



Summer of 24: Market Power and Price Formation in the European Electricity Market

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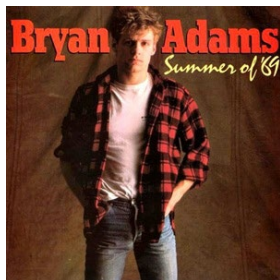
Outline

- Context and motivation
- Overview of the models
- Regional modeling through MPEC/EPEC
- EU-wide modeling through quadratic programming
- Conclusions

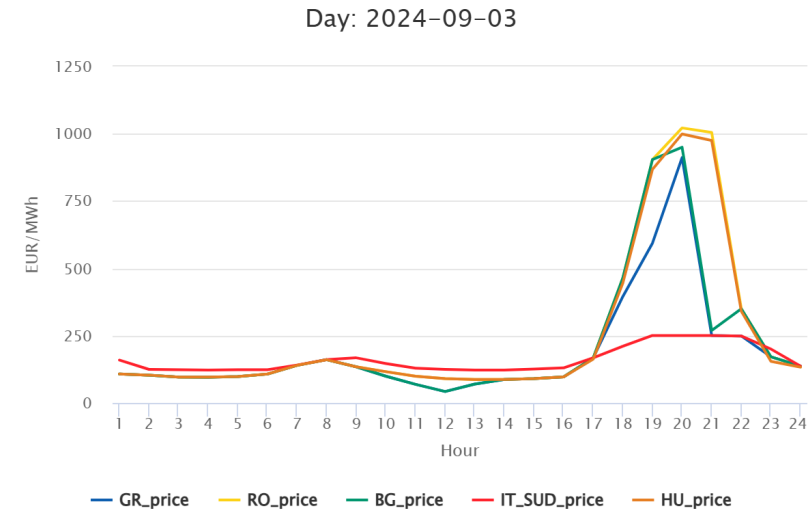
Context and motivation

Southeast Europe's 2024 summer price crisis

- During the summer of 2024, the electricity market zones of Southeast Europe experienced a prolonged period of **abnormally high prices** that lasted almost three months
- A main characteristic of this crisis was the periodic occurrence of **extreme price spikes** during the evening hours, which significantly raised the average prices in both forward and real-time markets



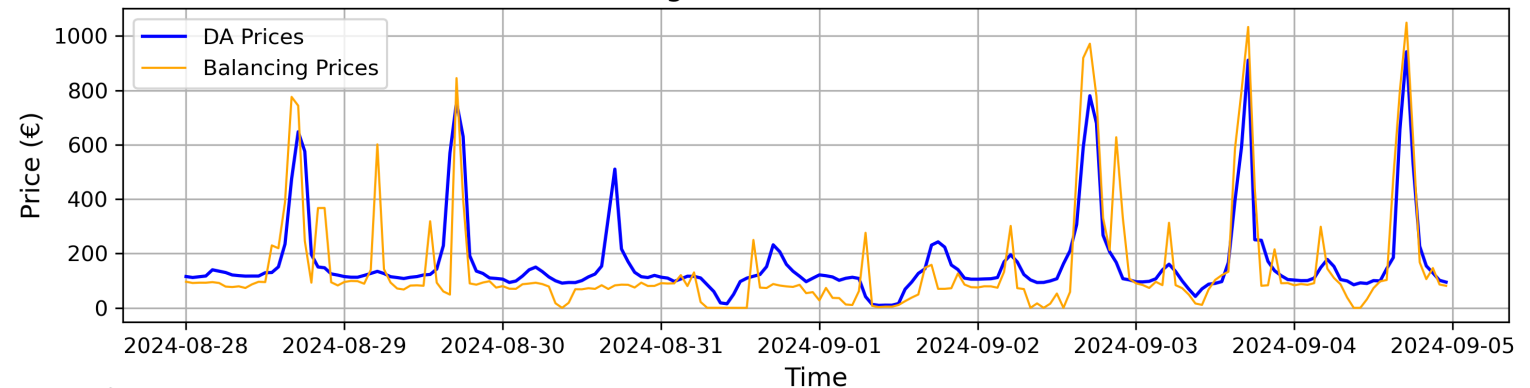
Hit song about a more romantic summer



*Data Sources: EnergyLive through ENEX (GR_price), Gestore Mercati Energetici (IT_SUD_price), IBEX (BG_price), OPCOM (RO_price), HUPX (HU_price).

*Time: UTC+2:00

DA vs Balancing Prices in GR (Corelation = 0.617)



*Data Sources: ENEX, ADMIE

Institutional context



COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS

Action Plan for Affordable Energy

26 February 2025



2.4.2. Analysis of bidding curves during high prices in South-East Europe during summer 2024 - A case study considering Greece

5 November 2025

Action Plan for Affordable Energy

- Main drivers of price spikes:
 - Limited cross-border capacity
 - Insufficient grid flexibility
- Price crisis preparedness:
 - Establish and maintain a fully interconnected EU market

ACER's 2025 Monitoring Report

- Main drivers of price spikes:
 - Extreme heatwaves
 - Increased exports to Ukraine
 - Plant outages
 - Low hydro level
 - **Limited cross-border capacity**
 - **Possibility of strategic bidding**
 - Economic theory predicts that exercise of market power becomes more profitable during tight hours
 - Greek order books publicly available

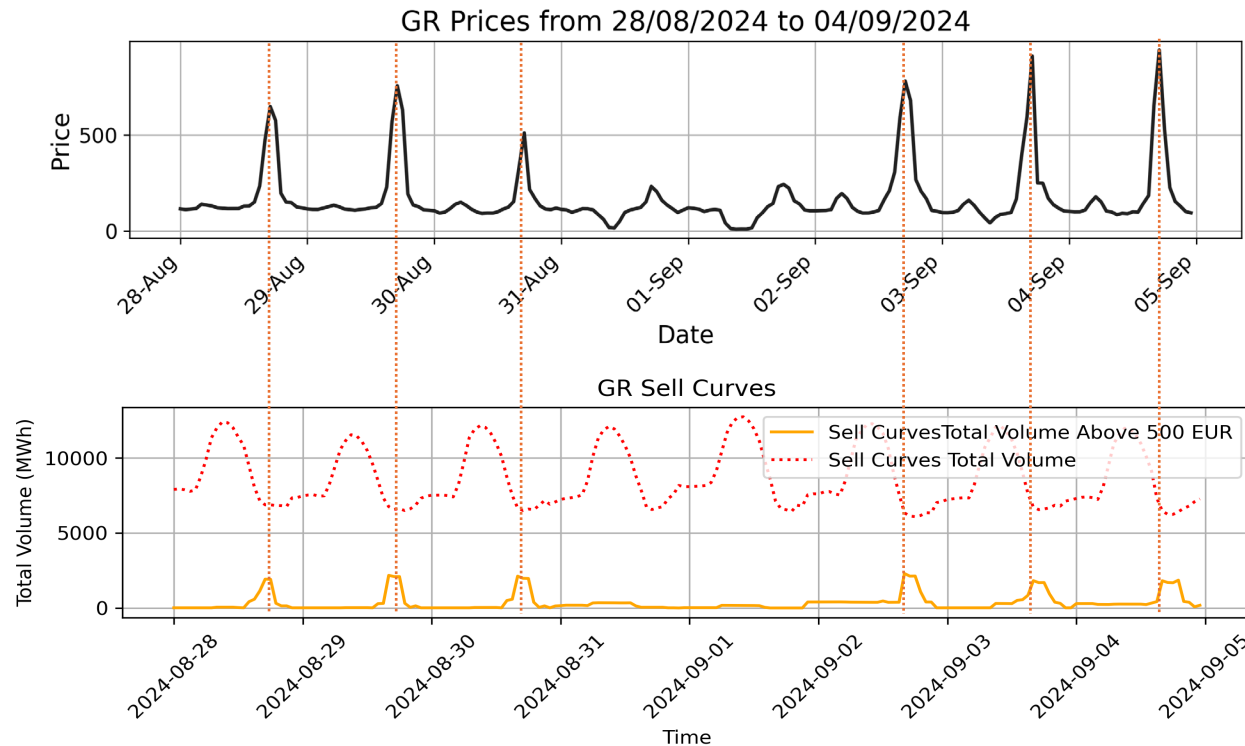
Regulatory Context



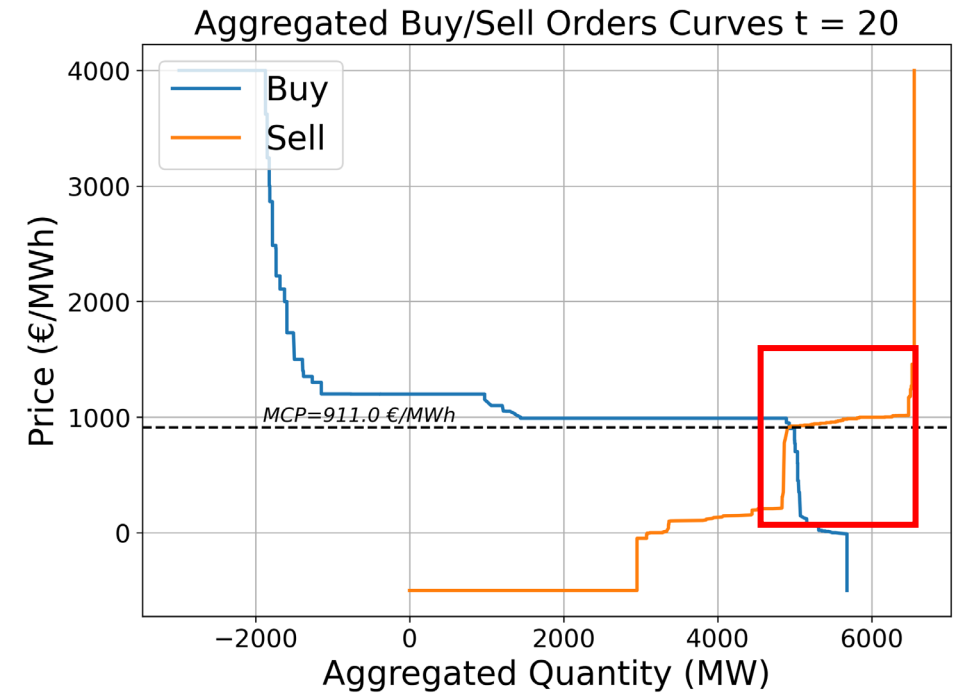
- *“Electricity generation capacity withholding can occur in two ways, namely via economic withholding or physical withholding.”*
- **Economic withholding:** *“Actions undertaken to offer available generation capacity at prices which are above or at the market price and do not reflect the marginal cost (including opportunity cost) of the market participant’s asset, which results in the related wholesale energy product not being traded or related asset not being dispatched.”*
- **Physical withholding:** *“Actions undertaken in the form of not offering the available generation capacity at any price.”*

Sell curves in Greece

Indicators of Strategic Behavior: Periods of system stress were characterized by a significant increase in high-priced supply bids.



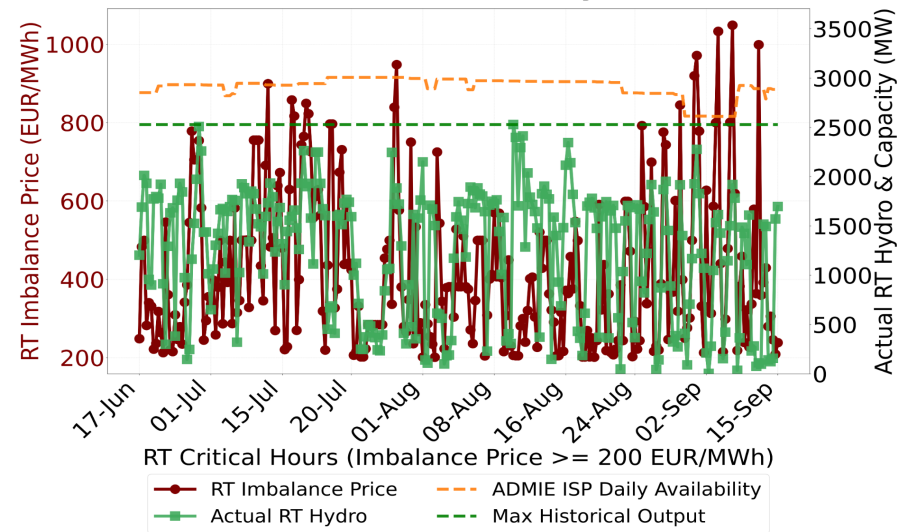
*Data Sources: ENEX



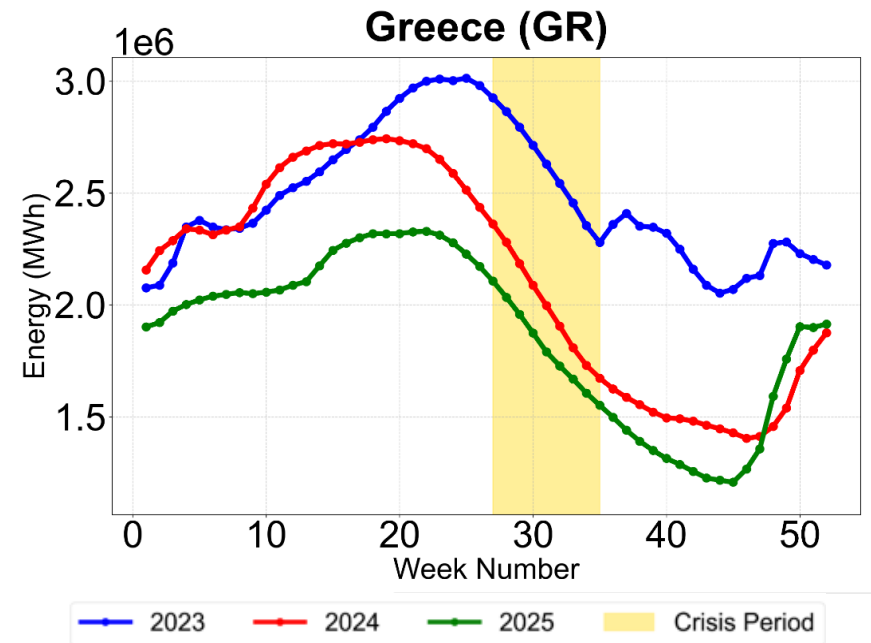
Hydro utilization during the crisis period

- During the high priced hours there is a persistent gap between the available capacity of hydro plants and the hydro capacity utilized.
- This could be driven by operating constraints like the depleted water reservoir levels.

RT Imbalance Price vs Actual RT Hydro (Critical Hours)



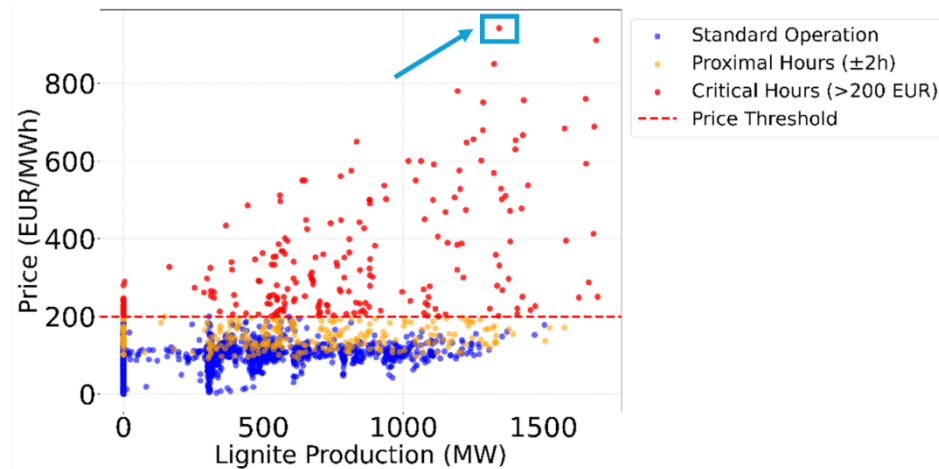
Imbalance price (IPTO 2024) and actual hydro generation (ENTSO-E 2024) against available capacity (Independent Power Transmission Operator (IPTO/ADMIE) 2024) for the hours where imbalance price is greater than or equal to 200 €/MWh.



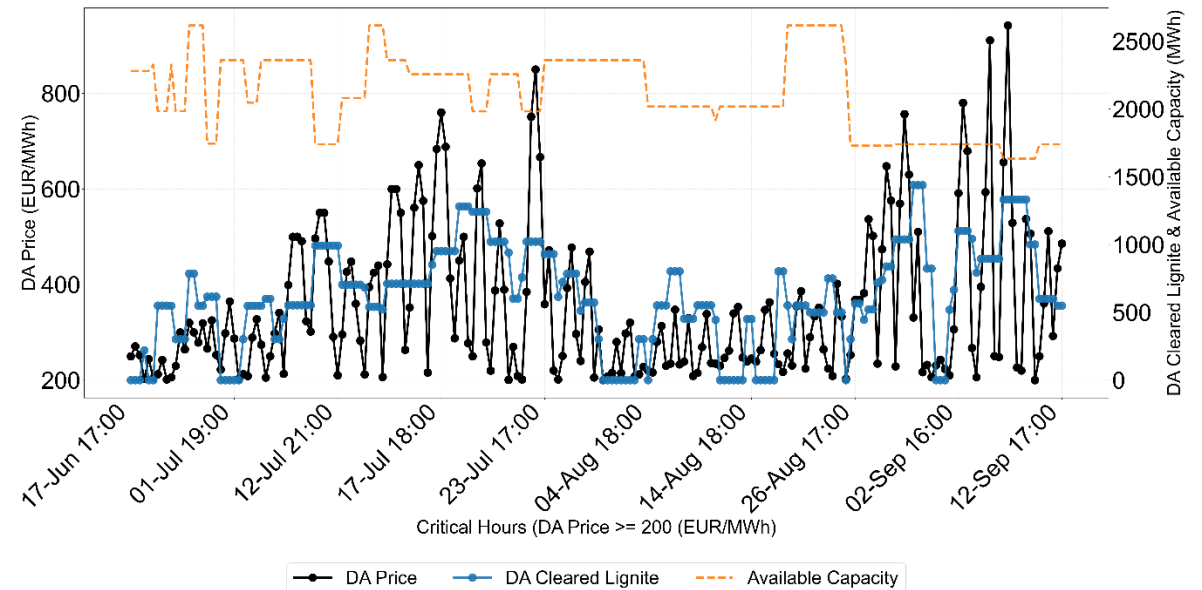
Water reservoir levels for the years 2023-2025.
Source: (ENTSO-E 2024).

Lignite utilization during the crisis period

- Across both the day-ahead and real-time markets, there is a persistent gap between the available capacity of lignite plants and the lignite capacity utilized.
- Unlike hydro, where unutilized capacity could reflect reservoir depletion, unutilized lignite capacity is very difficult to justify by physical constraints during the extreme price spikes.



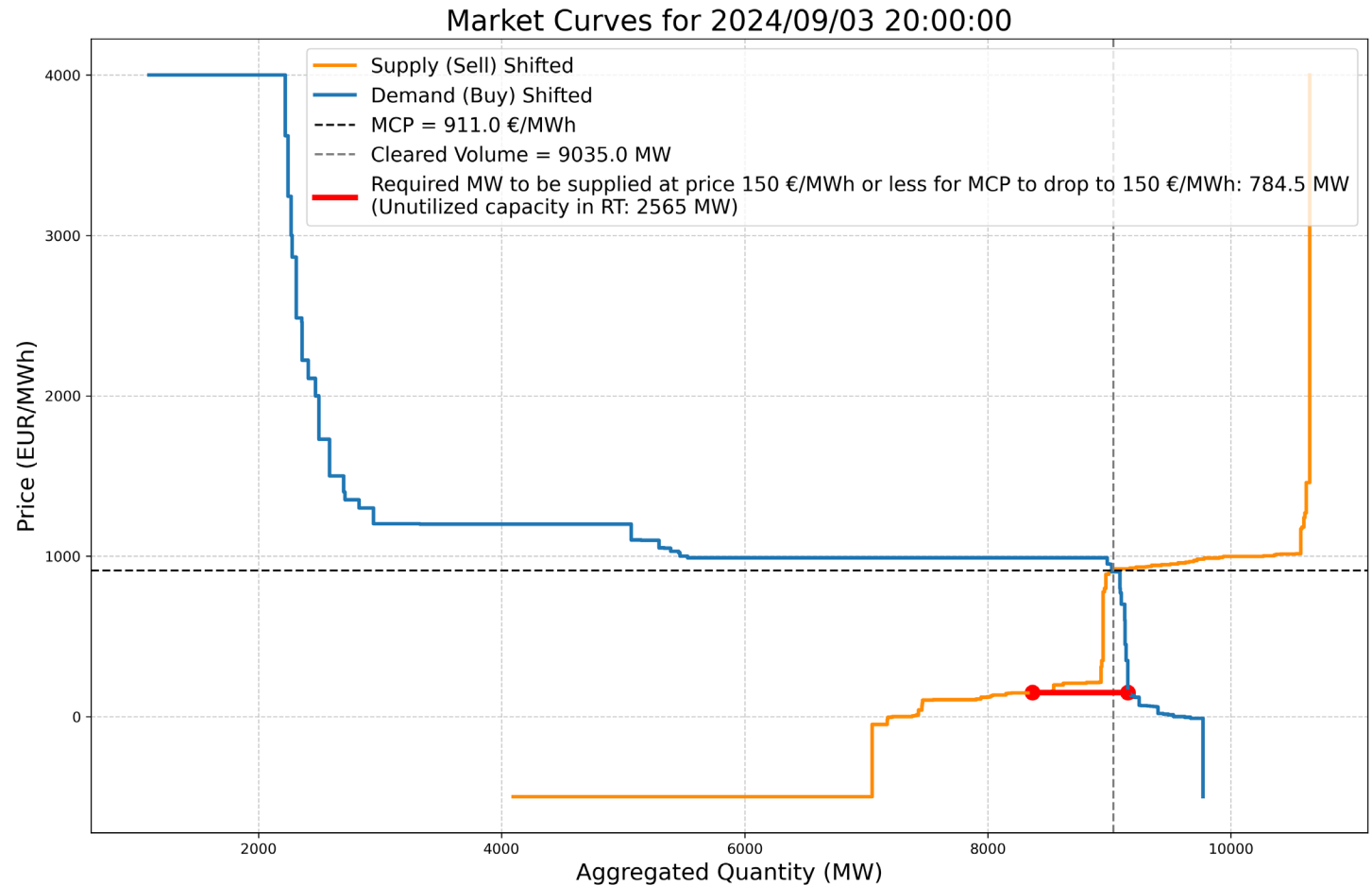
Lignite Production against DA price for the Greek zone during the 2024 SEE crisis. The blue box and arrow indicate a time unit of market clearing observed in the actual market which is suspect of exercise of market power.



Day-ahead price and cleared lignite (EnEx Group 2024) against lignite available capacity (ENTSO-E 2024) for the hours when day-ahead price is greater than or equal to 200 €/MWh.

Capacity Required for Price Relief

- On average, for all the hours where DA Price exceeded 200 €/MWh, an additional 375.4 MW of capacity bid at or below 150 €/MWh would have been required to drop the DA price to a price of 150 €/MWh.



*Data Sources: ENEX

Research agenda

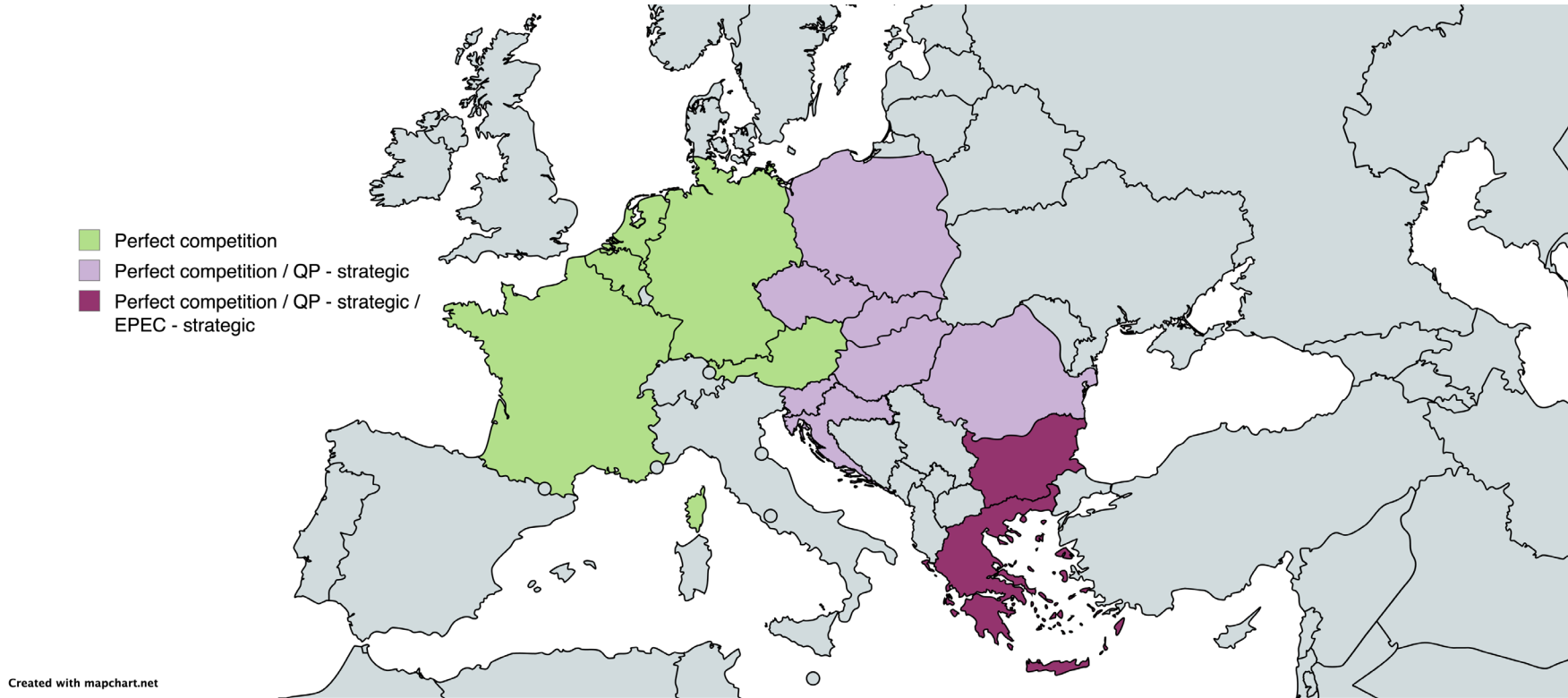
We aim at quantifying the effects of **strategic interactions** and **flow-based network constraints** across Central Western and Southeast Europe

Proposed modeling framework

1. **Regional modeling of Greece and Bulgaria:** MPEC and EPEC models for a detailed regional analysis of the Greek and Bulgarian zones
2. **EU-wide scope:** Nash-Cournot competition based on quadratic programming for simulating outcomes across the full EU integrated market

Overview of the models

Geographical scope of the models



- The model can represent the interaction between perfectly competitive and strategic (Nash-Cournot) markets
 - Green zones: assuming perfect competition
 - Purple zones: assuming strategic firms and perfectly competitive firms
- More detailed regional modeling of Bulgaria and Greece through MPECs/EPECs

Overview of the models

Modeling framework	Formulation	Scalability	Characteristics	Comments
Perfect competition	Market model - QP	Tractable	• Market model for CORE + BG + GR • Wide range of market configurations • Mixture of perfectly competitive zones and strategic players • For each strategic zone • Strategic firms can own/partially own/not own hydro • Strategic firms can be two-sided (i.e. can also serve load)	Requires linearization of demand functions
Nash-Cournot Competition				
MPEC / EPEC		Non-tractable	• Regional model for BG + GR • Better represents market behavior • We can feed the actual demand functions	• Exogenous hydro modeling • No temporal coupling between hours

Overview of the models (II)

Characteristic	Description	Comments
Geographical coverage	A total of 14 zones: 12 CORE zones + 2 non-CORE zones	
Generation	Unit-based model (min up/down times, startup of units, ramp up/down)	• Data gathered from PyPSA • Strategic firm parameters sourced from Global Energy Monitor
Availability factors	Availability factors to model the available capacity	Data gathered from ENTSO-E's transparency platform
Transmission network	• Zonal model • Flow-based model for CORE region • ATC model for non-CORE zones	Data gathered from JAO website
Hydrology	• For QP: hydrologic profiles optimized per day • For EPEC/MPEC: hydrologic profiles fixed	Data gathered from ENTSO-E transparency platform
Demand	• Inelastic loads based on historical profiles • Elastic loads based on demand curves	• Inelastic load gathered from ENTSO-E platform • IBEX, HENEX, NordPool provide demand curves • Elastic part of GR demand curves used for zones where data is not available
RES	RES fixed to historical profiles	Data gathered from ENTSO-E platform
Time horizon	Hourly time steps for a 1-day horizon	Summer of 2024

Regional modeling through MPEC/EPEC

Giannakakis, N., Papavasiliou, A., & Ávila, D. (2026).
Regional Modeling of Market Power in Southeast Europe.
Under review at *The Energy Journal*.

Preprint



Mathematical programs with equilibrium constraints (MPECs)

- Leader-follower game:
 - Leader: Dominant firm(s)
 - Follower: Market
- MPEC solutions represent **Stackelberg equilibria**: the leader chooses its supply to maximize profit, subject to the market's welfare-maximizing response

(+) Detailed modeling of the strategic players' interaction with the market

(−) Market's complementarity system generates non-convex and non-smooth feasible regions:

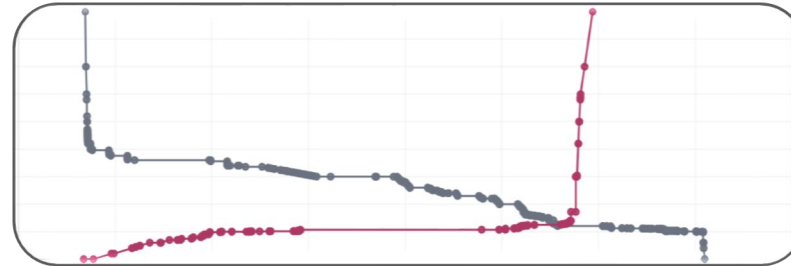
- Multiple local maxima
- No guarantee that diagonalization algorithms will converge to global optimum

Leader: dominant firm

Bid quantity Q that maximizes profits
subject to:

Follower: market auction

Clear bids/offers that maximize social welfare *with other players' strategies fixed.*



The Market Clearing Optimization Problem

$$(MCP): \max_{d,s,f} \sum_{i \in D_z, \forall z \in Z} PD_i d_i - \sum_{i \in S_S \cup S_C} PS_i s_i \quad (1)$$

$$(\lambda_z): \sum_{n \in N(z)} (f_{(z,n)} - f_{(n,z)}) = \sum_{i \in S_S \cup S_C} s_i + O_z - I_z - \sum_{i \in D_z} d_i \quad \forall z \in Z \quad (2)$$

$$(\mu_i): s_i \leq \bar{s}_i \quad \forall i \in S_S \cup S_C \quad (3)$$

$$(\gamma_i): d_i \leq D_i \quad \forall i \in D_z, \forall z \in Z \quad (4)$$

$$(\rho_k): f_{(z,n)} \leq F_{(z,n)} \quad \forall (z,n) \in L \quad (5)$$

$$d, s, f \geq 0 \quad (6)$$

$$MCP^{(j)} = MCP(\bar{s}^{(j)}, \bar{s}^{(-j)}).$$

$\bar{s}^{(j)}$ is the vector of quantities that firm j controls

$\bar{s}^{(-j)}$ the vector of quantities controlled by all the other firms apart from j

Sets

J	Set of all strategic firms
$S^{(j)}$	Set of supply blocks of strategic firm j
S_S	Set of supply blocks of all strategic firms
S_C	Set of supply blocks of competitive firms
D_z	Set of demand blocks of the elastic component of the demand function of zone z
Z	Set of modeled zones
$N(z)$	Set of modeled neighbors for zone z
L	Set of transmission links

Upper-level primal variables (that are lower-level parameters)

$\bar{s}_i$	Capacity of supply block i that the strategic firm bids in the market auction [MW]
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Lower-level primal variables

s_i	Active power cleared from supply block i [MW]
d_i	Active power cleared from demand block i [MW]
$f_{(z_1, z_2)}$	Active power flow from zone z_1 to zone z_2 [MW]

Lower-level Dual Variables

λ_z	Market clearing price of zone z [€/MWh]
μ_i	Scarcity rent of supply block i [€/MWh]
γ_i	Net surplus of demand block i [€/MWh]
ρ_k	Congestion rent of flow k

Parameters

PD_i	Price of demand block i [€/MWh]
PS_i	Price of supply block i [€/MWh]
S_i	Upper limit of supply block i [MW]
D_i	Upper limit of demand block i [MW]
I_z	Inelastic demand component for zone z
O_z	Demand curve offset for zone z [MW]
$F_{(z,n)}$	ATC upper limit of flow from z_1 to zone z_2 [MW]
$M_I^{(j)}$	Market share of inelastic demand component that is served by firm j

Index mappings

$z(j)$	Zone where firm j operates
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The MPEC formulation

- let $K(\bar{\mathbf{s}}^{(j)}, \bar{\mathbf{s}}^{(-j)})$ represents the set of primal and dual variables that satisfy the Karush–Kuhn–Tucker (KKT) conditions of MCP^(j)

$$\text{MPEC}^{(j)} = \max_{\mathbf{x}, \mathbf{y}, \bar{\mathbf{s}}^{(j)}} \lambda_{z(j)} \left(\sum_{i \in S^{(j)}} s_i - M_I^{(j)} \cdot I_{z(j)} \right) - \sum_{i \in S^{(j)}} PS_i s_i \quad (7)$$

$$\bar{s}_i \leq S_i, \quad \forall i \in S^{(j)} \quad (8)$$

$$\mathbf{x}, \mathbf{y} \in K(\bar{\mathbf{s}}^{(j)}, \bar{\mathbf{s}}^{(-j)}) \quad (9)$$

- Firm's net position: total generation $\sum_{i \in S^{(j)}} s_i$ minus the procurement required to serve its fixed residential retail share $M_I^{(j)} \cdot I_{z(j)}$
- We assume that industrial consumers buy energy at the wholesale price. Consequently, the cost for a vertically integrated firm to purchase this industrial volume from the wholesale market is canceled by the revenue collected from selling it at that same price

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How to compute a solution?

- Mixed integer linear programming reformulation [1]
 - Linearizes complementarity constraints using binary variables (big-M method).
- **Use of Gurobi's spatial branch and bound algorithm** [2, 3]:
 - Branching on domain of continuous variables
 - In each branch: convex relaxation of bilinear terms using McCormick envelopes
 - Searches the entire feasible space and can find a **globally optimal solution** (subject to tolerances)

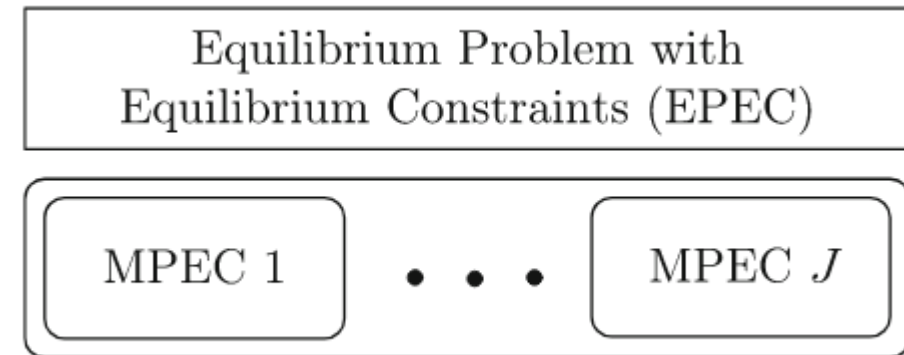
[1] C. Ruiz, A. J. Conejo, and Y. Smeers, "Equilibria in an Oligopolistic Electricity Pool With Stepwise Offer Curves," *IEEE Transactions on Power Systems*, vol. 27, no. 2, pp. 752–761, May 2012, doi: [10.1109/TPWRS.2011.2170439](https://doi.org/10.1109/TPWRS.2011.2170439).

[2] Gurobi Optimization, LLC. (2025). *Gurobi Optimizer Reference Manual* (Version 12.0). Gurobi Optimization. <https://www.gurobi.com/documentation/>

[3] Gurobi Optimization, LLC. (2020). *Non-Convex Quadratic Optimization (Gurobi 9.0)*. Gurobi Optimization. [2020-01-14_Non-Convex-Quadratic-Optimization-in-Gurobi-9.0-Webinar.pdf](https://www.gurobi.com/2020-01-14-Non-Convex-Quadratic-Optimization-in-Gurobi-9.0-Webinar.pdf)

Equilibrium problems with equilibrium constraints (EPECs)

- Modeling of the strategic behaviour of multiple leaders (dominant firms) that are constrained by a single follower (market auction)
- Solutions are Generalized Nash equilibria [4]: each dominant firm's decisions are constrained by the other dominant firms through the KKTs of the market clearing condition
- Solution methods:
 - **Best response (BR) algorithms** [5,6].
 - Non-linear programming reformulations [1].



Source [4]

- [4] C. Ruiz, A. J. Conejo, J. D. Fuller, S. A. Gabriel, and B. F. Hobbs, 'A tutorial review of complementarity models for decision-making in energy markets', *EURO Journal on Decision Processes*, vol. 2, no. 1–2, pp. 91–120, Jun. 2014, doi: [10.1007/s40070-013-0019-0](https://doi.org/10.1007/s40070-013-0019-0)
- [5] B. F. Hobbs, C. B. Metzler, and J.-S. Pang, 'Strategic gaming analysis for electric power systems: an MPEC approach', *IEEE Trans. Power Syst.*, vol. 15, no. 2, pp. 638–645, May 2000, doi: [10.1109/59.867153](https://doi.org/10.1109/59.867153)
- [6] X. Hu and D. Ralph, 'Using EPECs to Model Bilevel Games in Restructured Electricity Markets with Locational Prices', *Operations Research*, vol. 55, no. 5, pp. 809–827, Oct. 2007, doi: [10.1287/opre.1070.0431](https://doi.org/10.1287/opre.1070.0431)

Termination Rate and Price Inconsistencies

- Solving the EPEC through best response is known to produce price-inconsistencies [7].
- Price Inconsistency: each player can potentially assume one of many optimal clearing prices that is most profitable to them.
- For around 96% of the converged MTUs, the relative standard deviation (RSD) between the prices of the MPEC of each player is less than 2%.
- To illustrate the scale of this inconsistency, assuming a mean price of 100 Euro/MWh, a 2% RSD indicates that most players exit the algorithm with a perceived clearing price between 98 and 102 Euro/MWh. Additionally, only around 0.6% of MTUs present RSD more than 5%.

Model	Termination Rate (%)	RSD < 2% (%)	RSD > 5% (%)	Max RSD (%)
Oligopoly Single Sided	99.1	96.75	1.94	51.01
Oligopoly Baseline	98.3	95.08	0.5	10.92
Oligopoly FC 15%	97.98	95.15	0.37	10.61
Oligopoly FC 25%	98.43	95.95	0	4.74
Oligopoly FC 35%	98.79	97.05	0.14	14.74

[7] D. Pozo, E. Sauma, and J. Contreras, “Basic theoretical foundations and insights on bilevel models and their applications to power systems,” *Ann Oper Res*, vol. 254, no. 1–2, pp. 303–334, Jul. 2017, doi: [10.1007/s10479-017-2453-z](https://doi.org/10.1007/s10479-017-2453-z).

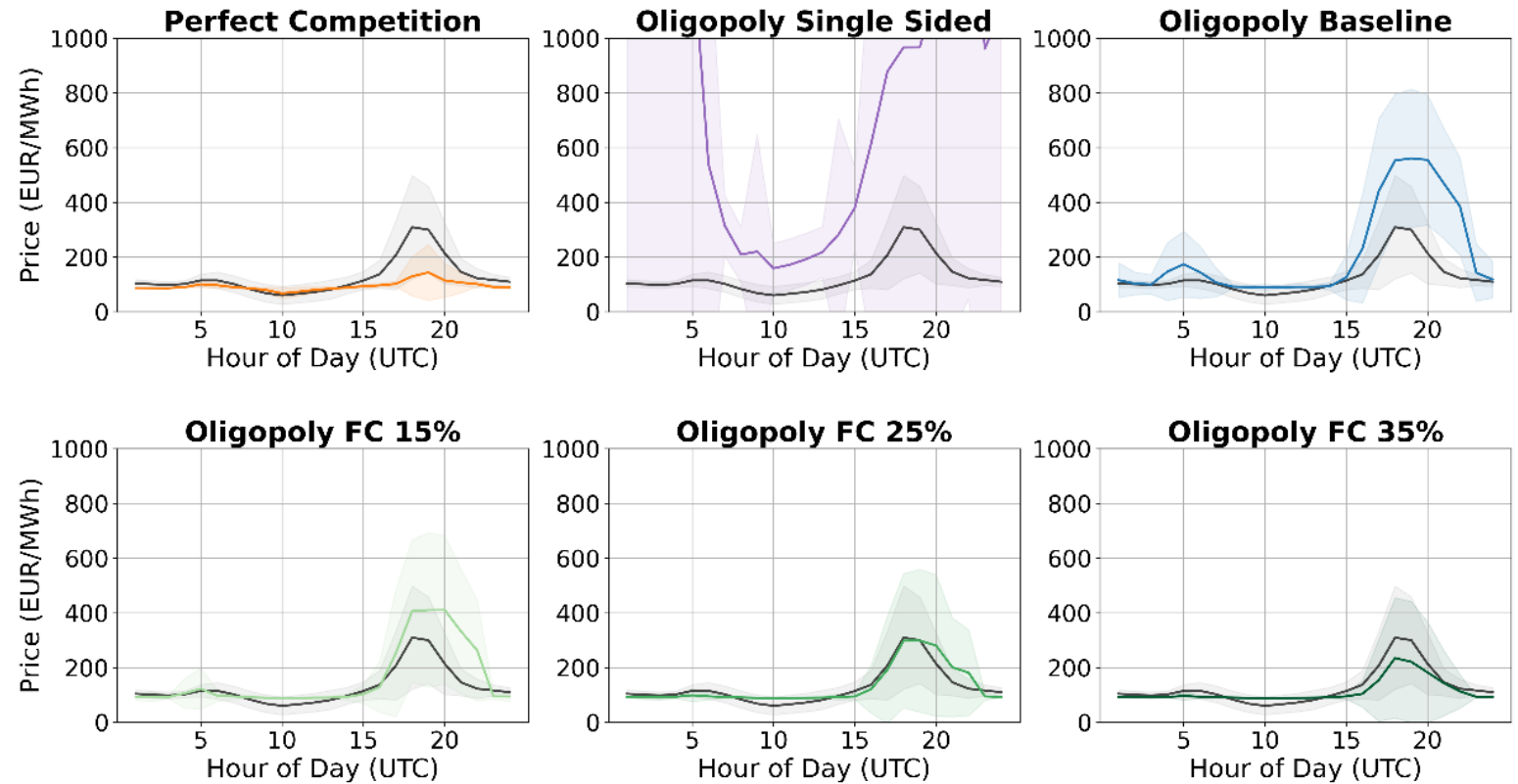
Regional Model Results

Comparison of strategic and perfect competition models

Testing the effect of hydro and cross-border flows

Regional Modeling: Average Performance and Hourly Price Profile

- Both model classes track off-peak prices well.
- Perfect competition assumptions alone cannot explain the price spikes observed during this period.
- Oligopoly models that simulate strategic withholding, but do not account for forward contracting and vertical arrangements, overestimate the crisis price spikes.
- Models produce price profiles that best reflect actual market outcomes when they incorporate:
 - Vertical interactions between production and retailing
 - The regulatory regime of Bulgaria
 - Forward contract positions



Price profile comparison. Hourly mean and variability for the whole crisis period

Classification results

Perfect competition	Actual positives (price $\geq$ 300)	Actual negatives (price $<$ 300)
Predicted positives (price $\geq$ 300)	5 (true positives)	0 (false positives)
Predicted negatives (price $<$ 300)	92 (false negatives)	2135 (true negatives)

Oligopoly single-sided	Actual positives (price $\geq$ 300)	Actual negatives (price $<$ 300)
Predicted positives (price $\geq$ 300)	96 (true positives)	1089 (false positives)
Predicted negatives (price $<$ 300)	1 (false negatives)	1046 (true negatives)

Oligopoly 35% FC (calibrated)	Actual positives (price $\geq$ 300)	Actual negatives (price $<$ 300)
Predicted positives (price $\geq$ 300)	56 (true positives)	33 (false positives)
Predicted negatives (price $<$ 300)	41 (false negatives)	2102 (true negatives)

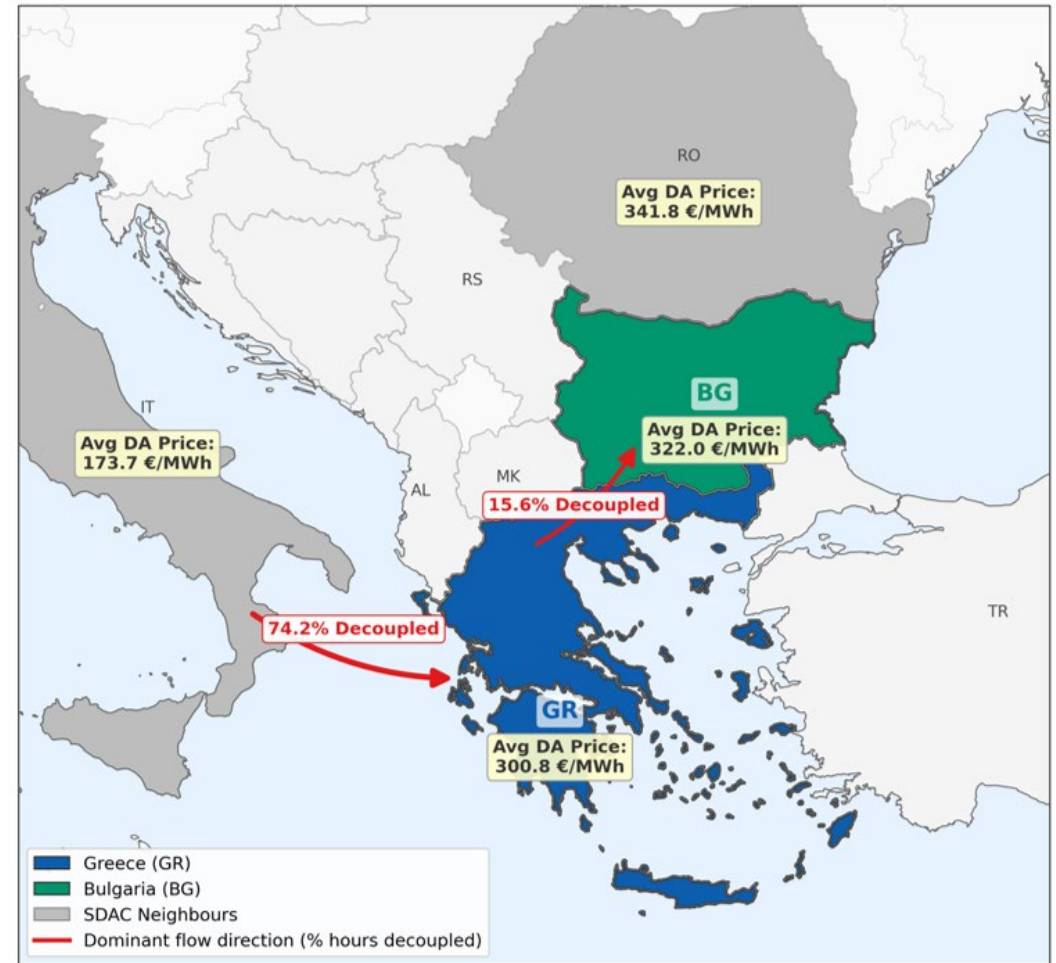
Regional Model Results

Comparison of strategic and perfect competition models

Testing the effect of hydro and cross-border flows

Fixing cross-border flows

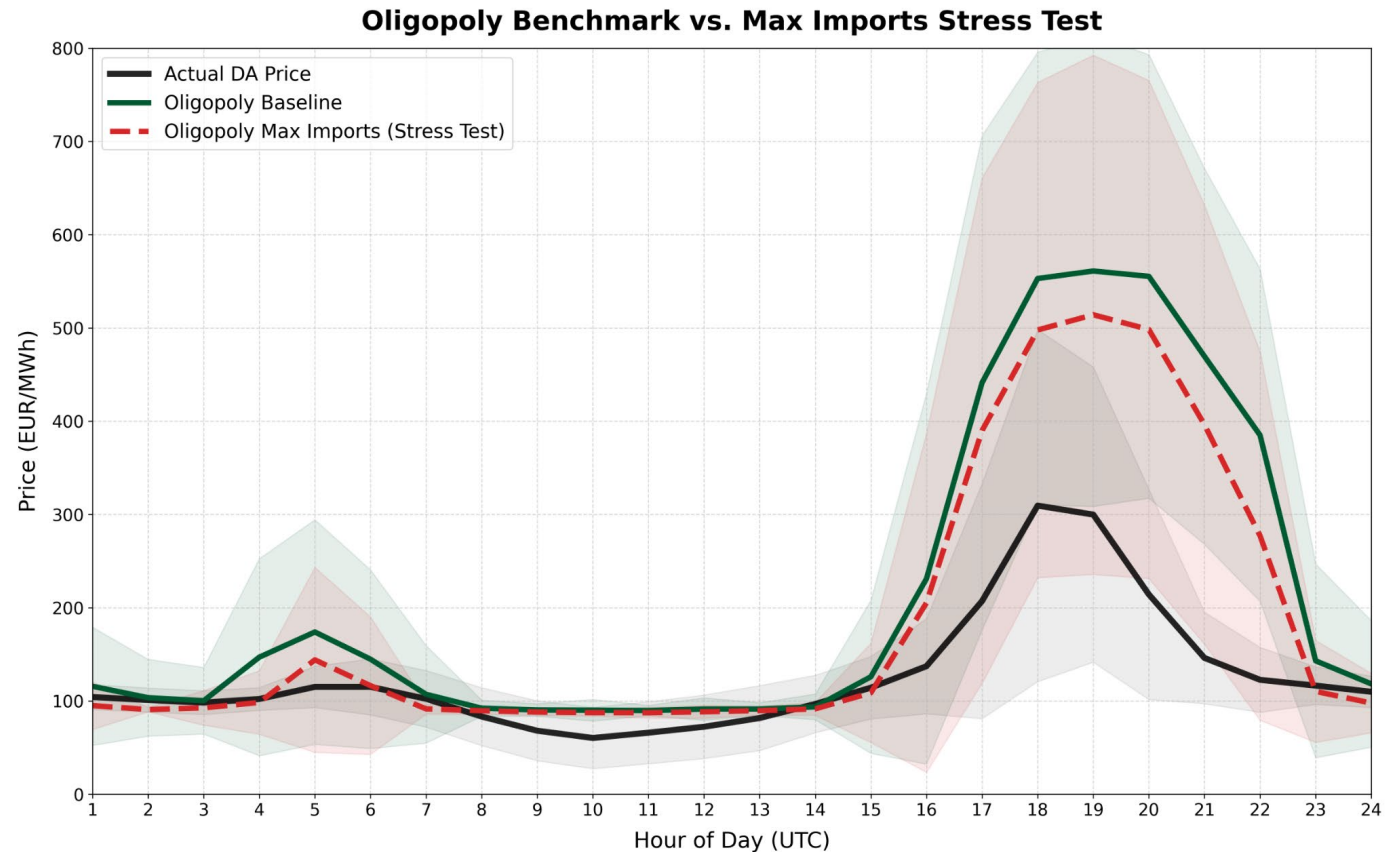
- Necessary due to the computational complexity introduced by the EPEC framework: we choose to endogenize the Bulgarian zone (DF with Fringe) and treat the Italian link as an exogenous fixed flow.
- To quantify the worst-case effect of this modeling decision on perfect competition: maximizing exports to the non-modeled neighboring SDAC zones (IT and RO) up to the ATC limits.



Historical outcomes (stressed hours): we model the coupled neighbor of Greece

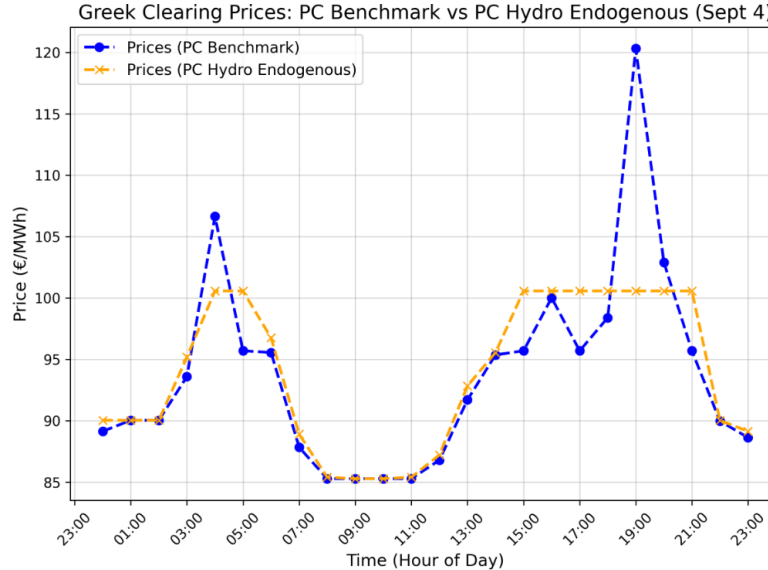
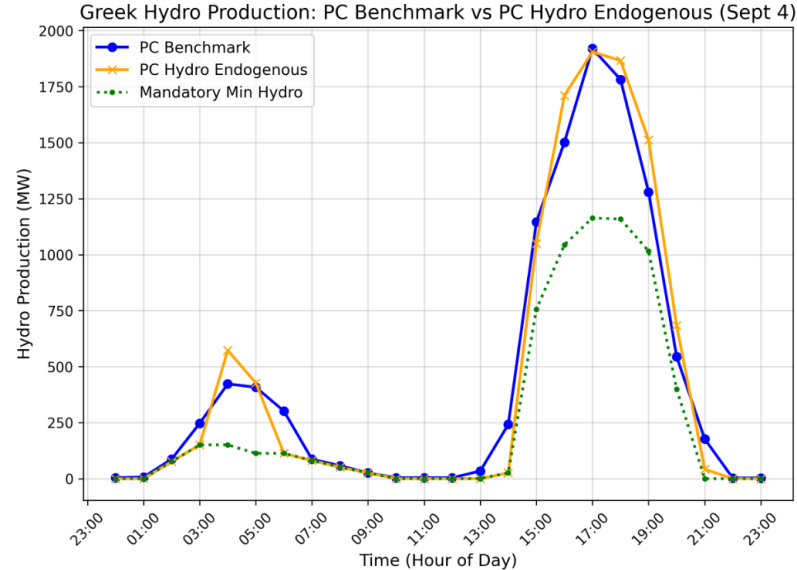
Effect of cross-border flows on strategic model

- Stress test: maximize the imports of the non-modeled neighboring SDAC zones.
- Even under the hypothetical maximum imports, regional strategic withholding remains strong enough to produce price spikes, confirming that modeled strategic markups are not an artifact of fixing cross-border flows to historical values.



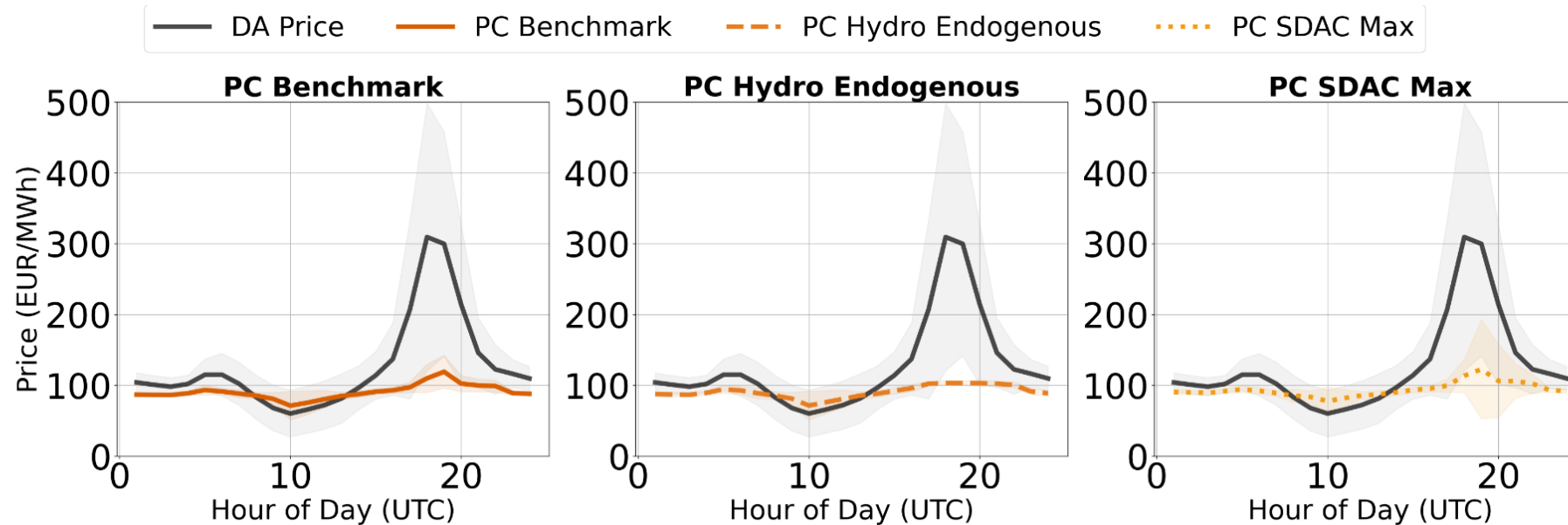
Effect of fixing hydro production on perfect competition results

- Opportunity costs exhibit circularity: opportunity cost calculation accounts for the expectation of future prices, which are affected by the strategic behavior of price-setting firms.
- We are interested in testing how sensitive the perfect competition model is to the effect of hydro
 - We cannot (because of computational reasons) do such tests for the oligopoly models
- Assumptions for endogenizing hydro in the perfect competition model:
 - Model with endogenous hydro production of the Greek zone within each day with the total hydro production capped at the total daily historical.
 - Lower bound the hydro production using the Minimum Hydro Requirement dataset published by the Greek TSO (Independent Power Transmission Operator (IPTO/ADMIE) 2024).



Effect of (i) hydro and (ii) fixed flows on perfect competition model

- Even when the system is under maximum physically available export stress, competitive thermal dispatch could keep prices significantly below crisis levels (right figure compared to left figure).
- Historical hydro schedule is not the optimal one under the perfectly competitive assumption (see previous slide).
- Fixing hydro to historical values does not suppress competitive prices and so it does not exaggerate strategic markups (middle figure compared to left figure).



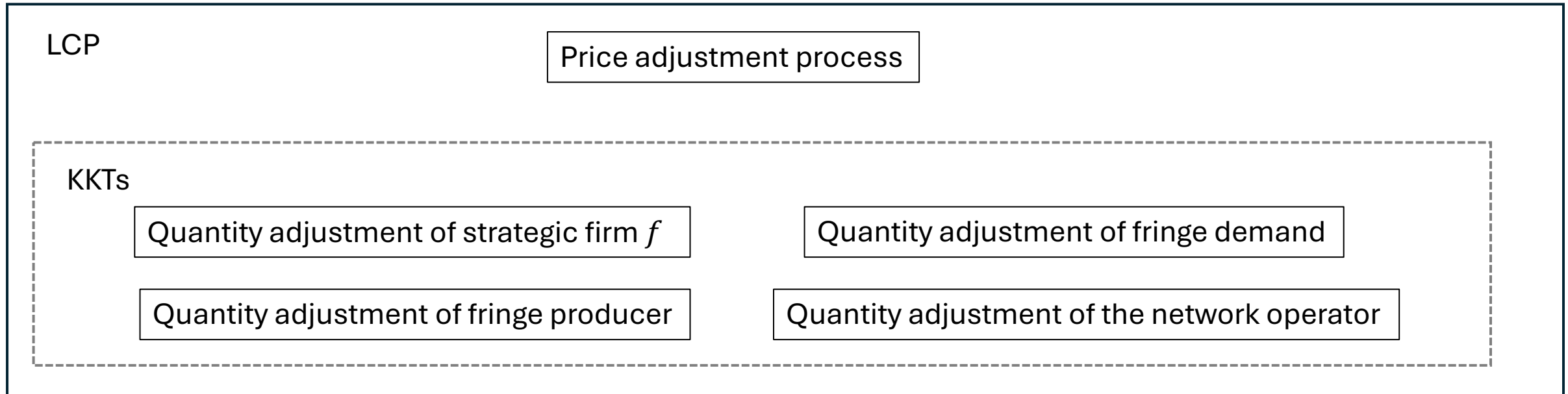
EU-wide modeling through
quadratic programming

Modeling strategic interactions as an LCP

- We formulate the strategic interaction between dominant firms in quantities over a network as a linear complementary problem (LCP)
- The basis of the LCP formulation is an assumption whereby firms assume that they are facing a linear net demand function
 - This is computationally viable: it implies that the reaction of the market to changes in the output of a strategic firm can be summarized by the slope of the net demand function
 - We avoid the basic complexity of MPECs (for single-leader) or EPECs (for multi-leader) formulations whereby the search for an equilibrium requires also discovering the relevant part of the demand function where the equilibrium lands

Derivation of the LCP formulation

- We formulate the **price adjustment** process of the market directly
- One **quantity adjustment** problem per market agent
 - Expressed equivalently as a set of KKT conditions



Quadratic programming reformulation of LCP

- To reformulate the LCP as a quadratic problem [8, 9, 10] we exploit the structure of the quantity adjustment problems
 - The quantity adjustment problem of each strategic agent is similar to that of a perfectly competitive firm
 - **But** an additional term is added to the marginal cost of the firm
 - Namely a term which captures the impact that the firm has on the market price by injecting additional power to the market



$$\sum_{t \in T} \sum_{f \in F} 0.5 \cdot BC_{n(f),t} \cdot s_{ft}^2$$

Nuances

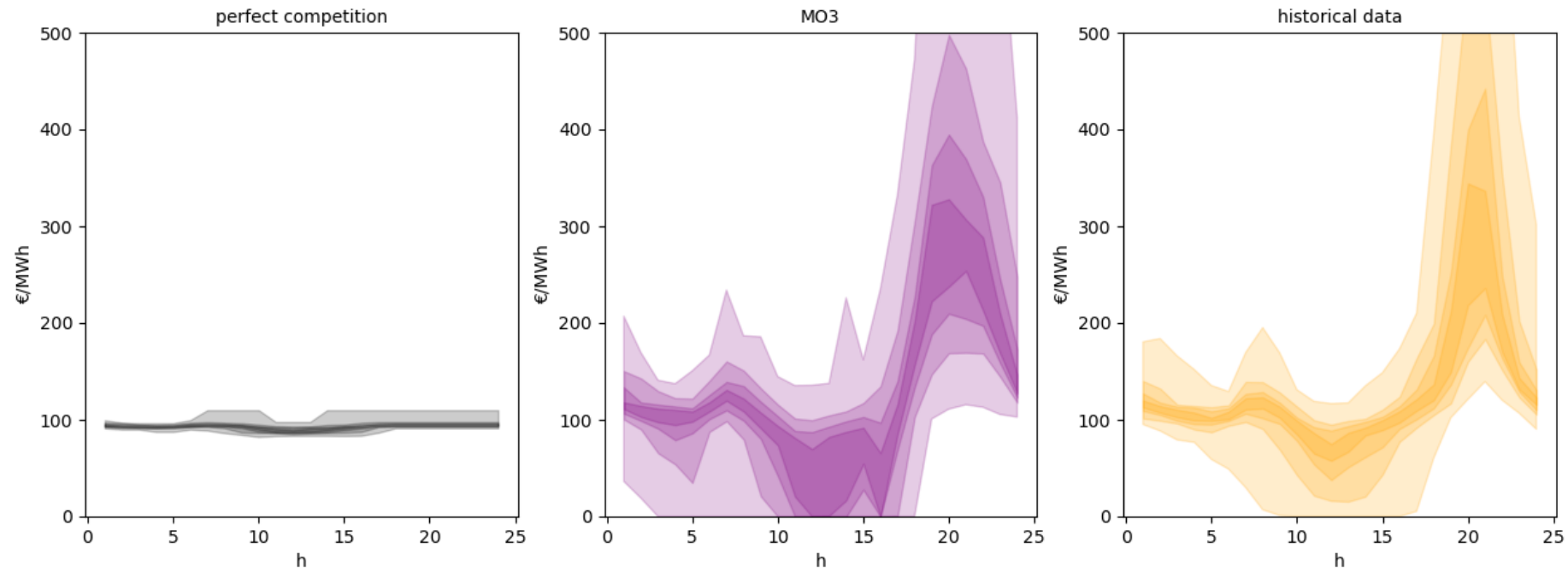
- Network
- Simultaneous versus sequential moves by fringe competitors
- Retail market share
- Forward contracts

All-EU Results

Industrial organization configurations

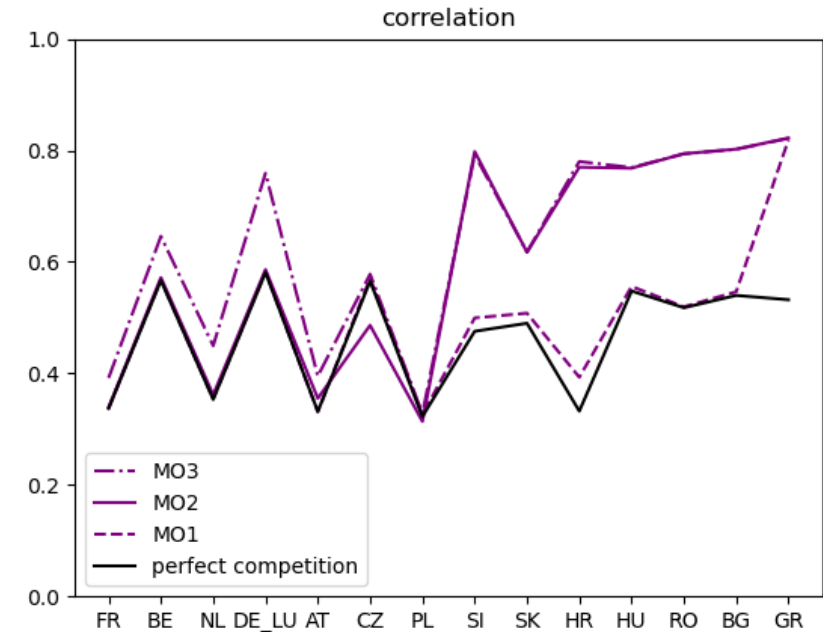
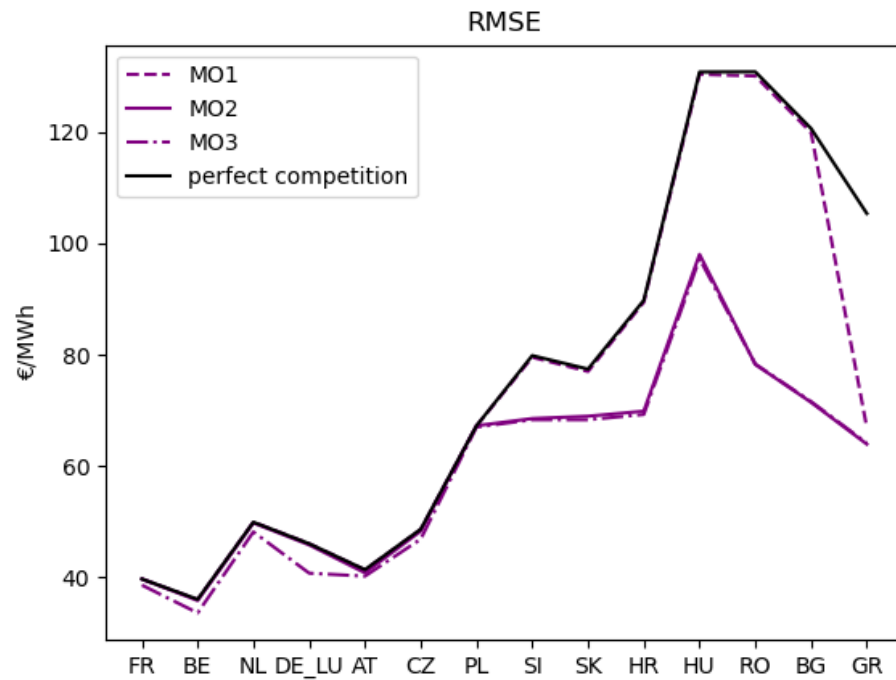
Market organization	Strategic zones	Retail market share of firms	Forward contracts
MO1	GR	PPC 56%	25%
MO2	GR, BG, RO, HU, HR	PPC 56%, HEP grupa 84%	25%
MO3	GR, BG, RO, HU, HR, BE, NL, DE	PPC 56%, HEP grupa 84%, ENGIE 50%	25%

Historical versus estimated prices



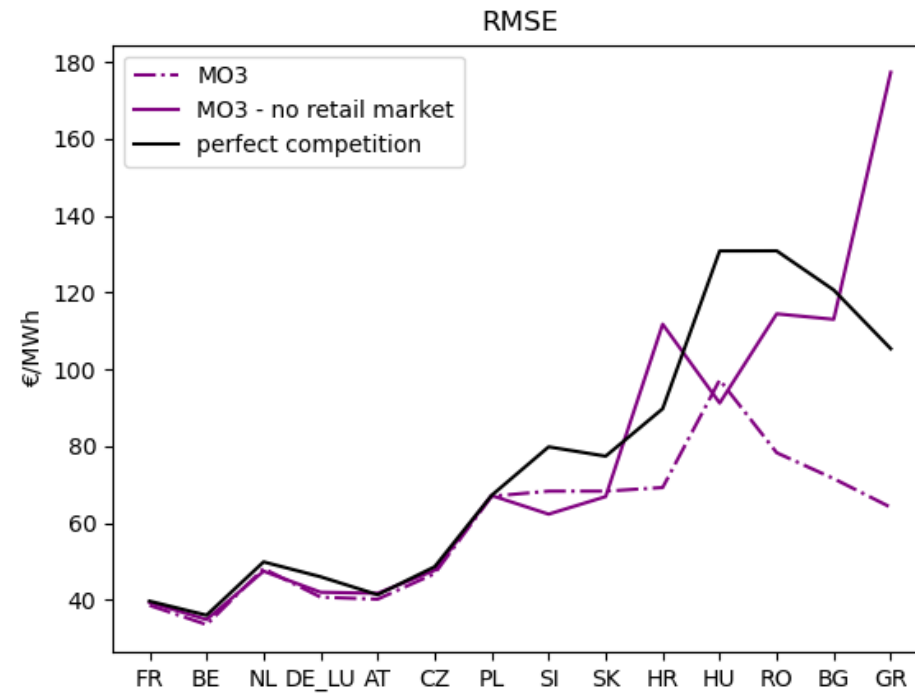
Takeaway: (Certain) strategic models much better at explaining historical outcomes compared to perfect competition

Historical versus estimated prices (II)



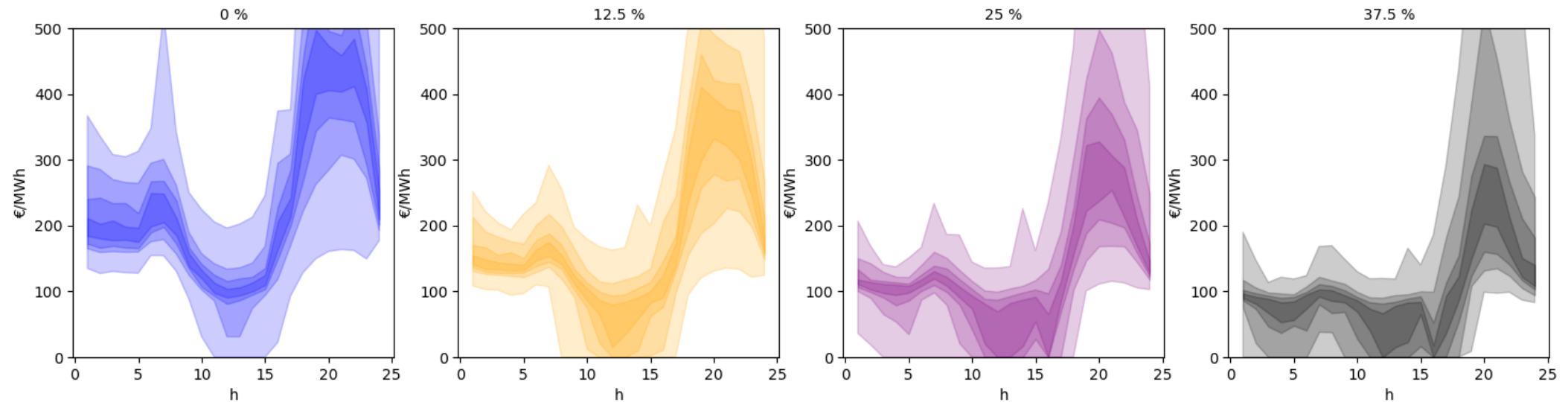
Takeaway: (Certain) strategic models much better at explaining historical outcomes compared to perfect competition

Role of retail market



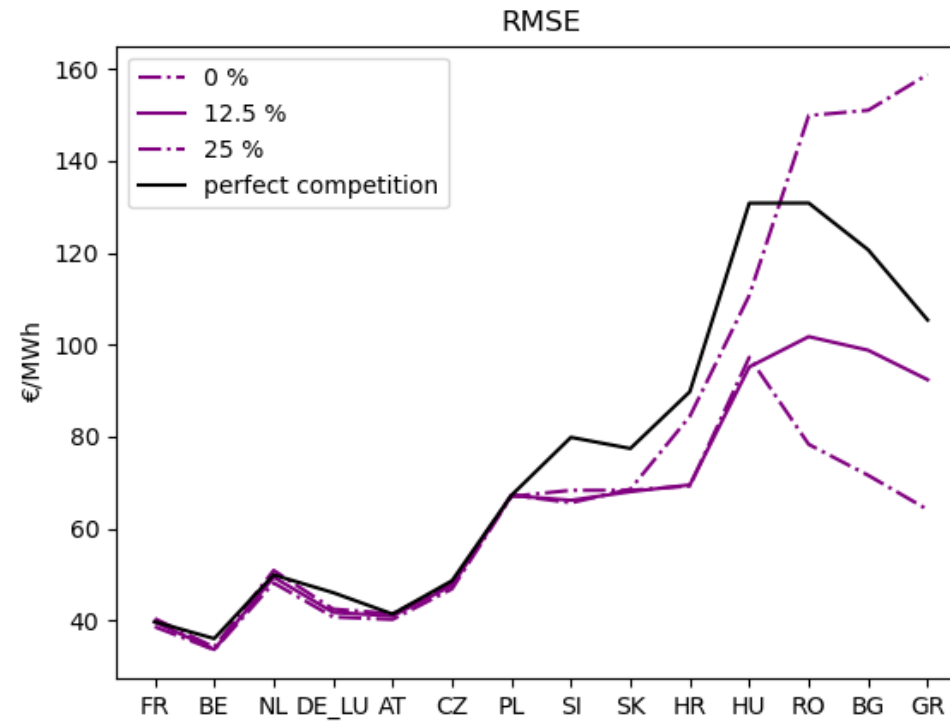
Takeaway: Assumption that strategic firm(s) serve retail load is crucial for accuracy of the model

Role of forward contracts



Takeaway: Degree of forward contracting of strategic firm(s) has strong influence on accuracy of the model

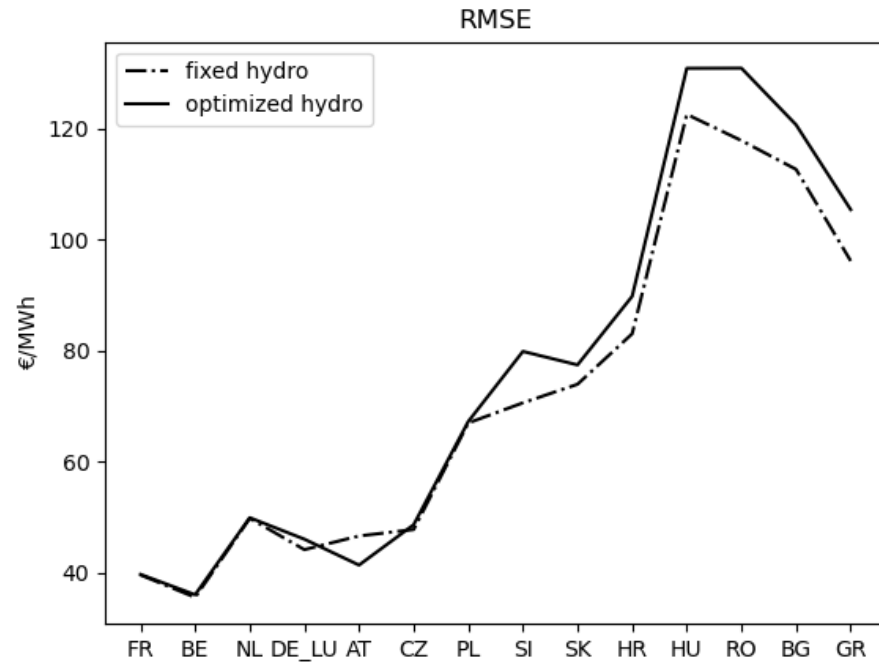
Role of forward contracts (II)



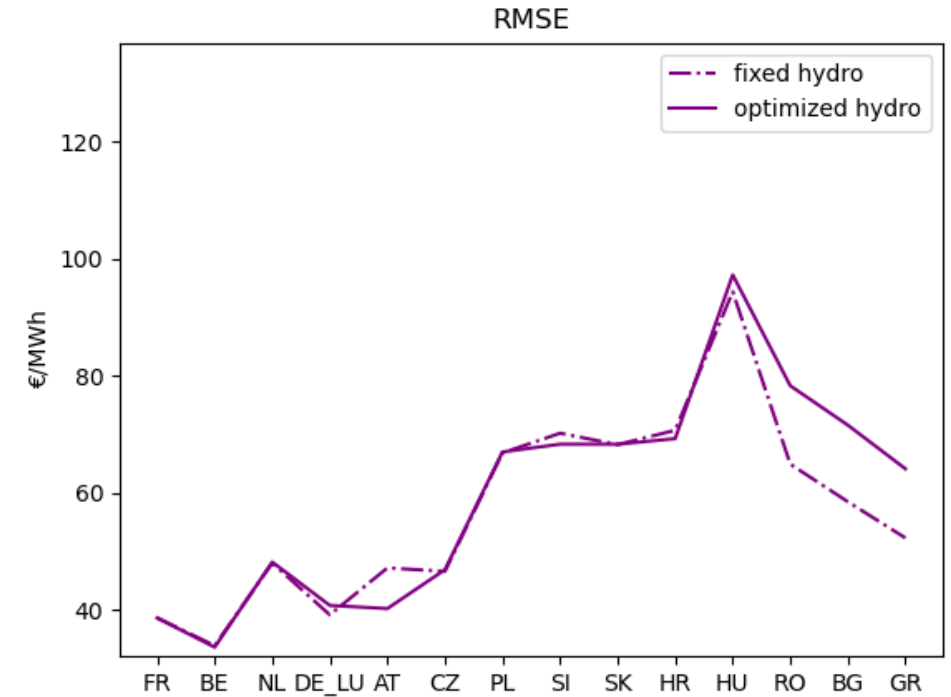
Percent corresponds to degree of forward contracting of strategic firms

Takeaway: Degree of forward contracting of strategic firm(s) has strong influence on accuracy of the model

Role of hydro



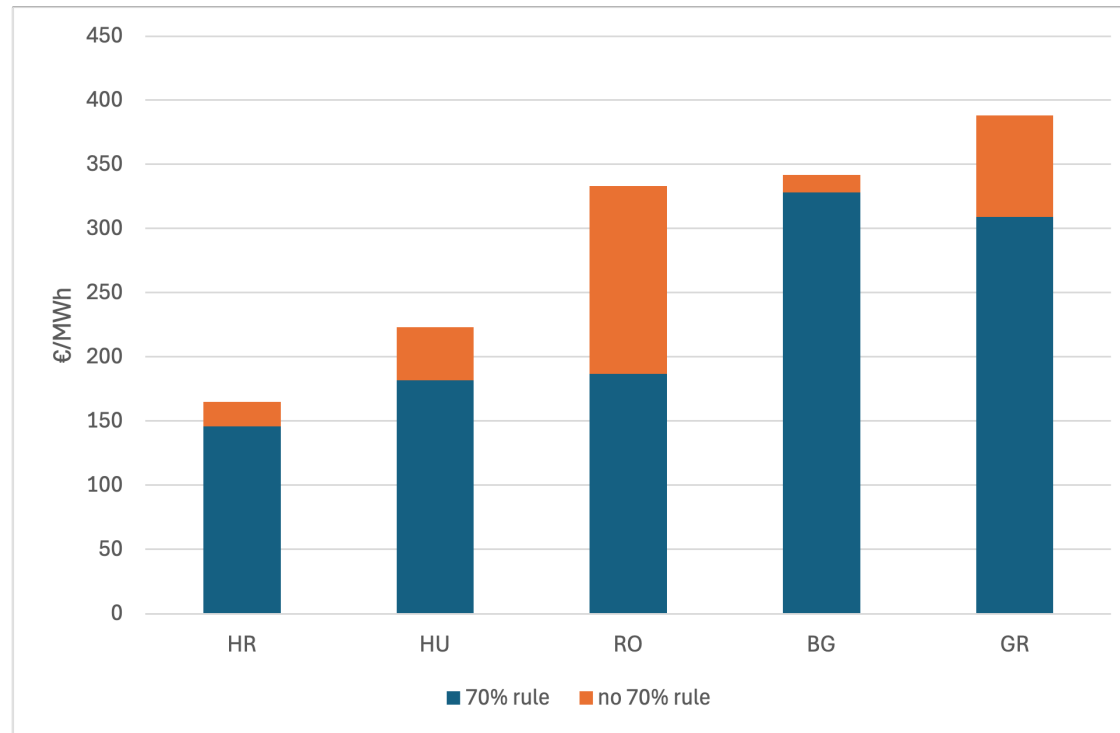
Perfect competition model with endogenous versus exogenous treatment of hydro



MO3 configuration with endogenous versus exogenous treatment of hydro

Takeaway: perfect competition worse at reproducing observed prices regardless of assumptions on hydro

Role of network availability



Takeaway: increased availability of RAM in CWE could have helped Eastern Europe (e.g. Greece), but not saved it

Conclusions

Conclusions

- A perfectly competitive market model fails to produce prices at the level of historically observed outcomes
- Not all strategic market organizations are better at aligning with historical outcomes, **but some are**
- The participation of strategic firms in the retail market and forward contracting can have appreciable effect on equilibrium outcomes
- Increased network availability, by full application of the 70% rule, would have helped but not solved the crisis

Thank you

Questions?

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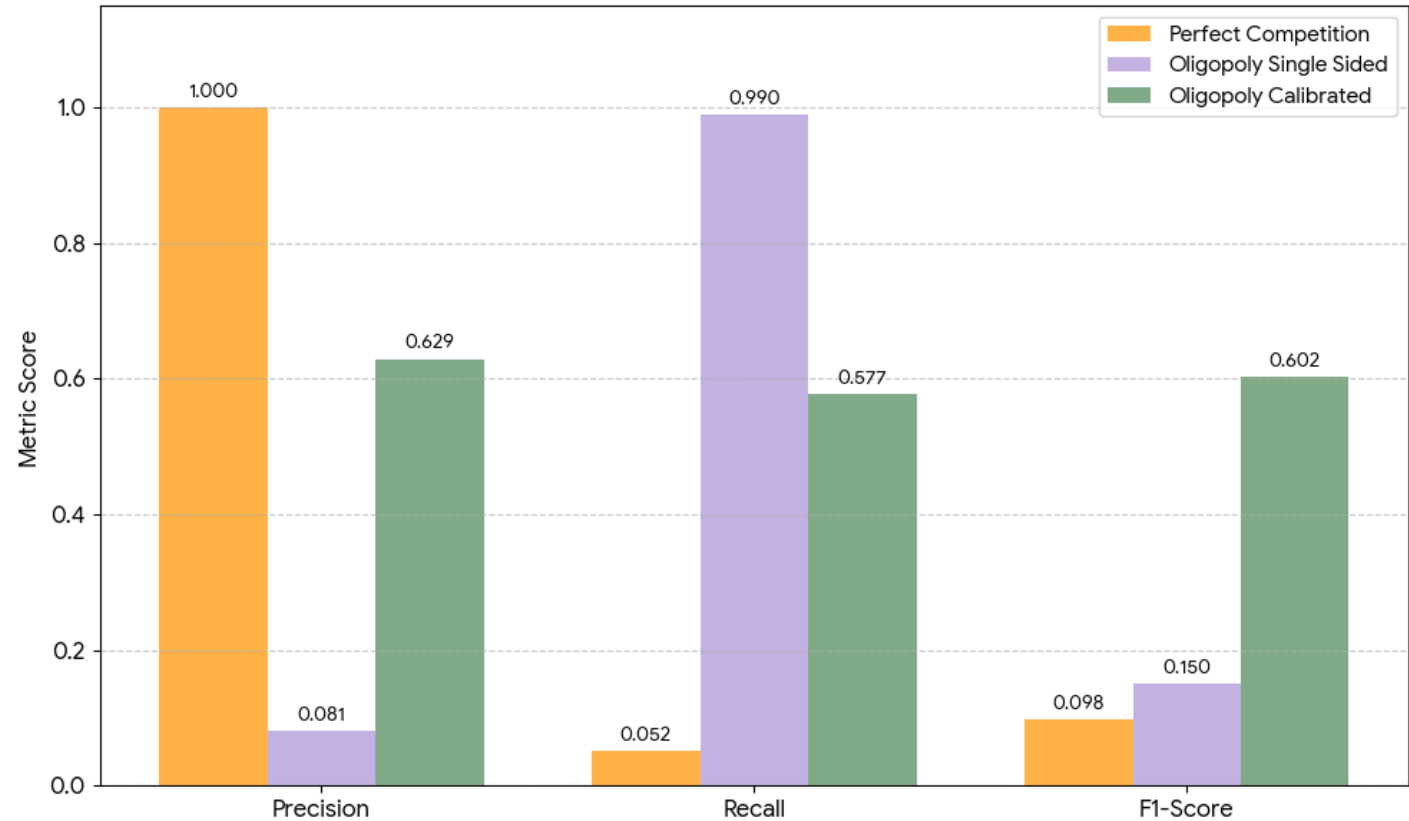
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Appendix

Regional Modeling: Crisis Classification Results

- **Perfect Competition:**
Shows perfect precision because it produced zero false positives, but it missed 92 of the 97 actual price spikes
- **Oligopoly Single Sided:**
Captures nearly all spikes with a recall of 0.990 but the results are filled with false positives
- **Oligopoly Calibrated:**
Shows the optimal balance among all tested models



Crisis classification results for threshold 300 €/MWh.

Definitions of recall, precision, F1-score

- Precision

$$P = \frac{TP}{TP + FP}$$

- Recall

$$R = \frac{TP}{TP + FN}$$

- F1 score: geometric mean of recall and precision:

$$F1 = 2 \frac{R \cdot P}{R + P}$$