

Multi-Market Coupling Model: A Residual Demand Approach

ENERDAY 2025, Dresden

Tobias Kargus, Marliese Uhrig-Homburg | April 04, 2025

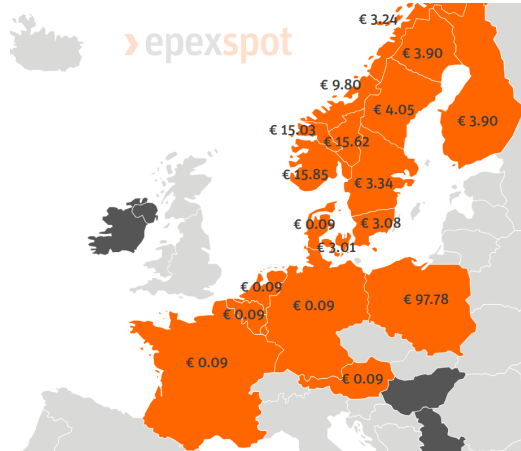
Agenda

1. Introduction
 - 1.1 Integrated European electricity market
 - 1.2 Residual demand
 - 1.3 Market coupling in the literature
2. Multi-Market Coupling Model
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 - 2.2 Two bidding zones with interconnector
 - 2.3 CWE bidding zones with interconnectors
3. Empirical analysis
 - 3.1 Model performance
 - 3.2 Expansion and price dynamics
4. Conclusion

Slides accessible under:



Integrated European electricity market



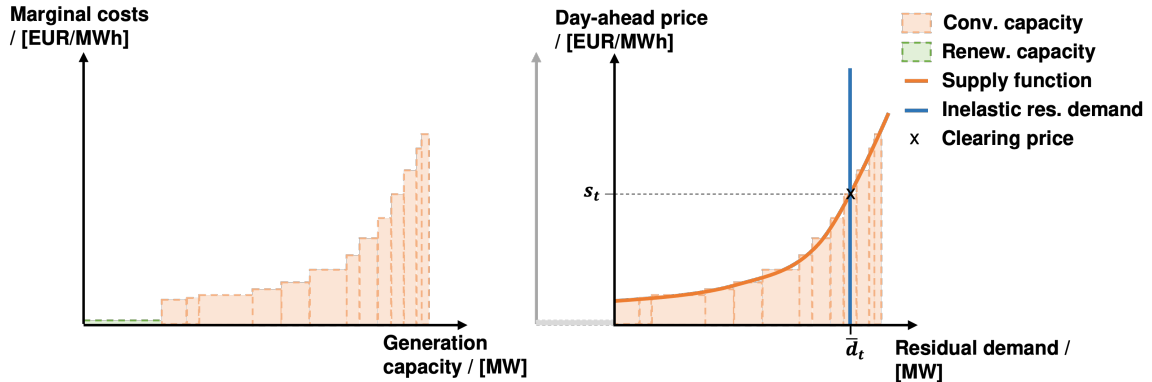
Day-ahead prices for delivery at March 30, 2025 05:00-06:00 from EPEX Spot (2025).

- One integrated European electricity market
- Groupwise convergences of bidding zones
- Flow-based Market Coupling (FBMC)
- Expansion of interconnection capacity

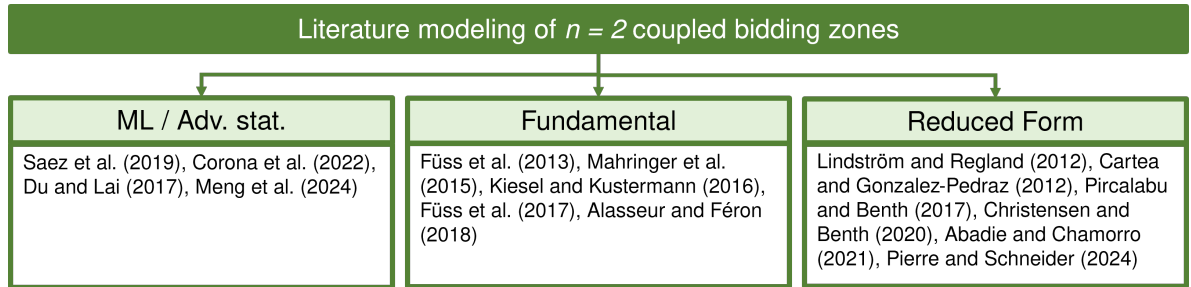
Research Questions:

How can we integrate FBMC in a residual demand framework to predict day-ahead prices in a mid-term horizon?

Residual demand



Market Coupling in the literature



- Models partially covering $n > 2$ bidding zones: Kiesel and Kusterman (2016), Bjørndal et al. (2018), Meng et al. (2024)

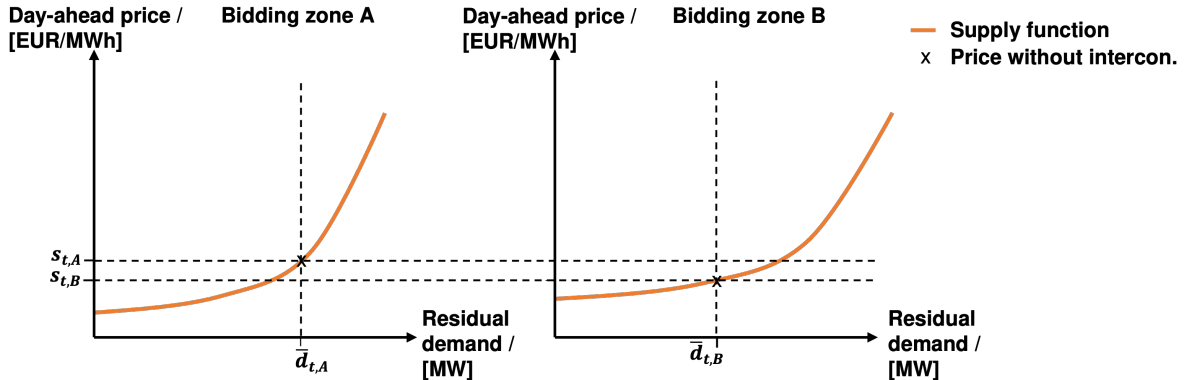
Two bidding zones without interconnector (1/2)

- Grid model:



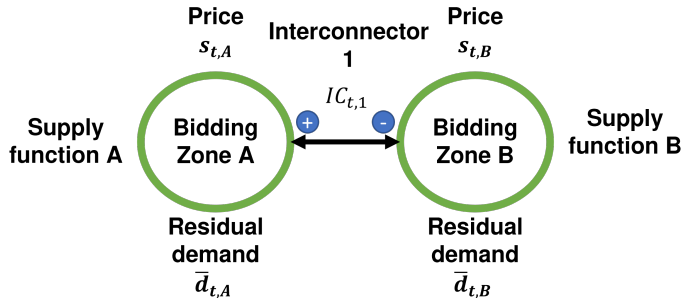
- Modeling supply functions of each bidding zone $i \in N = \{A, B\}$

Two bidding zones without interconnector (2/2)



Two bidding zones with interconnector (1/2)

- Grid model:



- Modeling supply functions of each bidding zone $i \in N = \{A, B\}$ correcting for $IC_{t,k} \forall k \in K = \{1\}$:
- Determining $IC_{t,1}$:
→ Optimization criterion
- Integrating interconnector limits
→ Side restrictions

Notation:

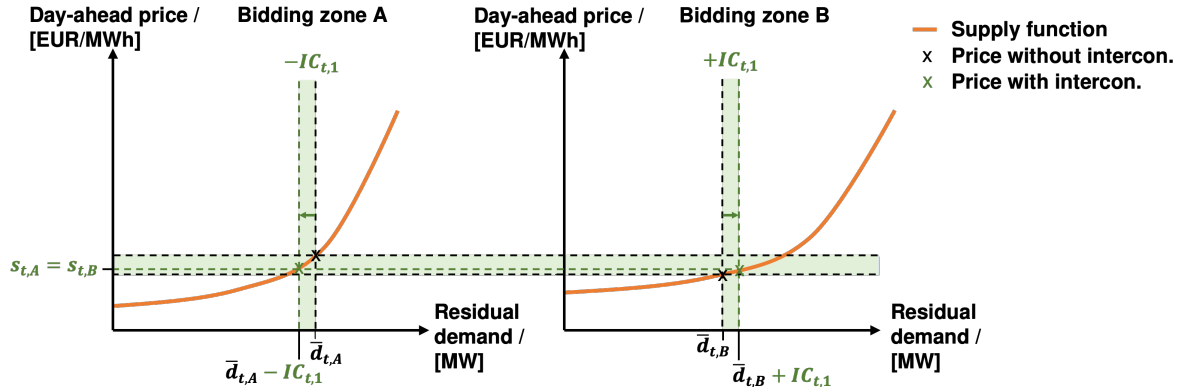
IC_t :

Interconnector flow at hour t

K :

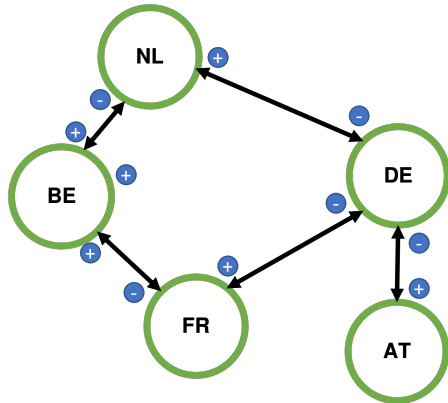
Set of all interconnectors

Two bidding zones with interconnector (2/2)



CWE bidding zones with interconnectors

- Grid model:



- Modeling supply functions of each bidding zone $i \in N = \{DE, FR, BE, NL, AT\}$ correcting for $IC_{t,k} \forall k \in K = \{1, \dots, 5\}$:
- Determining $IC_{t,k} \forall k \in K = \{1, \dots, 5\}$
 → Minimizing Total System Costs (TSK):

$$\min \sum_{i \in N} TSK_i$$
- Integrating interconnector limits
 → Remaining Available Margins (RAM)

$$RAM_{t,k}^{OPP} \leq IC_{t,k} \leq RAM_{k,1}^{DIR}$$

Notation:

DIR: Direction with pos. intercon. flow
OPP: Direction with neg. intercon. flow

Model performance

| Bidding zone | R^2_{pseudo} | | MAE | | RMSE | | \bar{s}_t |
|--------------|----------------|----------|-------|----------|-------|----------|-------------|
| | inter | no inter | inter | no inter | inter | no inter | obs |
| DE | 0.87 | 0.85 | 18.46 | 20.17 | 26.96 | 28.46 | 97.06 |
| FR | 0.91 | 0.90 | 18.36 | 19.13 | 25.89 | 26.63 | 109.31 |
| BE | 0.87 | 0.85 | 19.77 | 21.35 | 29.38 | 31.23 | 104.11 |
| NL | 0.86 | 0.80 | 19.45 | 22.92 | 28.51 | 33.95 | 102.92 |
| AT | 0.85 | 0.81 | 19.69 | 22.30 | 32.32 | 42.95 | 107.15 |
| All | 0.87 | 0.85 | 19.15 | 21.18 | 28.70 | 31.47 | 104.11 |

Table: Evaluation of the in-sample estimation with hourly data from January 01, 2021 to January 31, 2022, $T = 8240$.
Termination: $\Delta MAE < 0.01$

Expansion and price dynamics

- RAM extension of 1000 MW
- Base case: model without extension

| Interconnector | AT-DE | BE-FR | BE-NL | DE-FR | DE-NL |
|------------------------------|--------|--------|--------|--------|--------|
| $\Delta\mu(\hat{S}_{DE})$ | +0.41% | +0.44% | +0.31% | +1.09% | +0.64% |
| $\Delta\sigma(\hat{S}_{DE})$ | +0.26% | +1.44% | +0.69% | +2.23% | +0.68% |
| $\Delta\mu(\hat{S}_{FR})$ | +0.03% | -0.63% | -0.05% | -0.86% | -0.11% |
| $\Delta\sigma(\hat{S}_{FR})$ | +0.39% | -2.11% | +0.40% | -2.32% | +0.47% |
| $\Delta\mu(\hat{S}_{BE})$ | +0.23% | +1.69% | -0.33% | +0.26% | -0.16% |
| $\Delta\sigma(\hat{S}_{BE})$ | +1.56% | +7.46% | +0.12% | +2.67% | +1.51% |
| $\Delta\mu(\hat{S}_{NL})$ | +0.17% | +0.60% | +0.27% | +0.37% | -0.42% |
| $\Delta\sigma(\hat{S}_{NL})$ | +1.06% | +2.32% | +1.44% | +2.63% | +0.85% |
| $\Delta\mu(\hat{S}_{AT})$ | -1.00% | -0.33% | -0.47% | +0.14% | -0.28% |
| $\Delta\sigma(\hat{S}_{AT})$ | +1.32% | +1.94% | +1.19% | +2.88% | +1.25% |

Table: Changes of price dynamics due to RAM expansions

Conclusion

Contribution:

- Involving more than two bidding zones in market coupling model with interconnector capacities
- Using FBMC parameters to model day-ahead prices (grid dimension)
- Insights of interconnector expansions on price dynamics

Outlook:

- Bidding zones beyond CWE (after June 2022)
- Further benchmarking with literature (e.g. Pircalabu and Benth (2017))
- Valuation of interconnectors and the cannibalization after an expansion

Thank you for your attention

Tobias Kargus

Mail: tobias.kargus@kit.edu



Working Paper

Multi-Market Coupling Model



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Nomenclature and Abbreviations

| Symbol | Description |
|----------------|--|
| μ | Mean |
| σ | Volatility |
| A | Bidding zone A |
| B | Bidding zone B |
| \bar{d} | Residual demand |
| i | Specific bidding zone |
| IC_t | Interconnector flow at hour t |
| j | Specific bidding zone |
| K | Set of all interconnectors |
| k | Specific interconnector |
| N | Set of all bidding zones |
| n | Number of bidding zones |
| p_{gas} | Spot price for gas |
| p_{oil} | Spot price for oil |
| R_{pseudo}^2 | Coefficient of determination defined for non-linear fittings |
| s | Day-ahead electricity price |
| \hat{s} | Estimated day-ahead electricity price |
| t | Hour |
| T | Number of all hourly observations |

| Symbol | Description |
|------------|---|
| Adv. stat. | Advanced statistical models |
| AT | Austrian bidding zone |
| BE | Belgian bidding zone |
| CWE | Central Western Europe |
| DA | Day-ahead |
| DE | German bidding zone |
| DIR | Direction with positive interconnector flow |
| ENTSO-E | European Network of Transmission System Operators for Electricity |
| EUPHEMIA | Pan-European Hybrid Electricity Market Integration Algorithm |
| FBMC | Flow-based market coupling |
| FR | French bidding zone |
| IC | Interconnector |
| inter | Interconnectors / market coupling considered |
| MAE | Mean absolute error |
| ML | Machine Learning |
| NL | Dutch bidding zone |
| no inter | Interconnectors / market coupling not considered |
| OPP | Direction with negative interconnector flow |
| RAM | Remaining Available Margin |
| RMSE | Root-mean-square-error |
| TSO | Transmission System Operator |

| Model Component | Time | Source | Note |
|-----------------------|----------------------------|----------------|--|
| Day-ahead spot prices | Jan 1, 2021 - Jan 31, 2022 | ENTSO-E (2025) | hourly, ex post (realized prices) |
| Demand | Jan 1, 2021 - Jan 31, 2022 | ENTSO-E (2025) | hourly, ex ante (day-ahead forecast) |
| PV infeed | Jan 1, 2021 - Jan 31, 2022 | ENTSO-E (2025) | hourly, ex ante (day-ahead forecast) |
| Wind generation | Jan 1, 2021 - Jan 31, 2022 | ENTSO-E (2025) | hourly, ex ante (day-ahead forecast) |
| Oil price | Jan 1, 2021 - Jan 31, 2022 | Reuters (2025) | Closing price ICE Europe Brent Crude Electronic Future ("LCOc1"), (one day offset, mixed frequency) |
| Gas price | Jan 1, 2021 - Jan 31, 2022 | Reuters (2025) | Closing price TRPC Nartural Gas TTF Day 1 ("TRNLTTFD1"), (one day offset, mixed frequency) |
| RAM | Jan 1, 2021 - Jan 31, 2022 | JAO (2025) | hourly, base case, virgin domain, seasonal model, ex ante (day-ahead forecast) |