Flow-Based Market Coupling: Insights from Current Market Data and Theoretical Benchmarking

Dimitrios Glynos
Chair of Energy Economics
TU Dresden
Dresden, Germany
dimitrios.glynos@tu-dresden.de

Dominik Möst
Chair of Energy Economics
TU Dresden
Dresden, Germany
dominik.moest@tu-dresden.de

Andreas Büttner
Chair of Energy Economics
TU Dresden
Dresden, Germany
andreas.buettner@tu-dresden.de

***Abstract*—The European Union's decarbonisation strategy emphasizes the full integration of its electricity markets to enhance flexibility, competition, and overall efficiency. This study compares the existing Flow-Based Market Coupling (FBMC) mechanism with a theoretical model that incorporates all grid restrictions endogenously in the market clearing, avoiding heuristic assumptions. We address two primary research questions: how would market outcomes, prices, and the generation mix evolve under perfect market coupling, and what challenges persist in the current FBMC design? A three-month case study during the European energy crisis in 2023 provides the empirical basis. Our results reveal significant price convergence—with average prices decreasing by nearly 30 €/MWh—improved integration of renewable energy sources, and enhanced cross-border trade. However, the simplified grid representation to reduce the complexity of the problem may lead to congestion and welfare losses, underscoring the need for more efficient models and more active consideration of congestion management in the cross-border capacity allocation in the integrated European electricity market.**

***Index Terms*—flow based market coupling, electricity market, linear optimization**

I. Introduction

The full integration of European electricity markets is a pillar of the EU's decarbonization strategy. A unified market enhances both economic efficiency and security of supply by enabling better cross-border coordination, improved use of system flexibility, and more efficient integration of renewable energy sources (RES). The complementary generation profiles of RES across Europe help mitigate domestic volatility, while broader market access promotes competition, cost efficiency, and welfare gains. In addition, as prices converge and the market becomes more resilient to fluctuations and disturbances, overall security of supply is strengthened. However, limited cross-zonal capacity remains a major barrier to realizing the full benefits of market coupling [1].

In an attempt to improve cross-border trading by better reflecting grid constraints Flow-Based Market Coupling (FBMC) was introduced under the Capacity Allocation and Congestion Management (CACM) Regulation (EU) 2015/1222 [2]. However, the complexity of the problem of maximizing market welfare while respecting network constraints requires simplifications and assumptions in order to be solvable [3]. While it improves on earlier approaches, FBMC—and zonal market designs more broadly—face this fundamental trade-off: either trading capacities are too tight, limiting welfare, or too loose, causing grid congestion. This paper addresses these methodological limitations by introducing a more integrated zonal market design. To illustrate its implications, we apply it to a case study of the first months of 2023 during the European energy crisis. This allows us to highlight how deeper integration could have influenced market outcomes during a period of extreme stress—affecting prices, generation mix, distributional effects, and overall welfare. Our analysis is guided by two primary research questions:

- How would market outcomes, prices, and the generation mix evolve under a scenario of enhanced FBMC with better coupling of the European electricity markets? What benefits would a zonal market design with increased coupling have provided during the European energy crisis?
- Which challenges in achieving this idealized market persist, and how can the current market design be improved?

The next section introduces the modeling approach, scenario setup, and key differences between the current FBMC and the proposed model. This is followed by a case study analysis assessing the effects of deeper integration. Finally, we discuss the distribution effects between the countries and the implementation challenges of the proposed model.

II. Methodology

In the current market design, Transmission System Operators (TSOs) define the flow-based trading domains during the pre-coupling phase [4]. This process relies on heuristic approximations, focusing on a limited number of Critical Network Elements with Contingencies (CNECs)—grid lines with high congestion risk—based on reference flows from a base case market outcome [5].

From these reference flows, TSOs compute the Remaining Available Margin (RAM) for each critical line, which determines the boundaries within which market coupling operates. A central part of this process is the use of Generation Shift Keys (GSKs), which distribute changes in a bidding zone's net position to individual generators. Combined with zonal Power Transfer Distribution Factors (PTDFs), they estimate the physical impact on the network of changes in a bidding zone's net position [6]. However, the dependence on assumed

GSKs and reference flows introduces a circularity in the parameter estimation [7]. All these assumptions can result in overly conservative capacity limits—ultimately reducing market efficiency or bad constrained market coupling causing grid congestion that needs to be addressed by -expensive-redispatch measures [3]. In the study, the FBMC process is modeled using the ELMOD-ELTRAMOD framework in [8]. The model reproduces the sequence of the actual FBMC pre-coupling steps: (1) calculating a base case market clearing to estimate grid flows, (2) selecting critical network elements, and (3) determining the remaining margins that constrain flow-based trading. The objective function for all models is expressed as total system cost minimization in (1).

$$\min TC = \sum_{t,z} (CG_{t,z} + CC_{t,z} + CI_{t,z}) \tag{1}$$

The total system cost is calculated as the sum of generation costs $CG_{t,z}$, costs of curtailing renewable generation $CC_{t,z}$, and dumping costs for constraint relaxation $CI_{t,z}$ over all time steps t and zones z.

The next section provides the model description for the current FBMC design and outlines how the proposed model for higher zonal integration differs from the current FBMC implementation.

A. ELMOD

ELMOD is a linearized power flow model of the European transmission grid with high spatial resolution and a comprehensive set of techno-economic constraints. The power flow is modeled with a DC-approximation [8]. For this study, we use the PTDF-based formulation. This formulation is chosen not for computational convenience, but because it allows us to explicitly derive from node to line PTDF_N the Zone-to-line PTDFs. The zonal PTDFs trace how changes in zonal net positions affect power flows on individual transmission lines in FBMC.

$$\text{LINE\_F}(t,l) = \sum_{n} \text{NOD\_INJ}(t,n) \cdot \text{PTDF}_N(l,n) \tag{2}$$

$$\sum_{n} \text{NOD\_INJ}(t,n) = 0 \tag{3}$$

The line flow (LINE_F) is calculated by weighting the nodal injection (NOD_INJ) of each node n with the node to line PTDF_N values. To move from nodal to zonal representation, GSKs are applied, defining how marginal changes in a zone's net position are allocated across generators. In the literature several strategies exist to allocate these shifts among generators within a zone [6], [9]. In the current paper we adopt a static, flat GSK approach. Under this strategy, each generator's nodal injection is set proportional to its share of the total installed capacity in the zone and remains constant over time. The model's detailed nodal resolution also allows for the calculation of locational marginal prices (LMPs), which correspond to the shadow price of the nodal balance in (4).

$$\begin{aligned} \text{G\_P}(t,n) - \text{NOD\_INJ}(t,n) - \text{CURT}(t,n) = \\ \text{dem}(t,n) + \text{STORAGE}(t,n) - \text{DUMP}(t,n) \end{aligned} \tag{4}$$

These LMPs reflect the cost of supplying the electricity demand in each node given by the parameter (dem), accounting for the dispatch on the node (G_P), the curtailment of renewable energy sources (CURT) and the storage activity of hydro power plants and batteries (STORAGE) under given physical constraints of the grid and technical constraints of the generation units. The solution of the model corresponds to a N-0 security criterion, where no transmission line is allowed to fail [10]. All lines where the electricity load exceeds a threshold of 70% of the thermal capacity of the line are considered as critical network elements and are selected as boundaries for the market coupling, according to the current methodology in the European Electricity Market [11].

B. ELTRAMOD FBMC

ELTRAMOD is a linear optimization model of the European electricity market that minimizes total system costs through cost-optimal dispatch of generation units based on marginal costs. Cross-zonal trade is constrained by the FBMC trade capacities, as well as technical and availability constraints of generation and storage units. The model replicates the actual market clearing cascade for the CORE region under perfect foresight. Cross-zonal trade is represented as deviations in the net position (ΔNP) from a base case. This base case corresponds to the nodal dispatch and grid flows calculated by ELMOD. Trade with non-FBMC countries is modeled using historical Net Transfer Capacities (NTC_E).

$$\text{PTDF}(t,l,z) = \sum_{n \in \mathcal{N}_z} \text{PTDF}_N(l,n) \cdot \text{GSK}(t,n,z) \tag{5}$$

$$\text{RAM}(l) \geq \sum_{z} \text{PTDF}(t,l,z) \cdot \Delta\text{NP}(t,z) \tag{6}$$

$$\begin{aligned} \text{G\_P}(t,z) - \Delta\text{NP}(t,z) - \text{NTC\_E}(t,z) = \\ \text{dem}(t,z) + \text{STORAGE}(t,z) - \text{DUMP}(t,z) \end{aligned} \tag{7}$$

Equation (7) represents the zonal power balance. Deviations from the base case net positions must stay within the limits defined by the RAM on the CNEs in (6), which reflect the system's operational security margin. These RAMs are derived from the nodal solution and reflect the 70% minimum capacity target set by the European Commission [11] ensuring sufficient residual transmission capacity for real-time operations (e.g., intraday and balancing markets) and congestion management.

The resulting zonal power transfers are translated into line flows via reduced zonal PTDFs (Equation (5)), which are calculated from nodal PTDFs (PTDF_N) using GSKs. These parameters define how changes in zonal net positions impact individual network elements — a key feature of the zonal approach and a critical source of inefficiency in approximating the actual grid constraints.

C. ELTRAMOD FBMC fundamental

In the enhanced FBMC model with higher zonal integration, no predefined trade capacity domains are used. Instead, within the FBMC region, trade between zones is constrained directly by the thermal capacity of the lines. To estimate the load on each line, the load flow decomposition uses the nodal-to-line PTDF_N as in (2) across all grid elements, rather than a subset as in the current FBMC approach. This allows for a more accurate representation of physical power flows and eliminates the need for heuristic approximations based on reference flows or Generation Shift Keys. The resulting nodal injection of the cost minimizing generation units dispatch respects the thermal capacity of the grid elements in the FBMC-regions and the change in the net position is not relative to a reference case.

Consequently, in equation (7) ΔNP is replaced with the net position (NP) as a decision variable in the market clearing, while all other parameters remain the same. Power generation is dispatched according to system-wide marginal costs, while fully respecting the physical line constraints of the transmission grid from (2), (3). The interconnector capacities for non-FBMC countries remain fixed at historical NTC levels, as in the current market design. With the endogenous consideration of the grid constraints in the optimization problem, the solver maximizes trade between FBMC zones and reduces total system costs, aiming for less restrictive market coupling as defined by the European Commission [1]. The expected outcome is higher price convergence within the FBMC region, improved integration of renewables, and more efficient use of cross-border flexibility. These effects are assessed in the results section to highlight the potential welfare gains from deeper market integration—especially under the stress conditions of the 2023 energy crisis.

However, this formulation also has limitations. The simplified representation of grid topology outside the FBMC region, combined with the joint optimization of FBMC and NTC countries, may underestimate the risk of congestion and overstate achievable welfare. In particular, the exclusion of internal grid constraints in non-FBMC countries and the static treatment of NTC values may lead to unrealistic dispatch results. This highlights the need for a more comprehensive approach that accounts for dynamic interactions between the different regions in Europe, including their grid constraints, as well as the consideration of the necessary capacities for redispatch in the market clearing [12].

III. Data

All techno-economic assumptions regarding generation units, fuel prices, grid topology, plant availability, and weather data for the simulation period are based on the dataset presented in [13]. The model includes a detailed representation of the German power plants, taking into account their spatial distribution and physical connection points to the electricity grid. This includes all substations at the 380 and 220 kV levels, as well as interconnectors with neighboring countries. In contrast, the national grids of other European countries and their interconnections are represented through aggregated nodes, which reduces the complexity of the model while still capturing the key dynamics of transnational power flows. The case study covers a three-and-a-half-month period during the European energy crisis in 2023. The simulation period is chosen for three reasons: (1) it allows for computational feasibility without requiring simplification techniques; (2) it aligns with the available, peer-reviewed reference data from the actual market clearing; and (3) the energy crisis context provides a particularly relevant setting for analyzing the effects of deeper market integration.

IV. Findings and evaluation metrics

This section presents the evaluation of the enhanced Flow-Based Market Coupling (FBMC) model, which explores the outcome of a higher zonal market integration and harmonization across Europe during the energy crisis in the first months of 2023. The key metrics assessed include price convergence, the generation mix, total welfare, and the impact on grid congestion given the structural limitations of zonal market designs, where overly restrictive trading capacities reduce welfare, while looser restrictions risk increased congestion.

A. Price Convergence and Reduction of Price Spikes

As described in [1], one of the direct effects of the deeper market integration is the significant price convergence observed within the FBMC region. On average, the electricity price across the region has fallen by almost €30/MWh in our case study. This convergence predominantly benefits Western European regions, where prices show substantial reductions of over -20% in the electricity price in the enhanced FBMC scenario. In contrast, Central and Eastern European countries, which initially had lower prices in the reference scenario, show electricity prices rise as a result of market coupling in fig. 1.

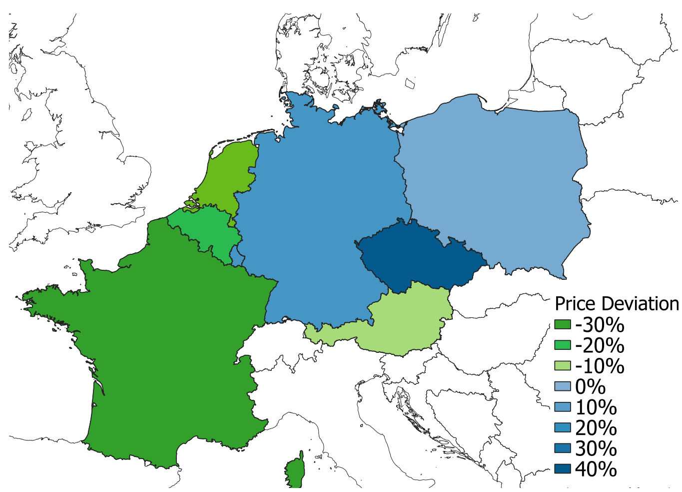

Fig. 1: Deviation of average electricity prices through deeper market integration in the selected countries of the FBMC-region

This shift reflects a reallocation of market benefits, aligning prices more closely with the cross-border marginal cost of generation. The integration also had a significant effect on the frequency and intensity of high-price episodes. Under the current market design, price spikes are often observed due to lower interconnection capacity for the market. These local scarcity situations, often intensified during times of crisis, could be significantly mitigated through a more flexible use of available cross-border capacity. The increased cross-border trade volumes, which nearly doubled in the enhanced FBMC design (see fig. 6), have drastically reduced the occurrence of such high prices in fig. 2 and lowered all price levels, as fig. 3 shows.

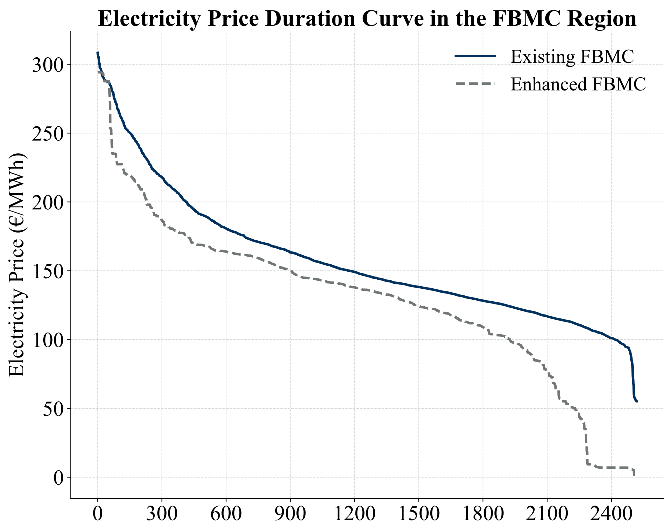

Fig. 2: Duration curve of the FBMC-models for the period from 01.01.2023 to 15.04.2023.

The frequency and intensity of the spikes of electricity prices above €250/MWh were particularly severe in the period analyzed. The increased use of cross-zonal flexibility could have mitigated this stress and reduced the potential for price extremes caused by local scarcity, as fig. 4 shows.

B. Generation Mix

Deeper market integration in the enhanced FBMC design leads to a more efficient dispatch of generation resources across Europe and higher integration of RES. In the selected FBMC region, the share of wind power increased from 32.8% to 35.2% of total generation, as a result of improved regional balancing and better alignment of renewable output with demand. Cross-border interconnection also facilitates greater use of flexible resources, particularly hydro storage, as demonstrated in the generation mix data in fig. 5. These capacities can be dispatched more strategically across zones, enabling surplus wind generation to be stored rather than curtailed. This integration helped reduce reliance on natural gas— the most expensive generation source during the crisis.

Overall generation in the FBMC region increased between the two designs by nearly 16 TWh, as the optimization model used renewable generation in the FBMC-region also

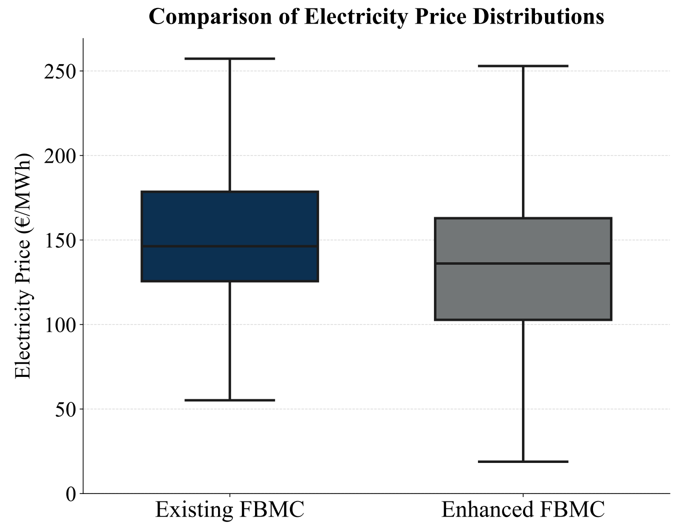

Fig. 3: Distribution of hourly prices in the period from 01.01.2023 to 15.04.2023. in the selected FBMC-region.

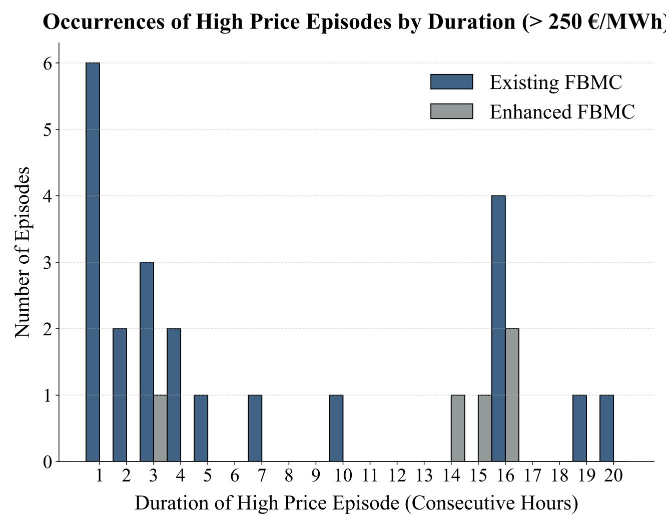

Fig. 4: Duration of the high price episodes in the period from 01.01.2023 to 15.04.2023.in the selected FBMC-region.

for supplying neighboring NTC countries with lower RES capacity.

C. Total Welfare: Price Drop and Trade Volumes

The deeper market integration and the resulting reduction in average electricity prices in the enhanced FBMC model lead to an increase in consumer surplus across the selected FBMC region. However, this price reduction results in a decrease in producer surplus, as illustrated in fig. 6. While producers show a decline in domestic revenue due to the lower prices, the overall increase in trade volumes provides a partial offset. Despite this, the revenue generated from exports is smaller than the revenue lost from lower domestic prices.

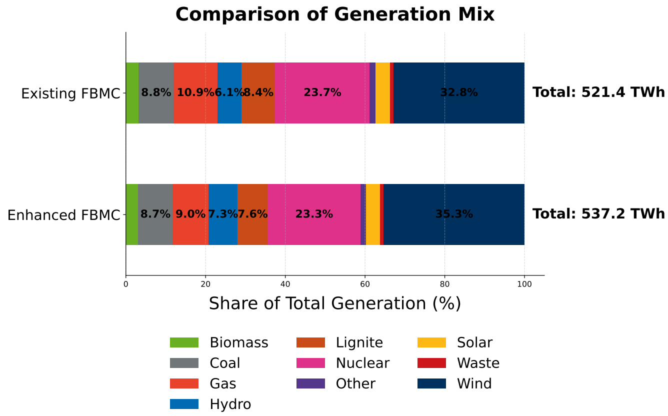

Fig. 5: Relative deviation in the generation by technology type

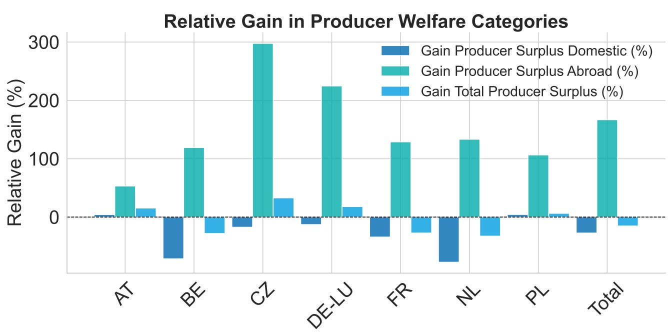

Fig. 6: Relative deviation in the producer surplus by country

Nevertheless, the gains in consumer surplus outweigh the losses in producer surplus, resulting in a net positive welfare effect for the selected FBMC countries, as illustrated in fig. 7. The enhanced model shows that when grid constraints are less restrictive and endogenously considered, the solver opts for significantly higher trade volumes. This reflects the presence of untapped cost-efficient generation potential that is not realized due to the more restrictive cross-border capacity in the current market design.

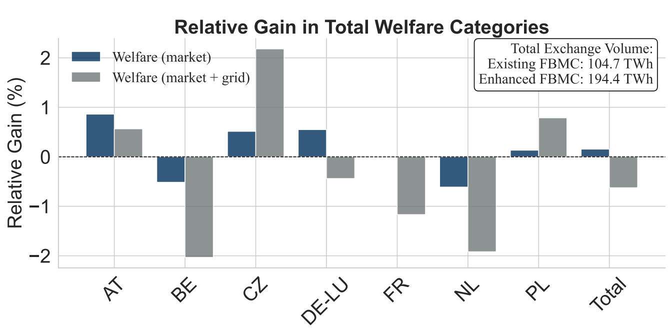

Fig. 7: Relative deviation in the producer surplus by country

However, this positive welfare effect must be seen in light of the fundamental trade-off in zonal market design. If trade capacities are too restrictive the market fails to exploit available low-cost generation, resulting in welfare losses. In contrast, if capacities are too generous without sufficient representation of the grid constraints, cross-border flows increase the risk of congestion. This is the case here, as shown in fig. 7, as the static interconnector capacities of NTC countries and the simplified representation of grid constraints in the case study result in market dispatch that overstretch the grid capacity leading to higher grid congestion volume and reducing the welfare. As FBMC expands to include more countries, this highlights the importance of a more precise calibration of trade capacities and the need for scalable models that accurately reflect both market dynamics and grid constraints.

V. Discussion

Deeper market integration through enhanced zonal coupling, as modeled by with the introduced FBMC approach in this study, shows substantial potential for increasing economic efficiency and mitigating price spikes—even under the exceptional stress conditions of early 2023 during the energy crisis. The model achieves significant price convergence, with the average electricity price of the selected countries in the FBMC region dropping by nearly 30 €/MWh. This convergence reflects a more efficient allocation of resources, but also redistributes market welfare between countries and market participants. The generation mix becomes more efficient as well. Renewable energy, especially wind power, is used more effectively across regions. Hydro storage is deployed in a more flexible way, and gas-fired generation is used less frequently. These changes reduce overall electricity costs. While consumers benefit from lower prices, producers earn less in domestic markets. Their losses are only partly compensated by higher export.

At the same time, the results illustrate a fundamental challenge of zonal market design. If cross-border capacities are set too low, available cheap generation cannot be used, which reduces welfare. If they are set too high without representing sufficiently the physical limits of the grid, the risk of congestion rises. This is the case in the current case study, as trade volumes grow, but the simplified grid representation and static NTC values in countries outside the FBMC region lead to unrealistic power flows that increase grid congestion, undermining total welfare when congestion costs are factored in. The need for a more detailed representation of grid constraints in the FBMC model is clear, but the computational complexity is high. Future work should incorporate decomposition and complexity reduction techniques or other methods for a better representation of the dynamic grid interactions and congestion management into the optimization process, ensuring that the market coupling mechanism remains efficient while accounting for the physical limitations of the transmission network.

References

[1] ACER, "Progress of eu electricity wholesale market integration 2024 market monitoring report," 11 2024. [Online]. Available: www.acer.europa.eu

[2] ENTSO-E, "Core-fb-launch of flow-based market coupling in the core region enhances energy transition flow-based market coupling mechanism optimises day-ahead european electricity market for 13 countries," 2022.

[3] B. Felten, P. Osinski, T. Felling, and C. Weber, "The flow-based market coupling domain - why we can't get it right," *Utilities Policy*, vol. 70, p. 101136, 6 2021.

[4] D. Schönheit, M. Kenis, L. Lorenz, D. Möst, E. Delarue, and K. Bruninx, "Toward a fundamental understanding of flow-based market coupling for cross-border electricity trading," *Advances in Applied Energy*, vol. 2, p. 100027, 5 2021.

[5] D. Schönheit, K. Bruninx, M. Kenis, and D. Möst, "Improved selection of critical network elements for flow-based market coupling based on congestion patterns," *Applied Energy*, vol. 306, p. 118028, 1 2022.

[6] D. Schönheit, R. Weinhold, and 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*, vol. 258, p. 114067, 1 2020.

[7] I. Aravena, Q. Lété, A. Papavasiliou, and Y. Smeers, "Transmission capacity allocation in zonal electricity markets," *Operations Research*, vol. 69, pp. 1240–1255, 7 2021.

[8] D. Schönheit, D. Hladik, H. Hobbie, and D. Möst, "Elmod documentation: Modeling of flow-based market coupling and congestion management," 2020. [Online]. Available: http://hdl.handle.net/10419/217278

[9] B. Riskutia, "Modelling flow-based market coupling in the core region a data-driven and interpretable approach," 2023. [Online]. Available: http://repository.tudelft.nl/.

[10] K. V. D. Bergh and E. Delarue, "An improved method to calculate injection shift keys," *Electric Power Systems Research*, vol. 134, pp. 197–204, 5 2016.

[11] ACER, "Of the european union agency for the cooperation of energy regulators of 2 may 2024 on the european resource adequacy assessment for 2023," 2024.

[12] M. Bucksteeg, S. Voswinkel, and G. Blumberg, "Improving flow-based market coupling by integrating redispatch potential—evidence from a large-scale model," *Energy Policy*, vol. 188, p. 114093, 5 2024.

[13] D. Glynos and H. Scharf, "Postponing germany's nuclear phase-out: A smart move in the european energy crisis?" *Energy Policy*, vol. 192, p. 114208, 9 2024.