# Open-Source Modeling of Flow Based Market Coupling

## Methods, Parametrization, and Analysis for Sustainable Power Systems

*Richard Weinhold*

Wissenschaftliche Aussprache – Scientific Defense

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Technische Universität Berlin
Workgroup for Infrastructure Policy (WIP)

# Overview

## Part I: Introduction

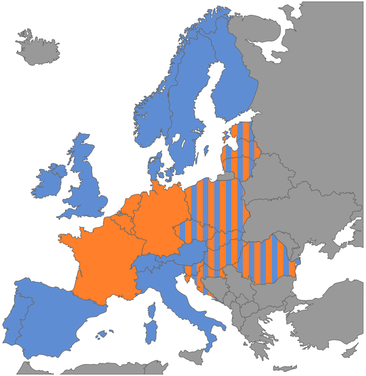
*Chapter 1:* Zonal Electricity Markets and Flow-Based Market Coupling

## Part II: Methodology

*Chapter 2*: Power Market Tool (POMATO) for the Analysis of Zonal Electricity Markets
*Chapter 3*: Fast Security-Constrained Optimal Power Flow through Low-Impact and Redundancy Screening

## Part III: Applications

*Chapter 4*: The impact of different strategies for generation shift keys on the flow-based market coupling domain
*Chapter 5*: Uncertainty-Aware Capacity Allocation in Flow-Based Market Coupling
*Chapter 6*: Evaluating Policy Implications on the Restrictiveness of Flow-based Market Coupling with High Shares of Intermittent Generation



Hauschild (2019)

Figure: Countries Participating in Price Coupling of Regions (blue), FBMC today (orange) Possible FBMC extension to CEE (orange, hatched)

### Context: European Electricity Markets

- From a system defined by vertically integrated utilities . . .
- . . . to an integrated European Market for electricity.

Own depiction based on ENTSO-E 2021

Figure: Countries Participating in Single Day-ahead Coupling (blue), FBMC today (orange) Possible FBMC extension to CEE (orange, hatched)

## Context: European Electricity Markets

- From a system defined by vertically integrated utilities . . .
- . . . to an integrated European Market for electricity.

## Capacity Allocation and Congestion Management

**Capacity Allocation**: Market mechanisms that define electricity trading volumes between market areas.
**Congestion Management**: Methods ensuring that the physical system state at time of delivery remains within its security margins.

Own depiction based on ENTSO-E 2021

Figure: Countries Participating in Single Day-ahead Coupling (blue), FBMC today (orange) Possible FBMC extension to CEE (orange, hatched)

**Methods for Capacity Allocation**

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"[a], with flow-based market coupling was inaugurated in 2015.

a. Amprion 2018.

## Illustrative Example

What is a good exchange capacity between *Zone 1* and *Zone 2* ?

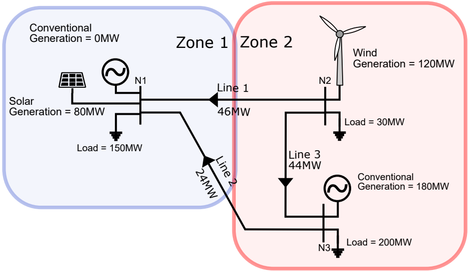



Figure: Exemplary three-node system with two zones.

$$\mathrm{PTDF}^n = \begin{pmatrix} 0 & 0.6 & 0.4 \\ 0 & -0.4 & -0.6 \\ 0 & 0.4 & -0.4 \end{pmatrix}$$

What is a good exchange capacity between *Zone 1* and *Zone 2* ?

- Uniform pricing reveals the physical limits.

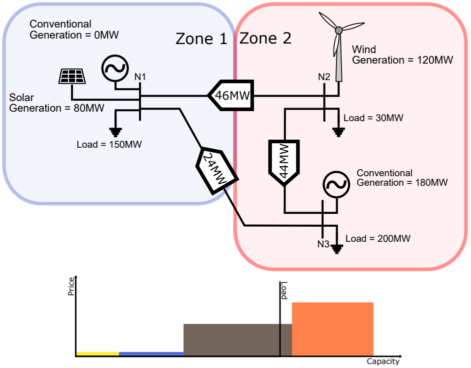



Figure: Uniform market clearing.

What is a good exchange capacity between *Zone 1* and *Zone 2* ?

- Uniform pricing reveals the physical limits.
- No exchange leads to inefficient outcome.

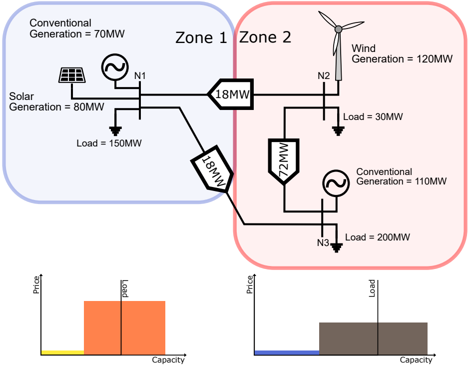



Figure: No exchange.

# Illustrative Example

What is a good exchange capacity between *Zone 1* and *Zone 2* ?

- Uniform pricing reveals the physical limits.
- No exchange leads to inefficient outcome.

Based on this solution (or a forecasted point of dispatch):

- anticipate direction of commercial exchange.
- anticipate which generators will serve additional exchange.

Limit exchange based on:

- line specific available capacities.
- which generators will serve additional exchange.

Allocate this capacity towards the net-position of each zone.

⇒ Flow-based Market Coupling

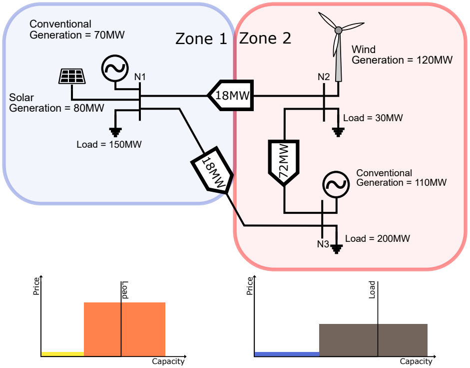



Figure: No exchange.

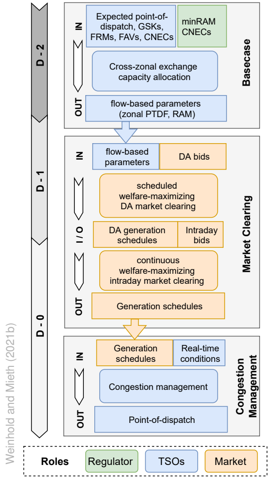



Figure: Flow-based Market Coupling process overview.

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.

The process consists of:

- **D-2 capacity forecast (basecase):** best estimate of the system state at delivery.
- **D-1 Day-ahead market stage:** Market coupling based on flow-based parameters.
- **D-0 Congestion management:** curtailment and congestion management.

# Formulation: Flow-based Parameters

$$\mathrm{PTDF}^{z}(np^{da} - np^{bc}) \leq \bar{f} - f^{bc} \qquad (1)$$

with $\mathrm{PTDF}^{z} = \mathrm{PTDF}^{n} \cdot GSK$

$$\mathrm{PTDF}^{z}\, np^{da} \leq \bar{f} - f^{bc} + \mathrm{PTDF}^{z}\, np^{bc} \qquad (2)$$

$$\mathrm{PTDF}^{z}\, np^{da} \leq \bar{f} - f^{ref} = RAM \qquad (3)$$

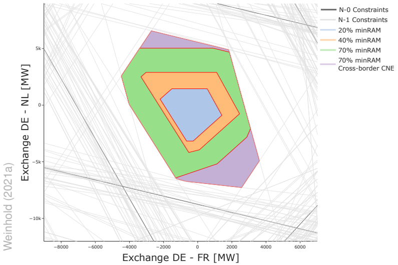



Figure: Visualization of the day-ahead capacity allocation for different minRAM configurations.

Based on a basecase net-position, day-ahead utilizes remaining capacity (1). Reformulating into (3) yields the network representation of D-1 that aligns with:

$$NP_t \in \mathcal{F}^{z} := \{x : \mathrm{PTDF}^{z}_{t}\, x \leq RAM_t\}$$

# Illustrative Example

$$\text{PTDF}^z(np^{da} - np^{bc}) \leq \bar{f} - f^{bc} \qquad \text{(1 revisited)}$$
$$\text{with } \text{PTDF}^z = \text{PTDF}^n \cdot GSK$$

$$\text{PTDF}^z\, np^{da} \leq \bar{f} - f^{bc} + \text{PTDF}^z\, np^{bc} \qquad \text{(2 revisited)}$$
$$\text{PTDF}^z\, np^{da} \leq \bar{f} - f^{ref} = RAM \qquad \text{(3 revisited)}$$

Based on the generators position and the separated market clearing as the basecase the flow-based parameters (line 1):

$$\begin{pmatrix} 0 & 0.4 \end{pmatrix} np^{da} \leq 22$$

That **allocate** capacity **unilaterally** based on forecasted:

- Remaining capacity on specific network elements.
- Generator availability and response.

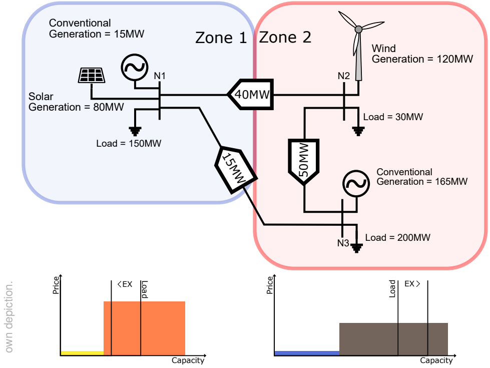



Figure: Capacity allocation by flow-based market coupling.

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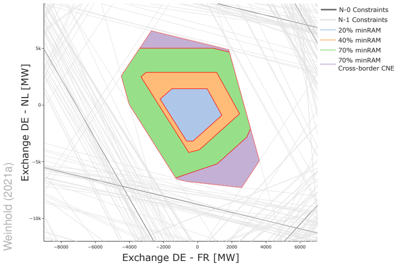


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Main components of the flow-based parameters:

- Selection of network elements that compose the PTDF matrix (CNECs)
- Set of plants that serve changes in net-position (GSK).
- Altering RAM values.

Evaluation and efficiency of these parameter choices a highly relevant.

## Reseach Questions

1. Fundamentals of the flow-based process.
2. Model/Method development.
3. Flow-based process:
   3.1 Basecase
   3.2 Day-ahead market stage
   3.3 Congestion Management
4. Impact of the main components:
   4.1 Generation Shift Keys (GSK)
   4.2 Critical Network Elements (CNE)
   4.3 Remaining available margin (RAM)
5. Compatibility with systems with high shares intermittent generation.

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David Schönheit, Richard Weinhold, and 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.” **Applied Energy** 258:114067

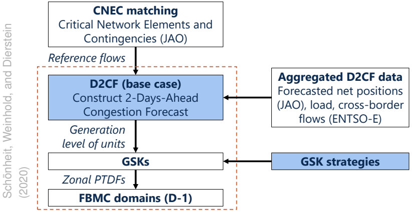
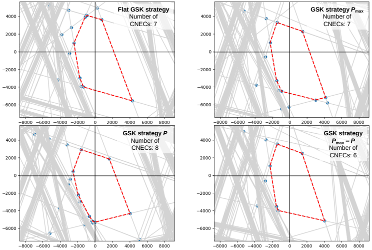



Figure: Overview of the applied methodology and data sources for the construction of base cases and computation of flow-based market coupling domains. Own figure.

**Why is it important:**
The importance of GSK strategies is discussed in official documents and academia but the effect of different strategies on the FBMC domain and individual network elements has not been thoroughly researched.

**What it is not about:**
The goal is not to identify better or worse GSK strategies (among the tested) but to quantify the GSK strategy’s effect on the FB domain and critical network elements.




Schönheit, Weinhold, and Dierstein (2020)

Figure: Two-dimensional domains for the borders DE-FR and DE-NL per GSK strategy

## Impact of GSKs on domains and CNECs

- Domains are often constrained by a few CNECs (often <10)
- Zonal PTDF-values vary across GSK strategies and contingencies.
- GSK strategies frequently determine if the element constrains the domain

## Framework

- Good representation of the basecase is important to test impact of GSK strategies
- Proposed approach increases transparency and traceability regarding the effect of GSK strategies.

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Richard Weinhold and Robert Mieth. 2021a. “Power Market Tool (POMATO) for the Analysis of Zonal Electricity Markets.” **SoftwareX** 16:100870

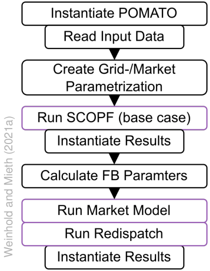


Figure: Steps to model flow-based market coupling.

## Motivation

Create a short-term electricity market model to synthesize FBMC:

- By providing the required flexibility regarding the network representation.
- Using open methods and open data.
- Python based user-interface, performant model core in Julia.

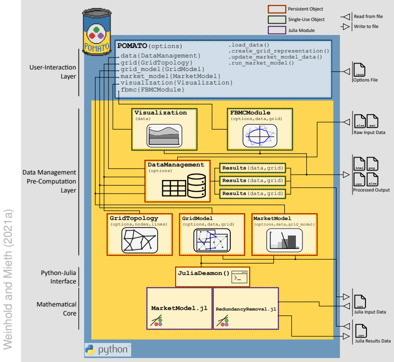


Figure: POMATO's layered architecture.

POMATO aims to facilitate reseach on FBMC by providing the required flexibility regarding the network representation:

- Compatibility with OPSD[a] and Matpower[b] data structures.
- Publicly available data pipeline to generate datasets using PomatoData[c].
- Exact SCOPF implementation, suitable for large-scale networks and multi-period analyses.
- Stochastic OPF using chance-constraints to analyze the impact of forecast errors.
- Visualization module for comprehensive analysis.

*a.* See Open Power System Data: Weibezahn et al. 2018 and Schlecht 2018

*b.* See: Zimmerman, Murillo-Sánchez, and Thomas 2011

*c.* See: Weinhold 2021b

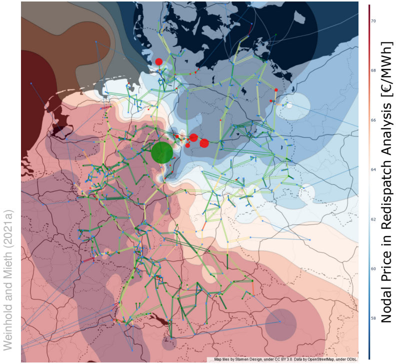

Figure: Geo-plot of market- and redispatch result for Germany.

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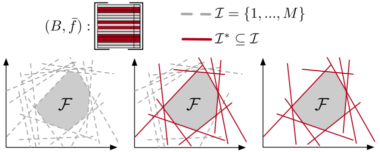


Weinhold and Mieth (2020)

Figure: Schematic representation of the equivalent description of a feasible region $\mathcal{F}(B, \bar{f}, \mathcal{I})$ by $\mathcal{F}(B, \bar{f}, \mathcal{I}^*)$ where $\mathcal{I} = \{1, \dots, M\}$ is the set of all indices of system $(B, \bar{f})$ and $\mathcal{I}^* \subseteq \mathcal{I}$ is the essential set of indices.

Power flow constraints can be expressed as a feasible region:

$$\mathcal{F}(B, \bar{f}) = \{x : -\bar{f} \leq Bx \leq \bar{f}\}$$

with a PTDF $B$ matrix that is composed by:

- a set of critical network elements (CNE)
- under a set of contingencies (C)

Considering all network elements under all possible contingencies requires $2L(L+1)$ inequalities to define feasible region $\mathcal{F}(B, \bar{f})$.

We propose a procedure based on Clarkson 1994 that discovers the minimal set of critical network elements and contingencies (CNECs) based on endogenous model parameters and exogenous data characteristics that defines $\mathcal{F}(B, \bar{f})$.

Richard Weinhold and Robert Mieth. 2020. "Fast Security-Constrained Optimal Power Flow Through Low-Impact and Redundancy Screening." **IEEE Transactions on Power Systems** 35 (6): 4574–4584

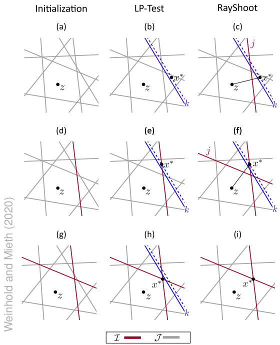


Figure: Graphical itemization of the Algorithm first described by Clarkson 1994

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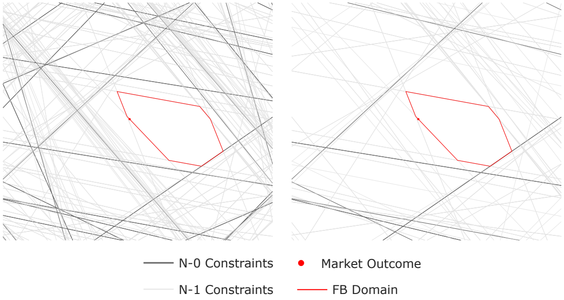
Table: DE case constraint and solve time reduction (25 time steps)

| | Full | Pre | RR | CRR |
|---|---|---|---|---|
| # Constraints | 967,140 | 14,523 | 10,695 | 2,629 |
| Solve Time [s] | NA | 1,707.56 | 714.37 | 89.53 |
| total constraint reduction*: | | 98.5% | 98.9% | 99.7% |
| additional constraint reduction*: | | 98.5% | 26% | 75% |
| total solve time reduction*: | | | 58% | 95% |

*Relative to "Pre"

Practical implementation has been done for small to large case studies:

- >95% of the constraints are identified as redundant.
- Significant improvements in solve time.
- A common ratio of 2.5 - 3 outages per line.
- Parallel execution provides significant speed ups in processing time.




Own depiction.

Utilization within POMATO:

- Precalculate sets of CNECs to guarantee SCOPF.
- Presolve flow-based domains for significantly reduced complexity.

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Richard Weinhold and Robert Mieth. 2021b. **Uncertainty-Aware Capacity Allocation in Flow-Based Market Coupling.** ArXiv preprint 2109.04968v2

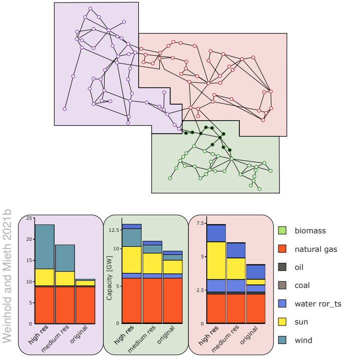


Figure: IEEE 118 bus network with extended renewable capacities based on Pena, Martinez-Anido, and Hodge 2017

## Motivation

- Formal description of FBMC, the involved parameters and policy considerations.
- Evaluate the effectiveness of FBMC against:
  - Zonal market clearing using static bilateral NTCs.
  - Nodal market clearing.

  in systems with **high shares** of intermittent renewable generation in terms of systems costs and costs/quantities for congestion management.

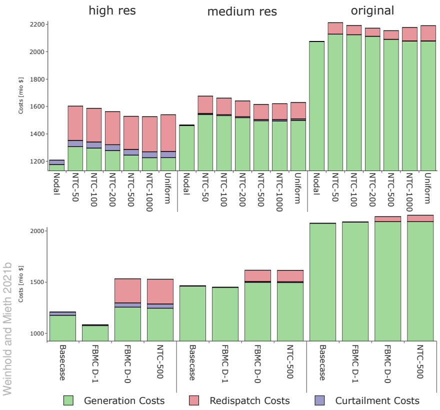


Figure: Cost composition of FBMC, NTC and Nodal market clearing. For each scenario: Basecase, D-1 zonal market clearing and D-0 redispatch.

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## Intermediate Results

- Generation cost decrease with higher shares of RES.
- We can quantify the trade-off between capacity allocation and congestion management.

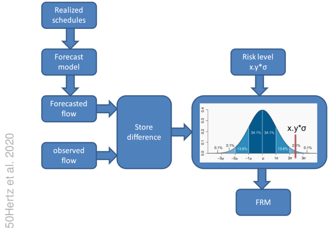


Figure: FRM Assessment Principle 50Hertz et al. (2020).

## Uncertainty Aware Formulation

Flow Reliability Margins reduce capacity on CNECs to account for system inherent uncertainty:

"*[F]or each Critical Network Element, a Flow Reliability Margin (FRM) has to be defined, that quantifies at least how [...] uncertainty impacts the flow on the Critical Network Element.*"

– 50Hertz et al. (2020, p. 47)

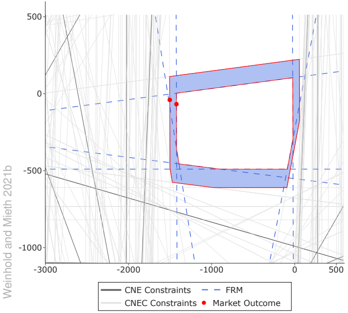


Figure: Flow-based domain with FRMs for exchange Zone 1 - Zone 2 and Zone 2 - Zone 3.

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The economic dispatch problem for the day-ahead is re-formulated to account uncertainty of intermittent generation using chance constraints.

- Initially system costs increase, due to more restricted exchange capacities.
- FRMs prove to be more robust and provide lower system when subjected to forecast errors.

Richard Weinhold. 2021a. **Evaluating Policy Implications on the Restrictiveness of Flow-Based Market Coupling with High Shares of Intermittent Generation: A Case Study for Central Western Europe.** ArXiv preprint 2109.04940v1

## Motivation

Describe the mid-term transformation towards a decarbonized electricity system for the central western European region and focus on the presumed **trade-off** between less constrained **capacity allocation** and increased **congestion management**.

## Open Data / PomatoData

Open, highly disaggregated and consistent dataset for the European electricity system based on various contributions to the open-data community.

Weinhold 2021a

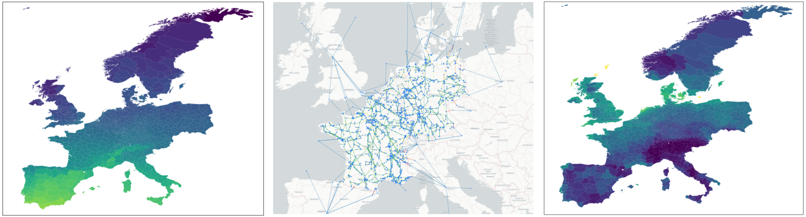

Figure: The geographical scope of the model application and mean solar (left) and wind (right) availability and the transmission network (middle)

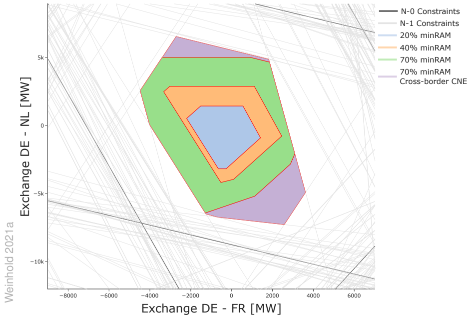


Figure: Total generation and congestion management by fuel-type for the *70% minRAM* configuration in 2020 (left) and 2030 (right)

**Costs:**

- Generation cost decrease with less constrained capacity allocation.
- Total system cost decrease with higher RES shares.
- Congestion management increases towards 2030.

**2020:**

- Least constrained domain provide lowest generation cost.
- Cost for congestion management increase when reducing the set of CNECs.

**2030:**

- Least constrained domain provide lowest overall cost.
- Increased congestion management is always overcompensated by reduced cost for generation.

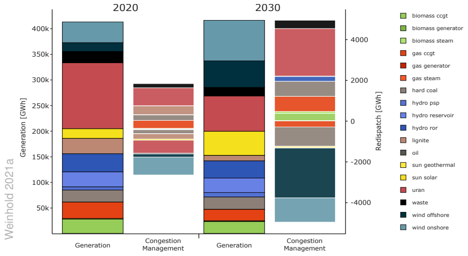


Figure: Total generation and congestion management by fuel-type for the *70% minRAM* configuration in 2020 (left) and 2030 (right)

Table: Total cost for generation, curtailment and redispatch in mio. €

| | | minRAMconfiguration | | | |
|---|---|---|---|---|---|
| | | 20% | 40% | 70% | 70%(onlyCB) |
| 2020 | Generation | 9,837 | 9,758 | 9,718 | 9,704 |
| | Curtailment | 104 | 108 | 111 | 117 |
| | Redispatch | 129 | 94 | 84 | 98 |
| | Total | 10,070 | 9,960 | 9,913 | 9,919 |
| 2030 | Generation | 6,926 | 6,905 | 6,888 | 6,864 |
| | Curtailment | 559 | 560 | 567 | 588 |
| | Redispatch | 180 | 160 | 155 | 146 |
| | Total | 7,665 | 7,625 | 7,610 | 7,598 |

**Costs:**

- Generation cost decrease with less constrained capacity allocation.
- Total system cost decrease with higher RES shares.
- Congestion management increases towards 2030.

**2020:**

- Least constrained domain provide lowest generation cost.
- Cost for congestion management increase when reducing the set of CNECs.

**2030:**

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- Increased congestion management is always overcompensated by reduced cost for generation.

Table: Total cost for generation, curtailment and redispatch in mio. €

| | | 20% | | 40% | | 70% | | 70%(onlyCB) | |
|---|---|---|---|---|---|---|---|---|---|
| | | $\lambda$ | $\Delta\lambda$ | $\lambda$ | $\Delta\lambda$ | $\lambda$ | $\Delta\lambda$ | $\lambda$ | $\Delta\lambda$ |
| 2020 | D-1 | 50.02 | 24.41 | 44.68 | 22.4 | 41.61 | 21.23 | 39.08 | 17.06 |
| | D-0 | 47.18 | | 48.13 | | 48.46 | | 47.88 | |
| 2030 | D-1 | 43.47 | 31.73 | 42.02 | 24.62 | 41.3 | 22.49 | 37.58 | 19.46 |
| | D-0 | 54.39 | | 55.48 | | 56.32 | | 57.67 | |

Weinhold 2021a

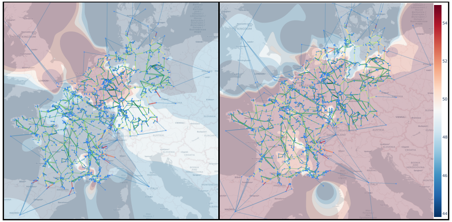


Figure: Average nodal marginal cost for congestion management in 2020 (left) and 2030(right) for the 70% minRAM configuration

A core metric of the European electricity market is **price convergence**:

- Market Prices (D-1) decreases with higher shares of RES and with increased exchange capacities.
- Total system cost decrease with higher RES shares.
- Price convergence indeed also increases with higher exchange capacities.
- Evaluating prices in D-0, so after congestion management indicates additional costs for electricity with nodal constraints present.
- Higher prices in D-0 indicate a higher network utilization with higher exchange capacities.

## Concluding Remarks

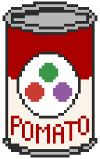
### Key Insights

- Flow-based market coupling represents an improvement over static methods for capacity allocation.
- FBMC offers a more general way to allocate capacity and includes the system state more explicitly.
- While more transparent the process is also more complex.

### Contributions

- This thesis aims to openly provide the necessary tools to perform quantitative analysis on zonal electricity markets.
- Open means in this context also accessible: Under open license, version controlled, tested and documented.
- This thesis contributes to a better fundamental understanding and better comperability.

## Thank You very much for Your attention!



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Appendix

This Defence's Knapsack Problem:

$$\max \sum_{i \in \mathcal{I}} v_i x_i$$

$$\text{s.t.} \quad \sum_{i \in \mathcal{I}} w_i x_i \leq W$$

$$x_i = 1 \quad \forall i \in \{3, 7\}$$

$$x_i \in \{0, 1\}$$

Table: Values and weights for potential additions to defence presentation

| i | description | value (v) | weight (w) |
|---|---|---|---|
| 1 | proper introduction | 10 | 50 |
| 2 | short (improper) introduction | 2 | 10 |
| 3-7 | Paper p $p \in \{1, \ldots, 5\}$ | 5 | 15 |
| 8 | memes | 117 | 5 |
| 9 | complete model description | 0 | 500 |
| 10 | stylized (& incorrect) model description | 10 | 20 |
| 11 | simpsons references | 99 | 7 |
| 12 | Description Input Data | 2 | 10 |
| 13 | Open-source Principles | 5 | 15 |

Total weight $W = 66$.

$\Rightarrow$ Non-Convex, non-trivial and proven infeasible.

$\Rightarrow$ Use greedy algorithm.

$\Rightarrow$ Start with Memes!

# Formulation: Economic Dispatch

$$
\begin{aligned}
\min \quad & \sum_{t\in\mathcal{T}} c(G_t) + p(e^T C_t) && && \text{(4a)}\\
\text{s.t.} \quad & 0 \le G_t \le \overline{g} && \forall t \in \mathcal{T} && \text{(4b)}\\
& 0 \le C_t \le r_t && \forall t \in \mathcal{T} && \text{(4c)}\\
& L_{t,s} = L_{t-1,s} - G_{t,s} + \eta_s D_{t,s} && \forall s \in \mathcal{ES}, t \in \mathcal{T} && \text{(4d)}\\
& 0 \le D_t \le \overline{d} && \forall t \in \mathcal{T} && \text{(4e)}\\
& 0 \le L_t \le \overline{l} && \forall t \in \mathcal{T} && \text{(4f)}\\
& \mathrm{m}^n G_t + \mathrm{m}^n(r_t - C_t) - \mathrm{m}^n D_t - d_t = I_t && \forall t \in \mathcal{T} && \text{(4g)}\\
& \mathrm{m}^z G_t + \mathrm{m}^z(r_t - C_t) - \mathrm{m}^z D_t - m^z d_t = NP_t && \forall t \in \mathcal{T} && \text{(4h)}\\
& NP_{t,z} = \sum_{z'\in\mathcal{Z}} \mathrm{EX}_{t,z,z'} - \mathrm{EX}_{t,z',z} && \forall t \in \mathcal{T}, \forall z \in \mathcal{Z} && \text{(4i)}\\
& e^T I_t = 0 && \forall t \in \mathcal{T} && \text{(4j)}
\end{aligned}
$$

$$
\begin{aligned}
NP_t \in \mathcal{F}^z &:= \{x : \mathrm{PTDF}^z_t\, x \le RAM_t\} && \forall t \in \mathcal{T}, && \text{(5a)}\\
I_t \in \mathcal{F}^n &:= \{x : \mathrm{PTDF}^n\, x \le \overline{f}\} && \forall t \in \mathcal{T}. && \text{(5b)}\\
EX_t \in \mathcal{F}^{ntc} &:= \{x : 0 \le x \le ntc\} && \forall t \in \mathcal{T}. && \text{(5c)}
\end{aligned}
$$

$$
\begin{aligned}
C(G^{red}) &= c^{red} \sum_{t\in\mathcal{T}} |G^{red}_t| && && \text{(6a)}\\
G_t - g^{da}_t &= G^{red}_t && \forall t \in \mathcal{T} && \text{(6b)}\\
C_t &\ge c^{da} && \forall t \in \mathcal{T}, && \text{(6c)}
\end{aligned}
$$

All FBMC stages are variations of the economic dispatch problem (4):

- Cost minimization (4a)
- Capacity (4b) and curtailment (4c)
- Storage constraints (4d) – (4f)
- Energy balances (4g) and (4g)

Subject to different network representations:

- Constraints on nodal power injections $I_t$ in (5b).
- Unilateral constraints on zonal net-positions $NP_t$ in (5a).
- Bilateral constraints on exchange $EX_t$ in (5a).

Including Congestion management defined by:

- Costs for Redispatch/Curtailment in (6a)
- Limits for changes in generation schedule (6b) and (6c)

Schönheit, Weinhold, and Dierstein (2020)

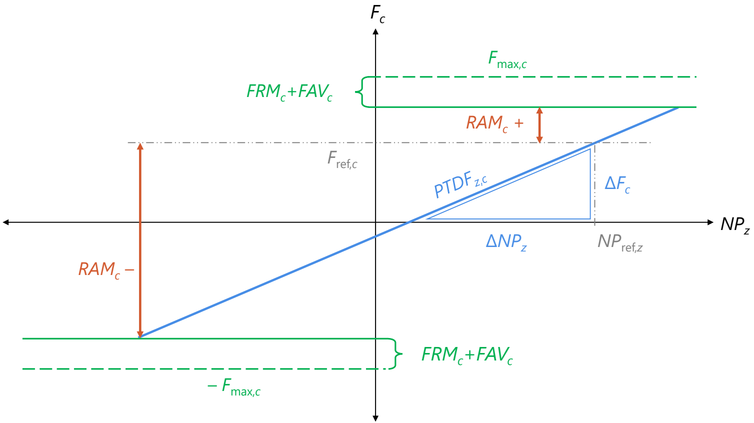



Figure: Zone-to-zone PTDF values – CNE „l961“ – day 2.

Depicted is the relation between the main flow-based market coupling parameters. The x-axis describes the net-position of a zone z and the y-axis the power flow on a CNEC c. The positive and negative Remaining Available Margins (RAMs) limit deviations from the expected reference flow and the corresponding net-position deviation. Source: Own figure based on Amprion

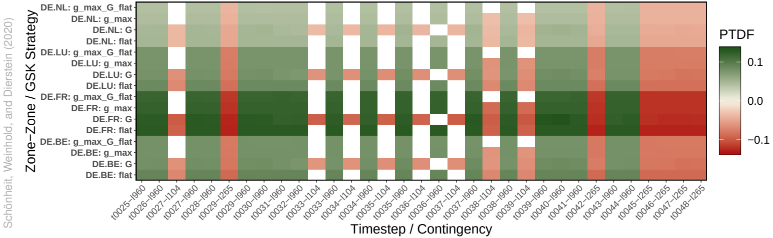
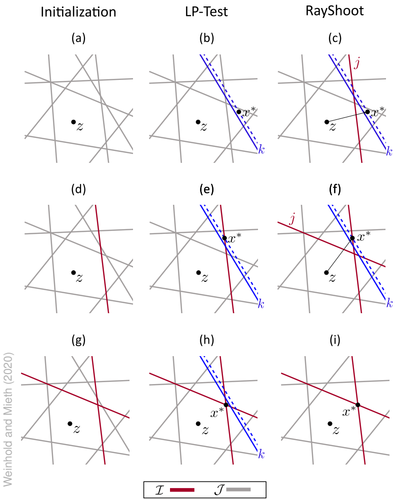



Figure: Zone-to-zone PTDF values – CNE „l961“ – day 2.

- CNE “l96” almost always constrains domain
- Under different contingencies (critical outages) per timestamp (either “l960” or “l104”)
- Changing PTDF values:
  - Under different GSK strategies
  - Due to different contingencies




a. Initial state with $\mathcal{J} = \{1, \ldots, M\}, \mathcal{I} = \emptyset$ and $z$ some interior point.

b. Some index $k$ is selected from $\mathcal{J}$ and LP-Test($B, \bar{f}, \mathcal{I}, k$) is performed.

c. Because $\mathcal{I}$ is empty in the initial iteration $k$ is always non-redundant against $\mathcal{I}$ and the most restricting constraint $j$ in the direction of $(x^* - z)$ is added to $\mathcal{I}$.

d. The next iteration starts with $\mathcal{I}$ now containing one essential index. +

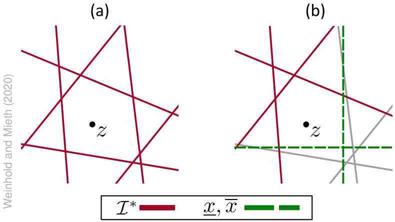
e. Because $k$ was non-redundant in the last step, it remains selected and LP-Test($B, \bar{f}, \mathcal{I}, k$) is performed.

f. Now, $k$ is again non-redundant against $\mathcal{I}$ and the most restricting constraint $j$ in the direction of $(x^* - z)$ is added to $\mathcal{I}$.

g. The next iteration starts with $\mathcal{I}$ now containing two essential indices.

h. Because $k$ was non-redundant in the last step, it remains selected and LP-Test($B, \bar{f}, \mathcal{I}, k$) is performed.

i. Index $k$ is now redundant against set $\mathcal{I}$ and is therefore removed from set $\mathcal{J}$; The procedure repeats until all elements have been removed from $\mathcal{J}$.

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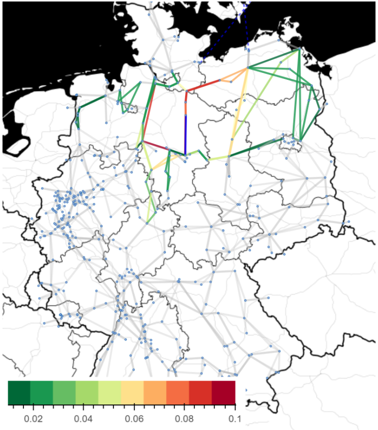



Weinhold and Mieth (2020)

- Contingencies are considered by computing how line flows are distributed across all other lines in the case of an outage.
- A large number of contingencies in great electrical distance have hardly any effect on post-contingency power flow of a line:

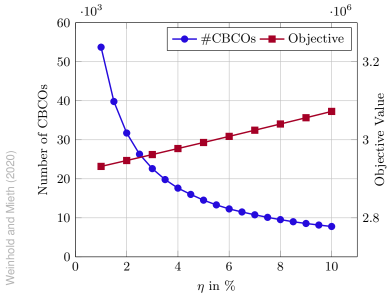
$$|f^{o}_{t,l} - f^{0}_{t,l}| = |\,\mathrm{LODF}_{lo}\, f^{0}_{t,o}| \leq |\,\mathrm{LODF}_{lo}\, \bar{f}_{o}|. \tag{7}$$

- By reserving a small capacity margin *eta* on each line, every outage that impacts this line by less than *eta* can be disregarded:

$$\frac{\mathrm{LODF}_{lo}\, \bar{f}_{o}}{\bar{f}_{l}} < \eta. \tag{8}$$

$\eta$ either reflects:

- a safety margin – reducing line capacity $(1 - \eta)\bar{f}_l$
- a *worst-case* short-term overload – increasing line capacity $(1 + \eta)\bar{f}_l$.

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- a safety margin – reducing line capacity $(1 - \eta)\overline{f}_l$
- a *worst-case* short-term overload – increasing line capacity $(1 + \eta)\overline{f}_l$.

$$
\begin{aligned}
\min \quad & \mathbb{E}[C(G(\omega))] && && \text{(9a)}\\
s.t. \quad & && && \\
& \mathbb{P}[0 \leq G_{g,t}(\omega) \leq \overline{g_g}] \geq 1-\epsilon && \forall t \in \mathcal{T},\ \forall g \in \mathcal{G} && \text{(9b)}\\
& \mathbb{P}[\mathrm{PTDF}^z_{j,t} \cdot NP_t(w) \leq \bar{f}_j - f^{ref}_{j,t}] \geq 1-\epsilon && \forall t \in \mathcal{T},\ \forall j \in \text{CNEC} && \text{(9c)}\\
& \mathrm{m}^z_g G_t(\omega) + \mathrm{m}^z_r r_t(\omega) - C_t - d_t = \mathrm{NP}_t(w) && \forall t \in \mathcal{T},\ \forall \omega \in \Omega. && \text{(9d)}
\end{aligned}
$$

Thus, the deterministic reformulation of (9) is given as:

$$
\begin{aligned}
\min \quad & C(G(\omega)) && && \text{(10a)}\\
s.t. \quad & G_t + z_\epsilon \alpha s \leq \bar{g} && \forall t \in \mathcal{T} && \text{(10b)}\\
& -G_t + z_\epsilon \alpha s \geq 0 && \forall t \in \mathcal{T} && \text{(10c)}\\
& \mathrm{PTDF}^z_{j,t}\, \mathrm{NP}_t \leq \bar{f}_j - f^{ref}_{j,t} - z_\epsilon T_{j,t} && \forall t \in \mathcal{T},\ \forall j \in \text{CNEC} && \text{(10d)}\\
& \|\mathrm{PTDF}^z_{j,t}(m^z_r - m^z_g \alpha e^T)\Sigma^{1/2}\|_2 \leq T_{j,t} && \forall t \in \mathcal{T},\ \forall j \in \text{CNEC} && \text{(10e)}\\
& \mathrm{m}^z_g G_t + \mathrm{m}^z_r \hat{r}_t - \mathrm{m}^z_d d_t = \mathrm{NP}_t && \forall t \in \mathcal{T} && \text{(10f)}\\
& e^T \alpha_t = 1 && \forall t \in \mathcal{T} && \text{(10g)}
\end{aligned}
$$

- Given uncertain injection from RES: $r_t(\omega) = r_t + \omega_t$
- $\omega_t$: zero-mean random vector of the forecast error
- Generator response: $G_t(\omega_t) = G_t - \alpha_t(e^T \omega_t)$
- Probelm (9) minimizes the exprected costs.
- s.t. probability of a generator to not supply the response or line over load is bound by $1-\epsilon$.
- (9) can be reformulated as (10) Bienstock, Chertkov, and Harnett (2014) and Mieth (2021).
- We interpret $z_\epsilon T_{j,t}$ as the endogenous FRM.

- FRMs prove to be more robust and provide lower system when subjected to forecast errors.
- The bands visualize the range of costs, subject to randomized real-time deviations.
- The solid lines are the hourly cost without real-time deviations
- The case with FRMs provides a tighter band that on average provides lower cost.

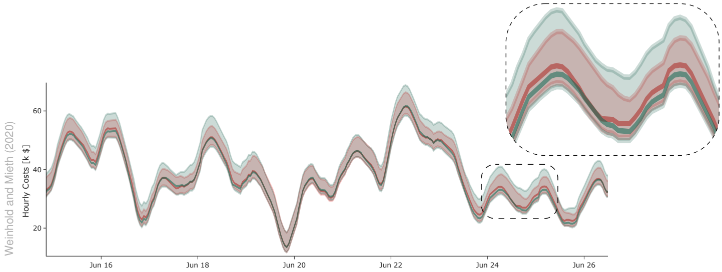


Figure: Range of hourly cost for congestion management for randomized real-time deviations $\omega$ for FBMC+ (blue) and FBMC+ CC (red)

Table: System cost including generation and congestion management (CM) for each scenario.

| | | FBMC | FBMC$^{+}$ | NTC-500 | Nodal |
|---|---|---|---|---|---|
| original | Generation | 2091.45 | 2083.82 | 2091.01 | 2075.16 |
| | Curtailment | 0.03 | 0.08 | 0.01 | 0 |
| | Redispatch | 48.76 | 89.28 | 62.89 | 0 |
| | total CM | 48.79 | 89.36 | 62.9 | 0 |
| | total | 2140.24 | 2173.18 | 2153.92 | 2075.16 |
| medium res | Generation | 1498.85 | 1499.01 | 1496.28 | 1461.68 |
| | Curtailment | 7.8 | 9.97 | 8.55 | 3.06 |
| | Redispatch | 110 | 115.91 | 110.61 | 0 |
| | total CM | 117.8 | 125.88 | 119.17 | 3.06 |
| | total | 1616.66 | 1624.89 | 1615.44 | 1464.74 |
| high res | Generation | 1256.1 | 1239.05 | 1245.6 | 1176.48 |
| | Curtailment | 42.1 | 42.73 | 41.57 | 31.81 |
| | Redispatch | 234.89 | 243.57 | 241.63 | 0 |
| | total CM | 276.99 | 286.29 | 283.2 | 31.81 |
| | total | 1533.09 | 1525.35 | 1528.8 | 1208.29 |

This is a giant table.

Table: Congestion management volumes in TWh

| | | minRAM configuration | | | |
|---|---|---|---|---|---|
| | | 20% | 40% | 70% | 70% (only CB) |
| 2020 | Curtailment | 1.05 | 1.09 | 1.11 | 1.17 |
| | Redispatch | 5.2 | 3.77 | 3.4 | 3.94 |
| | Total | 6.25 | 4.86 | 4.51 | 5.11 |
| 2030 | Curtailment | 5.6 | 5.6 | 5.68 | 5.89 |
| | Redispatch | 7.23 | 6.43 | 6.22 | 5.87 |
| | Total | 12.83 | 12.03 | 11.9 | 11.76 |

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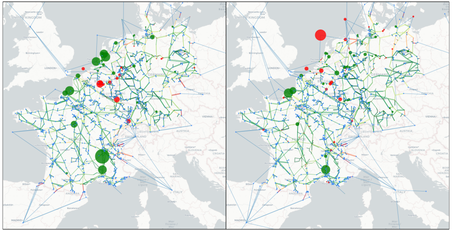

Figure: Difference in congestion management for 2020 (left) and 2030 (right) between the 20% minRAM and 70% minRAM configurations. Increased congestion management with 70% minRAM is indicated in red and less congestion management in green.

- In 2020 redispatch increases with higher exchange capacities.
- interestingly in 2030, congestion management decreases.
- Reasons are layered, increases need for flexibility, improper transmission infrastructure. . .
- Distributional effects can be made visible by looking at differences in redispatch.