slack node is the reference point in the PTDF matrix
- All PTDFs for the slack itself is zero (flow from slack to slack)
- The slack node is a necessary mathematical construct, but the choice of slack has no influence on the results
- All other "node to node flows" can be derived by the PTDF matrix:
- $PTDF_{i,j}^{n} = PTDF_{i,slack}^{n} - PTDF_{j,slack}^{n}$

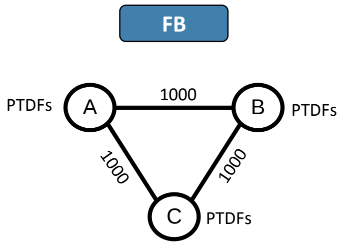


Line (CNE)	Max flows	PTDFs A	PTDFs B	PTDFs C
A -> B	1000 MW	33 %	- 33 %	0
B -> C	1000 MW	33 %	67 %	0
A -> C	1000 MW	67 %	33 %	0

FB vs CNTC







Max import/export in all BZs are 1500 MW

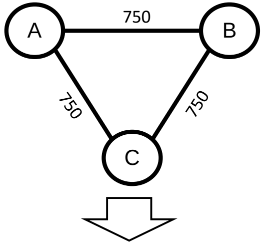
Max import/export in C is 2000 MW

Max import/export in A and B is 1000 MW

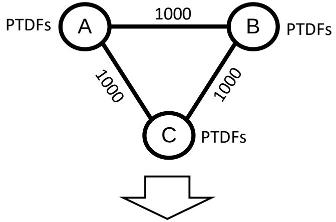
Max import/export in all BZs are 2000 MW (but not at the same time)

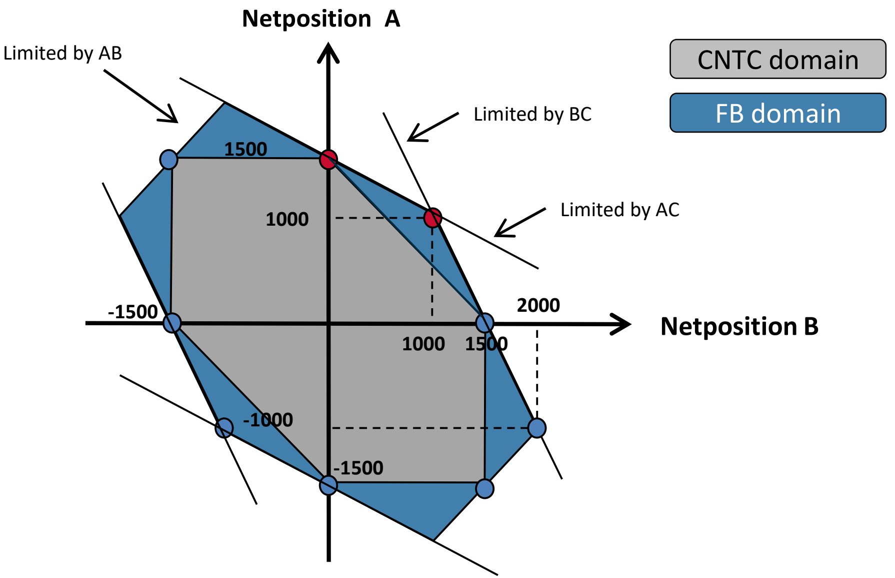
The FB and CNTC domains – Valid market positions

NTC (1)



FB

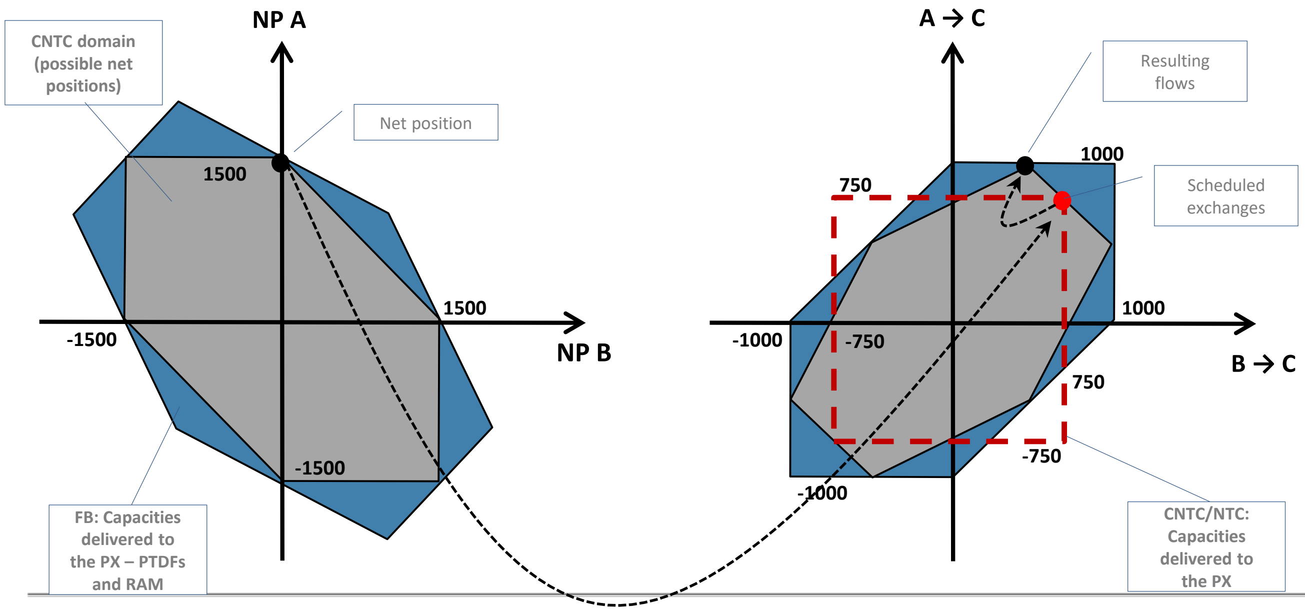




The security domains can be illustrated in two ways

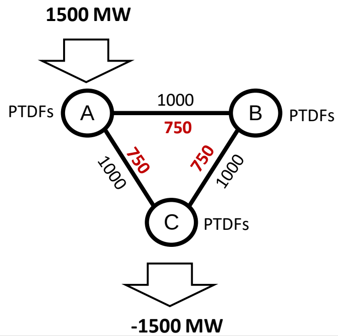
1. Which net positions are "allowed" in the market solution

2. Which flows are "allowed" in the market solution



The CNTC limits are imposed on the right hand figure, but it does not compare to the domains

- ✓ CNTC values shows valid bilateral exchanges
- ✓ The CNTC flow domain is not uniquely defined by one unique set of ATCs
- ✓ The flow-domains shows valid physical flows



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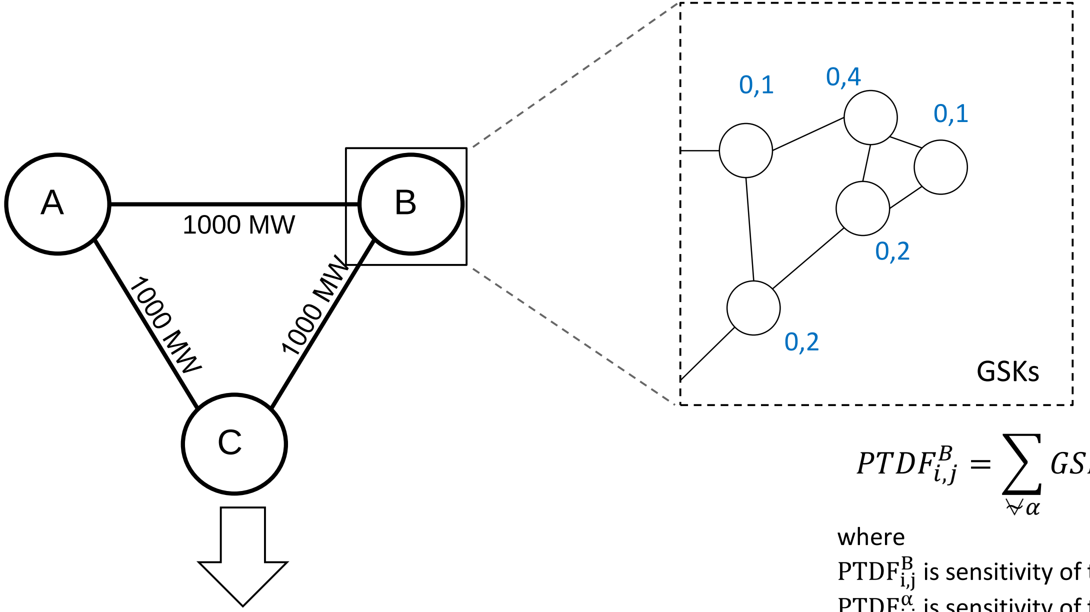
The zonal approach

- The FB and CNTC approach is based on the application of bidding zones (BZs)
- Each BZ contains multiple nodes (generation or consumption units) with a unique influence (nodal PTDF) on each constraint (CNE)
- BZs are not copperplates, but are perceived as copper plates by the market
  - All nodes inside each BZ will have the same BZ-specific influence on each CNE in the electricity market
  - Internal trades are not constrained

Generation Shift Keys (GSKs)



GSKs define how a net position change, in a given bidding zone, should be distributed to each production and load unit on that bidding zone

GSKs are used to calculate zone-to-CNE PTDFs, both for internal CNEs and interconnectors

$$PTDF_{i,j}^{B} = \sum_{\forall \alpha} GSK^{\alpha} PTDF_{i,j}^{\alpha} \quad \text{and} \quad \sum_{\forall \alpha} GSK^{\alpha} = 1$$

where

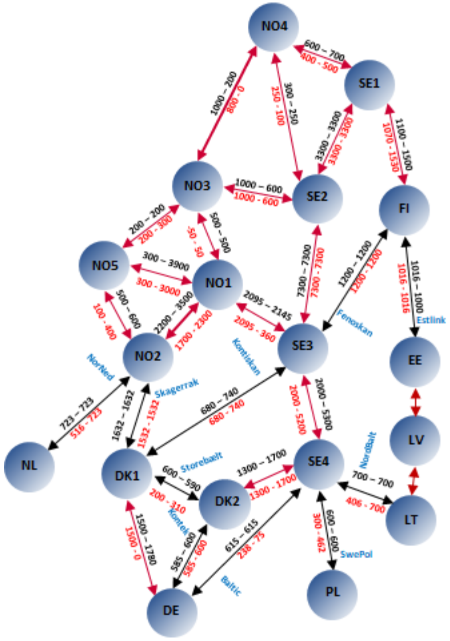
$\mathrm{PTDF}_{i,j}^{B}$ is sensitivity of transmission element *i,j* to injection in bidding zone B;

$\mathrm{PTDF}_{i,j}^{\alpha}$ is sensitivity of transmission element *i,j* of injection in node α; and

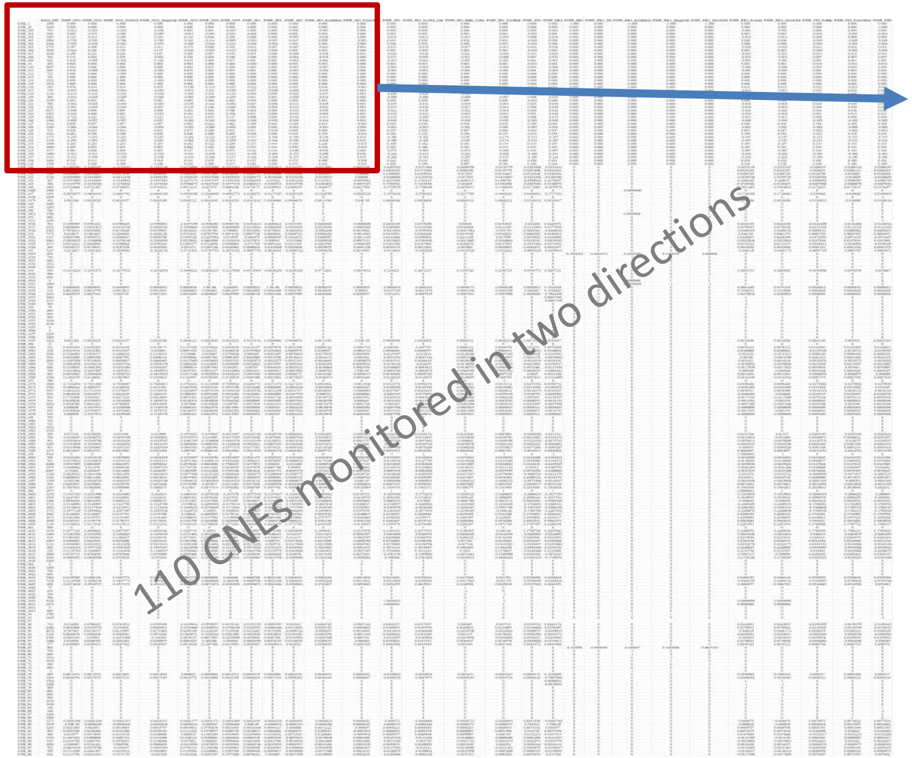
GSK^{α} is weight of node a on the PTDF of zone B.

It gets slightly more complicated in the real world,……..

- 12 BZs in the Nordics + 14 more virtual BZ to manage the HVDCs
- 70-90 limiting CNEs monitored in both directions for every hour
- Both internal and cross-zonal CNEs
- Application of remedial actions, contingencies and reliability margins for all CNEs



A real world PTDF matrix – 27/02 2017 Hour 0



	RAM_MW	PTDF_NO1	PTDF_NO2	PTDF_NO2_NorNed	PTDF_NO2_Skagerrak	PTDF_NO3	PTDF_NO4	PTDF_NO5	PTDF_SE1	PTDF_SE2	PTDF_SE3	PTDF_SE3_KontiSkan
CNE_1	1500	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
CNE_10	1245	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
CNE_100	753	-0.012	-0.254	-0.250	-0.258	0.003	0.001	-0.019	0.000	0.000	0.000	-0.001
CNE_101	826	0.005	-0.271	-0.261	-0.289	-0.013	-0.003	-0.043	-0.001	0.000	0.001	0.001
CNE_102	1427	0.125	0.213	0.199	0.184	0.144	0.036	0.305	0.009	0.005	-0.007	-0.018
CNE_103	1964	-0.735	-0.783	-0.786	-0.789	-0.401	-0.114	-0.699	-0.030	-0.017	0.015	0.058
CNE_104	2362	-0.059	-0.849	-0.863	-0.879	-0.069	-0.016	-0.214	-0.004	-0.002	0.003	0.008
CNE_105	1775	0.197	0.409	0.411	0.411	0.174	0.046	0.350	0.012	0.007	-0.007	-0.023
CNE_106	1025	-0.024	0.168	0.150	0.147	-0.024	-0.007	-0.015	-0.002	-0.001	0.001	0.004
CNE_107	1036	0.259	0.221	0.204	0.187	0.200	0.057	0.344	0.015	0.008	-0.008	-0.029
CNE_108	761	0.171	0.022	0.018	-0.003	0.100	0.029	0.160	0.008	0.004	-0.004	-0.015
CNE_109	922	0.010	-0.098	-0.362	-0.182	0.015	0.004	0.037	0.001	0.001	-0.001	-0.002
CNE_11	303	0.002	0.002	0.002	0.002	0.004	0.080	0.002	-0.002	0.000	0.001	0.001
CNE_110	3807	0.004	0.868	0.880	0.896	0.063	0.015	0.200	0.004	0.002	-0.003	-0.007
CNE_111	922	0.010	-0.098	-0.362	-0.182	0.015	0.004	0.037	0.001	0.001	-0.001	-0.002
CNE_112	723	0.000	0.000	-1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
CNE_113	723	0.000	0.000	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
CNE_114	1532	0.000	0.000	0.000	-1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
CNE_115	1532	0.000	0.000	0.000	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
CNE_116	543	0.076	0.034	0.034	0.035	-0.198	-0.110	-0.015	-0.022	-0.002	0.010	0.016
CNE_117	779	-0.033	-0.030	-0.030	-0.030	-0.074	-0.411	-0.038	0.047	-0.006	-0.009	-0.015
CNE_118	1310	-0.115	-0.103	-0.102	-0.100	-0.295	0.219	-0.142	0.050	0.005	-0.020	-0.037
CNE_119	485	-0.032	-0.029	-0.029	-0.028	-0.083	-0.269	-0.039	0.011	0.004	-0.006	-0.012
CNE_120	1459	0.001	0.001	0.001	0.001	0.005	0.966	0.002	-0.001	0.000	0.000	0.001
CNE_121	788	-0.044	-0.040	-0.040	-0.040	-0.105	-0.442	-0.052	0.047	-0.004	-0.011	-0.019
CNE_122	918	-0.053	-0.048	-0.048	-0.047	-0.125	0.246	-0.062	0.050	-0.001	-0.013	-0.022
CNE_123	6437	-0.048	0.890	0.893	0.896	0.282	0.062	0.766	0.016	0.009	-0.014	-0.030
CNE_124	3181	-0.035	0.009	0.001	-0.010	0.191	0.042	0.456	0.011	0.006	-0.010	-0.020
CNE_125	6261	-0.722	0.221	0.222	0.223	0.113	0.034	0.147	0.008	0.004	-0.018	-0.013
CNE_126	1360	-0.059	-0.057	-0.057	-0.057	-0.082	-0.222	-0.062	-0.399	-0.018	-0.029	-0.044
CNE_127	1412	0.059	0.057	0.057	0.057	0.082	0.222	0.062	0.399	0.018	0.029	0.044
CNE_128	1380	-0.002	-0.002	-0.002	-0.002	-0.004	-0.080	-0.002	0.002	0.000	-0.001	-0.001
CNE_129	523	0.026	0.024	0.024	0.023	0.071	0.209	0.032	0.011	-0.005	0.005	0.009
CNE_130	1334	0.201	0.199	0.199	0.199	0.228	0.288	0.205	0.320	0.169	0.115	0.170
CNE_131	1173	-0.255	-0.253	-0.253	-0.253	-0.282	-0.322	-0.259	-0.337	-0.344	-0.150	-0.216
CNE_132	1172	-0.255	-0.253	-0.253	-0.253	-0.282	-0.322	-0.259	-0.337	-0.344	-0.150	-0.216
CNE_133	1599	0.255	0.253	0.253	0.253	0.282	0.322	0.259	0.337	0.344	0.150	0.216
CNE_134	1600	0.255	0.253	0.253	0.253	0.282	0.322	0.259	0.337	0.344	0.150	0.216
CNE_135	1417	0.061	0.056	0.056	0.055	0.127	0.131	0.071	0.102	0.116	-0.056	-0.045
CNE_136	1490	-0.313	-0.311	-0.310	-0.310	-0.341	-0.279	-0.317	-0.153	-0.250	-0.173	-0.256

Zone to slack PTDFs

4. Different perspectives of FB and CNTC

The FB and CNTC market coupling - Euphemia

FB MC:

Max Σ (PS + CS + CI)

Subject to:

PTDF * NP ≤ RAM

Σ NP = 0

CNTC MC:

Max Σ (PS + CS + CI)

Subject to:

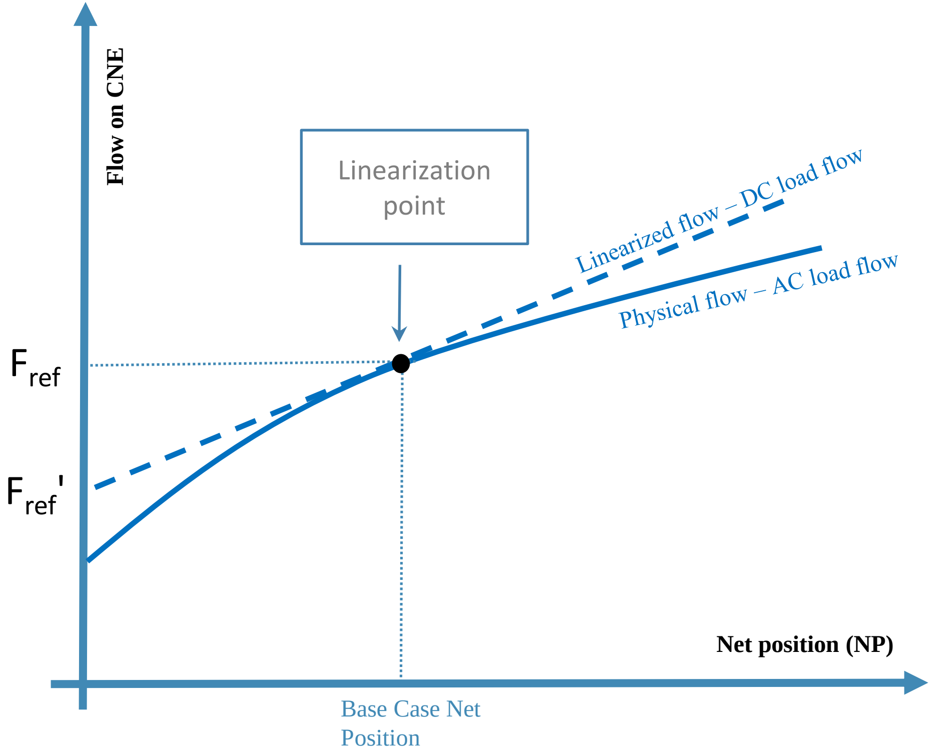
$NP \leq \Sigma_{\forall j} ATC_j$ (Exp)

$NP \geq \Sigma_{\forall j} -ATC_j$ (Imp)

Σ NP = 0

- The objective functions are the same for FB and CNTC
- The constraints are different
- The constraints provide the solution spaces, which define the full space of valid market solutions
- When the same physical constraints are imposed on both FB and CNTC, the CNTC solution space is fully covered inside the FB solution space
- FB can provide market solutions not available to CNTC
- CNTC cannot provide market solutions unavailable to FB
- CNTC provides unique solutions for prices and net positions
- FB provides unique solutions for prices, net positions, and flows

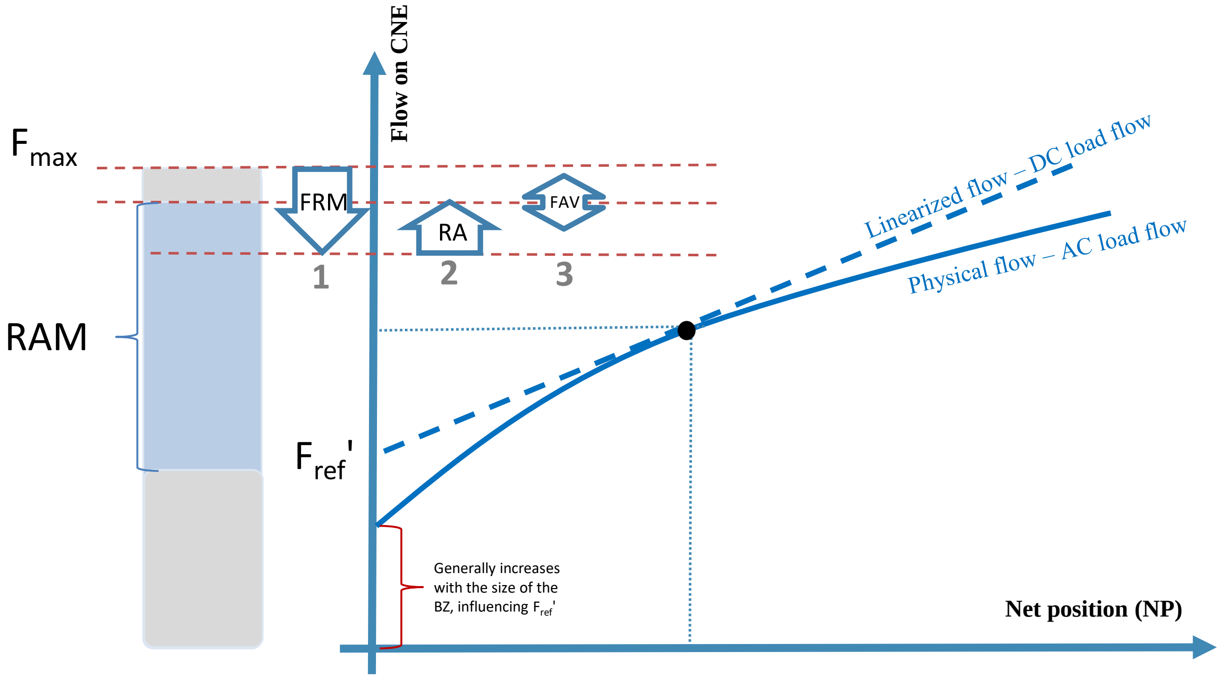
How the PTDFs are derived



- Physical flows are non-linear functions of power injections (NP)
- The PTDFs represent a linearization of these non-linear flows, calculated by a DC-load flow analysis based on the CGM
- For the PTDF to be as precise as possible, the linearization is made in the base case (forecasted market position)
- The forecasted flow is:

$$F_{ref} = F_{ref}' + PTDF * NP$$

How the margins of the CNEs are derived



- The max allowed flow (F_{max}) on the CNE are calculated in a (if necessary dynamic) grid model
- The max allowed flow is reduced / altered in three steps
  1. Subtract the flow reliability margin (FRM)
  2. Add Remedial actions (RA)
  3. If necessary, adjust the final result by last minute information (FAV), zero in the figure
- The constraint (Capacity) for the market becomes:

$$F_{ref}' + PTDF * NP \leq F_{max} + RA - FRM - FAV$$

⇩

$$PTDF * NP \leq F_{max} + RA - FRM - FAV - F_{ref}'$$

⇩

PTDF * NP ≤ RAM

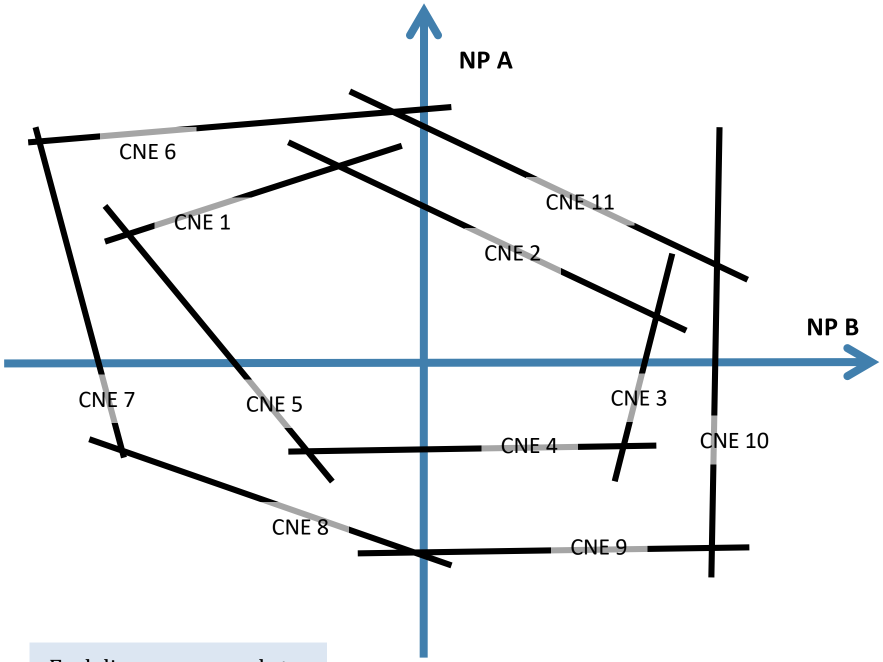
Ingredients of capacity calculation

- Input to capacity calculations
  - ✓ Common Grid Model (CGM)
  - ✓ GSKs
  - ✓ CNEs
  - ✓ Operational security limits
  - ✓ Contingencies
  - ✓ Remedial Actions (RA)
  - ✓ Reliability Margin (RM/FRM)
  - ✓ Final Adjustment Value (FAV – Applied in the final validation phase)
  - ✓ AAC (Already-allocated capacity)
  - ✓ Allocation constraints

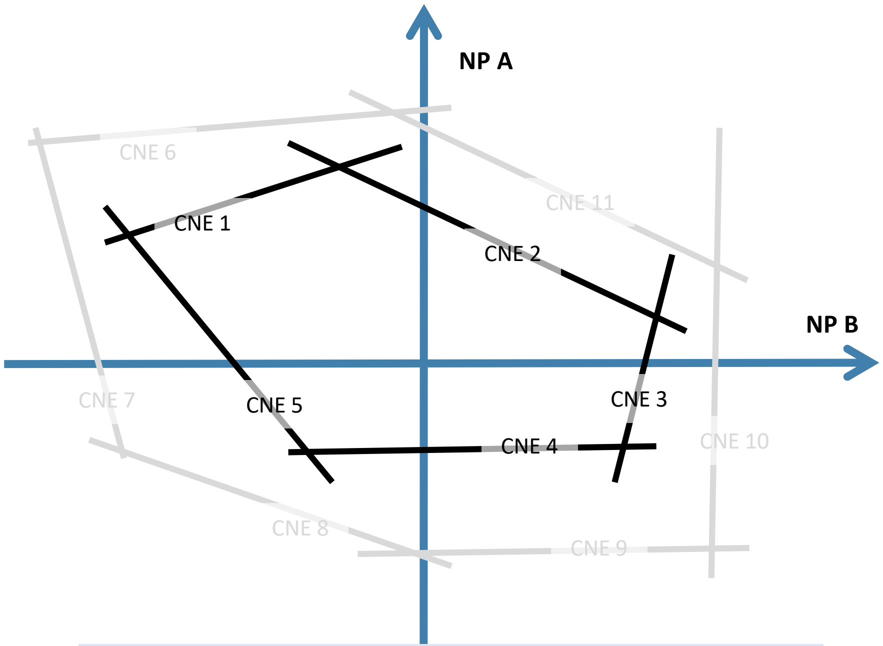
- Output from the market optimization
  - ✓ BZ prices (FB and CNTC)
  - ✓ BZ Net positions (FB and CNTC)
  - ✓ Flows (FB)
  - ✓ Shadow prices (FB and CNTC)

- The input data to CNTC and FB is the same
- The most important difference is the way grid constraints are provided to the market coupling and the fact that flow determination is a post process in CNTC with multiple possible solutions

Redundant CNEs and pre-solve



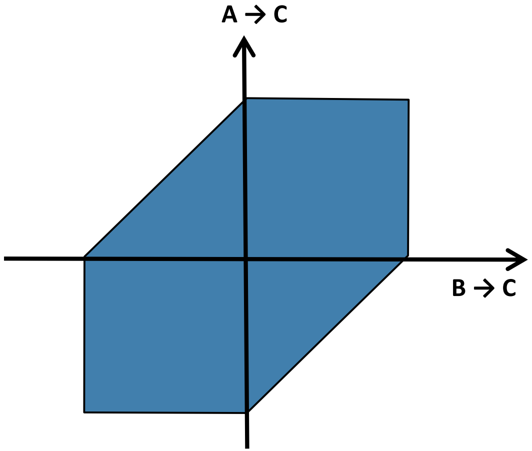
Each line corresponds to
$PTDF \times NP = RAM$
for a given CNE



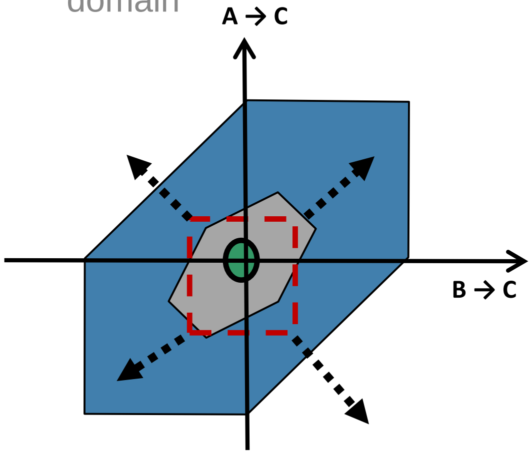
All CNEs in light grey are redundant because they do not limit the market coupling algorithm. These CNEs' constraints are located beyond other, non-redundant, CNE constraints (in black)

Principles for deriving a CNTC respecting the boundaries of the security domain

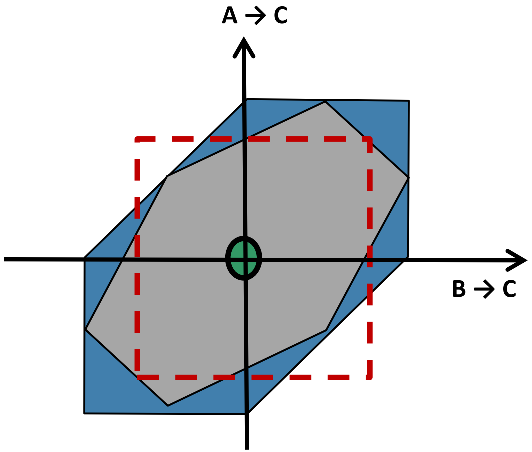
Step 1: define the security domain



Step 2: Define the objective function and constraints to find an optimal CNTC-domain from the security domain



Step 3: Extract the final and optimized CNTC values



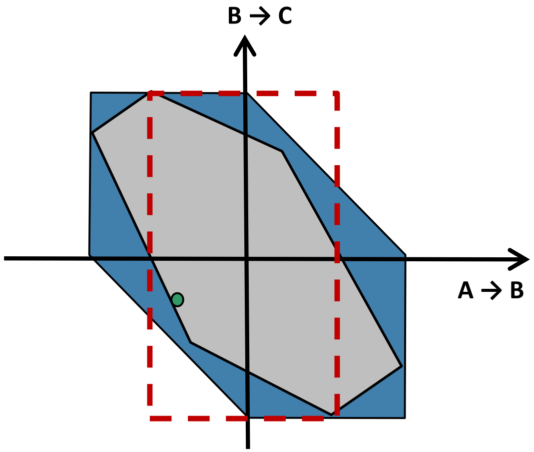
Possible approach: Maximize the product of "CNTC values"

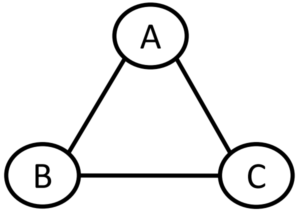
Subject to "All allowed flows shall be inside the security domain"

Relaxation of the constraints for the CNTC optimization

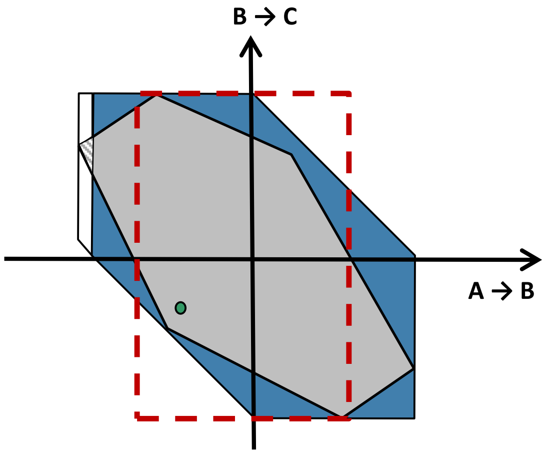
1. Let's assume the optimization provided the CNTC domain below. This has left "secure room" to move the base-case (expected market position, the green dot) "to the left"
2. By relaxing one limiting constraints in the upper left corner of the security domain, we can add extra CNTC capacity for B → A with relatively low risk for the operational security
3. This comes at the cost of a small operational security risk for the opposite direction of the expected flow B → C (the small triangular shaded area)

➢ Also applicable for FB

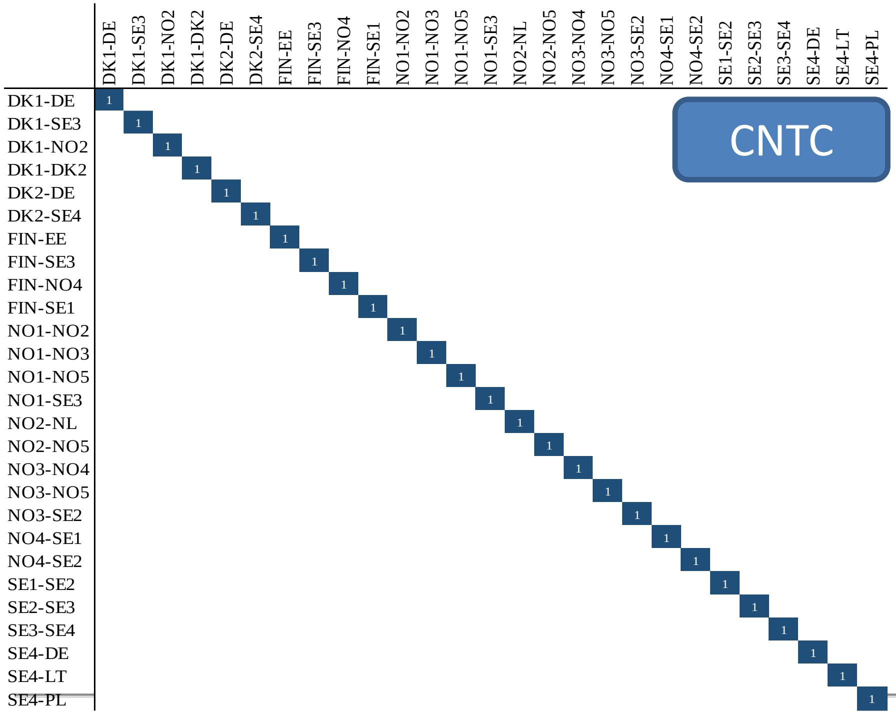


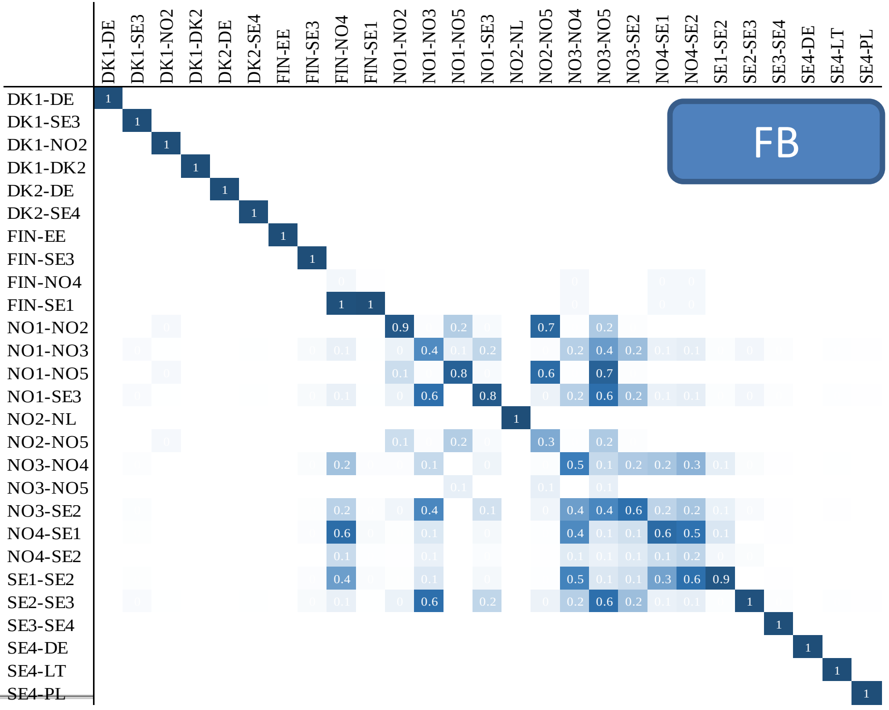


PS!
The model has been flipped



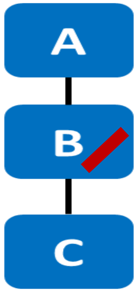
How bilateral exchanges are perceived by the market algorithm in FB and CNTC





Managing internal CNEs in FB and CNTC

Flow based method



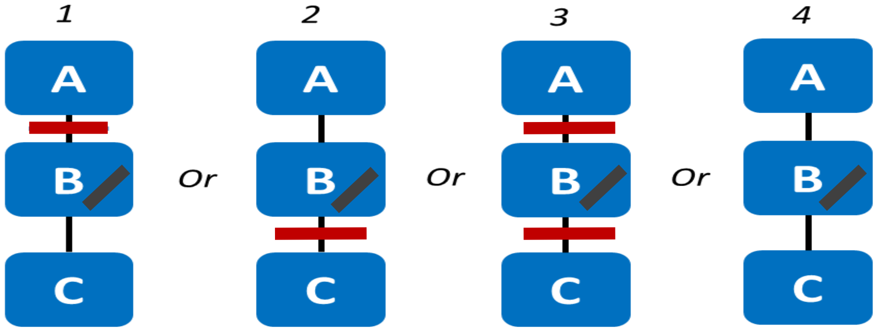
Internal constraint modelled directly

The internal constraint can be modelled directly

Capacity is allocated according to willingness to pay, and the difference in influence on the constrain from the different bidding areas

Add as a CNE to the PTDF-matrix

CNTC method



1

Constraint moved to border A-B

Exchange between area B and C is prioritized

Area A cannot utilize transmission capacity not used by areas B and C

No limit on exchange between B and C can lead to overloads

2

Constraint moved to border B-C

Exchange between area A and B is prioritized

Area C cannot utilize transmission capacity not used by areas A and B

No limit on exchange between A and B can lead to overloads

3

Constraint on border A-B and B-C

All trade restricted

Distribution of capacity not according to willingness-to-pay

Capacity not used by one area cannot be used by another

No overloads on internal constraint from cross border exchange

4

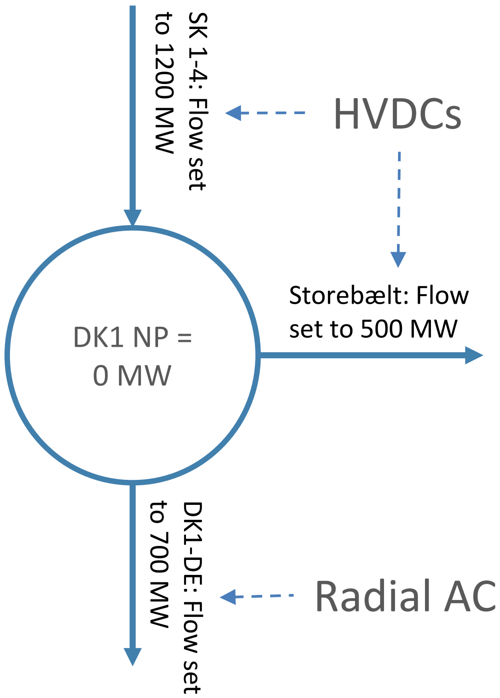
Constraint disregarded

No restrictions

Overloads to be solved by costly remedial actions

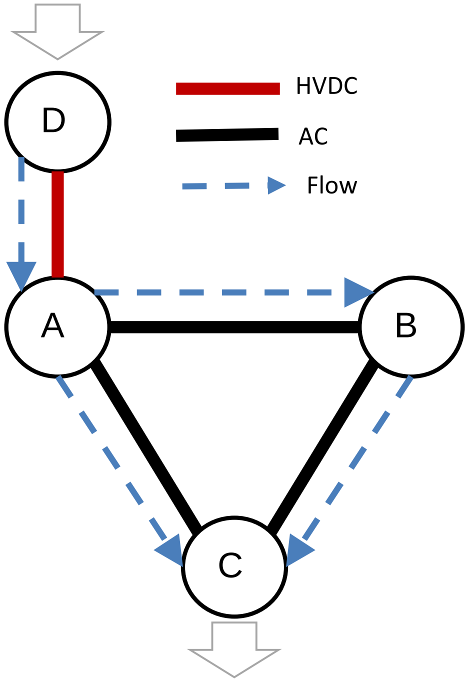
Managing HVDC connections

- While the flows in an AC grid fans out according to physical laws, the flow on an DC connection (or a radial AC connection) is fully manageable by the operator → don't need PTDFs to manage flows <u>on</u> an HVDC (or a radial AC connection) connection
- If all connections were either HVDC and/or radial, the CNTC approach would provide the same efficiency/market solution as FB
- With HVDC we can let the market decide the flows and simply set the system to realize the scheduled flows

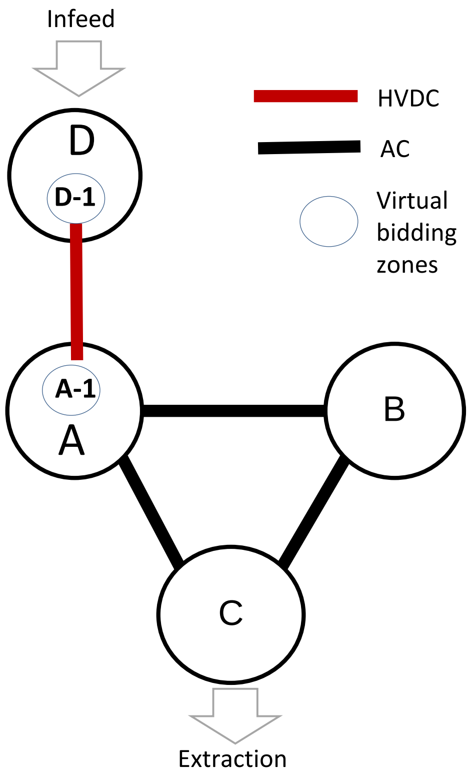


HVDC flows needs to be managed in the AC grid

- When the flows from HVDCs (and radial AC connections) enter the meshed AC grid, they will fan out according to the physical laws and occupy the limited capacity on the grid components
- Flows coming from HVDC (and radial AC) connections need to be managed in the AC grid
- The HVDC functions like a remote generator, creating the same flows in the AC grid as an internal generator



Equal access for HVDC are implemented by "virtual bidding zones"

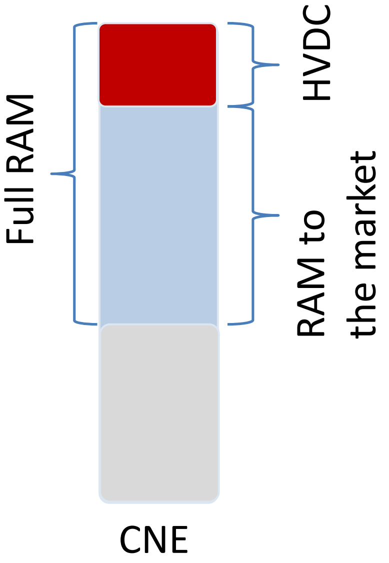


Line (CNE)	Max flows	PTDF A	PTDF B	PTDF C	PTDF A-1
A -> B (CNE 1)	1000 MW	33 %	- 33 %	0	45%
B -> C (CNE 2)	1000 MW	33 %	67 %	0	45%
A -> C (CNE 3)	1000 MW	67 %	33 %	0	55%

- ✓ A new bidding zone, A-1, is introduced in the PTDF matrix (for the "southern" control area)
- ✓ The HVDC is connected to the virtual bidding zone
- ✓ The virtual bidding zone is "empty", it contains no bids
- ✓ The virtual bidding zone will have a unique price in the coupling process, but will receive the price of the surrounding zone in the settlement process

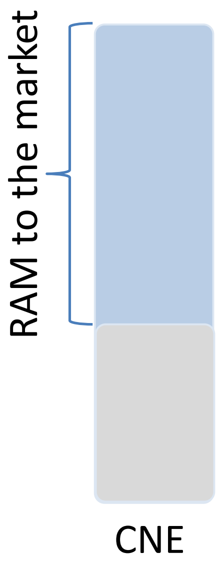
Two ways to manage HVDCs

Priority access = Standard hybrid coupling



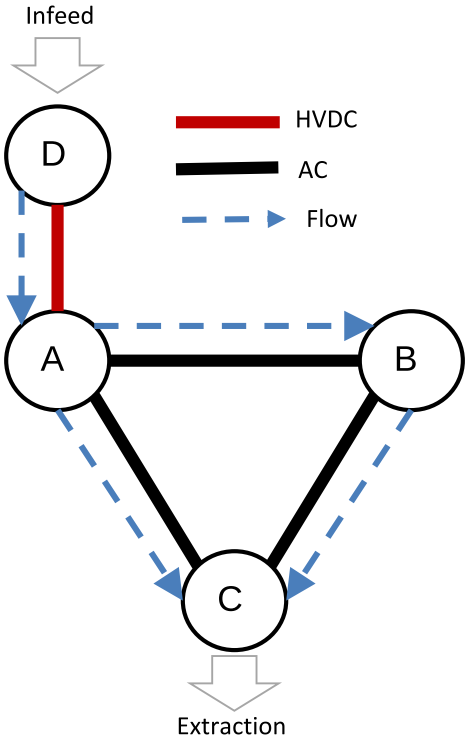
- ✓ Flows on AC components from HVDCs are calculated by PTDFs and flow prognoses for the HVDC
- ✓ Capacity are reserved on <u>all</u> influenced CNEs
- ✓ Less capacity for all other trades
- ✓ If the HVDC flow falls short of the expected flow, capacity is unused
- ✓ SHC is applied to minimize the influence on "the external" side of an interconnector

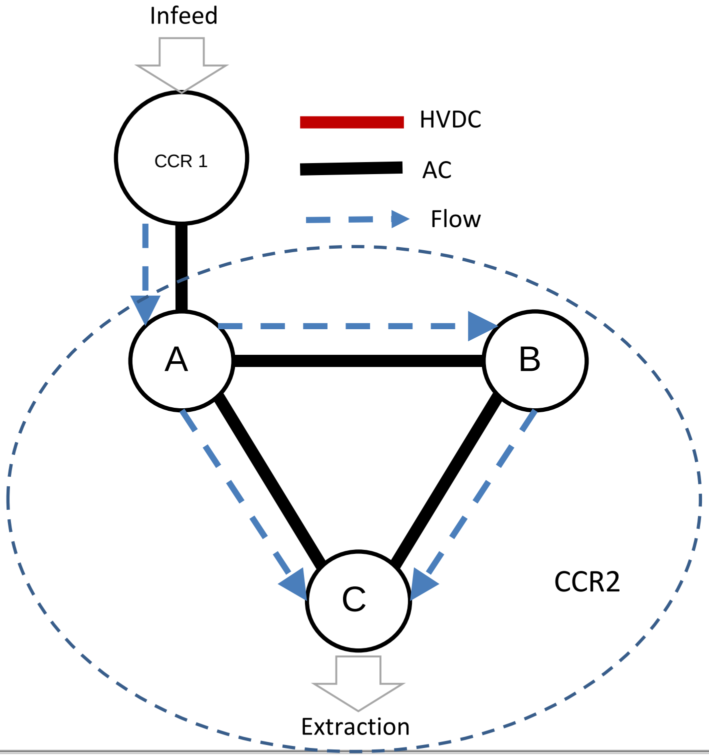
Equal access = Advanced hybrid coupling



- ✓ Flows on AC components from HVDCs are calculated during market coupling using PTDFs for the transformer station
- ✓ No capacity are reserved on any influenced CNEs
- ✓ Full capacity for all trades
- ✓ Flows from HVDCs compete for capacity with all other trades → normal flow competition
- ✓ If the HVDC flow falls short of the expected flow, all capacity is still available for other trades

Advanced Hybrid Coupling can manage HVDC, but also couple two CCRs with radial AC connection





"Non-intuitive" flows

- A non intuitive flow is a flow from a high price to a low price BZ
- Non intuitive flows are a result of the FB market optimization
- Non-intuitive flows occur to relieve congestions on constrained grid elements
- 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
- By relieving capacity on congested grid elements, non-intuitive flows contribute positively to the overall market efficiency, and thus generate a market wide efficiency gain
- In equilibrium, the marginal value of all trades are equal
- Non intuitive flows are applied in existing nodal price systems, and in the current Nordic market by enforcing the power to flow in a certain direction (NO1-NO3, and NO5-NO3)

Welfare optimum

- *The first order condition for a global welfare optimum is:*

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

P^i = The price/marginal value of power in BZ i
λ = The marginal value of power in the slack node (not the system price)
ρ_n = Shadow price of the constraining grid element n
$PTDF_n^i$ = The PTDF to the slack for BZi on CNE n

- *The marginal value of a bilateral trade from BZi to BZj can be derived from the f.o.c.:*

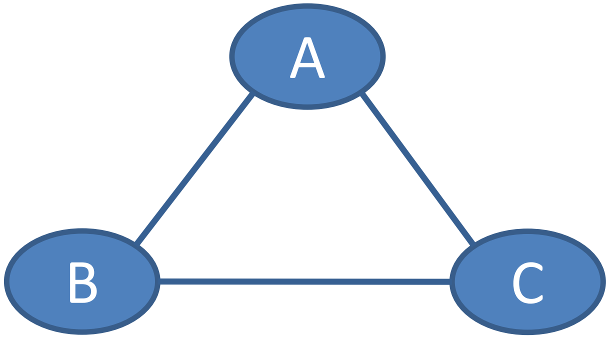
$$\rho_k \geq 0 \text{ and } \rho_k\left(\sum_i NP_i * PTDF_k^i - RAM_k\right) = 0$$

$$\left(\frac{(P^j - P^i)}{\sum_n \alpha_n\left(PTDF_n^i - PTDF_n^j\right)}\right) = \sum_k \rho_k \qquad \alpha_n = \frac{\rho_n}{\sum_k \rho_n}$$

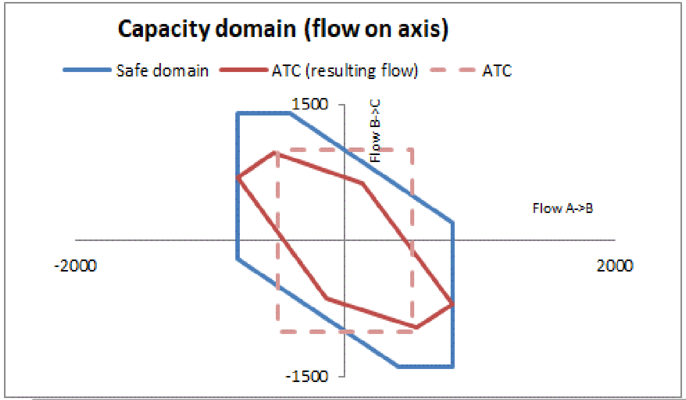
k = the set of all limiting grid elements, $n \in k$

- *Non-intuitive flows are non-intuitive, not non-efficient*

Example - Non intuitive flow

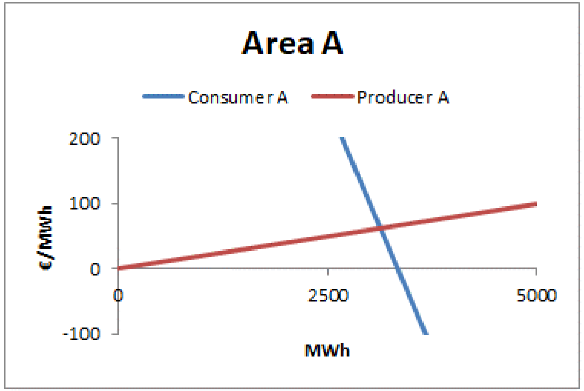


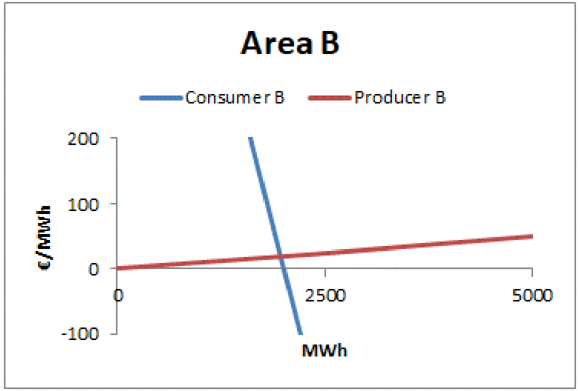
Line (CNE)	Max flow	Min flow	PTDF A	PTDF B	PTDF C
A -> B (CNE 1)	800 MW	-800 MW	33 %	- 33 %	0
B -> C (CNE 2)	1400 MW	-1400 MW	33 %	67 %	0
A -> C (CNE 3)	1000 MW	-1000 MW	67 %	33 %	0

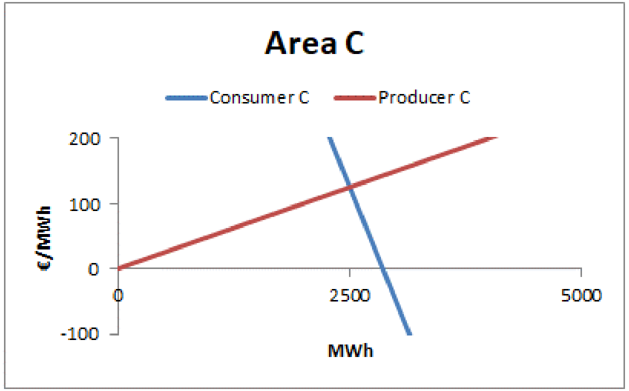


Line	Max NTC	Min NTC
A -> B	500 MW	-500 MW
B -> C	1000 MW	-1000 MW
A -> C	400 MW	-400 MW

Example – The market

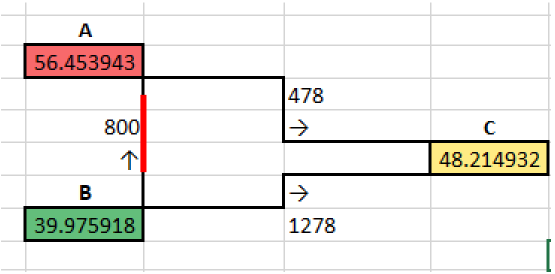




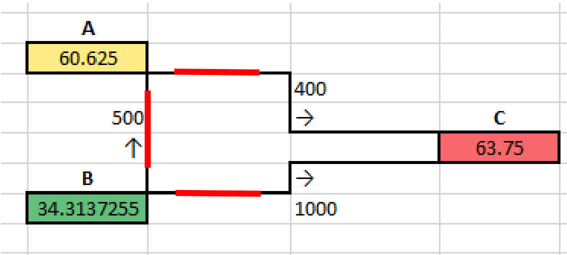


FB and CNTC market solution

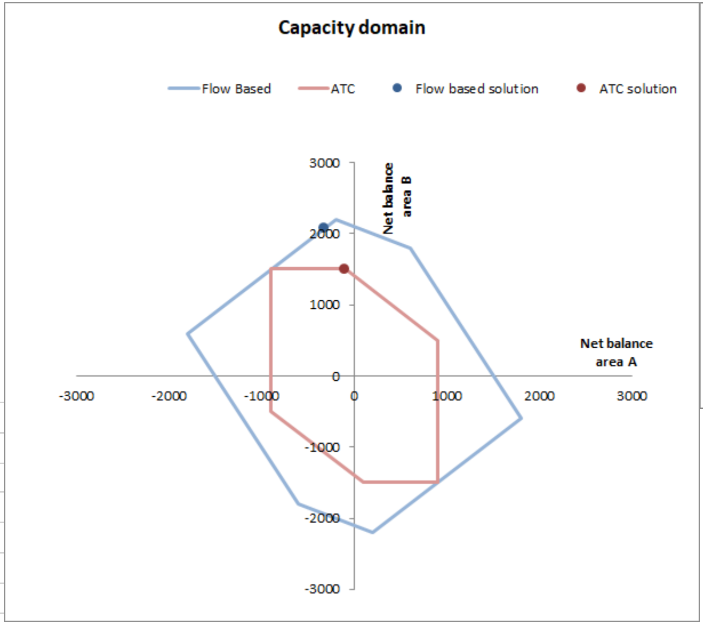
FB: B-A congested
Non-intuitive flow A-C
Global optimum

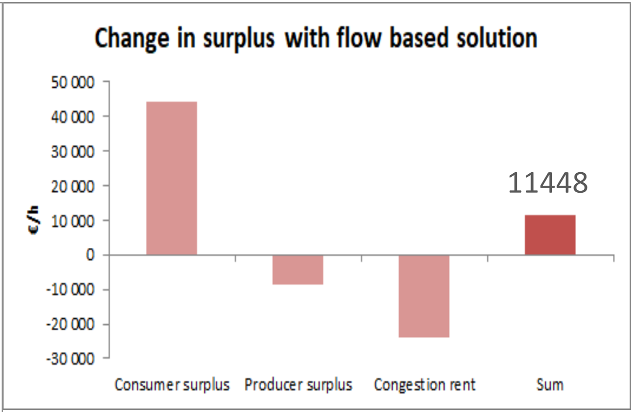


NTC: All lines congested



Marginal value of bilateral trades in FB						
A-B	B-A	B-C	C-B	A-C	C-A	Sum shadow prices
24.717	24.717	24.717	24.717	24.717	24.717	24.717

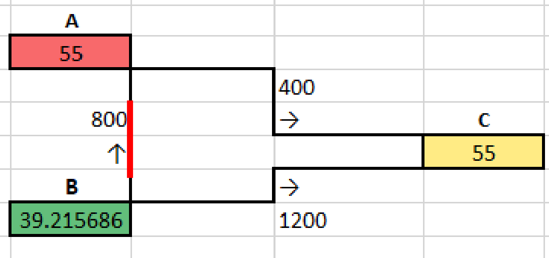




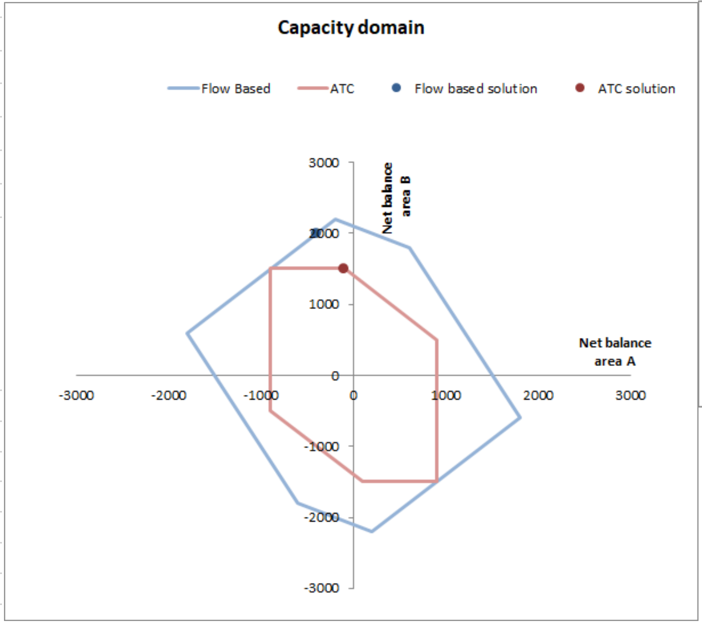
Intuitive FB and CNTC market solution

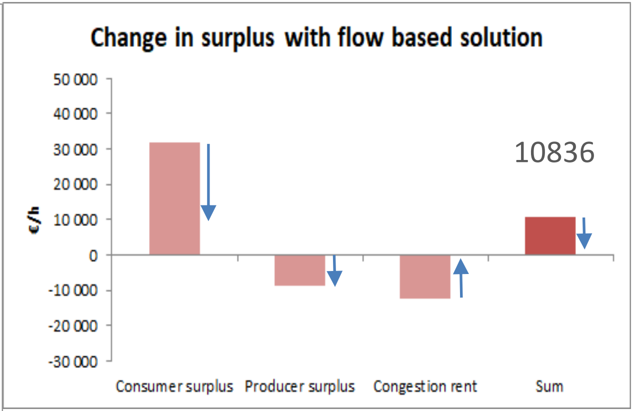
FB: B-A congested

Intuitive flow solution

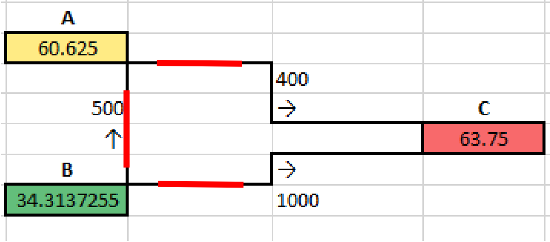


Marginal value of bilateral trades in FB						
A-B	B-A	B-C	C-B	A-C	C-A	Sum shadow prices
47.352	47.352	47.353	47.353	0.006	0.006	15.784





NTC: All lines congested

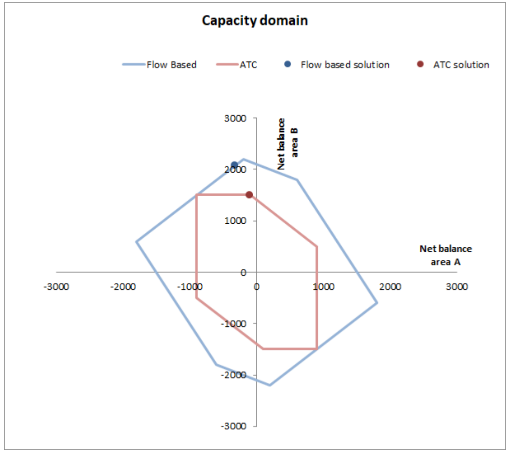


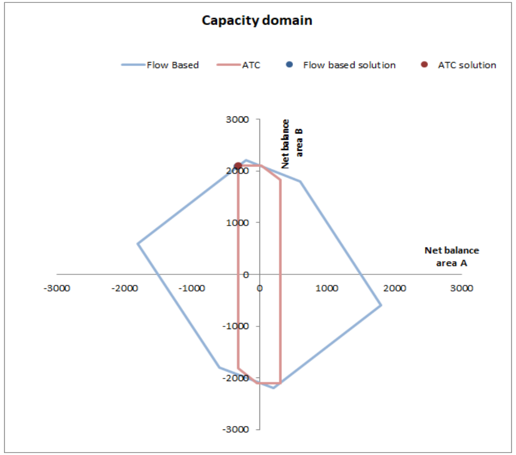
5% lower benefit from FB due to the non-intuitive constrain

FB vs CNTC

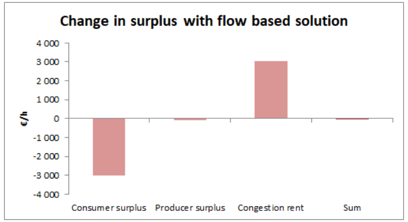
- It is possible for CNTC to go to the FB solution
- It comes at a cost of suppressing other borders (and BZs)

Line	Max NTC	Min NTC
A -> B	500 MW	-500 MW
B -> C	1000 MW	-1000 MW
A -> C	400 MW	-400 MW





Line	Max NTC	Min NTC
A -> B	140 MW	-140 MW
B -> C	1960 MW	-1960 MW
A -> C	170 MW	-170 MW



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Management of internal grid constraints

- Internal grid constraints (CNEs) can only be applied in capacity calculation when:
  - ✓ Temporal (which is an undefined entity), and
  - ✓ Discarding them within the market coupling does not pose a risk to operational security, and
  - ✓ Managing them by countertrade (CT) or redispatch (RD) in operation provides a welfare economic benefit

- These principles are embedded in the Nordic CCM:
  1. Operational security test: Assess the availability for potential counter trade and re-dispatch resources for all internal CNEs during capacity calculation, and assess how much capacity can be added to each internal CNE due to availability of CT & RD resources (not fully operationalized yet)

  2. Economic efficiency test: Assess the potential welfare economic benefit of applying CT & RD on each internal CNE

Economic efficiency test

- Rule: If the marginal cost of CT or RD is lower than the marginal value of a MW added to the most expensive border for the relevant BZ, increase the capacity on the CNE

The marginal value of a MW added on a BZ border is expressed by the relation: $\left(\frac{(P^j - P^i)}{\sum_n \alpha_n \left(PTDF_n^i - PTDF_n^j\right)}\right) = \sum_k \rho_k \qquad \alpha_n = \frac{\rho_n}{\sum_k \rho_n}$

- We don't know the shadow prices in D-2 (ρ), thus we have to simplify the expression and apply the border PTDFs directly

Operational economic efficiency test

The model below is not a final solution, but the starting point for further development

Cost(RD) = $\frac{|P^{\uparrow}-P^{\downarrow}|}{PTDF^{\uparrow\downarrow}}$

Cost(CNE) = $\frac{|P^{A1}-P^{A2}|}{PTDF^{A1-A2}}$

Criteria for preparing RD:

$$\frac{|P^{\uparrow}-P^{\downarrow}|}{PTDF^{\uparrow\downarrow}} \leq \frac{|P^{A1}-P^{A2}|}{PTDF^{A1-A2}}$$

This can be rearranged to yield:

$$\boldsymbol{PTDF^{\uparrow\downarrow}} \geq \frac{|P^{\uparrow}-P^{\downarrow}|}{|P^{A1}-P^{A2}|} * \boldsymbol{PTDF^{A1-A2}}$$

$\boldsymbol{P^{\uparrow}}$ = Up regulating price

$\boldsymbol{P^{\downarrow}}$ = Down regulating price

$\boldsymbol{P^{A1}}$ = Area 1 price

$\boldsymbol{P^{A2}}$ = Area 2 price

$\boldsymbol{PTDF^{A1-A2}}$ = Zone to zone PTDF for the relevant border

$\boldsymbol{PTDF^{\uparrow\downarrow}}$ = Node to node PTDF for the relevant CNE

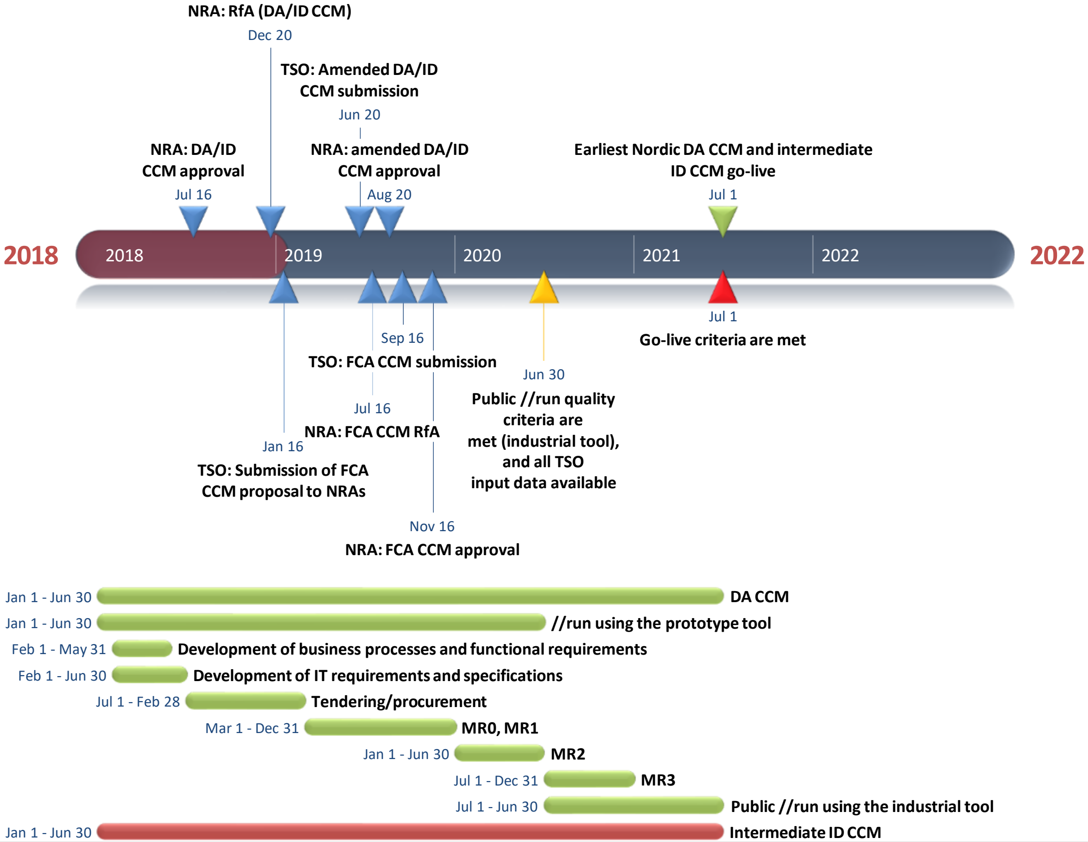
Known: $\boldsymbol{P^{\uparrow}}$, $\boldsymbol{P^{\downarrow}}$, $\boldsymbol{P^{A1}}$, $\boldsymbol{P^{A2}}$, $\boldsymbol{PTDF^{A1-A2}}$

Operator will asses the relevant $\boldsymbol{PTDF^{\uparrow\downarrow}}$

5. Market simulations of FB vs. NTC in the Nordics

- Simulation setup
- Social welfare
- Prices, flows
- Managing of West Coast corridor or others
- Power system impact analysis (overload of NTC and FB)
- Other relevant figures

6. Implementation of new CCM in the Nordics



6. Implementation of new CCM in the Nordics

Key learning's from CWE FB operation (from the 2018 visit to Tennet NL)

- Internal parallel run: information was published to the stakeholders
- Domain validation by the TSO operators: only important in the beginning. Trust has been built in the meantime, so that there is less need for the validation.
- FRMs are “operationally adjusted” (i.e. reduced when they are considered to be too large)
- Stakeholder involvement and transparency: leaflet / handbook, webinars
- Improvements ongoing on GSKs (important input parameter with a - potentially - large impact)
- Euphemia performance issues due to the DE-AT split (due to the virtual CNEs being applied for the LTA inclusion, the number of presolved CNEs increased to 500-800 with the DE-AT split)
- Relatively large welfare gains with the CWE going to FB compared to ATC.
- SPAIC analysis (Standard Process to communicate on and Assess the Impact of significant Changes) requires a lot of effort. A SPAIC analysis consists of a comparison of FB domains and market results for 12 typical “reference” days, commonly predefined by CWE TSOs, in order to estimate the impact of a change in grid topology or FB parameters.