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

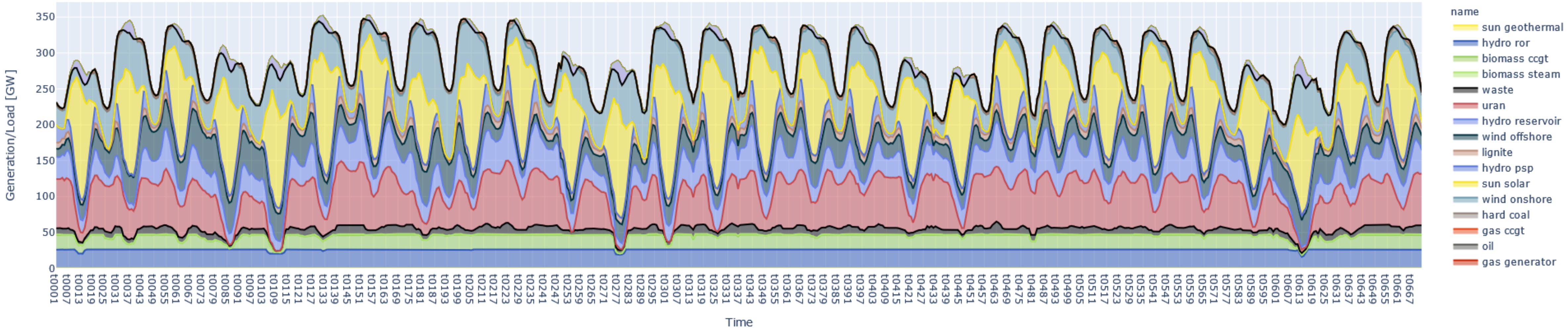
4. Application: CWE – 2020 & 2030

4.1 Underlying Data

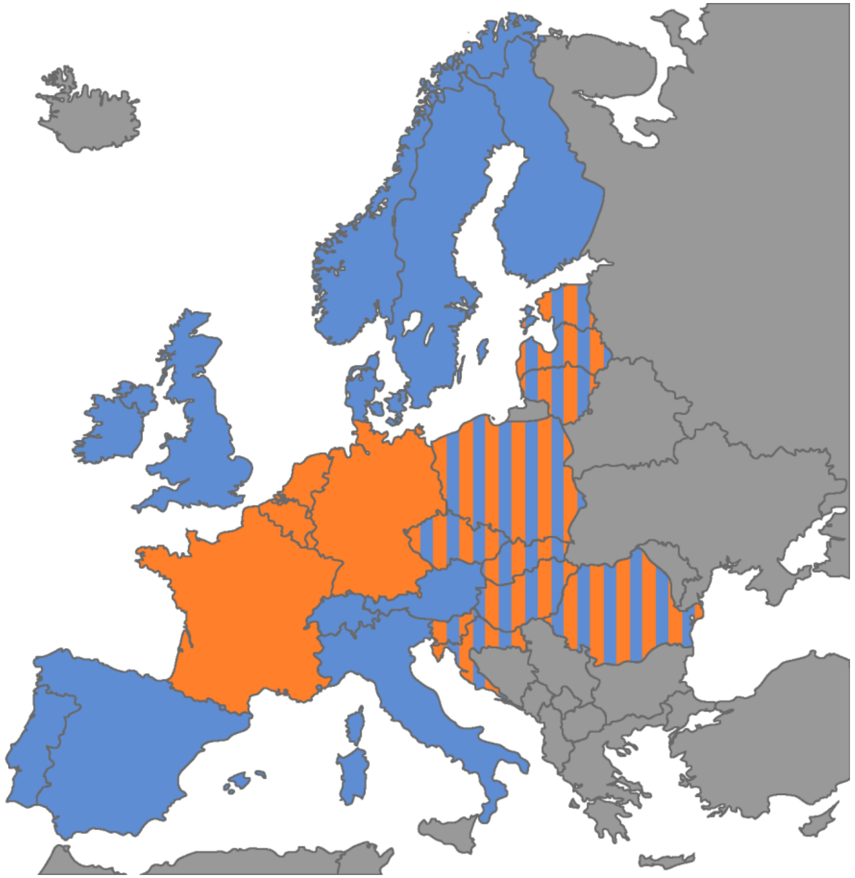
5. Results

5.1 Costs, Generation, Redispatch

6. Conclusions & Outlook



Motivation I: Zonal Market Coupling

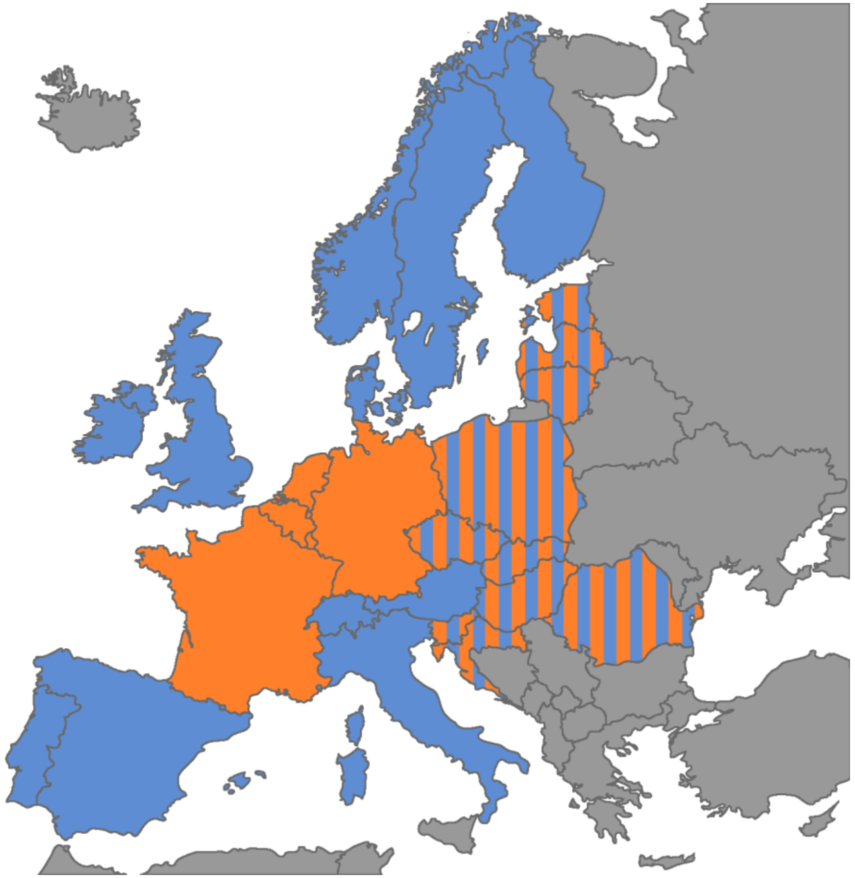


Countries Participating in PCR (blue), FBMC today (orange)
Possible FBMC extension to CEE (orange, hatched)
Source: Own depiction. *(PCR: Price coupling of regions)

- 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.

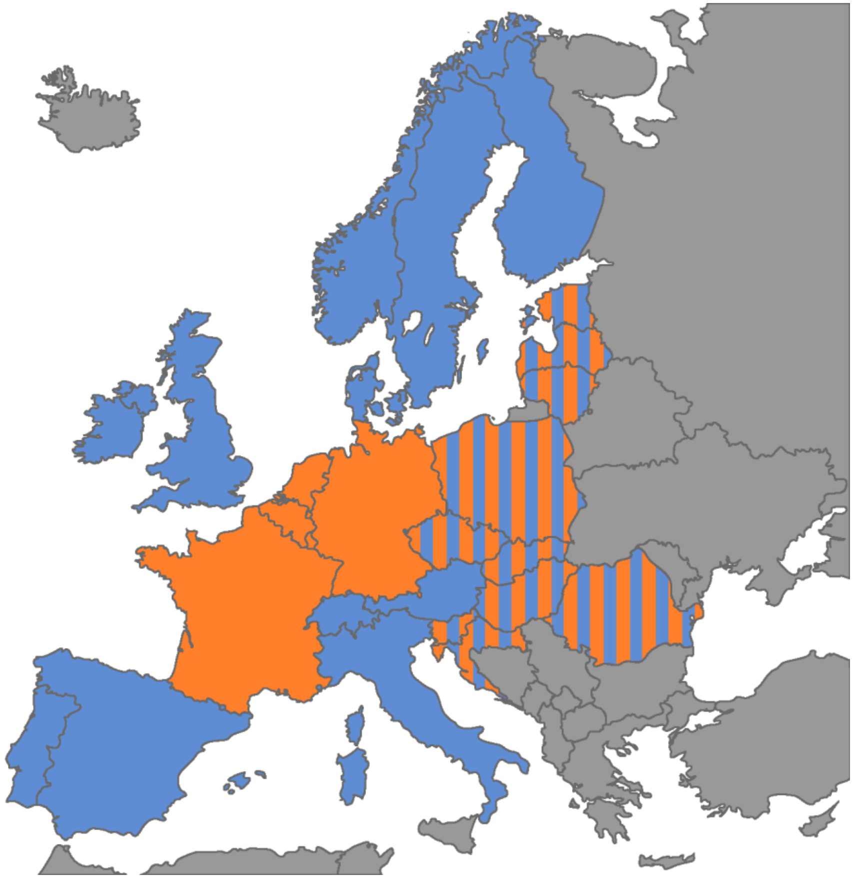
An informed discussion is required to address many topics/issues, related to the short-, medium- and long-term evolution of FBMC:

- 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:

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

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

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

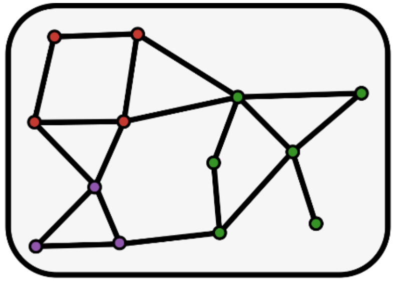
All FBMC stages are variations of the economic dispatch problem subject to

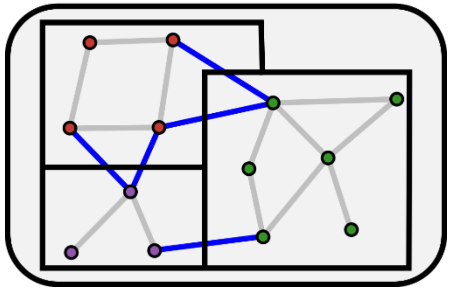
- Different network representations
  - 2a) node-line sensitivity for lines/contingencies
  - 2b) zone-line sensitivity for lines/contingencies
  - 2c) static commercial exchange
- Additional/different parameters
- Additional cost components

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

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

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

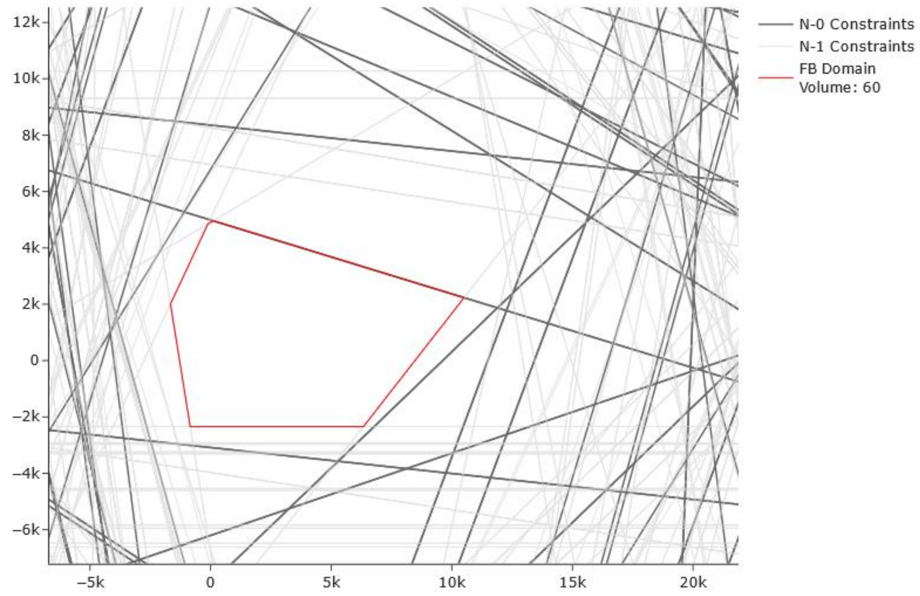




Formulation II: FB-Parameter

$$\mathrm{PTDF}^z(np^{da} - np^{bc}) \leq \overline{f} - f^{bc} \quad (4)$$
$$\text{with } \mathrm{PTDF}^z = GSK \cdot \mathrm{PTDF}^n$$

$$\mathrm{PTDF}^z\, np^{da} \leq \overline{f} - f^{bc} + \mathrm{PTDF}^z\, np^{bc} \quad (5)$$
$$\mathrm{PTDF}^z\, np^{da} \leq \overline{f} - f^{ref} = RAM \quad (6)$$



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, CNEC selection
- **More technically accurate**
  - GSK, FRM/FAV

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

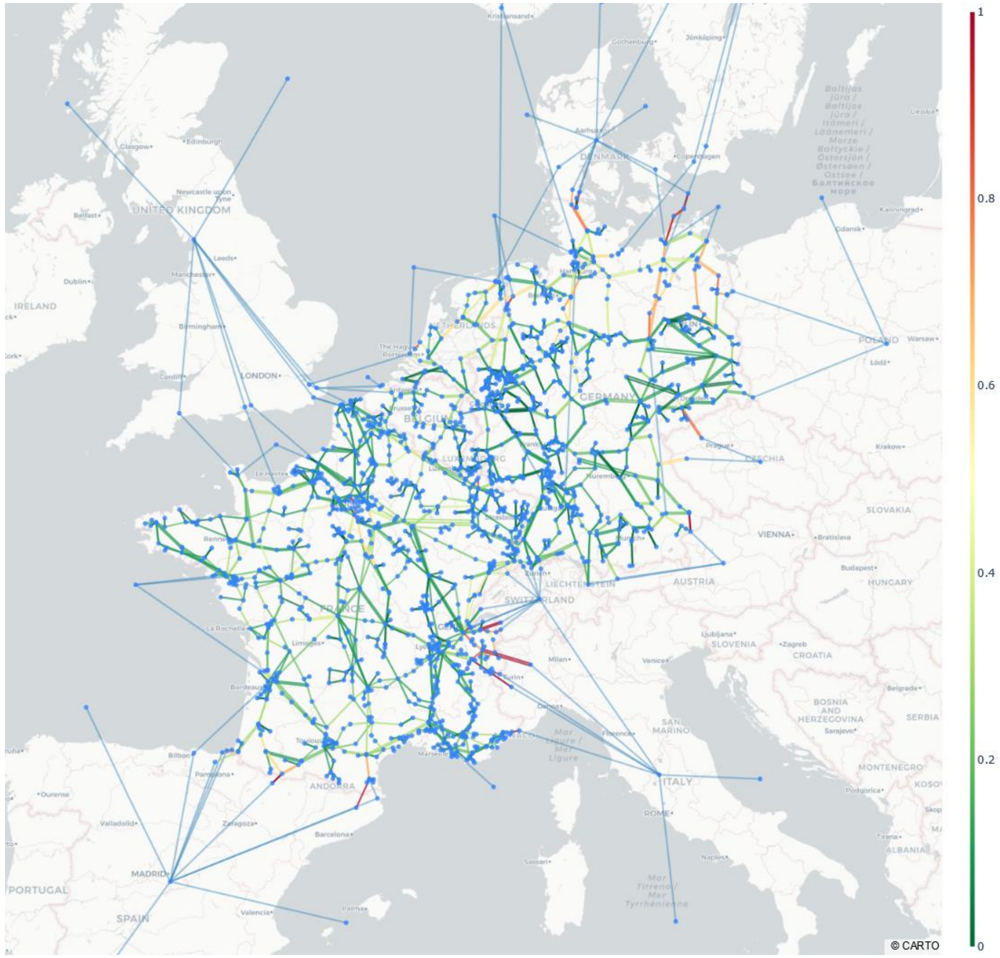
Literature II: Range of Core Assumptions

(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: CWE Data I

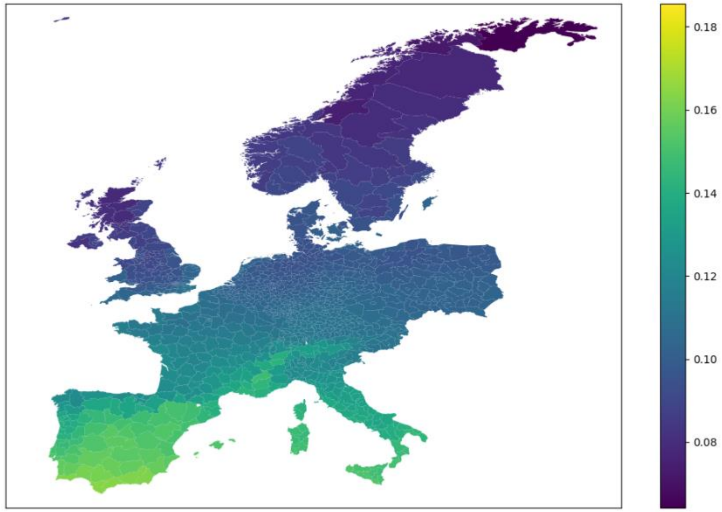


The data for the underlying data comes from multiple sources:

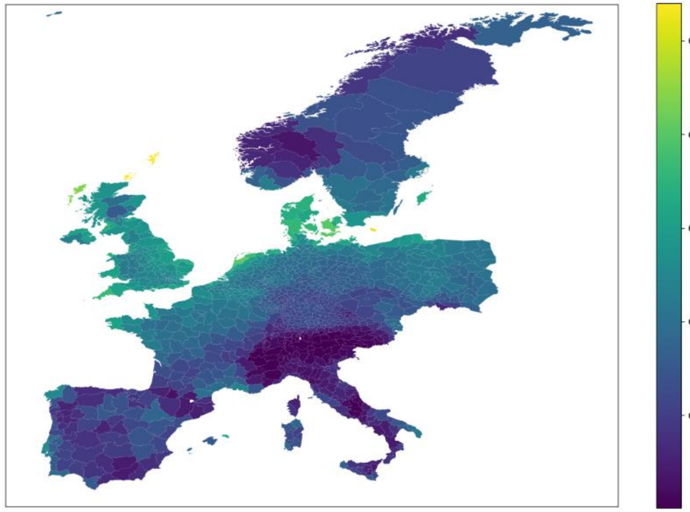
- Geodata from the ExtremOS project of FfEs Open Data Portal [2].
- Conventional power plant Open Power System Data Platform [1].
- Hydro plants JRC Hydro-power plants database [8].
- Grid data from (PyPSA) GridKit Project [5,6].

[1] open-power-system-data.org
[2] opendata.ffe.de/project/extremos/
[3] github.com/leonardgoeke/AnyMOD.jl
[4] github.com/PyPSA/atlite
[5] github.com/bdw/GridKit,
[6] github.com/PyPSA/pypsa-eur/tree/master/data/entsoegridkit
[7] diw.de/documents/publikationen/73/diw_01.c.528927.de/diw_datadoc_2016-083.pdf
[8] github.com/energy-modelling-toolkit/hydro-power-database
[9] transparency.entsoe.eu

Application: CWE Data II



Mean availability 2019 - PV (top) - Onshore wind (bottom)



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- Future wind and pv capacities from AnyMod [3]
  - distributed using the NUTS3 Potentials from FfE.
- Regionalized availabilities and inflows are generated with the atlite package [4]
- Generation costs are based on DIW DataDocumentation 83 [7].
- Load, commercial exchange from ENTSO-E Transparency platform [9].
  - Regionalized to nuts3 via sector specific gdp and standard load profiles [7]

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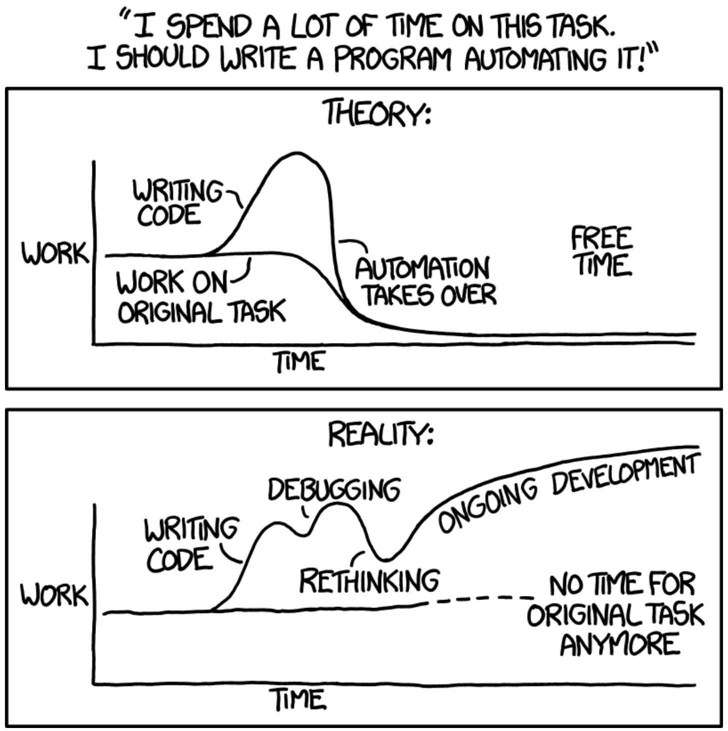
[6] github.com/PyPSA/pypsa-eur/tree/master/data/entsoegridkit
[7] diw.de/documents/publikationen/73/diw_01.c.528927.de/diw_datadoc_2016-083.pdf
[8] github.com/energy-modelling-toolkit/hydro-power-database
[9] transparency.entsoe.eu

Application: CWE Data III



https://xkcd.com/1319/

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  - Regionalized to nuts3 via sector specific gdp and standard load profiles [7]

Soon™ available on github as PomatoData

[1] open-power-system-data.org
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[4] github.com/PyPSA/atlite
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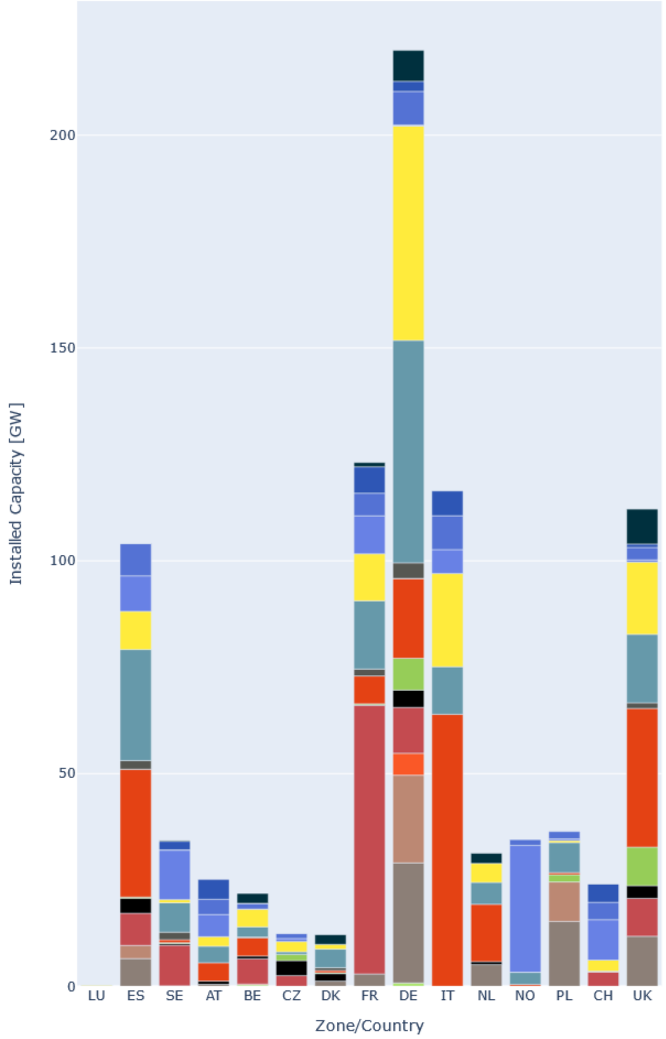
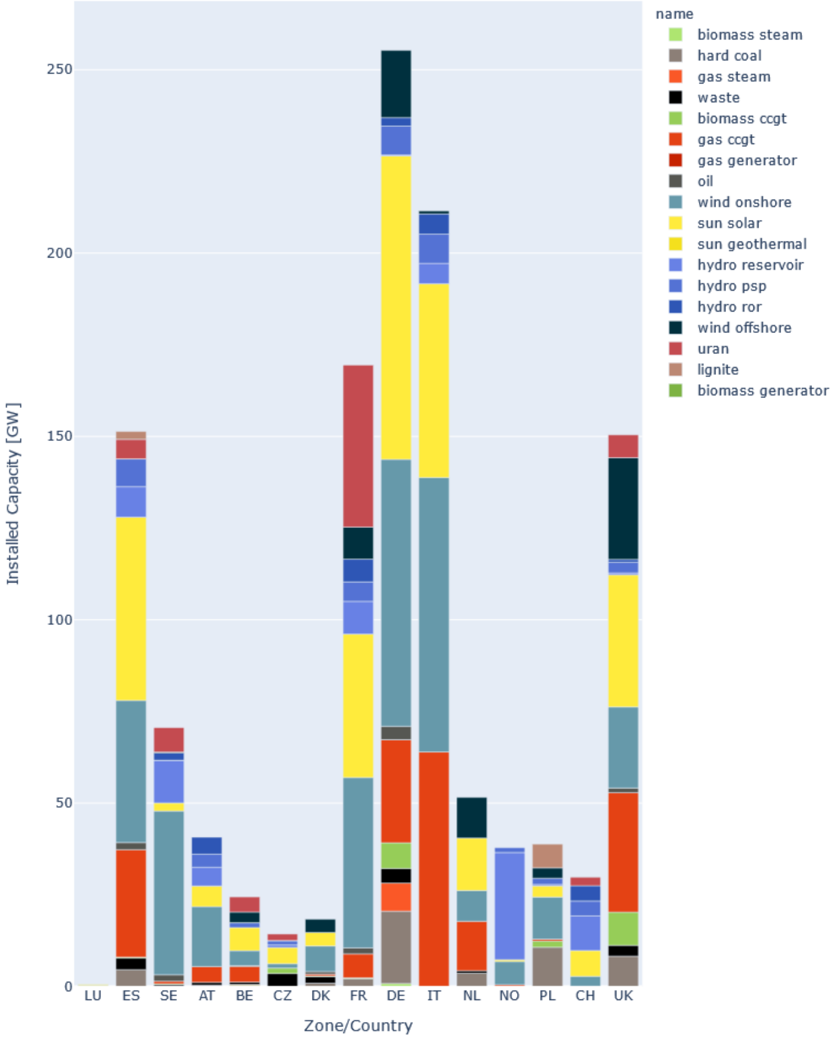
[9] transparency.entsoe.eu

Application: Scenario I

2020



2030



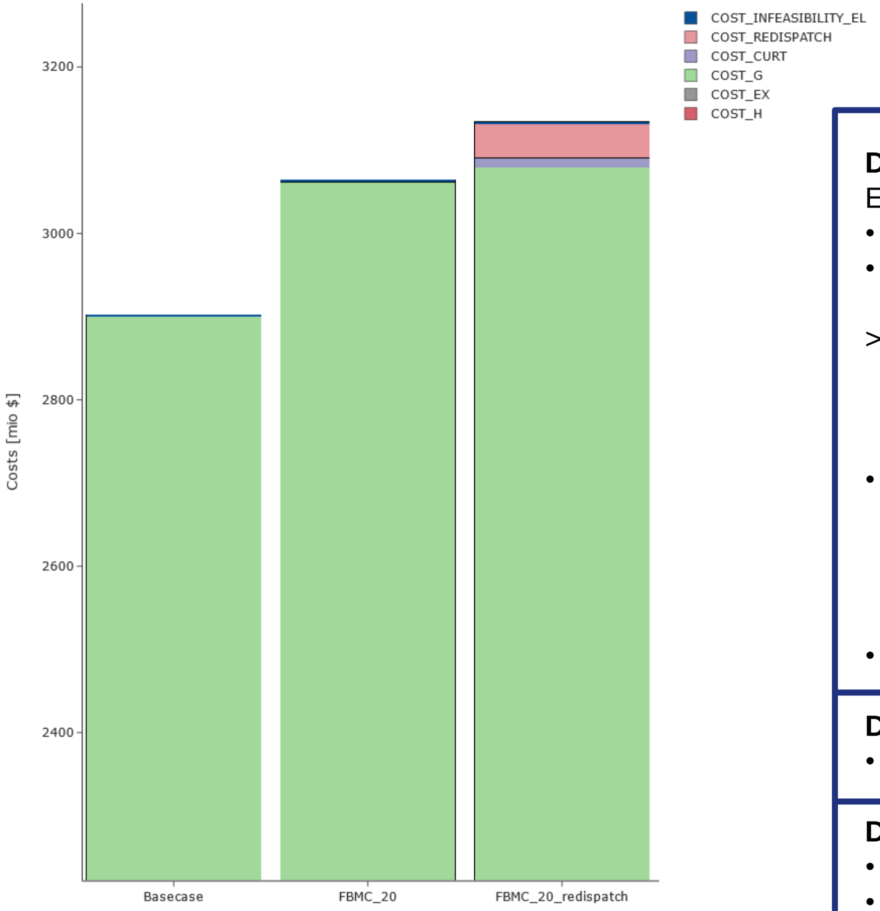
- Status Quo 2020 / Target Year 2030
- 2019 timeseries

Solved using our electricity market model POMATO

- Results presented are **May 2019,** full year calculations pending

- Grid Expansion:
  - GridKit Data includes lines under construction
  - Parameter estimation described in POMATO Documentation
  - DC Links from TYNDP
- Installed Capacity:
  - Wind/PV from capacity expansion model
  - Conventional, manual decommissioning (its difficult)
- NTC derived from commercial exchange 2019

Application: Scenario II



D-2 (Basecase)
Economic Dispatch s.t.

- Full network representation (3200 lines).
- Solved in a rolling horizon of 24h

>FB Parameters:

$$\mathrm{PTDF}^z\, np^{da} \leq RAM$$

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

- Zonal PTDF composed of:
  - CNEs which are sensitive to commercial exchange in CWE Contingencies which impact CBs significantly
- For 2030 442 CNEs, 3438 CNECs

D-1 (Day Ahead):

- FB Parameters

D-0 (Redispatch): s.t.

- full network
- generation schedule D-1
- non-storage plants within CWE

- Status Quo 2020 / Target Year 2030
- 2019 timeseries

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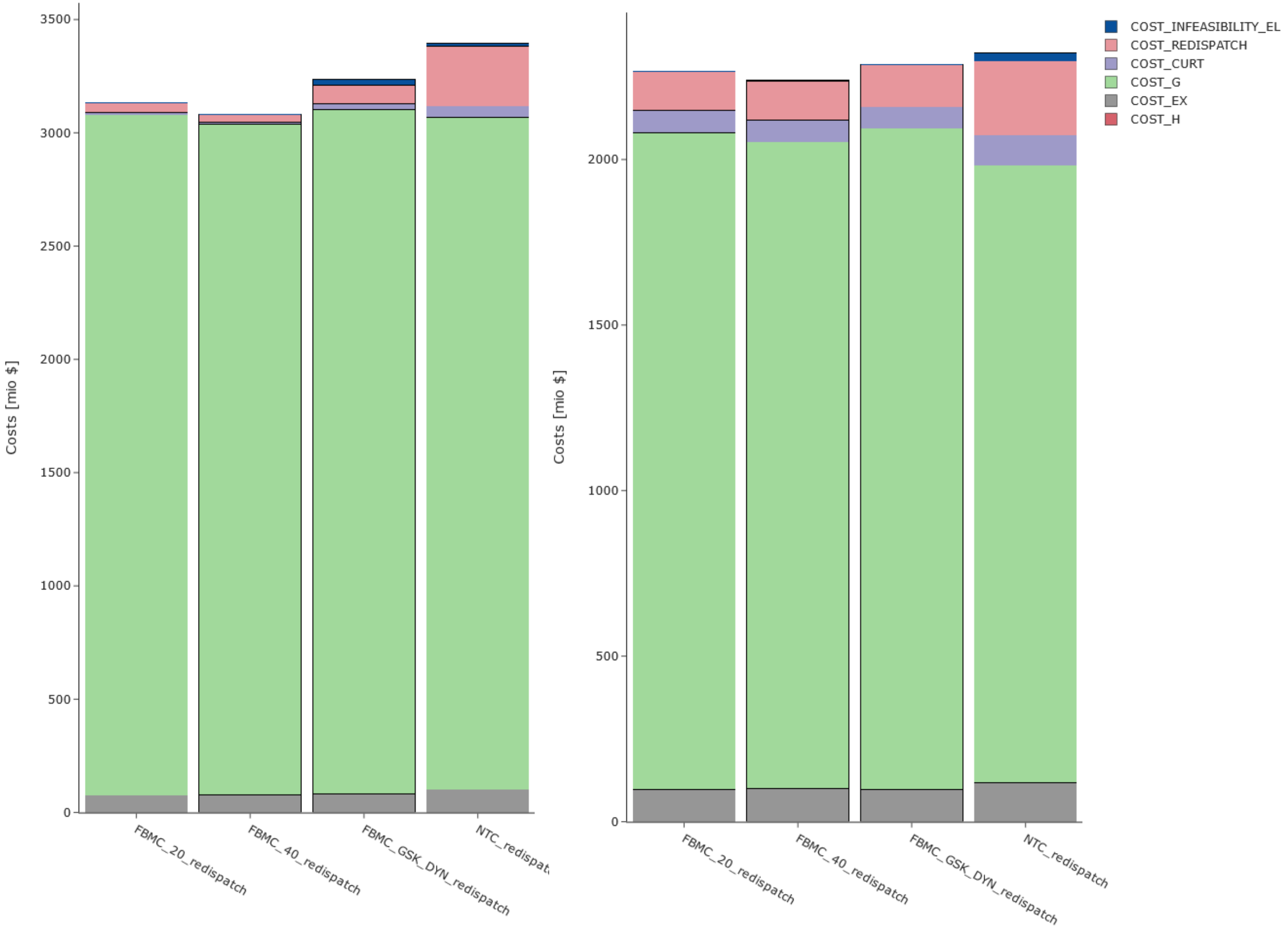
- Installed Capacity:
  - Wind/PV from capacity expansion model
  - Conventional, manual decommissioning (its difficult)
- NTC derived from commercial exchange 2019

- FB Parametrization:
  - Nodal Basecase
  - CNE selection threshold 5%
  - Contingency selection threshold 20%
  - minRAM 20% and 40%
  - GSK: Gmax, Pro-Rata

Results: System Cost I

2020 2030

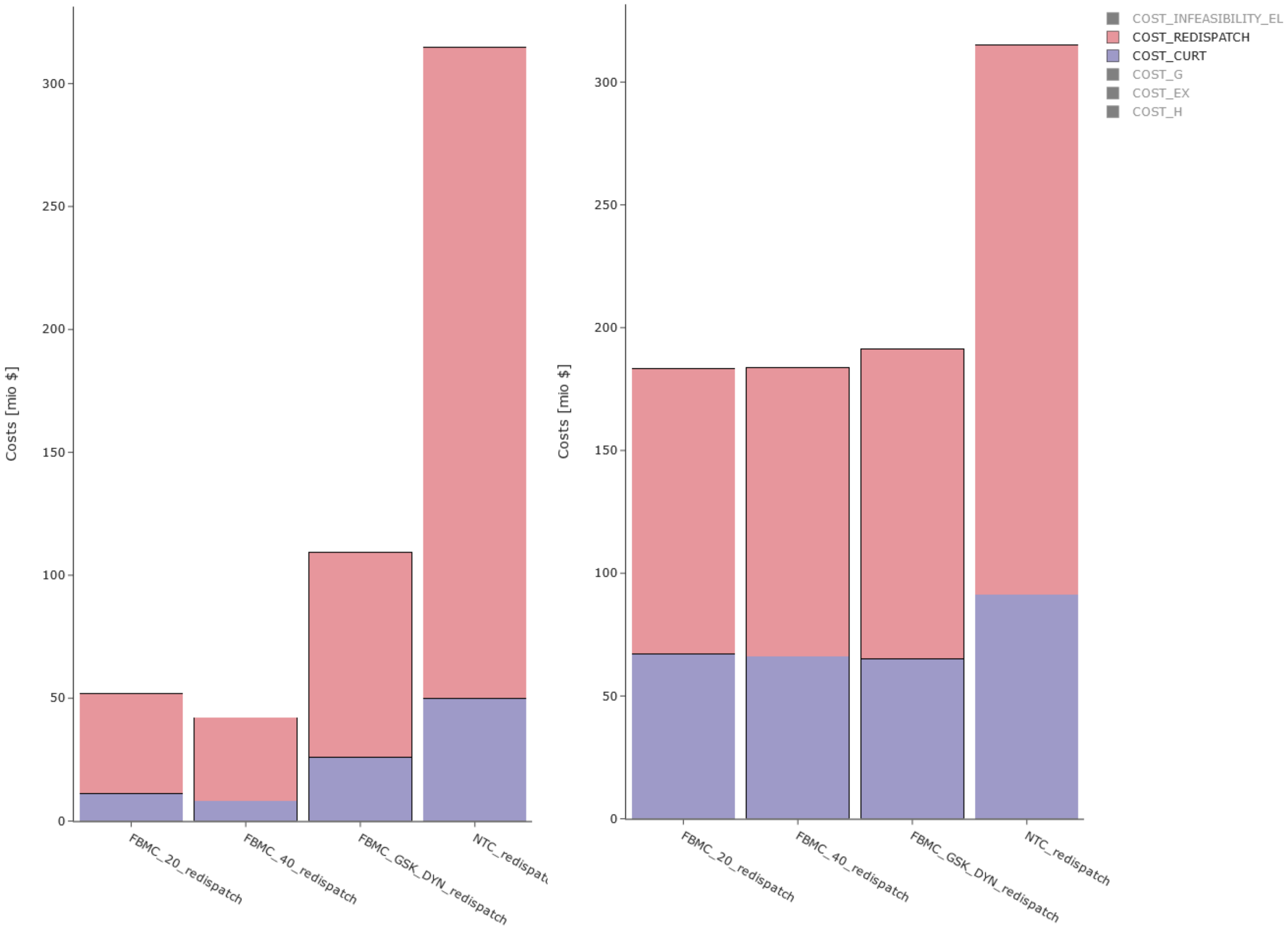


Cost Comparison 2020 > 2030

- Generation costs generally decrease
- FBMC Remains Effective
  - Total costs are systematically lower than with NTC, independent of specific parametrization
  - and lower costs for congestion management
  - FB parametrization matters, albeit with lower effect

Results: System Cost II

2020 2030



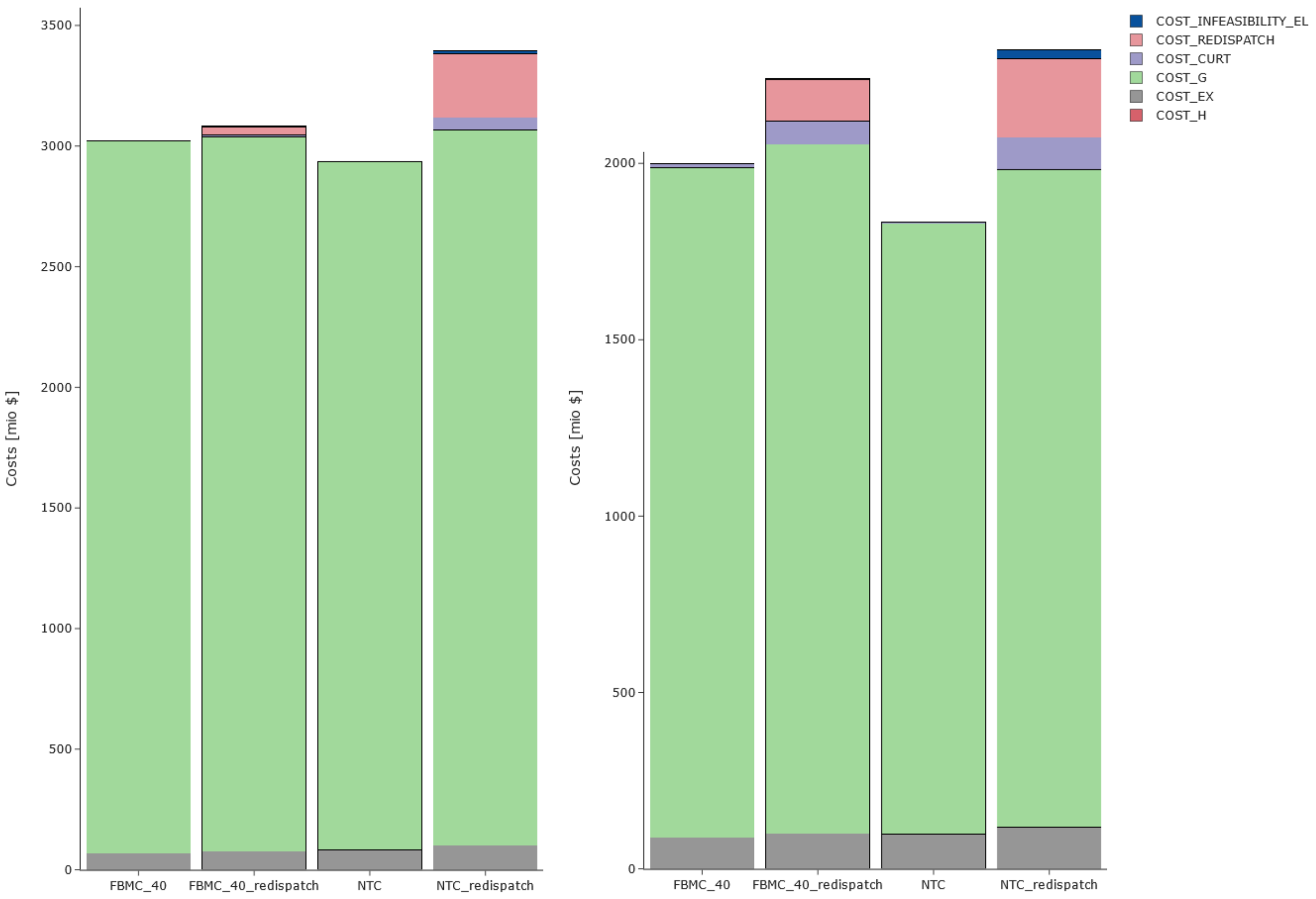
Cost Comparison 2020 > 2030

- Generation costs generally decrease

- FBMC Remains Effective
  - Total costs are systematically lower than with NTC, independent of specific parametrization
  - and lower costs for congestion management
  - FB parametrization matters, albeit with lower effect
  - Differences are lower in the 2030 scenario
  - Redispatch Costs/Quantity increase for FB scenatios

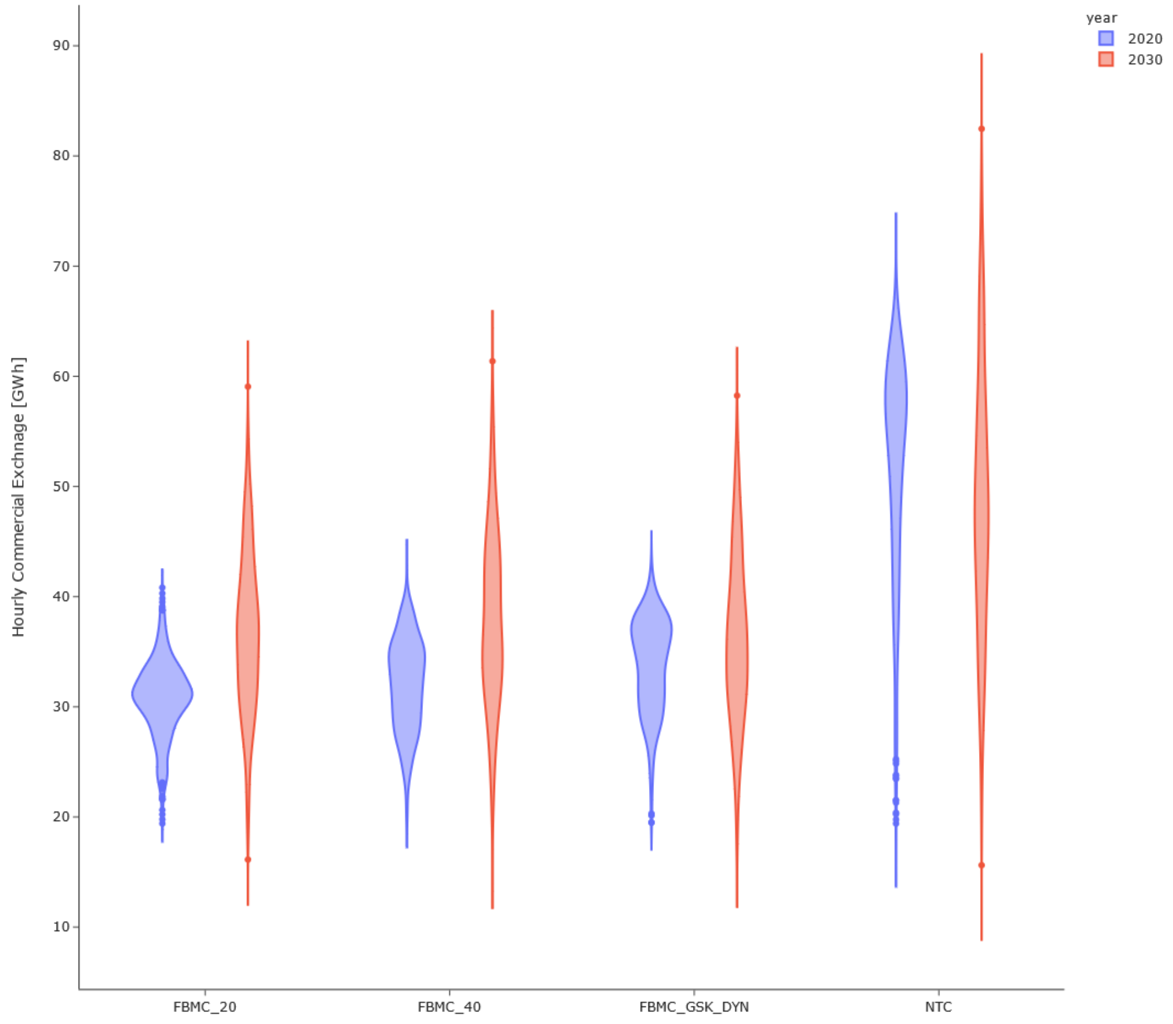
Results: System Cost III

2020 | 2030



- FBMC is more restrictive compared to the NTC solution
  - Indicated by the higher cost in D-1 market result
  - …which is always outweighed by lower redispatch costs.

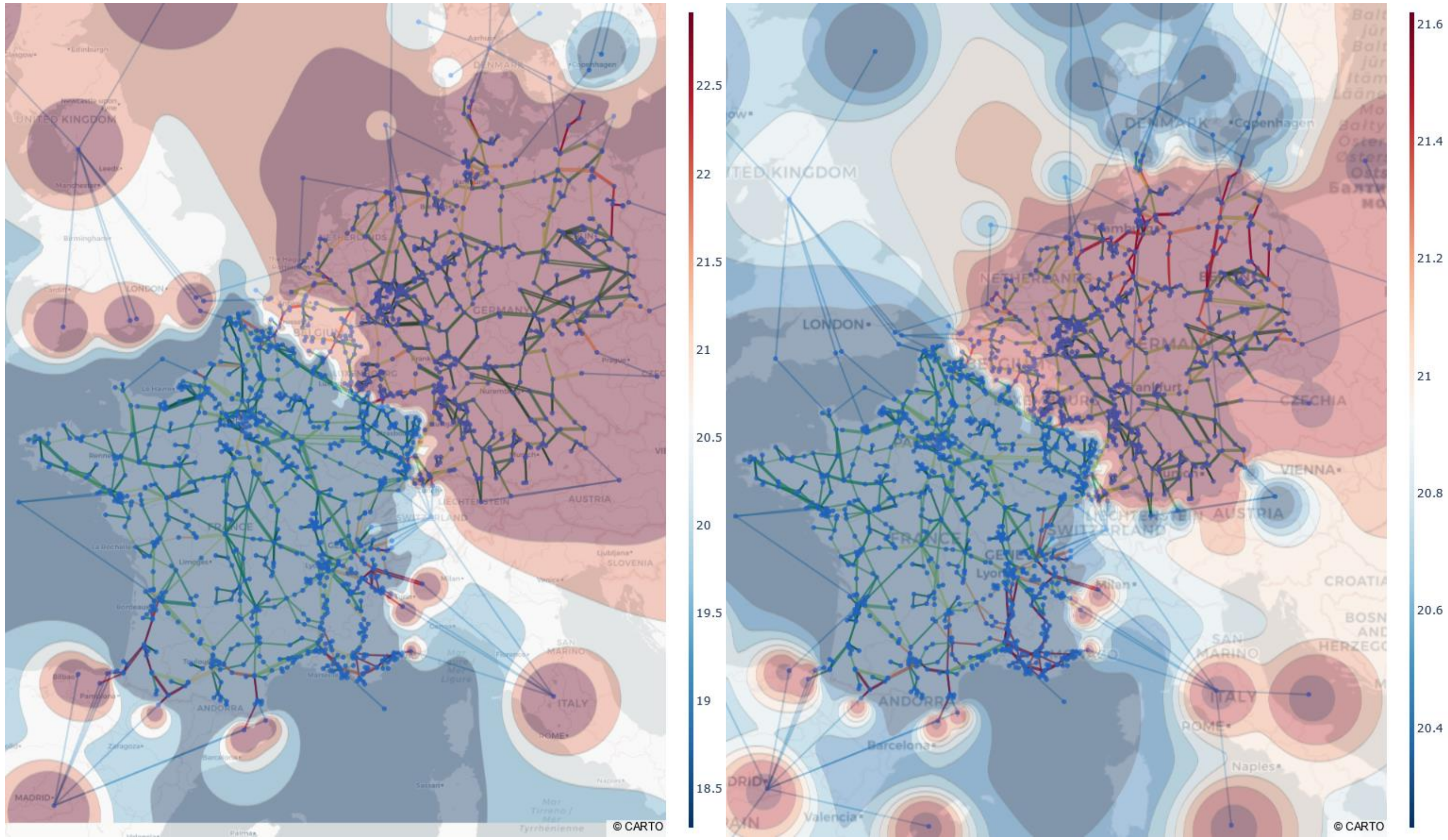
Results: Exchange



- FBMC is more restrictive compared to the NTC solution
  - Indicated by the higher cost in D-1 market result
  - …which is always outweighed by lower redispatch costs.
- We can confirm generally higher commercial exchange in the D-1 market result with the NTC solution.
- Note the change in range of values in 2030.

Results: Shadow Price NTC I

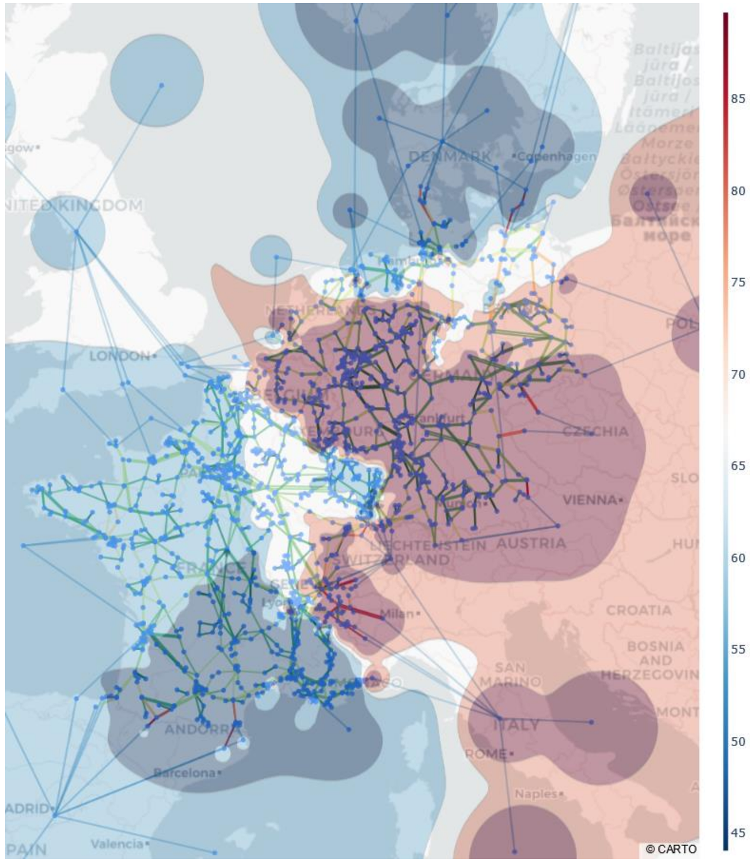
NTC (Market Result): 2020 (left) – 2030 (right)

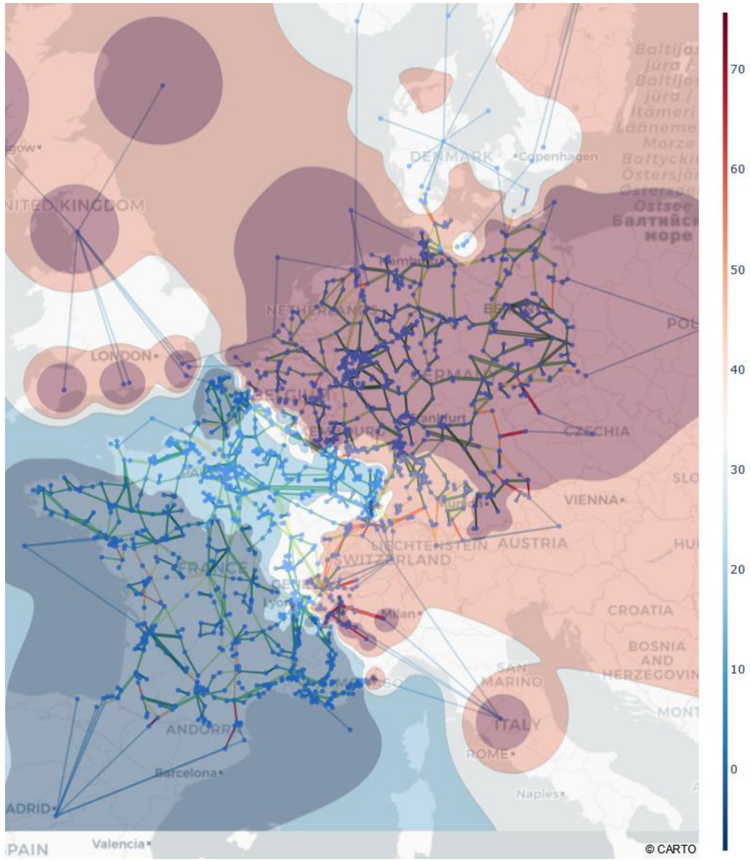


- FBMC is more restrictive compared to the NTC solution
  - Indicated by the higher cost in D-1 market result
  - …which is always outweighed by lower redispatch costs.
- We can see similar effects when looking into the dual price at D-1 market clearing stage and D-0 redispatch.
- Here we see little price differences in the market clearing stage, so a high price convergence.

Results: Shadow Price NTC II

NTC (Redispatch Result): 2020 (left) – 2030 (right)





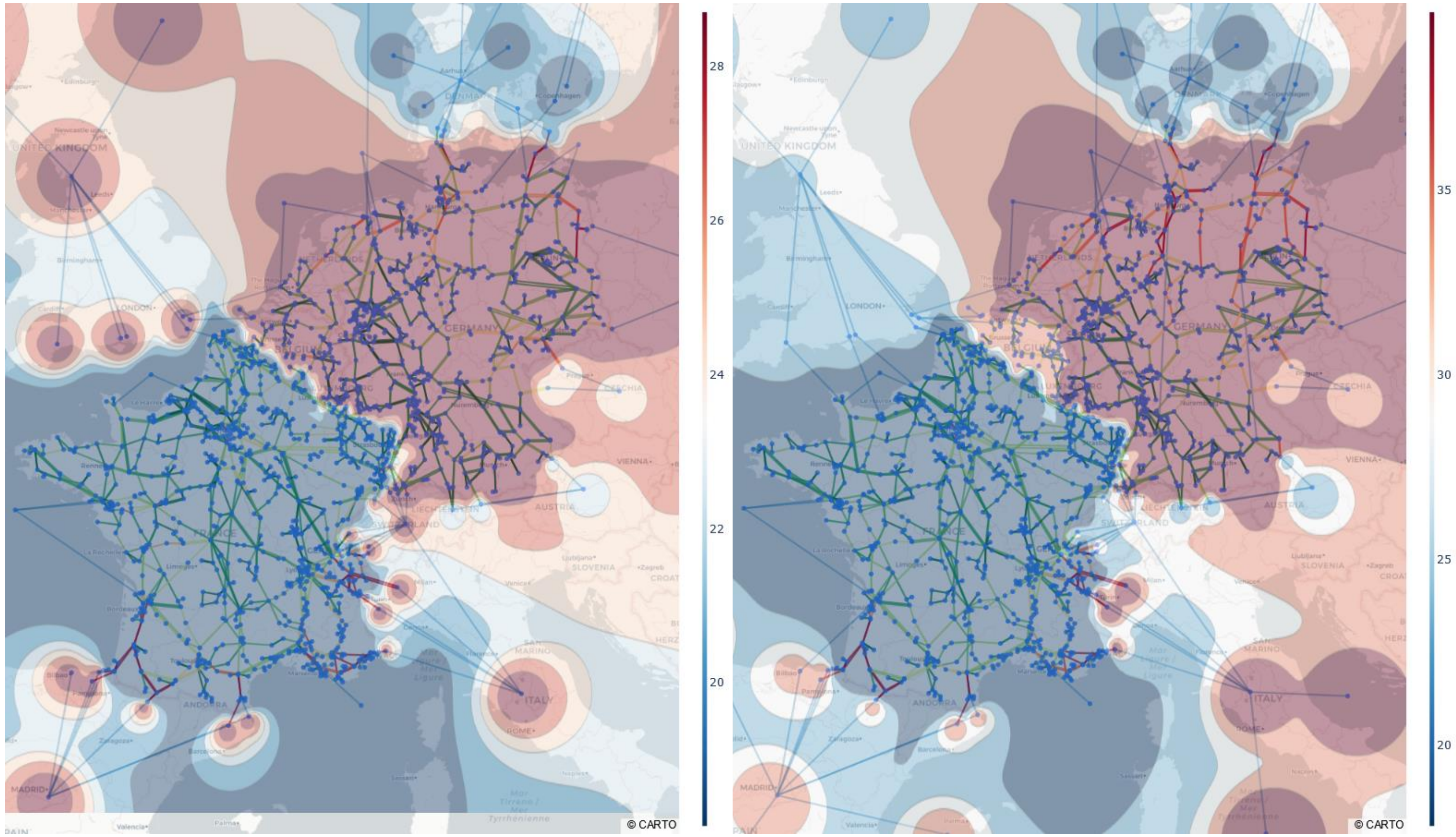
- FBMC is more restrictive compared to the NTC solution
  - Indicated by the higher cost in D-1 market result
  - …which is always outweighed by lower redispatch costs.

- We can see similar effects when looking into the dual price at D-1 market clearing stage and D-0 redispatch.

- Here we see little price differences in the market clearing stage, so a high price convergence.
- but due to high volume of redispatch the shadow price diverges in D-0.

Results: Shadow Price FBMC II

FBMC – 40% minRAM (Market Result): 2020 (left) – 2030 (right)



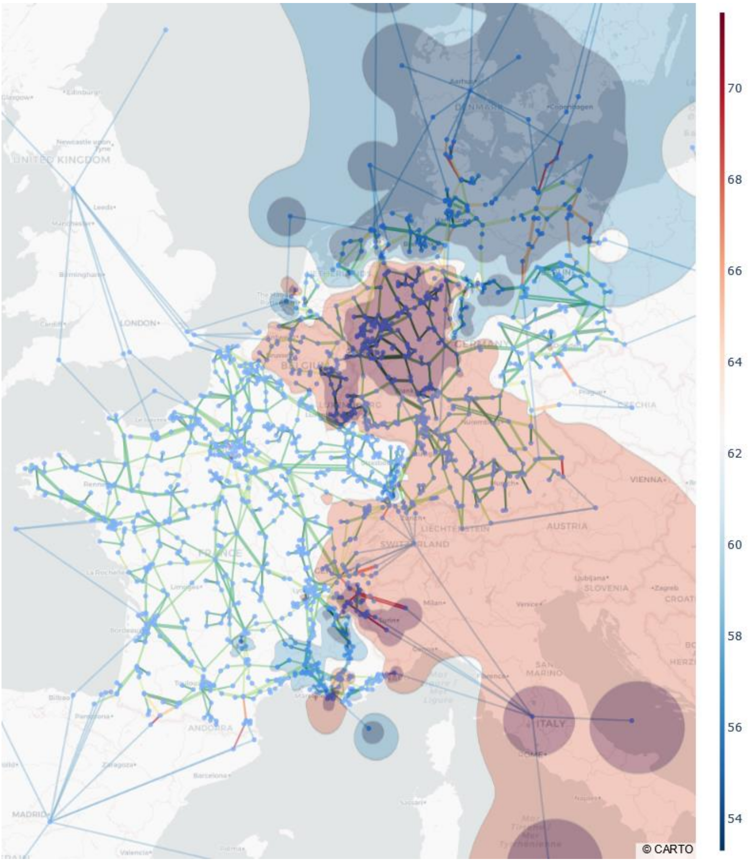
- FBMC is more restrictive compared to the NTC solution
  - Indicated by the higher cost in D-1 market result
  - …which is always outweighed by lower redispatch costs.

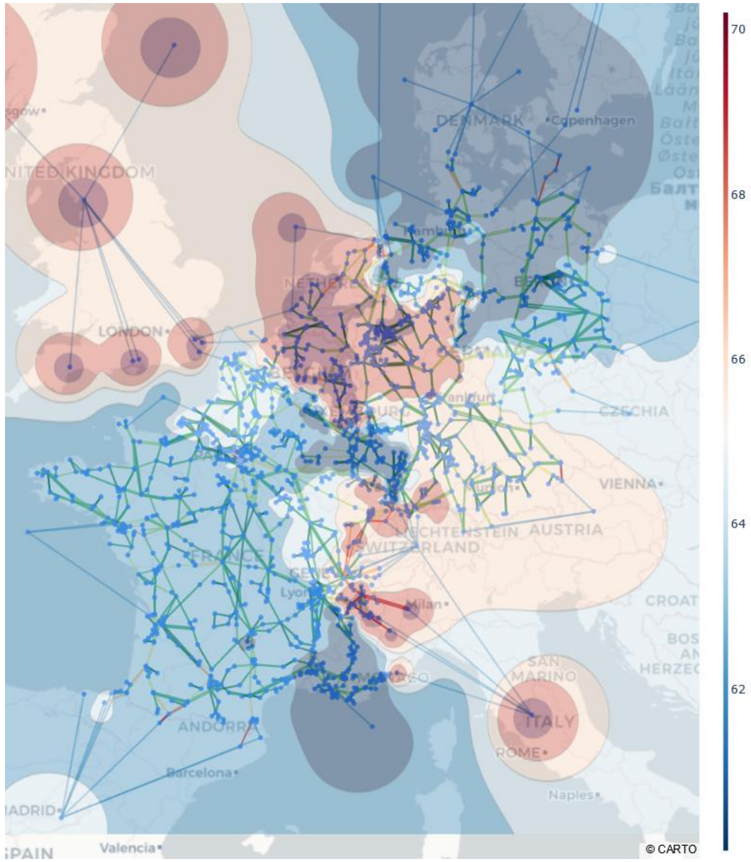
- We can see similar effects when looking into the dual price at D-1 market clearing stage and D-0 redispatch.

- For the 40% minRAM we see a lower price convergence in D-1

Results: Shadow Price FBMC II

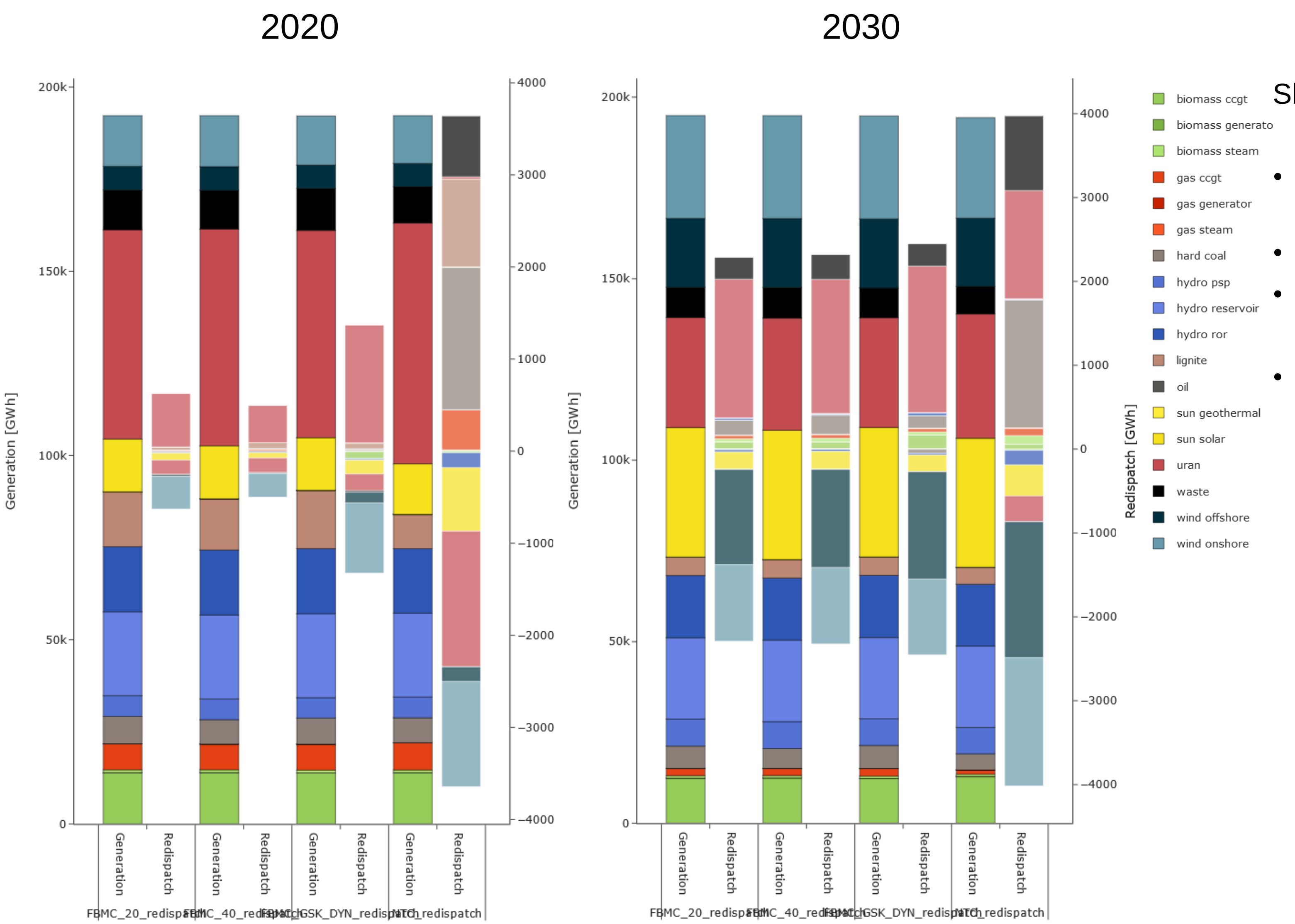
FBMC – 40% minRAM (Redispatch Result): 2020 (left) – 2030 (right)





- FBMC is more restrictive compared to the NTC solution
  - Indicated by the higher cost in D-1 market result
  - …which is always outweighed by lower redispatch costs.
- We can see similar effects when looking into the dual price at D-1 market clearing stage and D-0 redispatch.
- For the 40% minRAM we see a lower price convergence in D-1
- … but lower shadow prices in D-0 and smaller range of prices between region.
- Valid for both 2020 and 2030.

Results: Re-Dispatch I



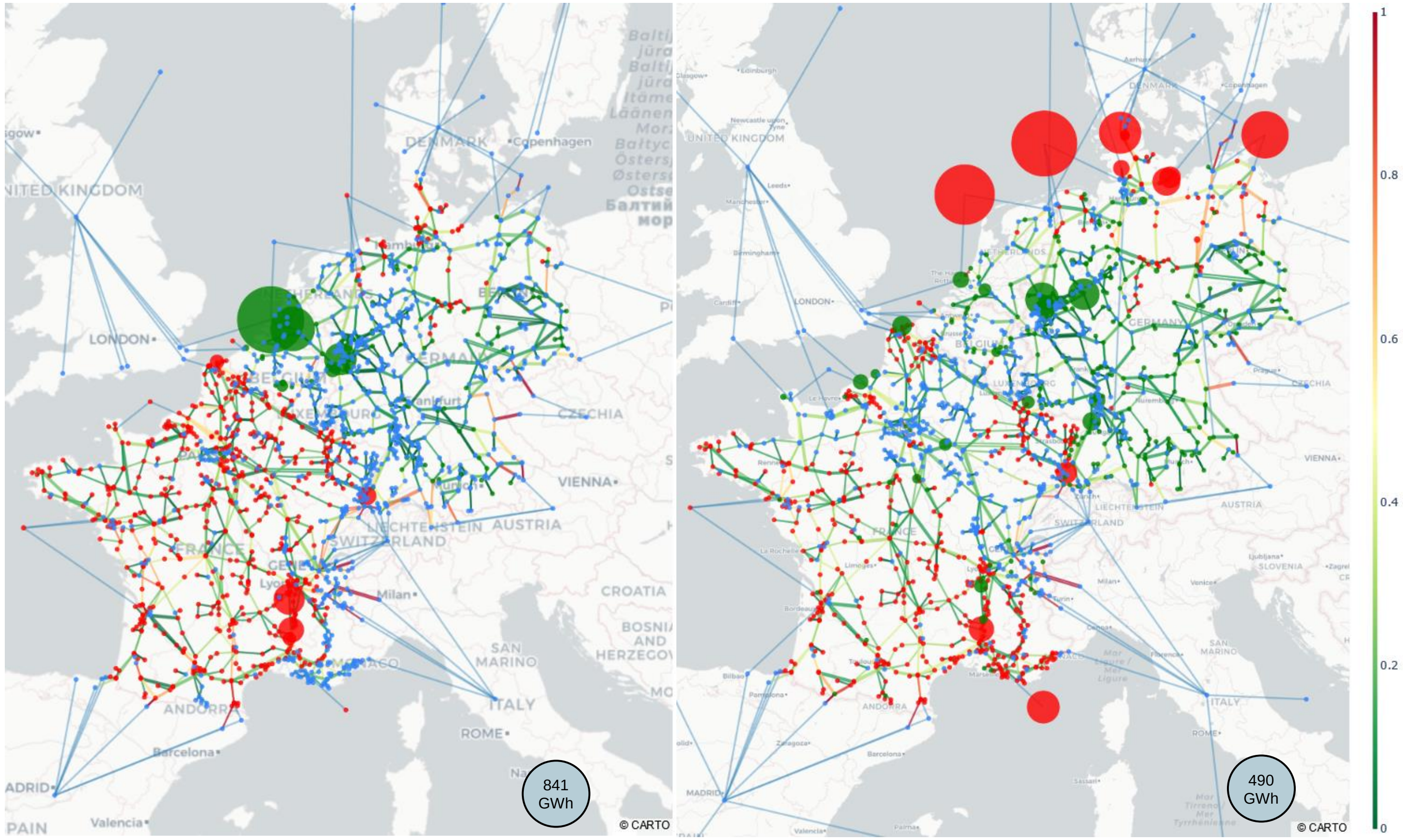
Share of RES is around 50% for 2020 and 70% in 2030

- Negative redispatch is mostly composed of intermittent generation (solely in 2030)
- Positive redispatch follows the merit order
- More redispatch > less integration of renewables

- Redispatch quantity constant in the NTC scenario

Results: Re-Dispatch II

NTC: 2020 (left) – 2030 (right)



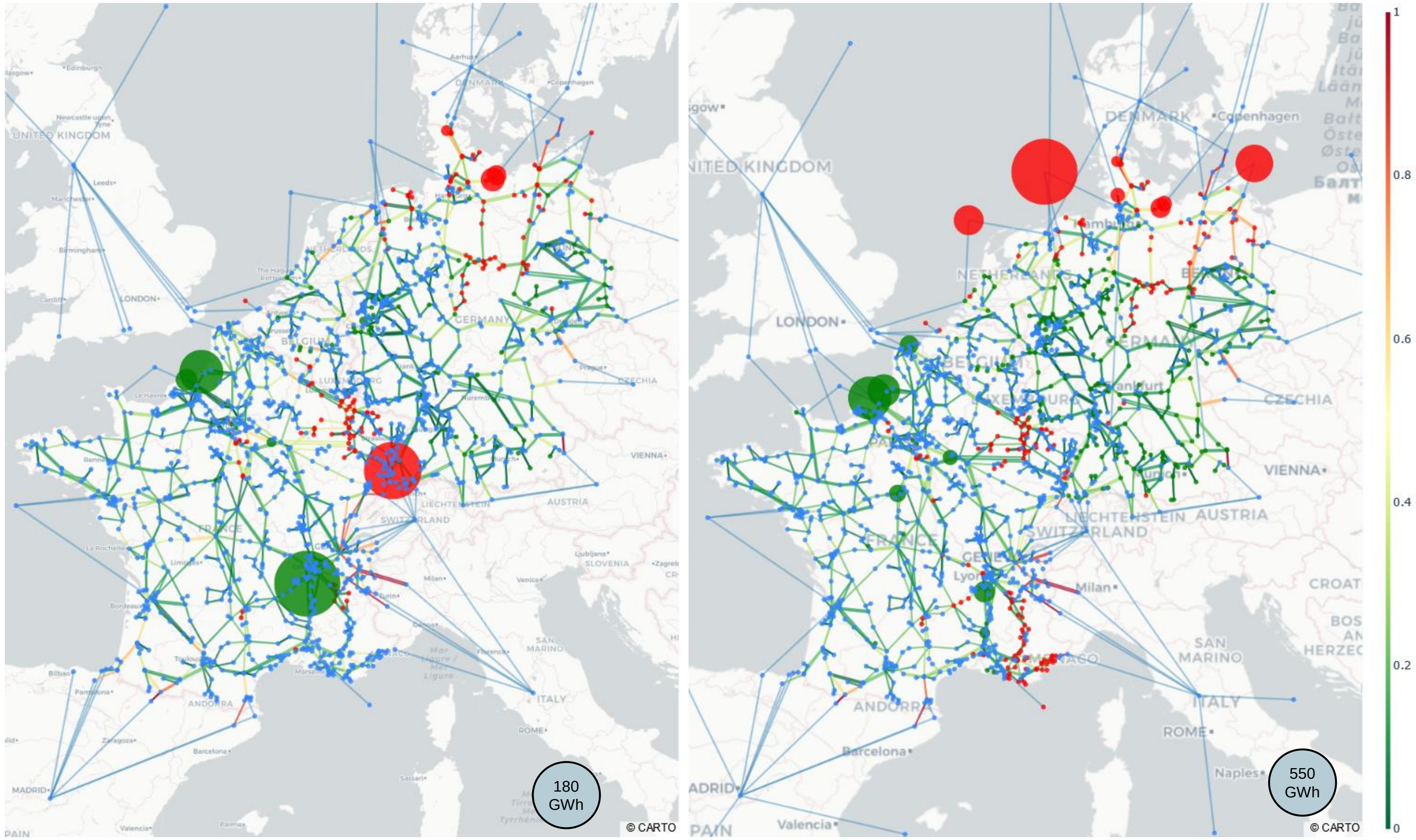
Share of RES is around 50% for 2020 and 70% in 2030

- Negative redispatch is mostly composed of intermittent generation (solely in 2030)
- Positive redispatch follows the merit order
- More redispatch > less integration of renewables

- Redispatch quantity constant in the NTC scenario
- .. but very different pattern

Results: Re-Dispatch III

FBMC 40% - minRam: 2020 (left) – 2030 (right)



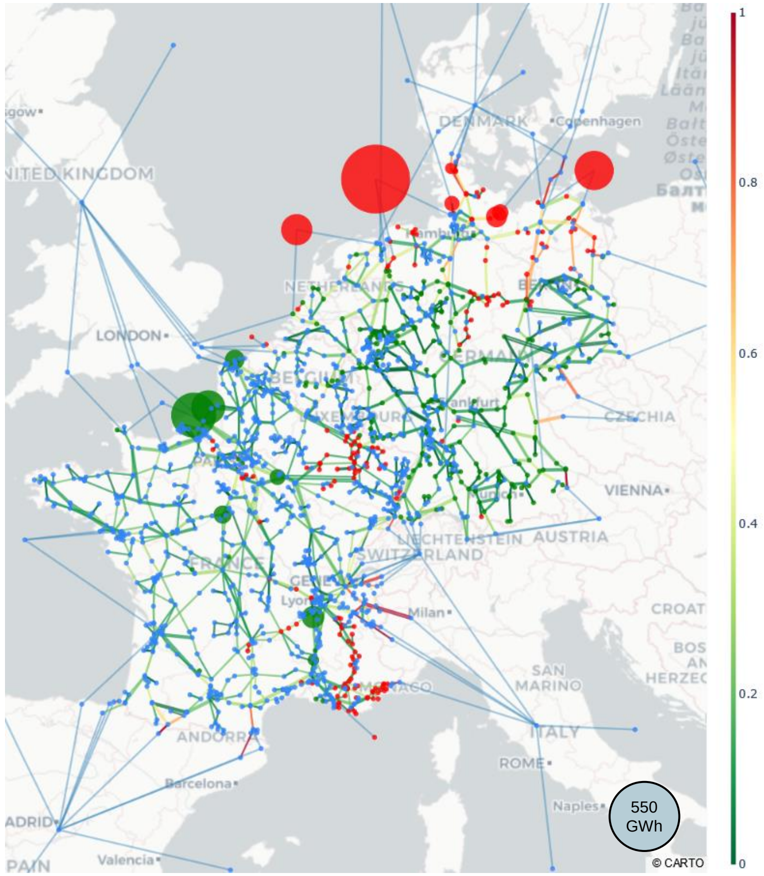
Share of RES is around 50% for 2020 and 70% in 2030

- Negative redispatch is mostly composed of intermittent generation (solely in 2030)
- Positive redispatch follows the merit order
- More redispatch > less integration of renewables

- Redispatch quantity constant in the NTC scenario
- .. but very different pattern

- For the FB 40%minRAM scenario, the pattern remains similar, but quantities change.

Conclusions



Restrictiveness/permissiveness of commercial exchange domains is central to effectiveness of capacity allocation and congestion management in zonal electricity markets.

In these examples FB parametrization was more restrictive than the reference NTC parametrization.

This resulted in (compared to the NTC reference):

- higher costs in the D-1 market clearing
- overall lower costs, due to less congestion management.

This effect can be seen in the resulting commercial exchange and resulting lower price* convergence in the market clearing stage but higher price convergence in D-0

The *regional* differences can be seen regarding prices* and redispatch patterns.

Outlook:

The question regarding a “good” NTC or FB parametrization remains.

Rolling horizon market clearing allows to run this model on modest hardware (!= HPC)

- suboptimal solutions, specifically regarding hydro reservoirs.

Further parametrization of input data: line expansion, conventional capacities, demand from additional sectors….

Full year results

*Model-endogenous shadow prices, only distant relatative to actual spot market prices.

Thank you for your attention!

POMATO - Power Market Tool

Main Branch: Python package passing | codecov 90%

Construction Branch: Python package passing | codecov 92%

Documentation Status: docs passing

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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.

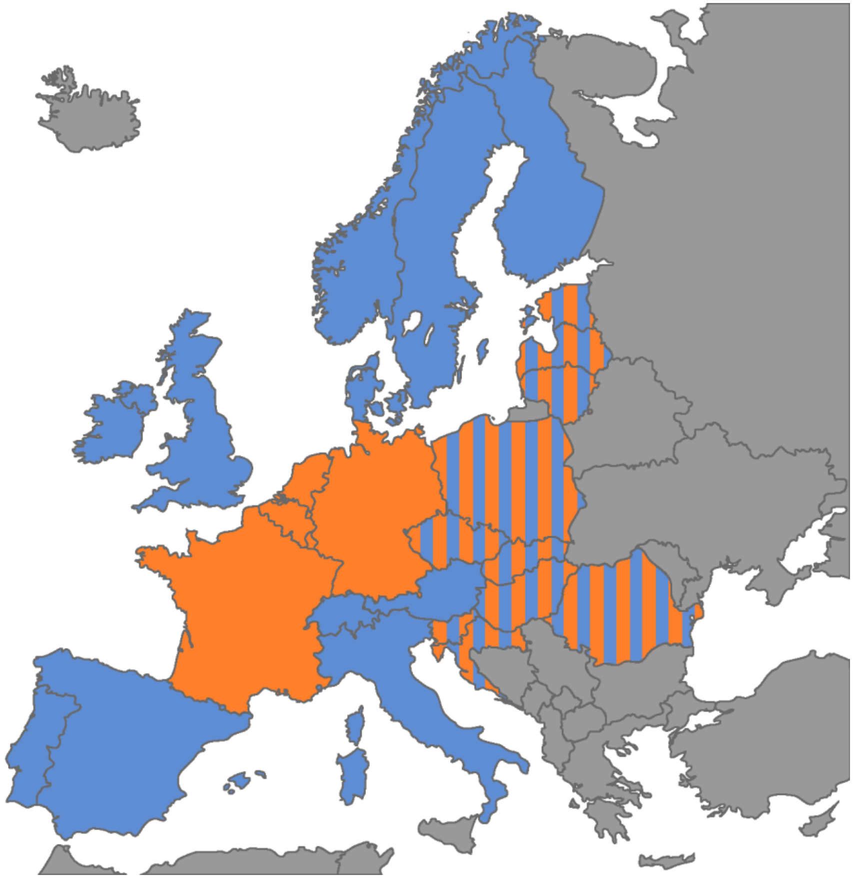
R. Weinhold und R. Mieth, „Fast Security-Constrained Optimal Power Flow through Low-Impact and Redundancy Screening", *IEEE Transactions on Power Systems*, 2020.

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.

MODEZEEN

Danish Energy Agency

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.

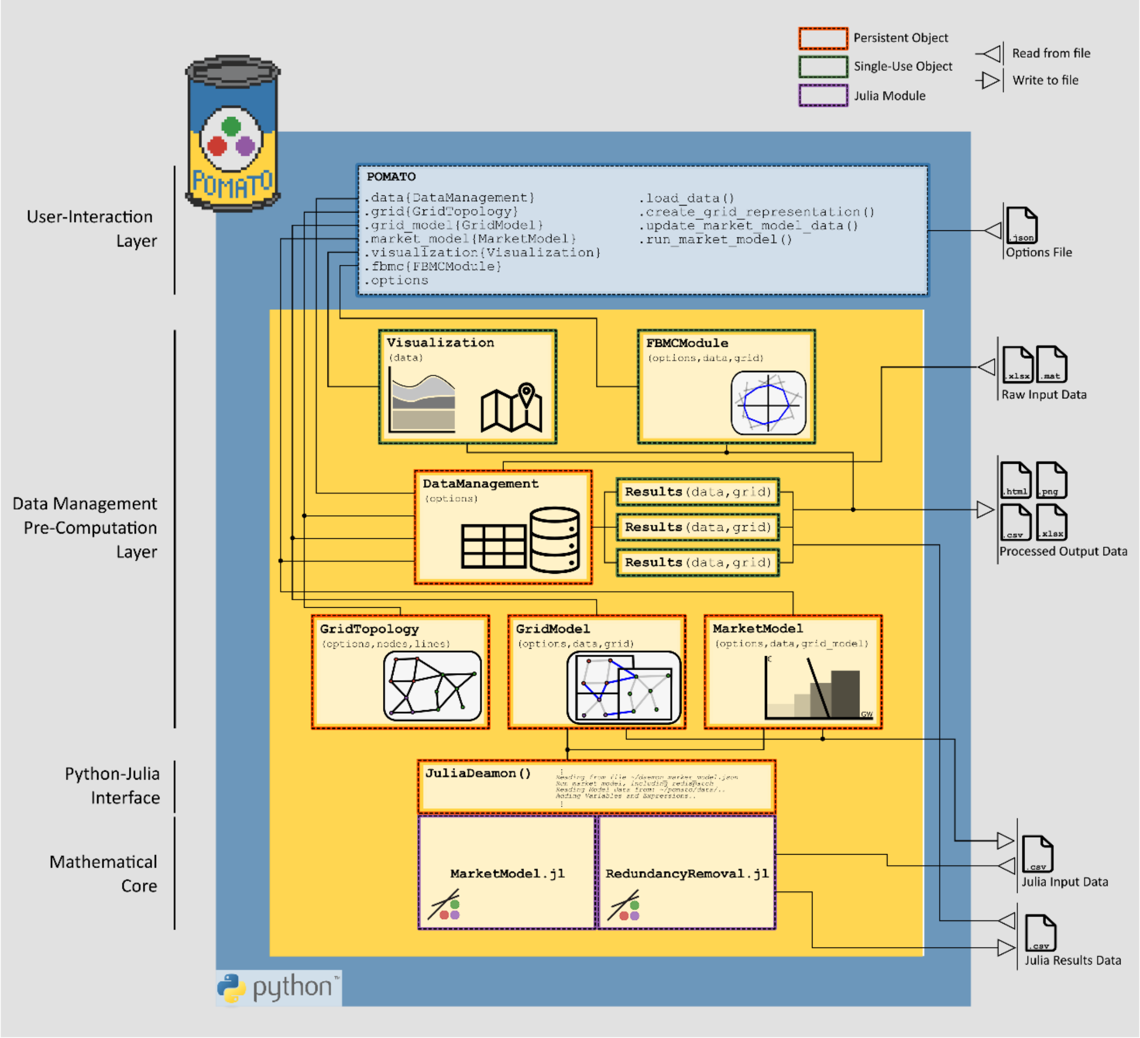
POMATO I: Description of POMATO

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.

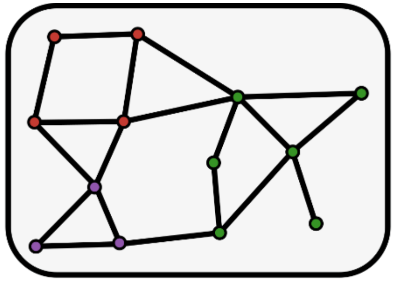
- (1b) – (1g) are activated and parametrized by POMATO "on the fly" based on user-defined options
- Definitions of balance (1f) and network constraints (1g) effectively characterize the modeled market:
- Nodal Markets:
  - Enforces an energy balance in for each node.
  - Exchanges are limited by physical 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.

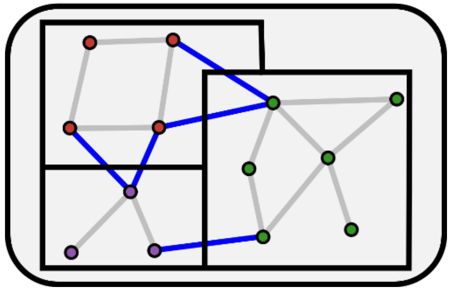
- Additionally, constraints to model CM (redispatch)
- System security requirements based on contingency (N-1) analyses and enforced through a suitable extensions of zonal and nodal PTDF matrices

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

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.

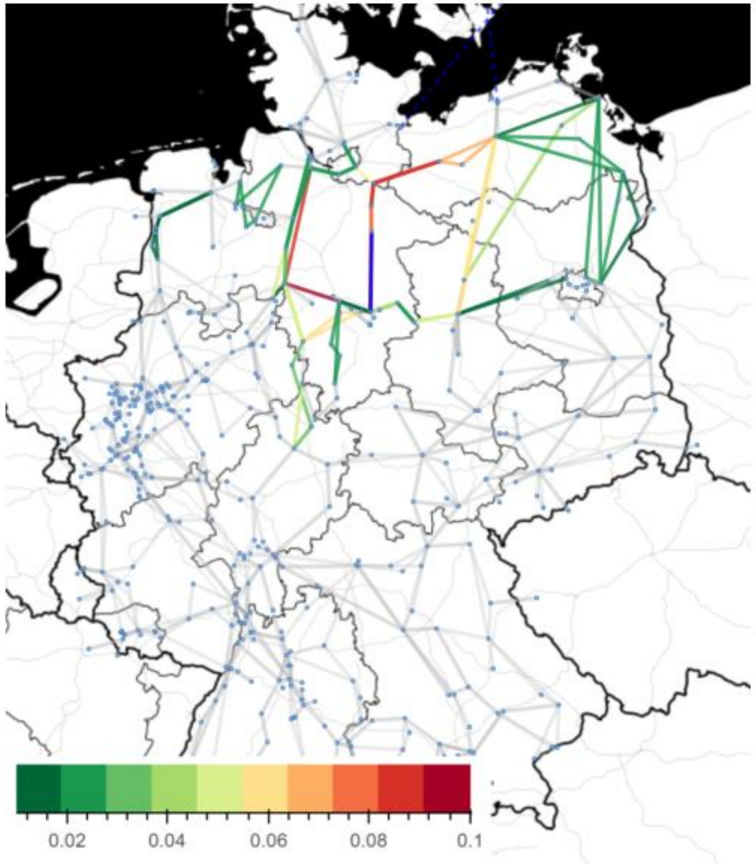


Fig. 5. Impact of outages towards the highlighted (blue) line; Grey lines indicate a sensitivity of less than 1 %.

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