Flow Based Market Coupling in Fundamental Electricity Market Models: Methods and Parametrization (for Renewable-Dominant Power Systems)

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Agenda

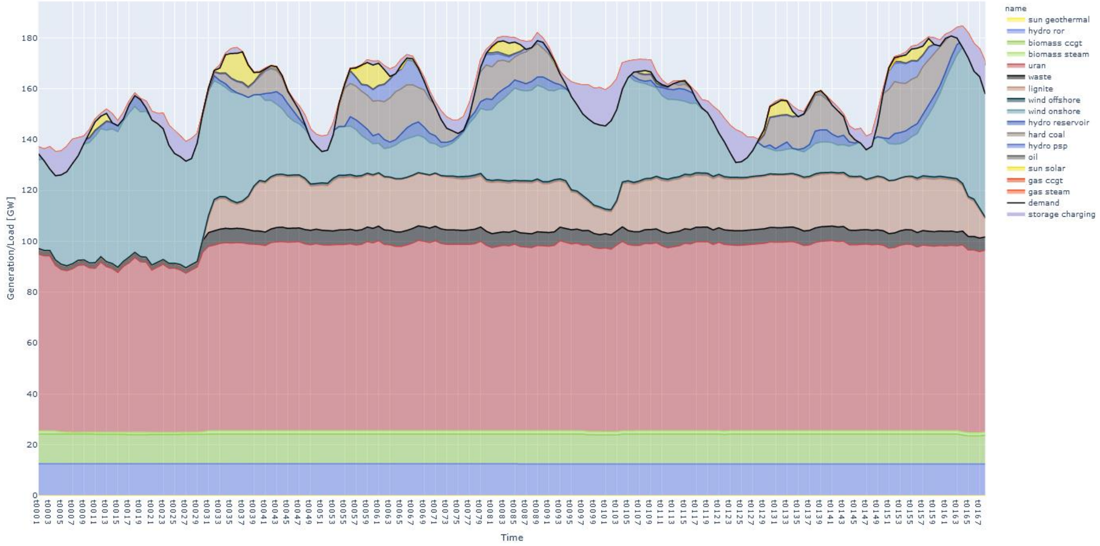
1. Motivation and Challenges
2. Modeling FBMC:
   - Three Step Process: D-2, D-1, D-0
   - Economic Dispatch Problem s.t. Grid Representation
3. FB-Parametrization:
   - Basecase, minRAM, CNEC, GSK, FRM
   - Literature Review
   - Parametrization process defines permissiveness of FB-Domain

4. Case Study: Extended IEEE 118 bus case
   - High share of intermittent generation.

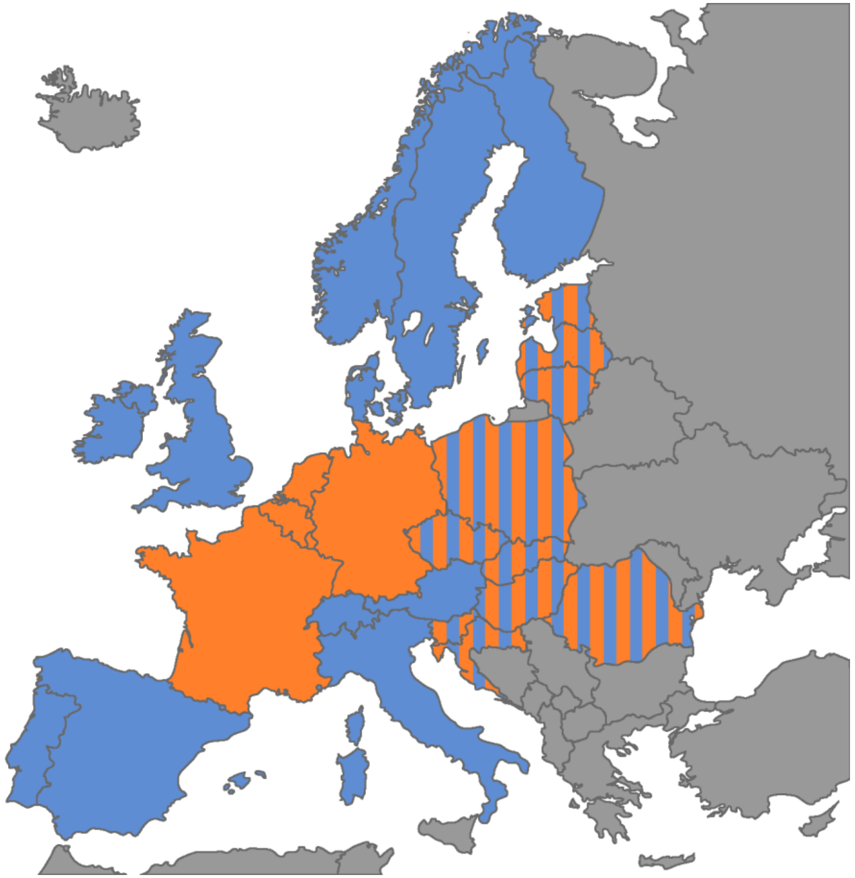
5. Results (variations of basecase, minRAM, LTA/NTC):

5.1 Including Chance Constraints

6. Conclusions



Motivation I: Zonal Market Coupling

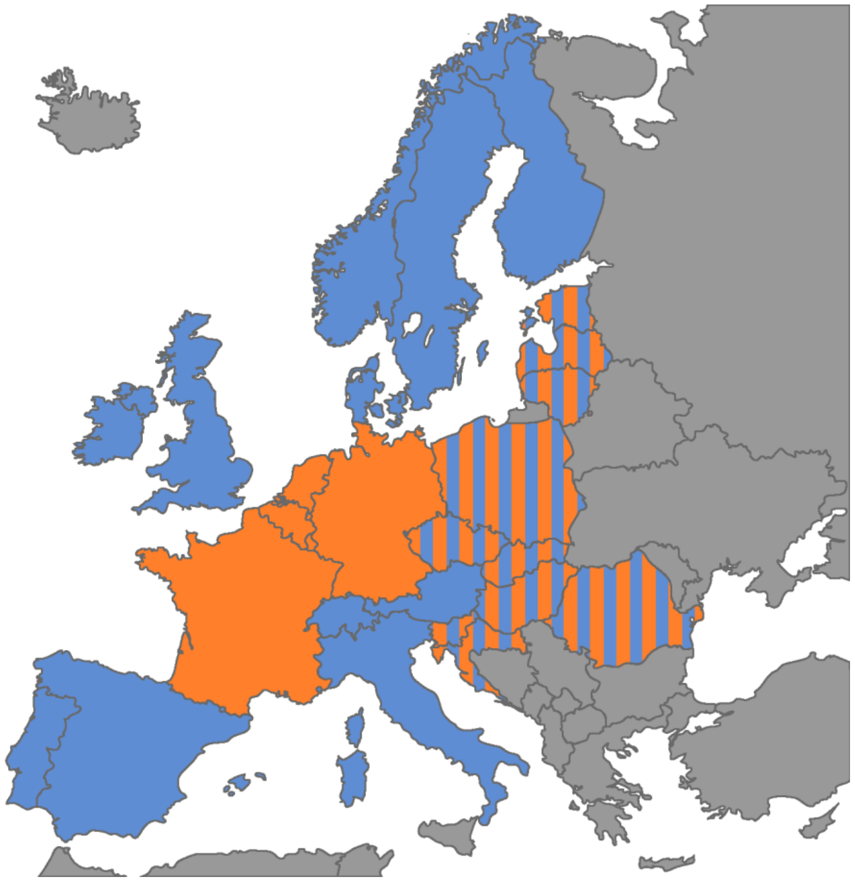


Countries Participating in PCR (blue), FBMC today (orange)
Possible FBMC extension to CEE (orange, hatched)
Source: Own depiction. *(PCR: Price coupling of regions)

- Europe's production from renewable energy resources (RES) increased, while conventional generation capacities [1]
  - High academic and political interest in the transmission system is ability to accommodate [2] this transition and the efficiency of **capacity allocation** and **congestion management** [3]**.**
- The “internal market in electricity” requires efficient **market coupling** of individual zones.
- Previously implemented **capacity allocation** policies are based on net-transfer capacities (NTCs) i.e., static capacities between markets.
  - Potentially being overly conservative…
  - .. while transmission assets within market zones are neglected
- To “move towards a genuinely integrated [European] electricity market“ [2], **flow-based market coupling** (FBMC) was inaugurated in 2015
  - A more complex CA policy that allows to account for zone-internal transmission limits and, thus, aims to enable more efficient cross-border trading.

[1] The European Commission, Commission Regulation (EU) no 2016/0860: Clean Energy For All Europeans”
[2] Amprion, *Flow Based Market Coupling – Development of the Market and Grid Situation 2015-2017*. 2018
[3] The European Commission, Commission Regulation (EU) no 2015/1222: Establishing a guideline on CA and CM

Motivation II: FBMC



FBMC is a multi-stage process that is coordinated by multiple TSOs and involves detailed zone-specific net-load forecasts and network models, which are not or only partially disclosed by the TSOs.

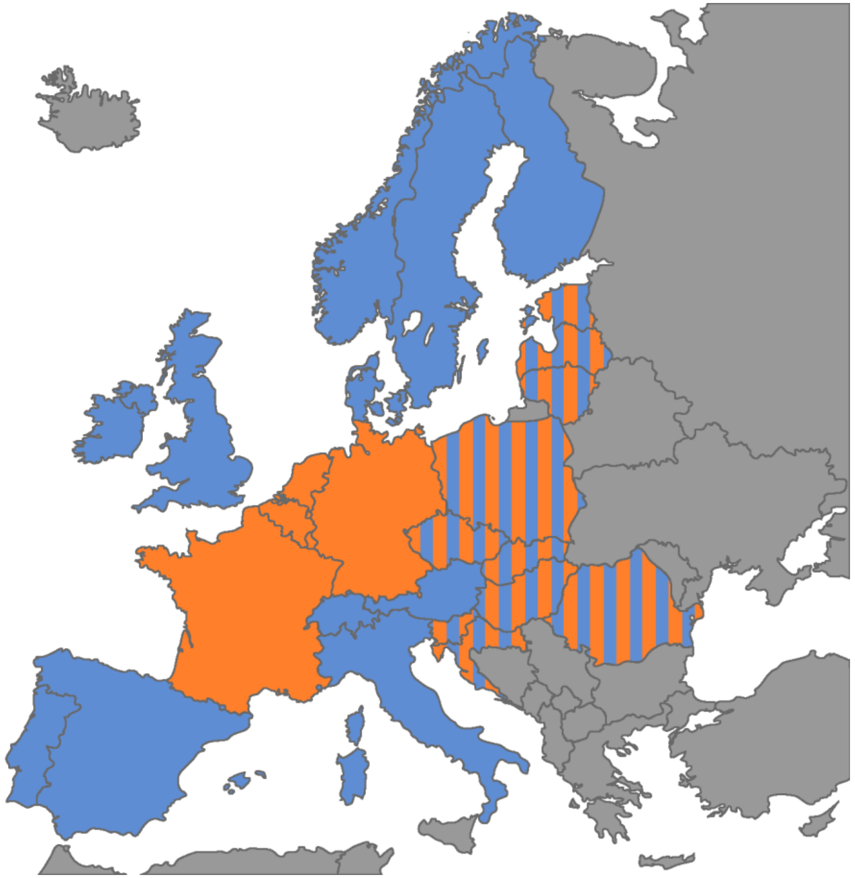
An informed discussion is required to address many topics/issues, related to the short-, medium- and long-term evolution of FBMC:

- More countries joining the coupled market (CORE region)
- Minimum capacity allocated with the FBMC process (minRAM).
- Current bidding zones declared inefficient TSO study [1].
- Inclusion of HVDC and phase-shifting transformers in the FB process.

- Notably, the bi-yearly federal report on the future of the grid in Germany (“*Netzentwicklungsplan*”), included a rudimentary FBMC representation for the first time in its 2018 edition [2], three years after FBMC implementation.

[1] ENTSO-E, First Edition of the Bidding Zone Review – Final Report. 2018.
[2] Genehmigung des Szenariorahmens für die Netzentwicklungsplanung, „Netzentwicklungsplanung 2019-2030 BNetzA, 2018.

Literature I: FBMC



FBMC is a multi-stage process that is coordinated by multiple TSOs and involves detailed zone-specific net-load forecasts and network models, which are not or only partially disclosed by the TSOs

- Academic Publications are steadily increasing and generally there is a consensus on the fundamental process:

Real World

D-2: Capacity Forecast
(also known as base case)

Expected grid load at point of dispatch:
- Previous market outcome
- Forecasted load & RES
- Pre-allocated exchange

Results: FB Parameters

D-1: Market Coupling
(Day-Ahead Market)

- Zonal market clearing
- Welfare Maximizing EUPHEMIA algorithm under FB parameters

Results: Generation schedule

D-0: Grid Operation
(physical delivery)

- Intra-day adjustments
- Congestion Management
  - Redispatch
  - Curtailment

Results: Final generation schedule

Modelling World (not real)

D-2: Capacity Forecast
(also known as base case)

Expected grid load at point of dispatch:
- Market simulation (NTC,N-0,N-1)
- Forecasted load & RES
- Pre-allocated exchange

Results: FB Parameters

D-1: Market Coupling
(Day-Ahead Market)

- Zonal market simulation:
  - Subject to FB parameters

Results: Generation schedule

D-0: Grid Operation
(physical delivery)

- Congestion Management
  - Redispatch
  - Curtailment
- Nodal market simulation (N-0, N-1)

Results: Final generation schedule

Formulation I:

$$
\begin{aligned}
\min \quad & C(G) + C(C) && && \text{(1a)}\\
\text{s.t.} \quad & 0 \leq G_t \leq \bar{g}_t && \forall t \in \mathcal{T} && \text{(1b)}\\
& 0 \leq C_t \leq r_t && \forall t \in \mathcal{T} && \text{(1c)}\\
& \mathrm{m}^n G_t + \mathrm{m}^n (r_t - C_t) - \mathrm{m}^n D_t - d_t = I_t && \forall t \in \mathcal{T} && \text{(1d)}\\
& \mathrm{m}^z G_t + \mathrm{m}^z (r_t - C_t) - \mathrm{m}^z D_t - d_t = \mathrm{NP}_t && \forall t \in \mathcal{T} && \text{(1e)}\\
& e^T I_t = 0 && \forall t \in \mathcal{T} && \text{(1f)}\\
& L_{t,p} = L_{t-1,p} - G_{t,p} + \eta D_{t,p} && \forall p \in \mathcal{ES}, t \in \mathcal{T} && \text{(1g)}\\
& 0 \leq D_t \leq \bar{d}_t && \forall t \in \mathcal{T} && \text{(1h)}\\
& 0 \leq L_t \leq \bar{l}_t && \forall t \in \mathcal{T} && \text{(1i)}
\end{aligned}
$$

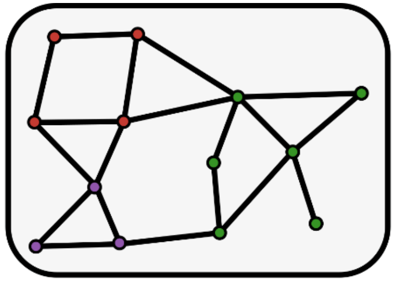
$$
\begin{aligned}
I_t \in \mathcal{F}^n(\mathrm{PTDF}^n, \bar{f}) &= \{x : \mathrm{PTDF}^n x \leq \bar{f}\} && \forall t \in \mathcal{T} && \text{(2a)}\\
\mathrm{NP}_t \in \mathcal{F}^z(\mathrm{PTDF}^n, \bar{f}) &= \{x : \mathrm{PTDF}^z x \leq \bar{f}\} && \forall t \in \mathcal{T} && \text{(2b)}\\
\mathrm{EX}_t \in \mathcal{F}^{ntc}(ntc) &= \{x : 0 \leq x \leq ntc\} && \forall t \in \mathcal{T} && \text{(2c)}
\end{aligned}
$$

$$
\begin{aligned}
C(G^{red}) &= c^{red} \sum_{t \in \mathcal{T}} |G_t^{red}| && && \text{(3a)}\\
G_t - g_t^{da} &= G_t^{red} && \forall t \in \mathcal{T} && \text{(3b)}\\
C_t &\geq c^{da} && \forall t \in \mathcal{T} && \text{(3c)}
\end{aligned}
$$

All FBMC stages are variations of the economic dispatch problem subject to

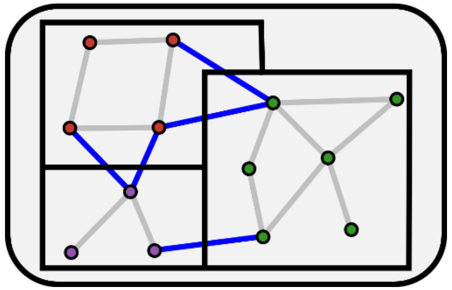
- Different network representations
  - 2a) node-line sensitivity for lines/contingencies
  - 2b) zone-line sensitivity for lines/contingencies
  - 2c) static commercial exchange
- Additional/different parameters
- Additional cost components

D-2: (1) s.t. 2a or 2b or 2c



D-1: (1) s.t. 2b

D-0: (1) s.t. 2a and (3)

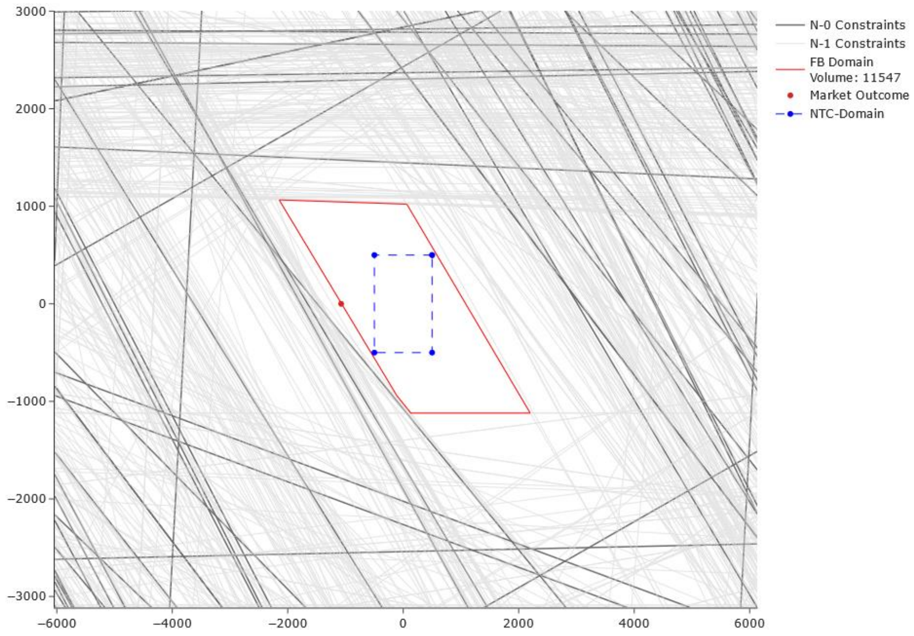


Formulation II: FB-Parameter

$$\mathrm{PTDF}^z(np^{da} - np^{bc}) \leq \overline{f} - f^{bc} \qquad (4)$$

$$\mathrm{PTDF}^z\, np^{da} \leq \overline{f} - f^{bc} + \mathrm{PTDF}^z\, np^{bc} \qquad (5)$$

$$\mathrm{PTDF}^z\, np^{da} \leq \overline{f} - f^{ref} = RAM \qquad (6)$$



Based on a basecase net-position, DA utilizes remaining capacity (4).

Reformulating into (6) yields the network representation of D-1 with

$$\mathcal{F}^z(\mathrm{PTDF}^z, RAM) = \{x : \mathrm{PTDF}^z\, x \leq RAM\}$$

Feasibility given only if feasible region non-empty:

- Requires parametrization of the basecase
  - Enforce margins on lines/contingencies
- or FB-parameters:
  - Select specific network elements and contingencies (CNECs)
  - Enforce ram to be >0, >minRAM
  - (Re)-move certain CNECs to include pre-existing trade domains

Generally, parametrization is done to:

- **Ensure secure operation** (less CM)
  - Security margins (FRM/FAV), CNEC selection, remedial actions
- **Enlarge the DA-domain** (more price convergence)
  - minRAM, include LTA/NTC/ATC domain, CNEC selection
- **More technically accurate**
  - GSK, FRM/FAV

Parametrization the FB-parameters is where most academic publications differ.

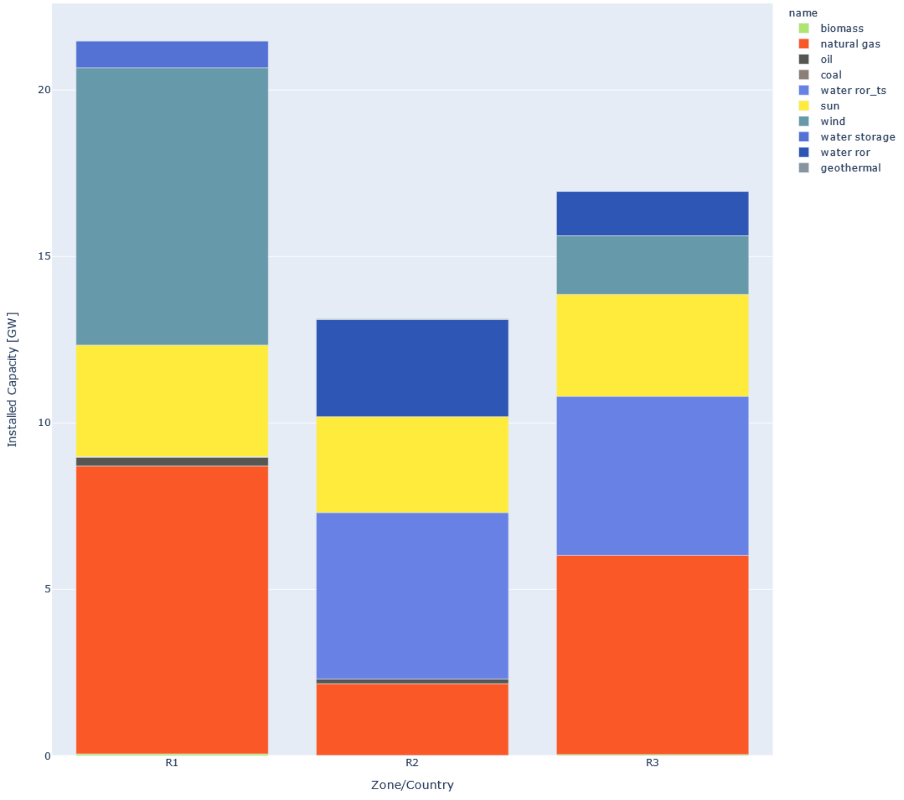
Literature II: Range of Core Assumptions

(or how not to make a slide)

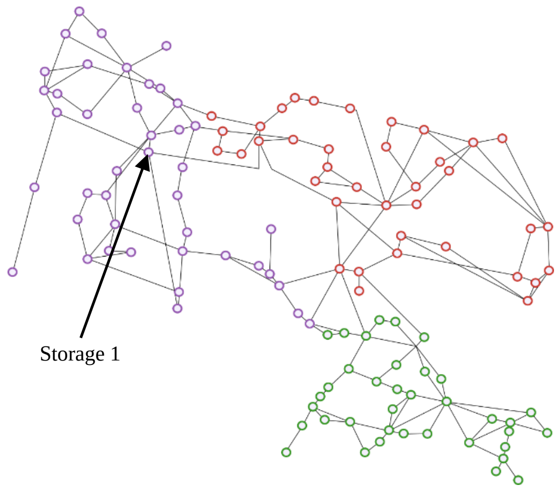
Authors	Year	Title	Basecase	CNE	C	minRAM	GSK
Rafael Finck, Armin Ardone, Wolf Fichtner	2018	Impact of Flow-Based Market Coupling on Generator Dispatch in CEE Region	NTCs	"critical"		0 ?	6 GSKs
Lothar Wyrwoll, Katharina Kollenda, Christoph Müller, Armin Schnettler	2018	Impact of Flow-Based Market Coupling Parameters on European Electricity Markets	NEX=0	0.05		0.8	Gmax
Marjanovic, I., v. Stein, D., van Bracht, N., and Moser, A	2018	Impact of an Enlargement of the Flow Based Region in Continental Europe	NTC	0.05	>50% N-1 Load	10	
Björn Matthes, Christopher Spieker, Dennis Klein, Christian Rehtanz	2019	Impact of a Minimum Remaining Available Margin Adjustment in Flow-Based Market Coupling	NTC		worst C	0 - 75%	Pro Rata GSK
Lothar Wyrwoll, Andreas Blank, Christoph Müller, Ralf Puffer	2019	Determination of Preloading of Transmission Lines for Flow-Based Market Coupling	NEX==0 & NTC/ATC	0.05	>65% N-0, >85% N-1 Load	0.7	?
Simnon Voswinkel, Björn Felten, Tim Felling, Christoph Weber	2019	Flow-Based Market Coupling–What Drives Welfare in Europe's Electricity Market Design?	N-0/FRM	5% or CB		0.8	7 different GSKs
Björn Felten, Tim Felling, Paul Osinski, Christoph Weber	2019	Flow-Based Market Coupling Revised - Part II: Assessing Improved Price Zones in Central Western Europe	N-0	CB, 5%			gmax
David Schönheit, Constantin Dierstein, Dominik Möst	2020	Do minimum trading capacities for the cross-zonal exchange of electricity lead to welfare losses?	N-0/FRM/NEX=0	0.08	2 worst C	20 - 70	Flat, G, Gmax
Ksenia Poplavskaya, Gerhard Totschnig, Fabian Leimgruber, Gerard Doorman, Gilles Etienne, Laurens de Vries	2020	Integration of day-ahead market and redispatch to increase cross-border exchanges in the European electricity market	Calibrated Flows	Custom Setup			
Conleigh Byers, Gabriela Hug	2020	Modeling flow-based market coupling: Base case, redispatch, and unit commitment matter	N-0 &NEX=0 & NEX=nex	0.05	None	None	pro rata
David Schönheit, Michiel Kenis, Lisa Lorenz, Dominik Möst, Erik Delarue and Kenneth Bruninx	2020	Toward understanding flow-based market coupling: An open-access model	N-0/FRM	0.1 - 20%		FRM 0 - 40	flat, P, Pmax
David Schönheit, Richard Weinhold, Constantin Dierstein	2020	The impact of different strategies for generation shift keys (GSKs) on the flow-based market coupling domain: A model-based analysis of Central Western Europe	Calibrated Flows on CNECs	Historical	Custom Setup		flat, P, Pmax, pro rata

- Large range of assumptions regarding grid representation of the basecase, minRAM and CNEC selection.
- Large variety of subjects of numerical analysis: Generation, net-position, net-exchange, prices, RAM, system costs (uniform, pay-as-bid), redispatch quantity and costs, welfare.

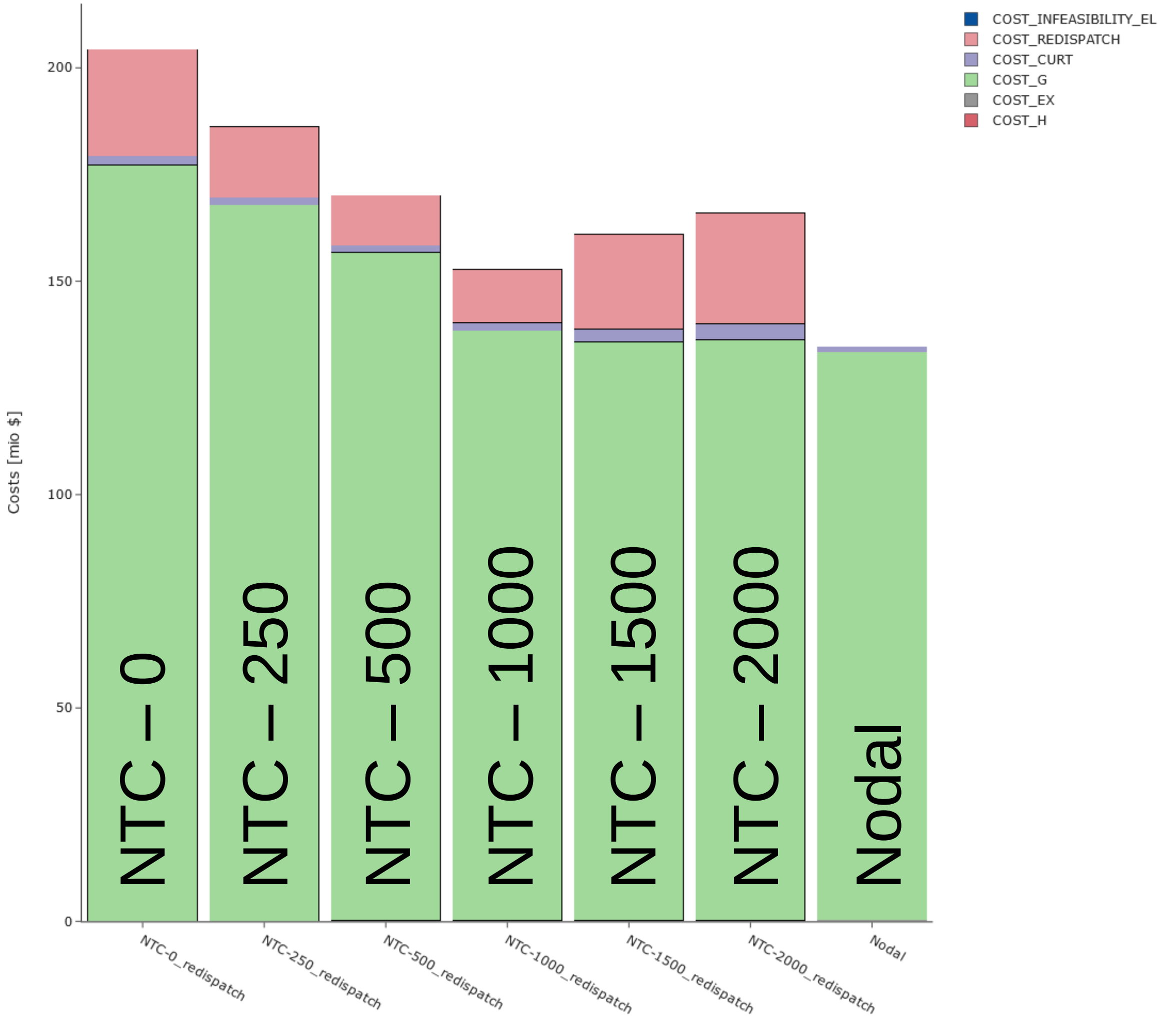
Application: Extended IEEE 118 Bus Network



- **NREL118 (2018):** An Extended IEEE 118-Bus Test System With High Renewable Penetration. doi:10.1109/TPWRS.2017.2695963.
  - Same topology as IEEE 118 case file, three regions
  - Increased RES with 8760 timesteps
  - Additional Storage
- POMATO to synthesize the FBMC process
  - Accounting for generation, curtailement and congestion management cost
  - Nodal as Benchmark, NTC as Reference
    - Benchmark different parameters
    - Basecase configuration, minRAM/LTA allocation, FRM
    - Other pameters: 5% CNE, 20% C, Gmax Gsk for both CNE and PTDF



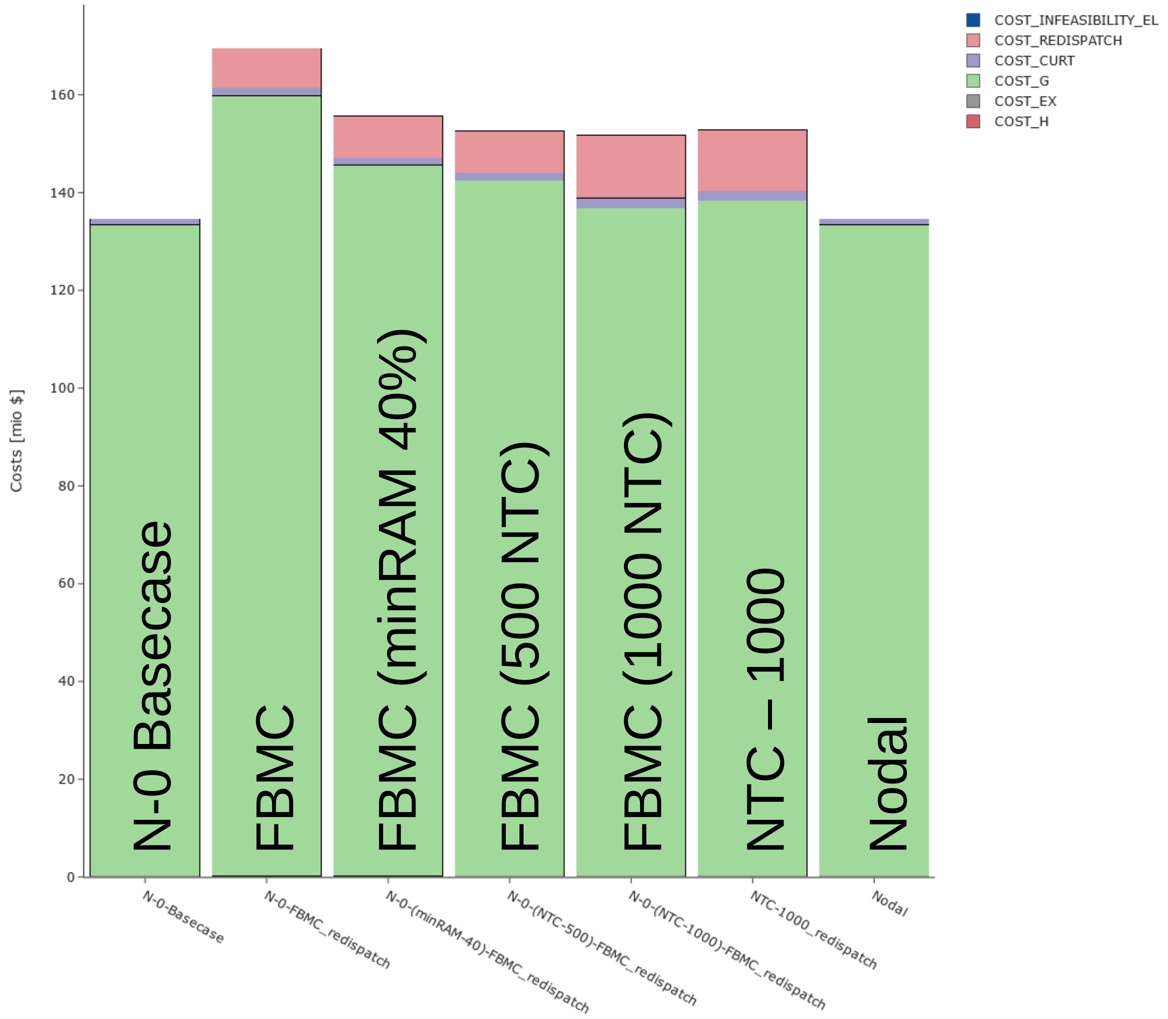
Results I: Nodal/NTC



NTC (Sanity Check):

- Nodal the most efficient allocation of generation capacity
- NTCs illustrate the trade-off between more/less restrictive commercial exchange capacities.

Results II: N-0 Basecase



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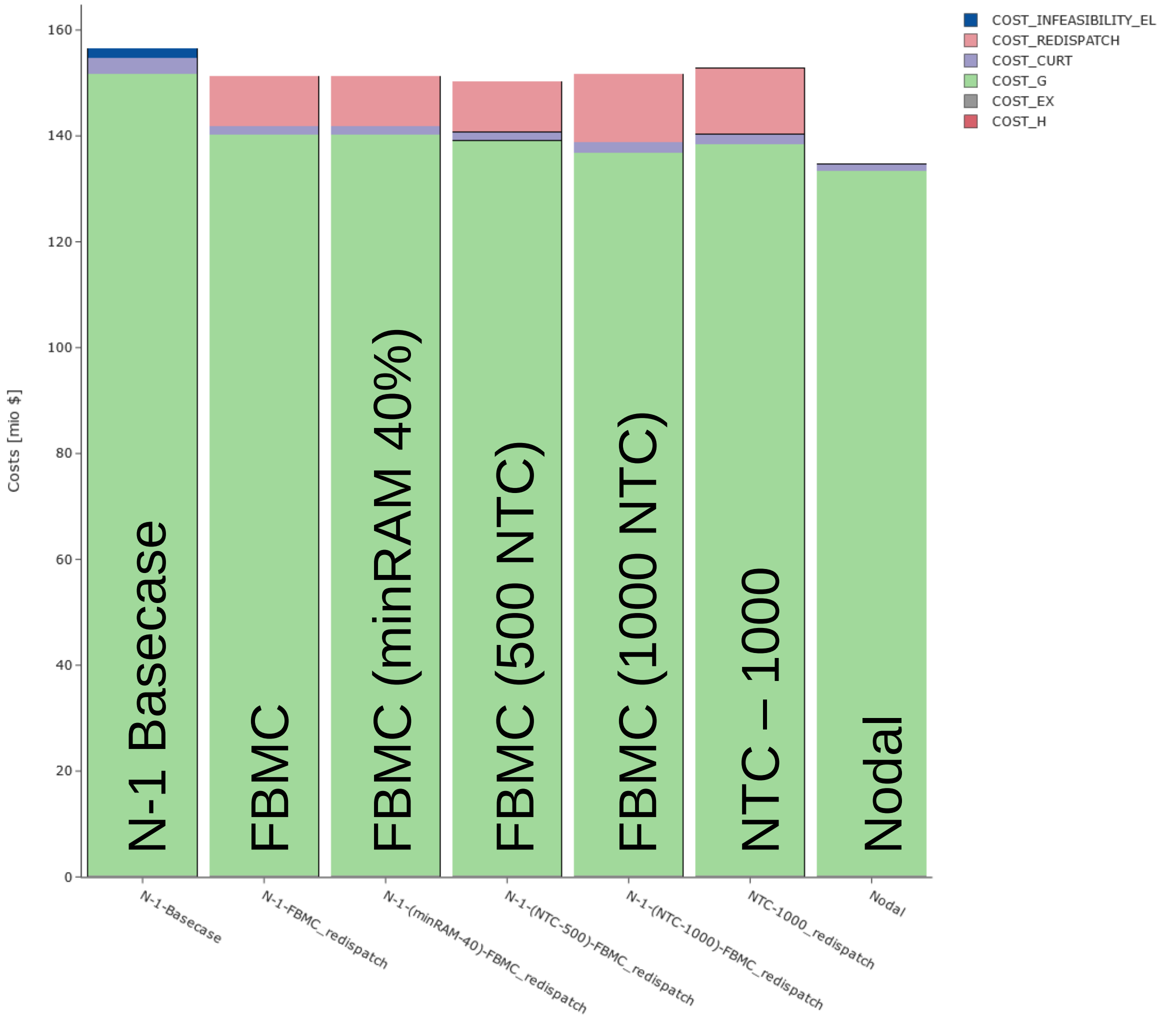
N-0 Basecase:

- Without domain enlargement FB solution is more restrictive
- Enforcing a NTC domain/minRAM equalizes results (they are slightly better)

Results II: N-1 Basecase



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N-0 Basecase:

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- Enforcing a NTC domain/minRAM equalizes results (they are slightly better)

N-1 Basecase:

- Results are more close
- More restricted BC flows, yield less restricted domains

Introducing Chance Constraints

$$
\begin{aligned}
& \min \mathbb{E}[C(G(\omega))] && && (7a) \\
s.t.\quad & \mathbb{P}[0 \leq G_t(\omega) \leq \overline{g}] \geq 1-\epsilon && \forall t \in \mathcal{T} && (7b) \\
& \mathbb{P}[\mathrm{PTDF}^z_t \, \mathrm{NP}_t(w) \leq RAM_t] \geq 1-\epsilon && \forall t \in \mathcal{T} && (7c) \\
& \mathrm{m}^z_g G_t(\omega) + \mathrm{m}^z_r(r_t(\omega)) - \mathrm{m}^z_{es} D_t - d_t = \mathrm{NP}_t(w) && \forall t \in \mathcal{T}, \omega \in \Omega && (7d) \\
& L_{t,p} = L_{t-1,p} - G_{t,p} + \eta D_{t,p} && \forall p \in \mathcal{ES}, t \in \mathcal{T} && (7e) \\
& 0 \leq D_t \leq \overline{d}_t && \forall t \in \mathcal{T} && (7f) \\
& 0 \leq L_t \leq \overline{l}_t && \forall t \in \mathcal{T} && (7g)
\end{aligned}
$$

FRMs are used in different ways among literature:

- As margins to reduce line capacity in the basecase
- As reduction of RAMs as a reliability margin (in line with Doc)

Chance Constraints represent a suitable extension to FBMC fundamental models by including:

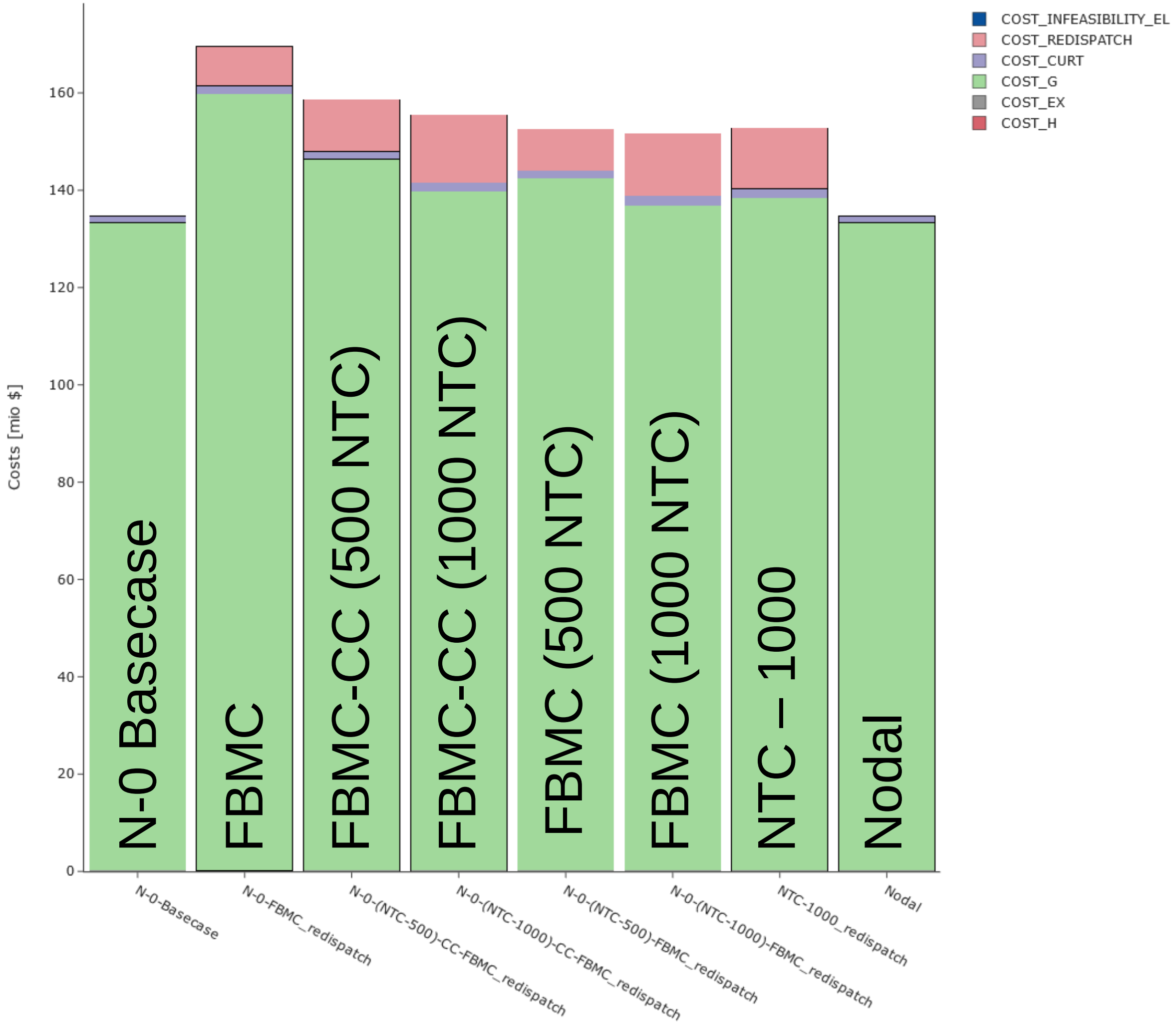
- Forecast errors of intermittent generation with known distribution
- System response of dispatchable unit
- Predefined risk-level, of constraint violations

Resulting in an uncertainty aware formulation, that co-optimizes risk and reserve margins on generation and transmission capacities.

The system response can be a decision variable and represents an online adjustment to the generation shift in response to CNECs that are heavily affected by forecast errors.

[1] R. Mieth, J. Kim, und Y. Dvorkin, „Risk- and variance-aware electricity pricing“, *Electric Power Systems Research*, Bd. 189, S. 106804, Dez. 2020.

Introducing Chance Constraints



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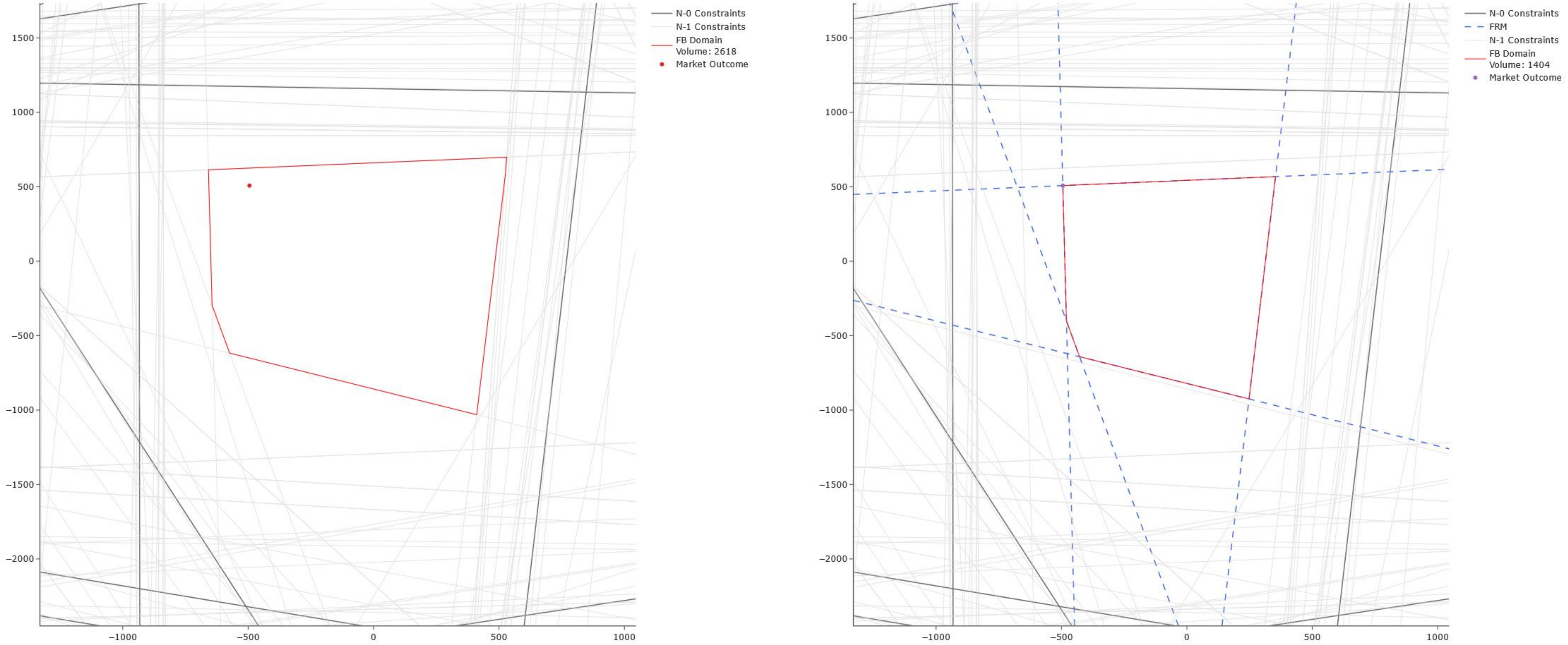
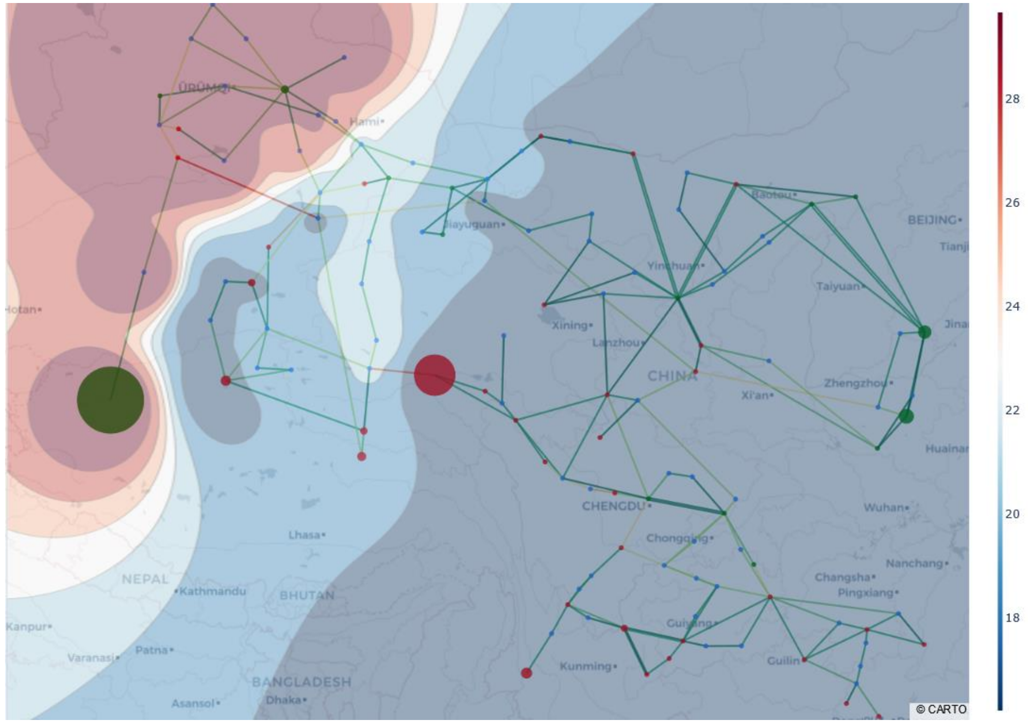
Visualization of FRMs by Chance Constraints



Conclusions



Restrictiveness/permissiveness of FB domain is central to effectiveness

- minRAM, LTA/NTC/ATC makes domain more permissive
- FRM makes domain more restrictive

Effectiveness of CM favors more permissive domains

- Parametrization of redispatch costs, curtailment constraints

Implementation of FRM through CC makes sense and improves utility of fundamental models.

(not shown today)

Selection of CNECs seems to be dominated by other parametrizations.

If you want to investigate the different parametrizations yourself, you can via the Dashboard functionality of POMATO hosted at

https://pomato.io/dashboard.html

(until my azure student credit runs out)

Thank you for your attention!

POMATO - Power Market Tool

docs passing | build passing

https://github.com/richard-weinhold/pomato

Contact: riw@wip.tu-berlin.de

Related publications:

R. Weinhold and R. Mieth (*preprint*), “Power Market Tool (POMATO) for the Analysis of Zonal Electricity Markets”, https://arxiv.org/abs/2011.11594, 2020.

R. Weinhold und R. Mieth, „Fast Security-Constrained Optimal Power Flow through Low-Impact and Redundancy Screening“, *IEEE Transactions on Power Systems*, 2020.

D. Schönheit, R. Weinhold, und C. Dierstein, „The impact of different strategies for generation shift keys (GSKs) on the flow-based market coupling domain: A model-based analysis of Central Western Europe“, *Applied Energy*, Bd. 258, S. 114067, 2020.

Acknowledgements / References

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Amprion, Flow Based Market Coupling – Development of the Market and Grid Situation 2015-2017. 2018.
I. Aravena, Q. Lété, A. Papavasiliou, und Y. Smeers, „Transmission capacity allocation in zonal electricity markets“, UCLouvain, 2020.
D. Schönheit, D. Hladik, H. Hobbie, und D. Möst, „ELMOD documentation: Modeling of flow-based market coupling and congestion management“, Working paper of the Chair of Energy Economics (TU Dresden), 2020.
C. Spieker, D. Klein, V. Liebenau, J. Teuwsen, und C. Rehtanz, „European electricity market and network simulation for energy system analysis“, in 2016 IEEE International Energy Conference (ENERGYCON), 2016, S. 1–6.
D. Schönheit, R. Weinhold, und C. Dierstein, „The impact of different strategies for generation shift keys (GSKs) on the flow-based market coupling domain: A model-based analysis of Central Western Europe“, Applied Energy, Bd. 258, S. 114067, 2020.
The European Commission, Commission Regulation (EU) no 2015/1222: Establishing a guideline on capacity aallocation and congestion management. 2015.
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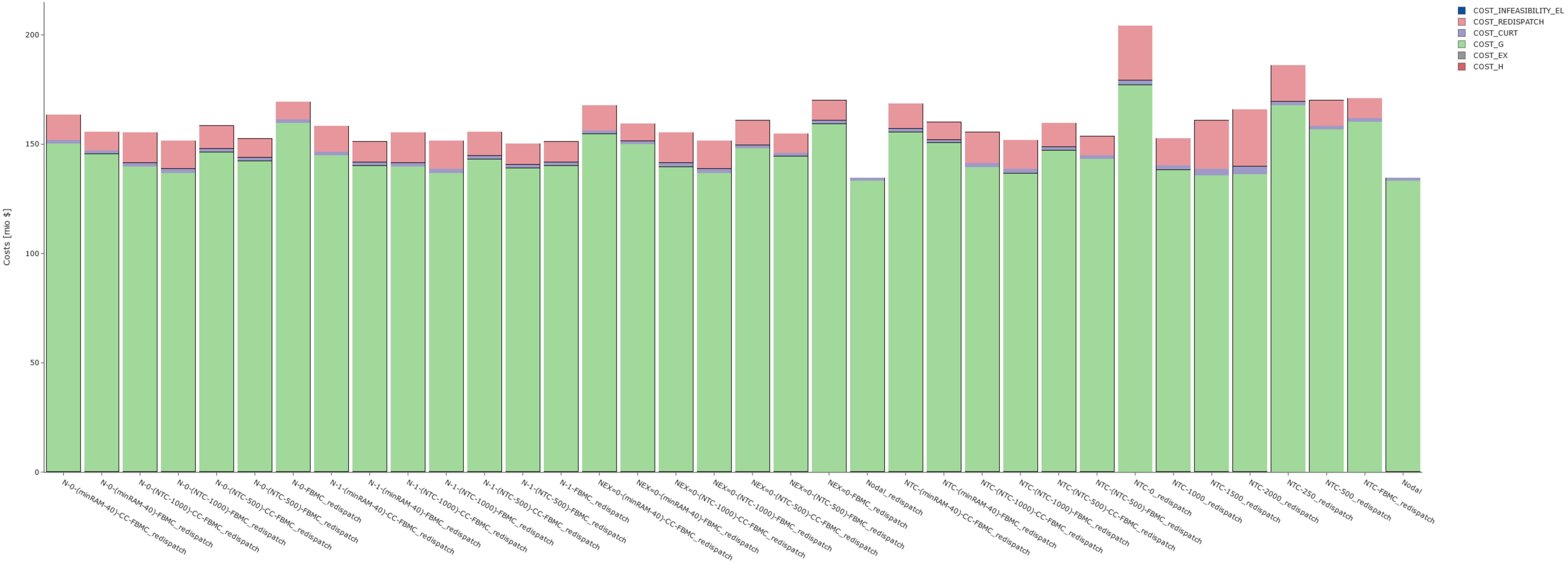
R. Weinhold und R. Mieth, „Fast Security-Constrained Optimal Power Flow through Low-Impact and Redundancy Screening“, IEEE Transactions on Power Systems, 2020.

Acknowledgements:

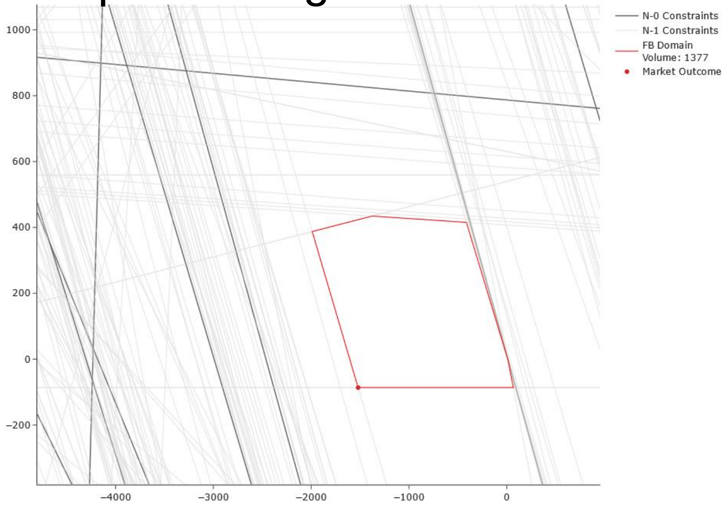
Richard and Robert would like to acknowledge the support of Reiner Lemoine-Foundation, the Danish Energy Agency and Federal Ministry for Economic Affairs and Energy (BMWi). Robert Mieth is funded by the Reiner Lemoine-Foundation scholarship. Richard Weinhold is funded by the Danish Energy Agency. The development of POMATO and its applications was funded by BMWi in the project (FKZ: 03EI1019A - D).



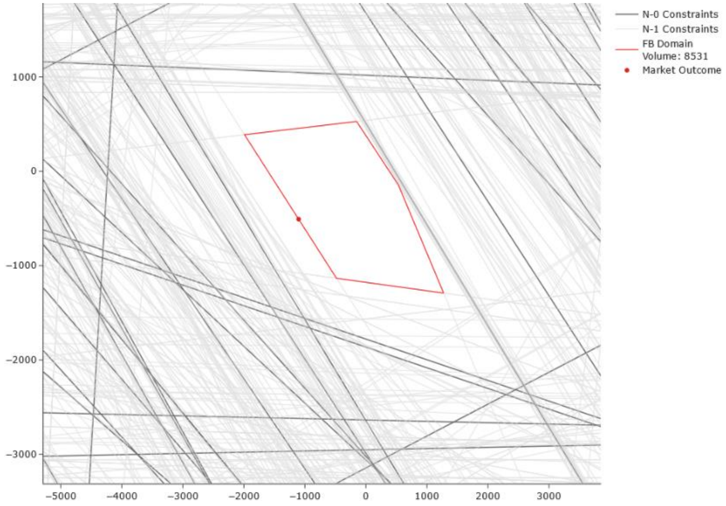
Costs [mio $]
0
50
100
150
200
COST_INFEASIBILITY_EL
COST_REDISPATCH
COST_CURT
COST_G
COST_EX
COST_H
N-0-(minRAM-40)-CC-FBMC_redispatch
N-0-(minRAM-40)-FBMC_redispatch
N-0-(NTC-1000)-CC-FBMC_redispatch
N-0-(NTC-1000)-FBMC_redispatch
N-0-(NTC-500)-CC-FBMC_redispatch
N-0-(NTC-500)-FBMC_redispatch
N-0-FBMC_redispatch
N-1-(minRAM-40)-CC-FBMC_redispatch
N-1-(minRAM-40)-FBMC_redispatch
N-1-(NTC-1000)-CC-FBMC_redispatch
N-1-(NTC-1000)-FBMC_redispatch
N-1-(NTC-500)-CC-FBMC_redispatch
N-1-(NTC-500)-FBMC_redispatch
N-1-FBMC_redispatch
NEX=0-(minRAM-40)-CC-FBMC_redispatch
NEX=0-(minRAM-40)-FBMC_redispatch
NEX=0-(NTC-1000)-CC-FBMC_redispatch
NEX=0-(NTC-1000)-FBMC_redispatch
NEX=0-(NTC-500)-CC-FBMC_redispatch
NEX=0-(NTC-500)-FBMC_redispatch
NEX=0-FBMC_redispatch
Nodal_redispatch
NTC-(minRAM-40)-CC-FBMC_redispatch
NTC-(minRAM-40)-FBMC_redispatch
NTC-(NTC-1000)-CC-FBMC_redispatch
NTC-(NTC-1000)-FBMC_redispatch
NTC-(NTC-500)-CC-FBMC_redispatch
NTC-(NTC-500)-FBMC_redispatch
NTC-0_redispatch
NTC-1000_redispatch
NTC-1500_redispatch
NTC-2000_redispatch
NTC-250_redispatch
NTC-500_redispatch
NTC-FBMC_redispatch
Nodal

Results II: N-0 Basecase

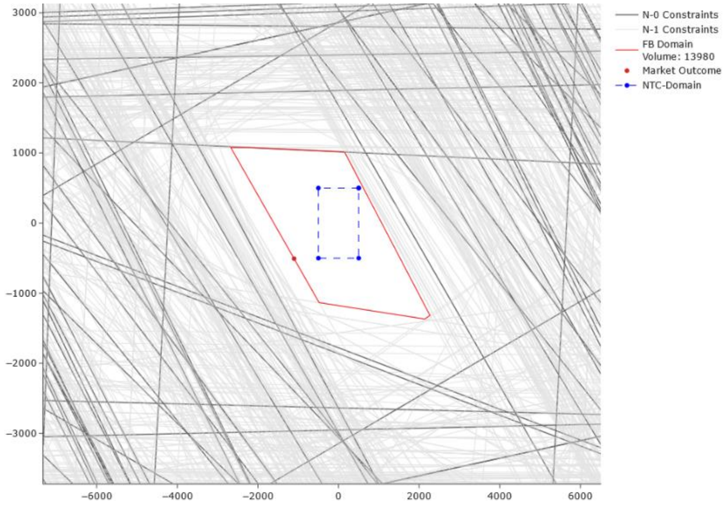
No processing



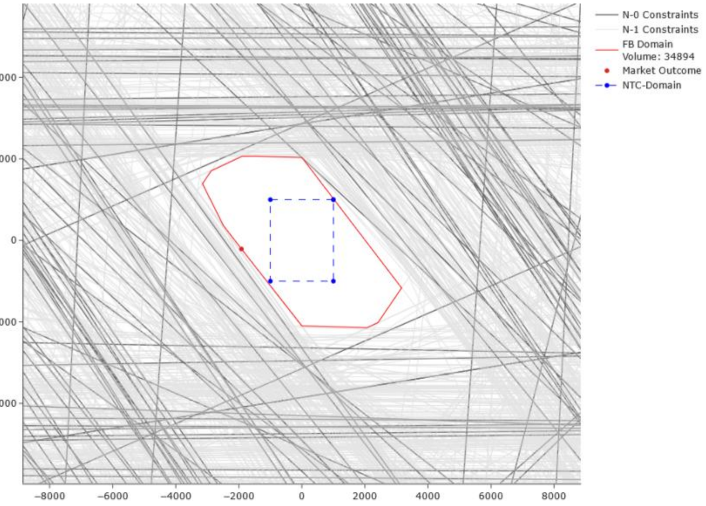
minRAM 40%



NTC 500

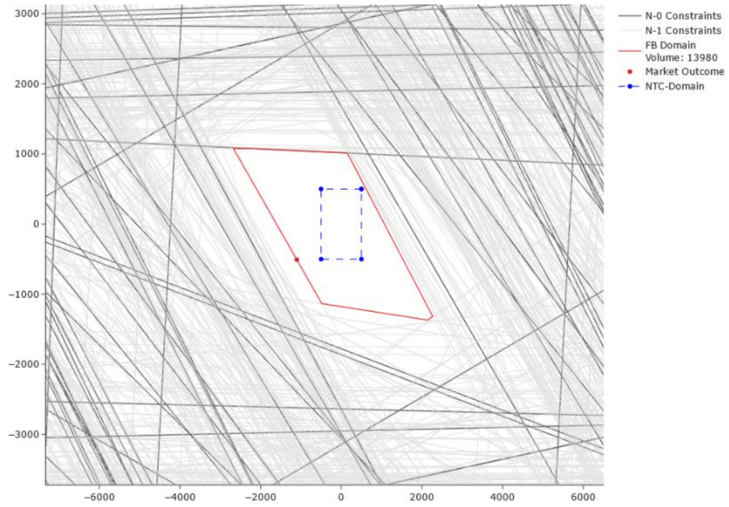


NTC 1000

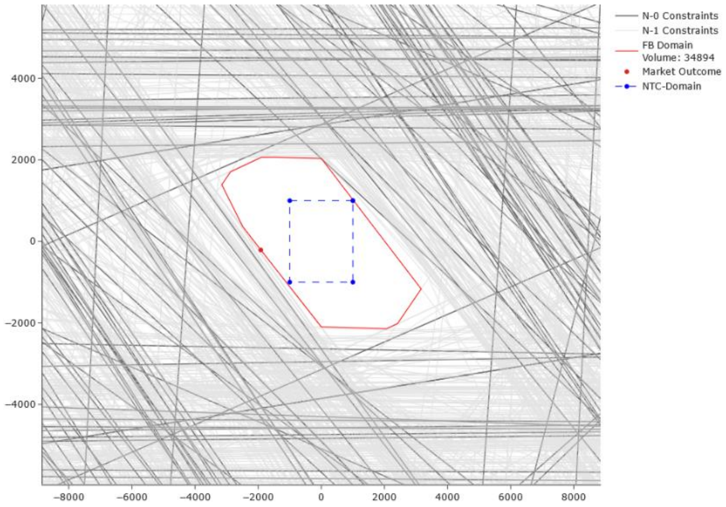


Results II: N-0 Basecase

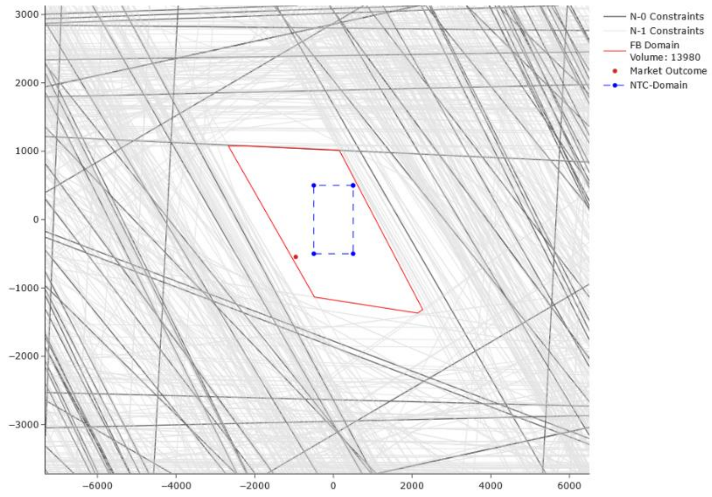
NTC 500



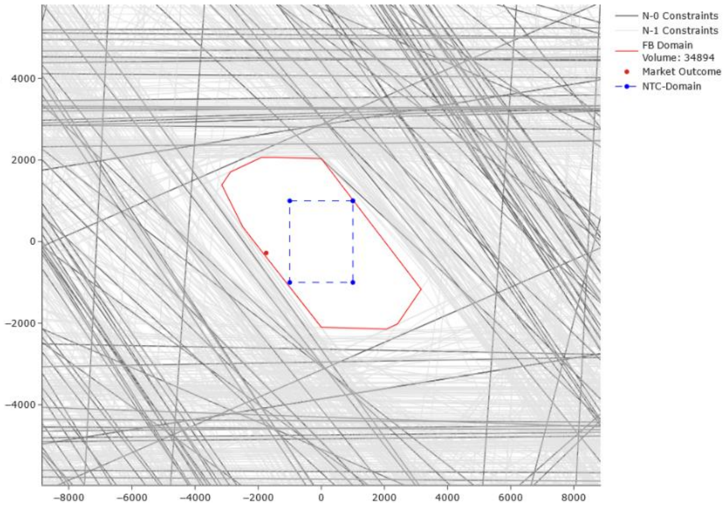
NTC 1000



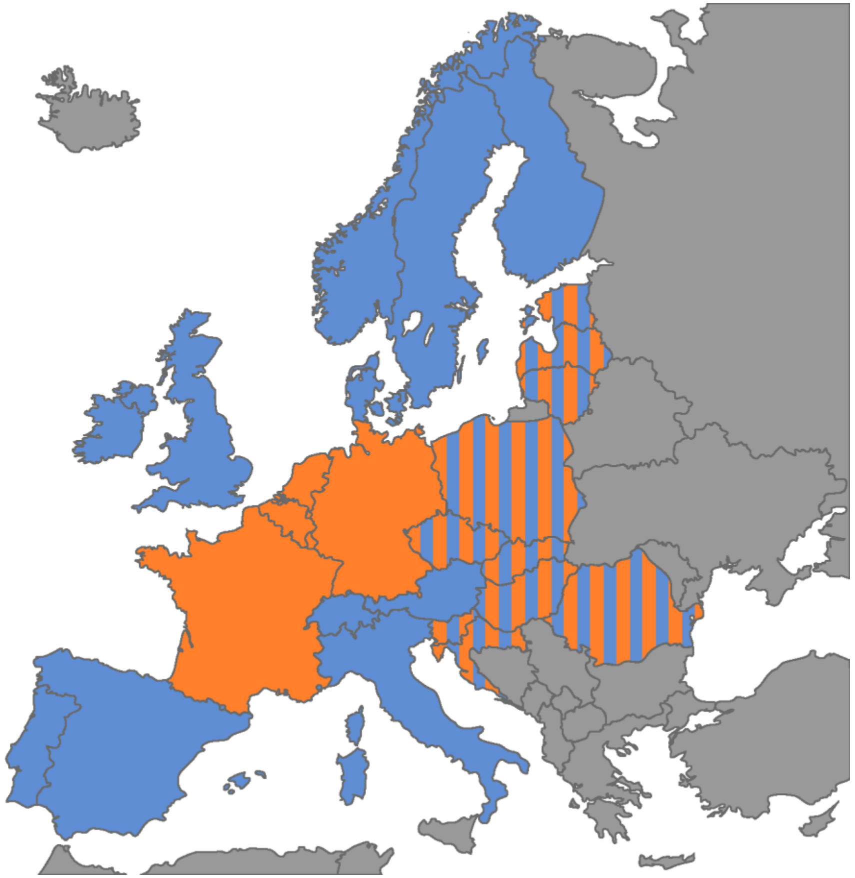
CC - NTC 500



CC - NTC 1000



Motivation III: Introducing POMATO



Countries Participating in PCR (blue), FBMC today (orange)
Possible FBMC extension to CEE (orange, hatched)
Source: Own depiction

[1] See: www.open-power-system-data.org/
[2] See: www.matpower.org/.

POMATO aims to facilitate this discussion and to provide an open model that can support the required flexibility regarding the network representation only using open data:

- Separation of data processing and optimization
  - a flexible Python-based user-interface
  - lean and performant implementation of the central optimization model in the well-readable JuMP algebraic modeling language

- Compatibility with Open Power Systems Data [1] and Matpower [2] data structures.
- Electricity market model with zonal and nodal market clearing and a module to synthesize the FBMC process.
- Exact N-1 secure dispatch implementation suitable for large-scale networks and multi-period analyses.

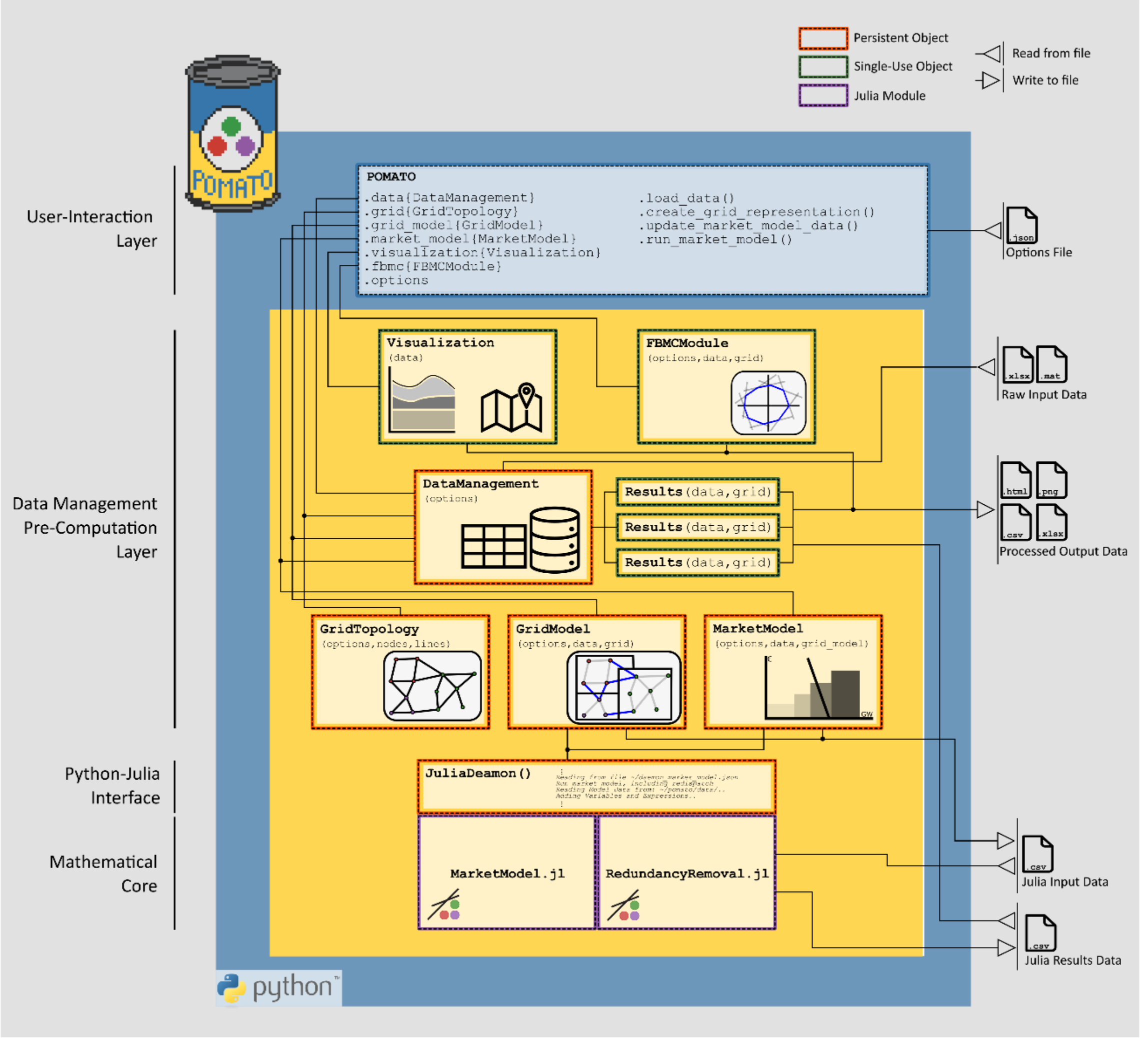
- POMATO can solve stochastic OPF using chance-constraints to analyze the impact of forecast errors from renewable energy sources.

- Visualization module that allows for comprehensive analysis of the modeled systems.

POMATO I: Description of POMATO

POMATO is structured in three layers:

- **Mathematical core:**
  - Represents the mathematical formulations.
  - `MarketModel.jl` and `RedundancyRemoval.jl`
  - Performs the computationally heavy task.
  - Interface to the required solvers.
- **Data processing** layer:
  - Automates parameter calculation and validation.
  - Provides the parameters to the model core.
  - Processes the resulting model output.
- **User Interface:**
  - Provides readable API-like commands
  - Interface to visualization functionality



POMATO II: MarketModel

- **MarketModel.jl**: An optimization problem that finds cost optimal allocation of generation capacities to satisfy demand and all technical constraints.

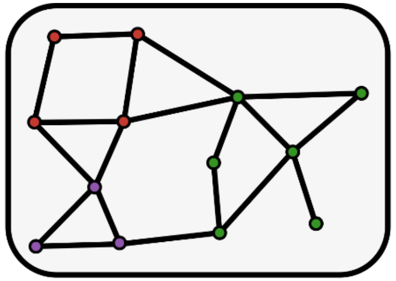
- (1b) – (1g) are activated and parametrized by POMATO "on the fly" based on user-defined options
- Definitions of balance (1f) and network constraints (1g) effectively characterize the modeled market:
- Nodal Markets:
  - Enforces an energy balance in for each node.
  - Exchanges are limited by physical power flow and the capacities of the transmission system.
- Zonal Markets:
  - Aggregated energy balance for an entire zone.
  - Exchanges with neighboring zones are limited:
    - Explicitly by NTCs.
    - Implicitly through constraints on net positions.

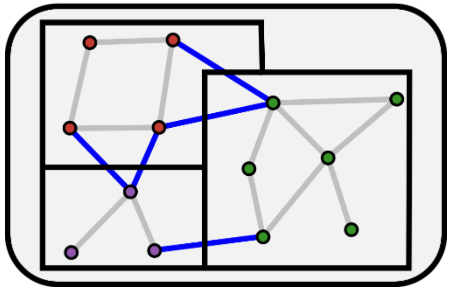
- Additionally, constraints to model CM (redispatch)
- System security requirements based on contingency (N-1) analyses and enforced through a suitable extensions of zonal and nodal PTDF matrices

$$\min \ \text{OBJ} = \sum COST\_G + COST\_H + COST\_CURT + OOM\_PEN \qquad (1a)$$

s.t.

Cost Definition	(1b)
Generation Constraints	(1c)
Heat Constraints	(1d)
Storage Constraints	(1e)
Energy Balances	(1f)
Network Constraints.	(1g)





POMATO III: RedundancyRemoval, Julia

RedundancyRemoval.jl:

- Ensuring feasibility in a system for all potential unplanned line outages increases the amount of constraints
  - The resulting problem quickly becomes unsolvable for multi-period economic analyses

- However, it has been shown [1] that many (in fact most) of these constraints **redundant**, i.e. never binding in the optimal solution due to the existence of more restrictive constraints,
- To ensure feasible solution times for real-world networks over non-trivial time horizons, POMATO **model core** includes additional functionality to identify these redundant constraints.

Using Julia/JuMP:

- The methods and algorithms implemented in the model core can be computationally expensive.
- The open-source Julia Language provides a competitive combination of performance and readability and the well-readable and flexible JuMP
- These Julia modules **MarketModel.jl** and **RedundancyRemoval.jl** are parameterized and called automatically by the higher POMATO layers.

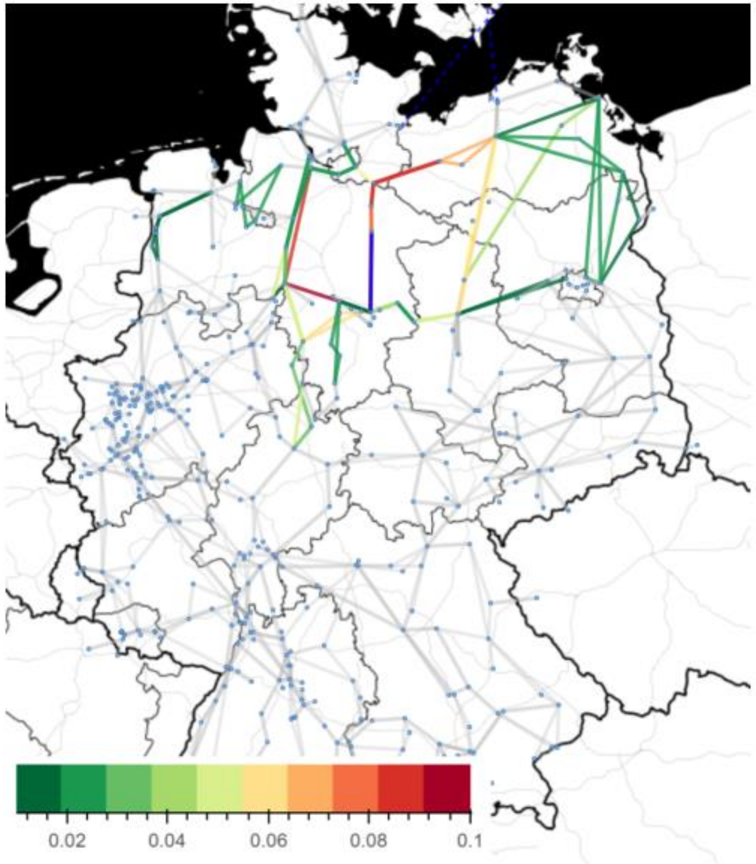


Fig. 5. Impact of outages towards the highlighted (blue) line; Grey lines indicate a sensitivity of less than 1 %.

[1] R. Weinhold und R. Mieth, „Fast Security-Constrained Optimal Power Flow through Low-Impact and Redundancy Screening", IEEE Transactions on Power Systems, 2020.