Interdependencies between short-term electricity markets

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Overview (1)

- Motivation: Comparison of revenue potential of flexible capacities on intraday (IDM) and balancing energy (BEM) markets for Germany
- Modelling distributions of the German intraday price in the last 30 min before delivery (SDAT phase)
  - Literature focusses mainly on ID3 / ID1 window
  - Market is treated as one integrated pool
- SDAT phase largely ignored:
  - Structural break 30 min before delivery
  - Trading becomes control-area specific → no longer single market
  - Liquidity fragments heavily, very different in individual area
  - Possibly zero-trade intervals, no observable price at all

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Overview (2)

- But: Absence of trades ≠ absence of executable price
- Move analysis from realized transaction prices to executable prices derived from the order book
- Extract volume-weighted executable prices from bid and ask sides of reconstructed order book
- Concentrate on 15 min products; bid sizes 1 MW, 2 MW, …
- Model capacity as financial option (strike = variable generation costs)
  - Generation: Sell to bid
  - Consumption: Buy at ask
- Model revenues from BE activation

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Context: Project DigIPlat

- DigIPlat = Digital Solutions for Interoperability of Flexibility Platforms
- Consortium of research institutions and transmission system operators (funded by ERA-Net, see footer)
  - Development of new digital approaches for interoperability along the ICT, process-related, and economic dimensions
  - Standardized framework for interoperable platforms and flexibility requirements
  - Use cases for cross-border and cross-platform coordination of flexibility for redispatch, balancing energy, and intraday markets (focus on DACH region)

AIT Austrian Institute of Technology · APG · FICHTNER IT Consulting · KIT Karlsruher Institut für Technologie · THU Technische Hochschule Ulm · TRANSNET BW · University of St.Gallen Institute for Operations Research and Computational Finance

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DigIPlat: Economic Evaluation of Use Cases

- Aspect of interoperability: "All-rounder product"
  - Coordinated procurement of balancing power and redispatch (Zobernig et al., 2025)
  - Integration of bids for 15' products from the intraday market (IDM) order book into the bid list on the balancing energy market (BEM) before its gate closure
    → our focus for market area DE (liquidity, data availability)
- Bids on the IDM & BEM are not fully compatible from an economic perspective:
  - Will a bid on the BEM be accepted and then actually activated?
  - Different energy deliveries and compensation (IDM: traded quantity over a full 15 minutes; BEM: activation duration uncertain)
- Questions:
  - Supplier perspective: Are additional incentives needed (e.g., premiums) so that qualified suppliers allow the transfer of ID bids to the BEM?
  - Transmission system operator (TSO) perspective: Potential increase in the volume of available bids on the BEM?

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Short-term markets for flexibility

- Intraday Market (IDM):
  - Allows trading based on new information after the closing of the day-ahead market; 60' and 15' products
  - DE: Continuous trading from 3:00 PM (D – 1) until 5 minutes before delivery begins; SIDC until T – 60, trading within DE until T – 30, then only within the respective control area (SDAT)
  - Each transaction has its own price
- Balancing Energy Market (BEM) for Automatic Frequency Restauration Reserve (aFRR):
  - 15' product time slices each for positive & negative aFRR
  - Gate Closure at T – 25 (Auction): Awarded suppliers on the balancing capacity market must submit a bid; additional free bids are possible
  - Since June 2022: Bids are forwarded to the European PICASSO platform (December 2022: no release of unapproved bids), activation after merit order
  - Settlement of the delivered energy at the uniform price (CBMP)

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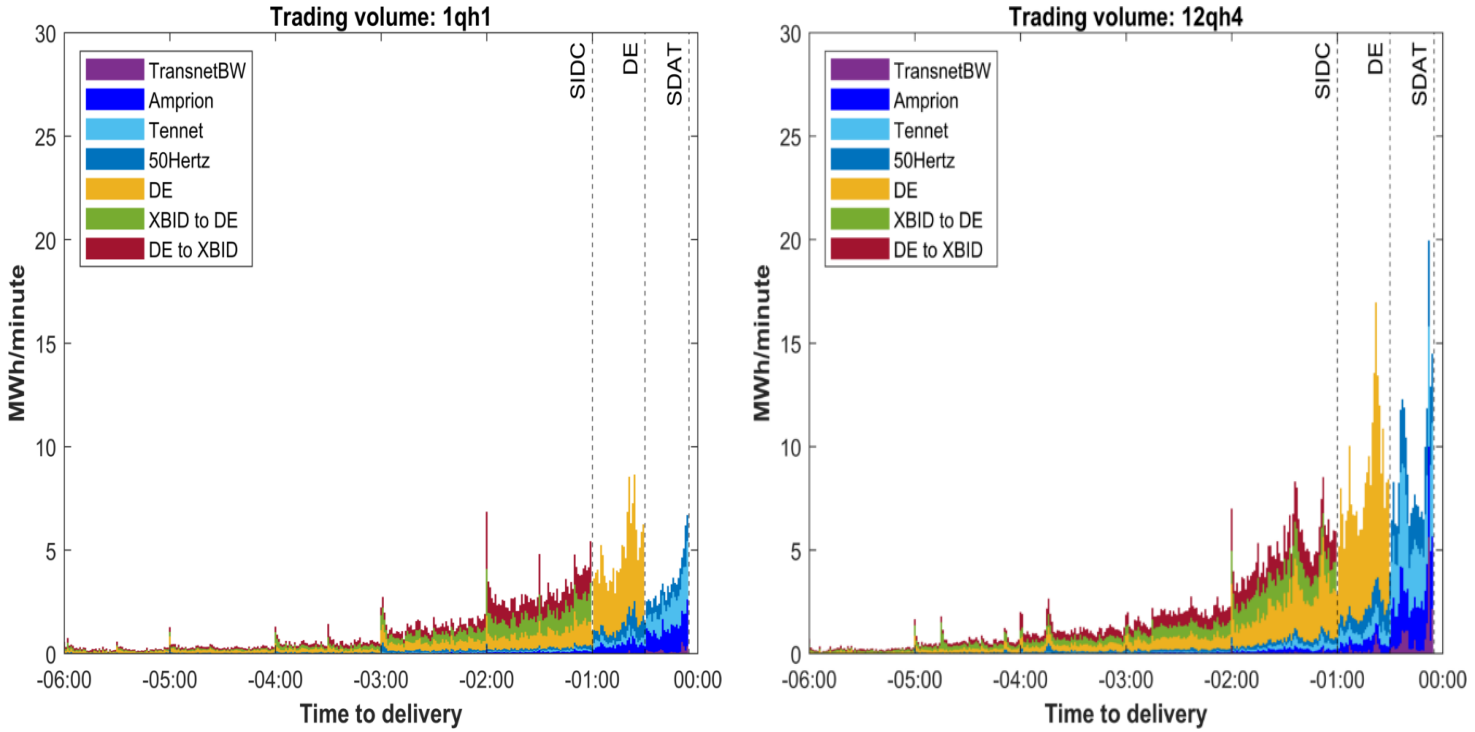
Trading volumes IDM (15 min products)

- Trading volume varies depending on the product and tends to increase significantly towards the end of the trading session.
- Three different trading phases:
  (1) SIDC
  (2) Trading within DE and
  (3) own balancing area (SDAT)
- Significantly different liquidity depending on the balancing area (trading volume, bid-ask spreads)
- In "illiquid" area possibly no transaction in last 30 min



Transaction volume per minute for a 15-minute product with delivery at night (00:00 – 00:15, left) and during the day (11:45 – 12:00, right) in the last six hours of trading. Colors correspond to the respective areas.

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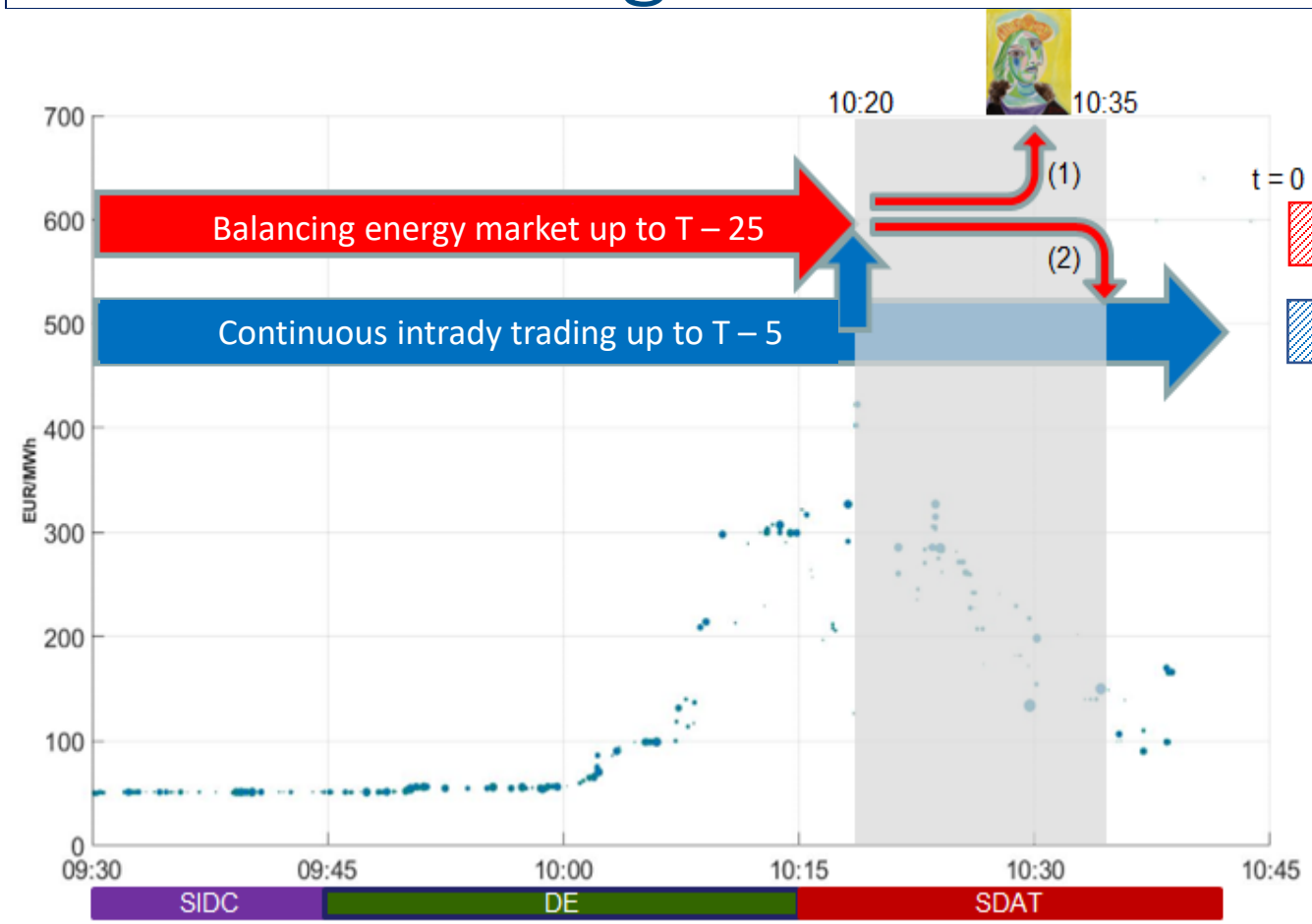
Use Case: Integration of IDM and BEM



t = 0

Delivery

Compensation uncertain
(duration, activated energy, price)

Delivery

If executed, compensation at transaction price for full 15'

BEM as an additional trading option, however, no participation in ID trading between GC on BEM and publication of the considered bids.

(1) Original bids from BEM are forwarded to the European Picasso platform.

(2) Unsuccessful bids that were taken over by IDM are returned there ("release") and can be traded there during the remaining trading time.

- *Incentives required to transfer bid IDM → BEM?*
- *Potential increase of free bids at BEM?*

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Bids BEM (aFRR) after go-live PICASSO

Currently, for positive and negative reserve energy, the maximum price of ±15,000 EUR/MWh is practically always offered in the last considered bid, i.e., every lower bid is automatically considered.
⇒ No option from the release of unsuccessful bids from the IDM.

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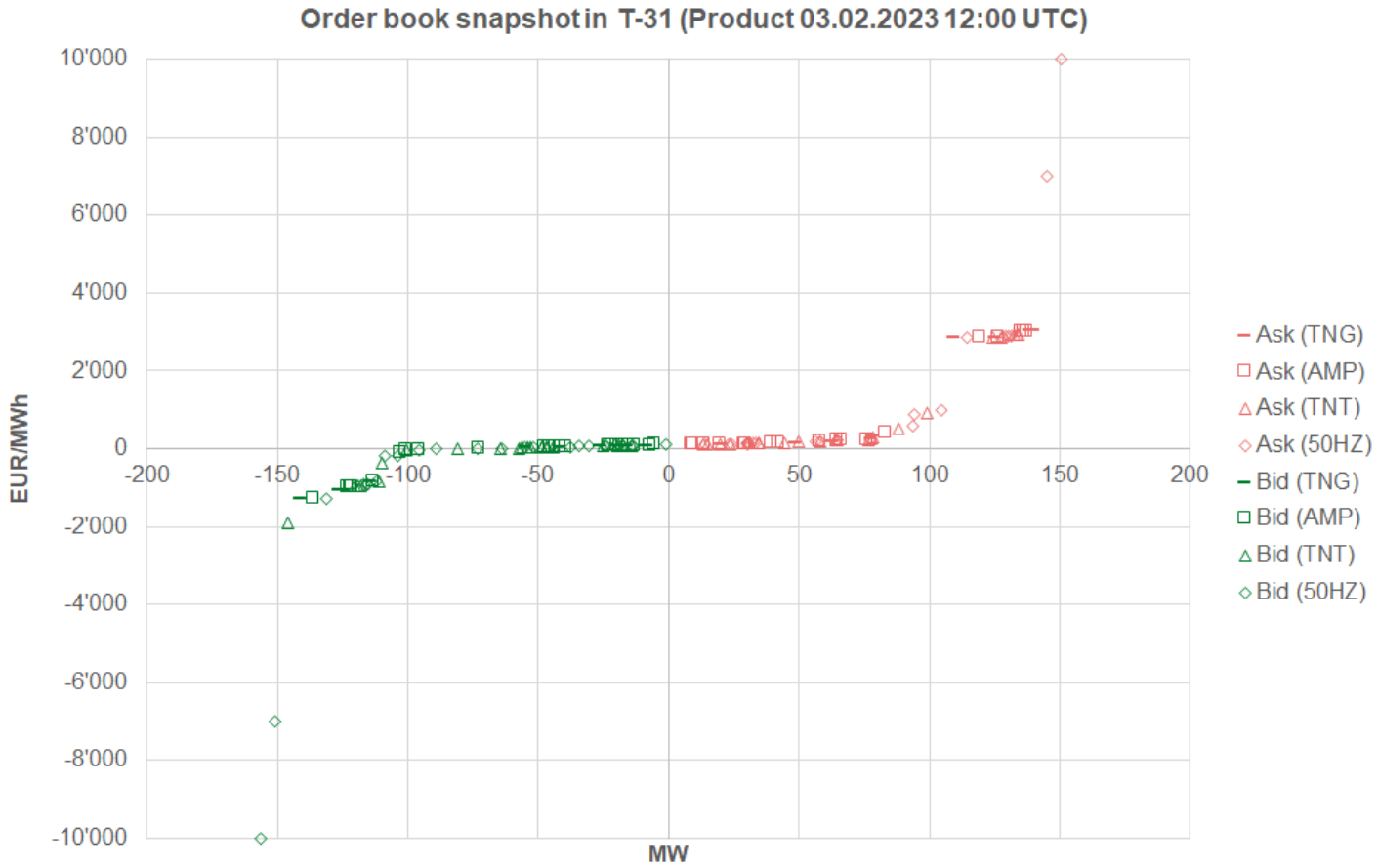
Market liquidity and order book depth: DE



- Order book shapshots in 1' intervals were constructed from all bids in 2023 for the market area DE (42 GB data); this resulted for the SDAT phase in 43 million data points
- Order book depth = cumulated volume of buy or sell orders
- Relevant for buying and selling of a certain amount X
- An effective transaction price results from the volume-weighted ask- or bid prices of those "best" bids whose cumulated volume equals X

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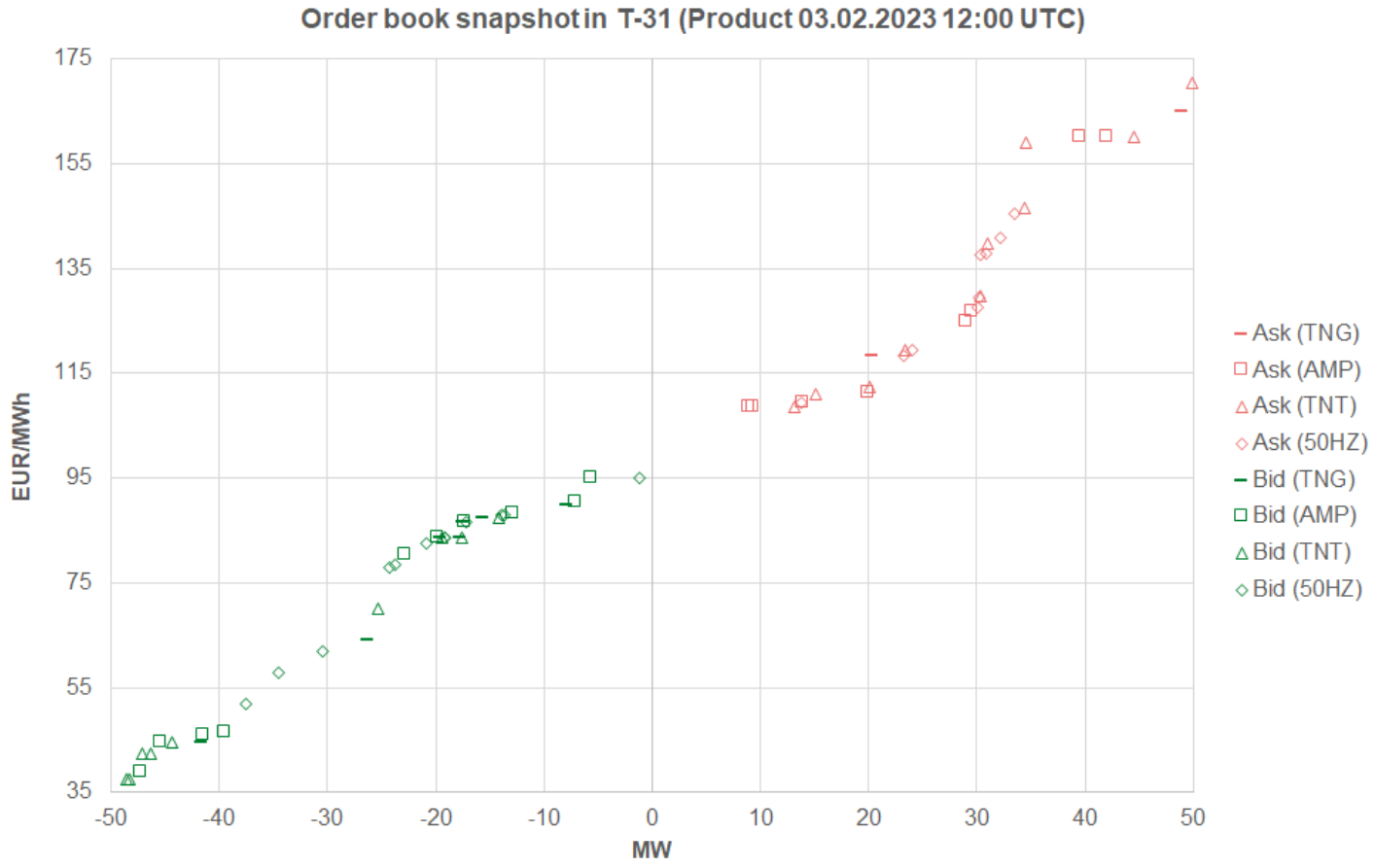
Market liquidity and order book depth: DE



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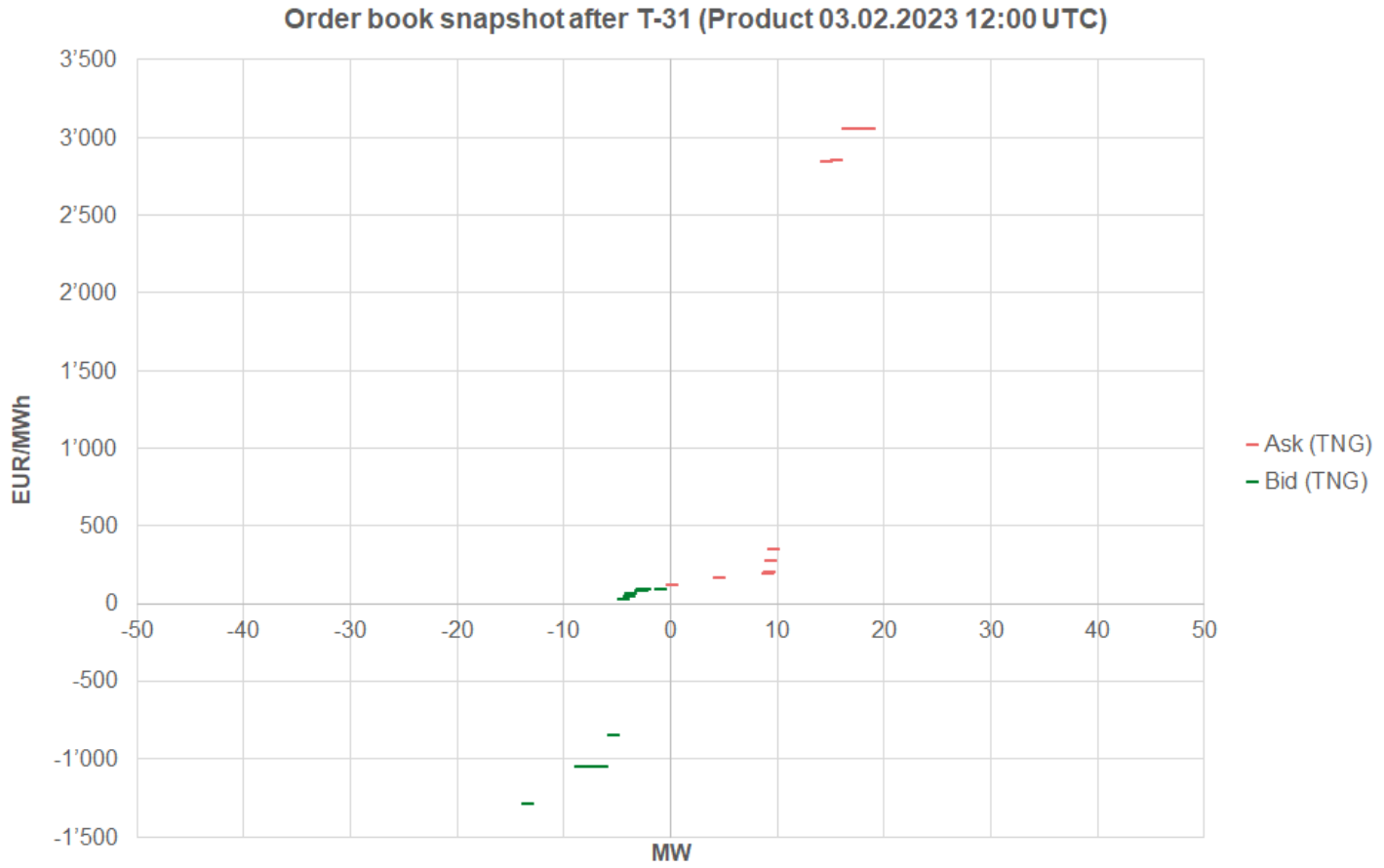
Market liquidity and order book depth: TNG



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Bid-Ask-Spreads [EUR/MWh] in [T – 25, T – 5)

Tennet/TNT control area (2023)

time to delivery (min)	Time of day (hours) [0,6)	[6,12)	[12,18)	[18,24)
25	16.32	15.45	16.42	21.79
24	16.40	17.00	17.76	22.82
23	16.50	18.09	18.29	22.26
22	14.66	17.91	16.98	21.07
21	14.62	17.82	16.80	20.43
20	15.22	19.39	17.60	21.94
19	21.14	24.88	23.72	28.38
18	21.27	24.05	24.65	27.90
17	19.66	20.49	22.20	26.25
16	20.22	21.07	22.85	27.20
15	20.93	20.92	22.09	26.32
14	14.92	14.38	15.55	17.82
13	13.79	13.54	14.30	15.35
12	11.70	11.58	11.85	11.97
11	11.80	11.56	12.29	13.37
10	11.67	13.37	14.03	14.65
9	16.17	17.83	19.33	18.68
8	15.78	18.24	17.68	19.06
7	14.20	18.00	18.04	16.78
6	21.32	26.44	27.52	27.54

TransnetBW/TNG control area (2023)

time to delivery (min)	Time of day (hours) [0,6)	[6,12)	[12,18)	[18,24)
25	81.28	61.36	67.86	96.09
24	87.86	70.47	75.82	104.92
23	87.84	66.31	70.09	105.40
22	77.79	57.81	63.46	86.27
21	70.56	53.87	60.12	83.16
20	67.62	53.34	57.39	82.07
19	186.19	141.02	155.05	213.73
18	187.52	136.54	154.89	213.84
17	162.89	117.09	126.39	182.67
16	160.02	114.01	124.56	173.37
15	157.66	111.70	123.02	167.90
14	285.40	210.46	218.22	296.05
13	264.99	191.05	198.67	269.10
12	198.56	142.91	151.70	195.63
11	183.37	134.69	139.86	178.65
10	183.84	135.27	141.09	179.06
9	247.01	172.44	185.05	244.73
8	188.15	131.80	143.15	186.91
7	171.36	114.58	126.59	164.93
6	170.55	116.73	129.18	166.24

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Comparison revenues IDM vs. BEM

- Flexible capacity offered in the last 25' before delivery at IDM or BEM at variable costs (assumption: gas-fired plant)
- Trading volume 1 MW (increase or decrease of generation)
- Different market liquidity in SDAT phase depending on balancing area implies different revenue potential at IDM
- Ex-post calculation of potentially realizable revenues from volume-weighted bid- and ask-prices of derived order books (historic data for 2nd half of 2023):
  - Selling, if ID price (bid) > variable costs
  - Buying, if ID price (ask) < variable costs
- Comparison with revenues from aFRR activations:
  - Provision of positive balancing energy, if CBMP > variable costs
  - Provision of negative balancing energy, if CBMP < variable costs

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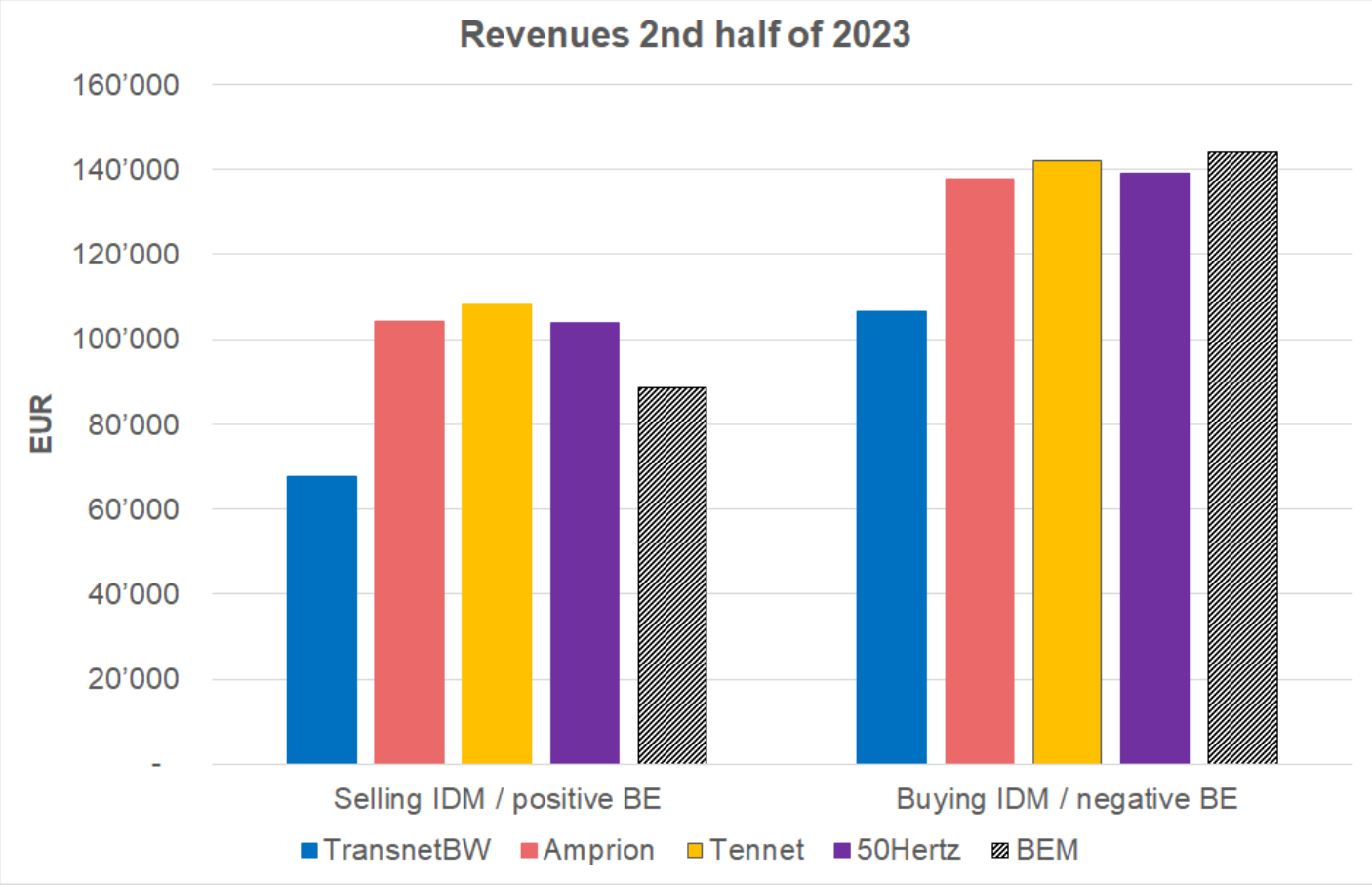

- A limit order / bid is placed in the last 25' either at the IDM or the BEM
- Potentially realizable revenues in both markets comparable (exception: illiquid TransnetBW area)
- IDM and BEM similarly attractive
- Providers would have been indifferent in which market they place a bid (or if a bid is transferred to the BEM or remains in the IDM)
- What if a provider bids in the market that appears *currently* more attractive?
- Model-based approach (valuation of both alternatives as financial options)

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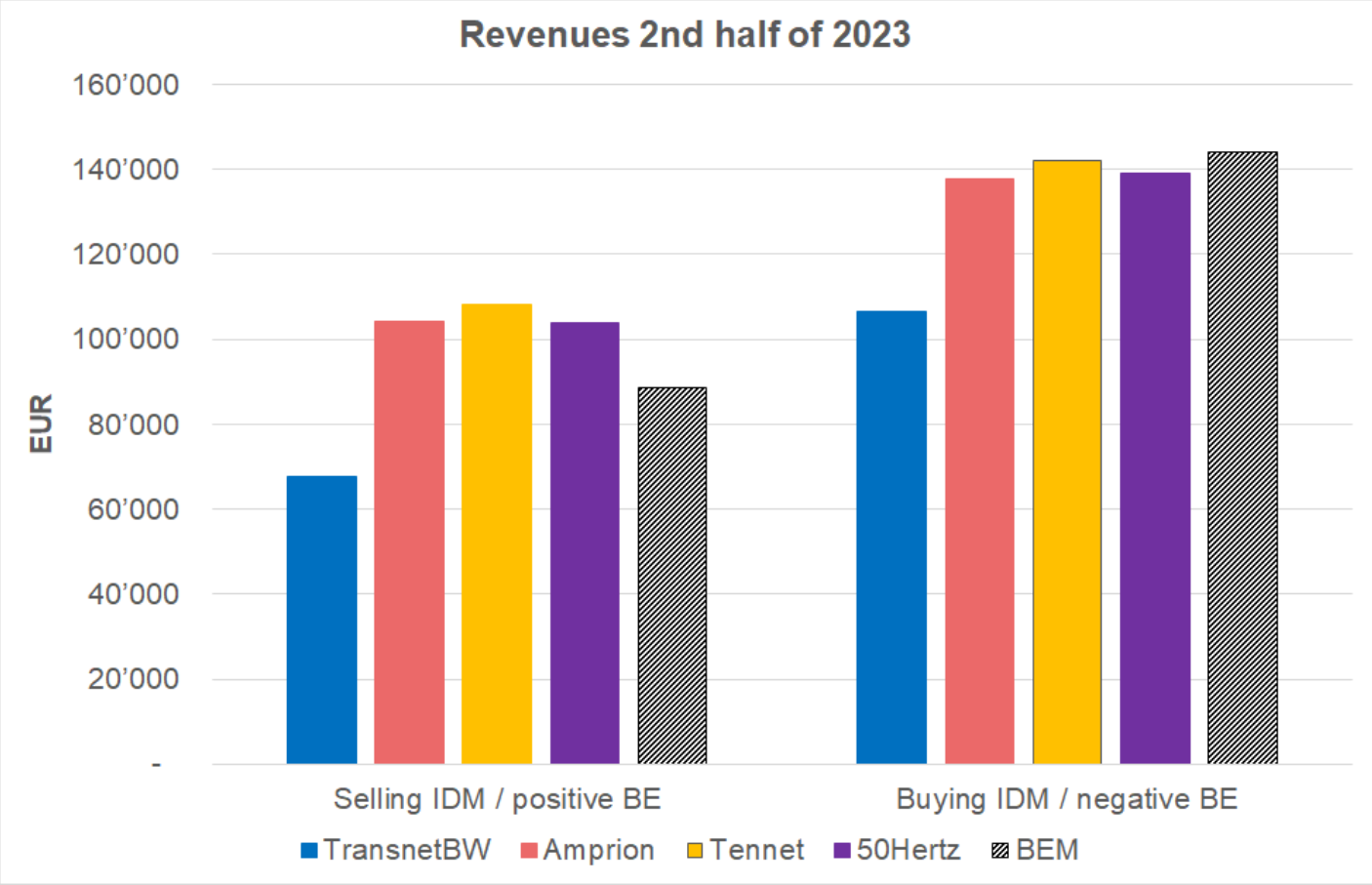

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Valuation as financial options

- Idea: Flexible capacity is comparable to a financial option that is "in the money" when the market price exceeds the strike price X (= variable generation cost) for a call option (the opposite for a put option).
  - Value the 15-minute option product on the intraday market (IDM).
    - Expected value (μ) = VWAP of previous 15' trading period, adjusted for historical spreads.
  - Compare with the option value on the balancing energy market (BEM): 225 options with delivery over 4-second intervals (frequency of activation signals).
    - Expected prices (μ) = last known mean CBMP values at activation of POS or NEG (publication with a 15-minute delay).
- If a bid at the BEM is not awarded, one would receive a short-term option on the IDM; this is disregarded (all bids better than ±15,000 EUR/MWh are accepted).
- Offer in the market with the higher option value.

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Valuation as financial option (IDM and BEM)

- Normally distributed prices imply use of Bachelier-type formula[1)]
- Call option: Sale of energy from increased production when the market price exceeds marginal costs (strike X):

$$V_C = \int_{-\infty}^{+\infty} \max(p - X, 0)\, f_p(p) dp = \cdots = \sigma(d\Phi(d) + \phi(d))$$

- Put option: Repurchase of energy and reduction of production when the market price is below marginal costs (strike X):

$$V_P = \int_{-\infty}^{+\infty} \max(X - p, 0)\, f_p(p) dp = \cdots = \sigma(\phi(d) - d\Phi(-d))$$

- $d = \frac{\mu - X}{\sigma}$; Φ, ϕ cdf. /pdf. standard normal distribution

[1)] See also Weber (2015) and BDEW guidelines for the remuneration of redispatch (2018) with opportunity costs from the ID1 price

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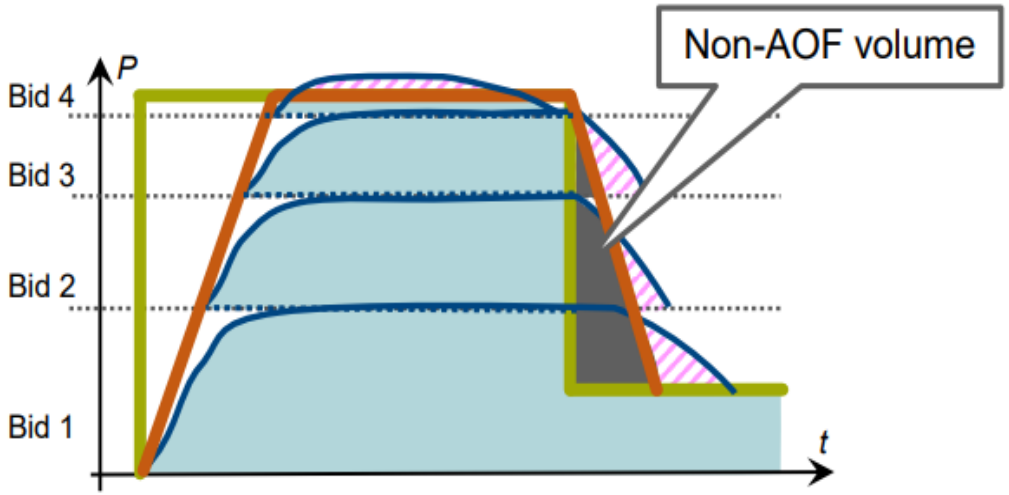
Compensation balancing energy

- Due to the respective ramps, the providers follow the activation signal of the PICASSO platform with a delay (within predefined tolerance bands).
- Only provided energy is compensated at the maximum of cross-border marginal price (CBMP) of the PICASSO platform and the bid price.



Assumptions for calculating option values:

- Provider can adjust performance immediately (according to the Activation Optimization Function, AOF).
- Only CBMP at the time of an activation in German control areas is considered for evaluation.
- A new signal is calculated by the AOF every 4 seconds.
- Volatility is derived from the fluctuation of CBMP around the mean of the corresponding interval.

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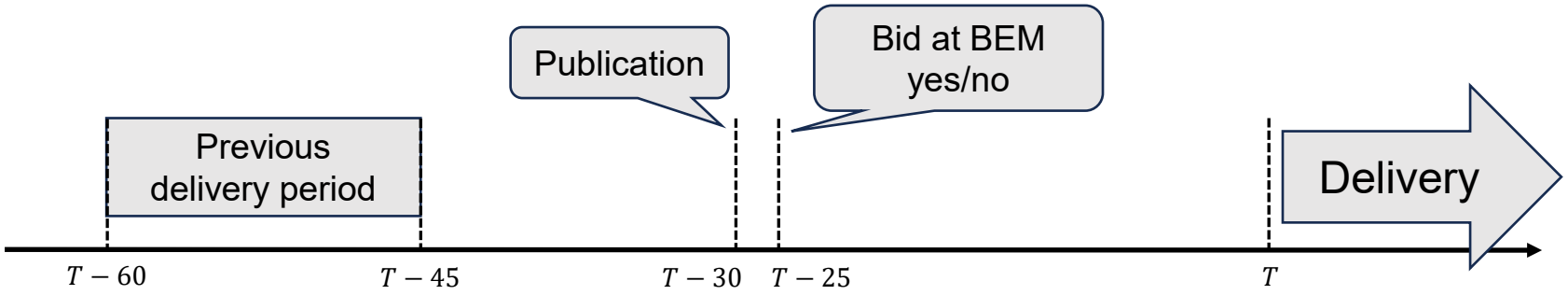
Assumptions for modelling BE option

- We need a forecast model for the duration of activation (percentage of the 225 options that are exercised during the 15 min period):

$$P_T^{act,+} = c^+ + a^+ \cdot P_{T-60}^{act,-} + b_1^+ \cdot P_{T-60}^{act,+} + b_2^+ \cdot P_{T-120}^{act,+}$$
$$P_T^{act,-} = c^- + a^- \cdot P_{T-60}^{act,+} + b_1^- \cdot P_{T-60}^{act,-} + b_2^- \cdot P_{T-120}^{act,-}$$

- Low coefficient of determination (≈12%)



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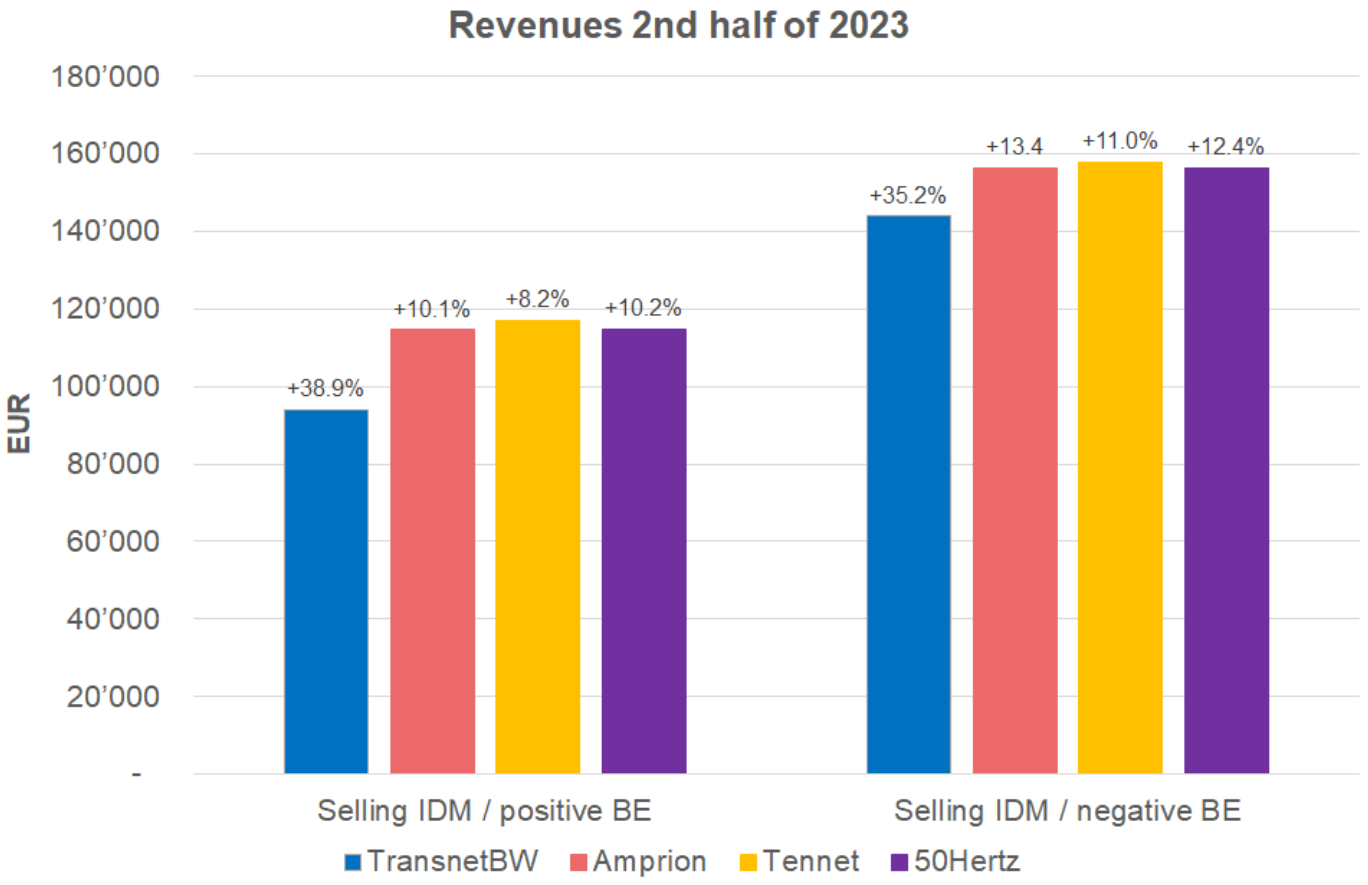
Revenues combined strategy IDM & BEM



- Bid in market with higher option value
- Model parameters from historical data, 1st half of 2023
- Determination of revenues with realized prices for 2nd half of the year (volume-weighted bid/ask prices IDM; CBMP for balancing energy)
- Figures above the bars show change compared to ID trading only
- Improvement in generation (selling at IDM, positive BE) and consumption (buying at IDM, negative BE), in particular in "illiquid" region

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Summary

- Model-based approach for deciding which market to offer
- Value of flexibility is modeled analogously to a financial option
- Concentration on SDAT phase with trading in individual control areas
  - Realized transaction prices often unavailable
  - Use of executable prices derived from order book
    → synthetic prices at which 1 MW, 2 MW, … could be traded
  - Economically more relevant for power plant to monetarize output is not an observed midpoint price, but price at which a certain volume can be bought or sold, conditioned on area, prevailing order book depth and bid-ask spread

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Outlook

- Combined bidding leads to higher revenues than acting in one market only → model is economically meaningful despite its simplicity
- Normality assumption as convenient start, but optimistic in fragmented markets with large spreads (skewness, fat tails, …)
- Ad-hoc approach for volatility estimation intraday price:
  For each product, variation of executable prices around adjusted VWAP during calibration period
- Volatility may depend on level of liquidity, fundamental factors, …
- Choice of test period 2023 due to availability of order book data, extension to other periods outstanding

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Appendix: Assessment of use-case

- Use case: Integration of IDM bids into the BEM bid list, considered from the perspective of providers and grid operators
- Revenue opportunities in both markets are comparable; suppliers should be indifferent as to whether their bid is passed on to the BEM or remains in the IDM
- By transferring bids from the ID order book to the BEM, its merit order would shift to the right, thus potentially reducing the costs of balancing power
- Potentially available volume is lower than available bids on the RAM; the assumption that all bids >= 1MW are prequalified is rather unrealistic
- The attractiveness of the RAM would decrease due to lower compensation for activations; likewise, the liquidity of the IDM would decline

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Appendix: Fundamental model ID price – variables

- ID prices: aggregated to 1 min time steps (volume-weighted averages)
- Distinction between time to delivery, not products!
- aFRR activation: second-based values from regelleistung.net, aggregated to 1 min
- mFRR activation: sum of values reported by all TSOs (assumption: signal comes 12.5' before 15' delivery period)
- aFRR publication: known 9' after end of 15' delivery period
- mFRR publication: known 0' after end of 15' delivery period
- Control area balance (TSO publication): known 15' after end of 15' delivery period
- Symmetric imbalance price (TSO publication): known 15' after end of 15' delivery period (NEW)
- Solar/wind generation (TSO publication): known 60' after end of 15' period
- Load (TSO publication): known 45' after end of 15' period
- Errors for solar/wind/load are differences to day-ahead forecasts
- Intraday-updated forecasts of wind & solar generation unavailable for 2023

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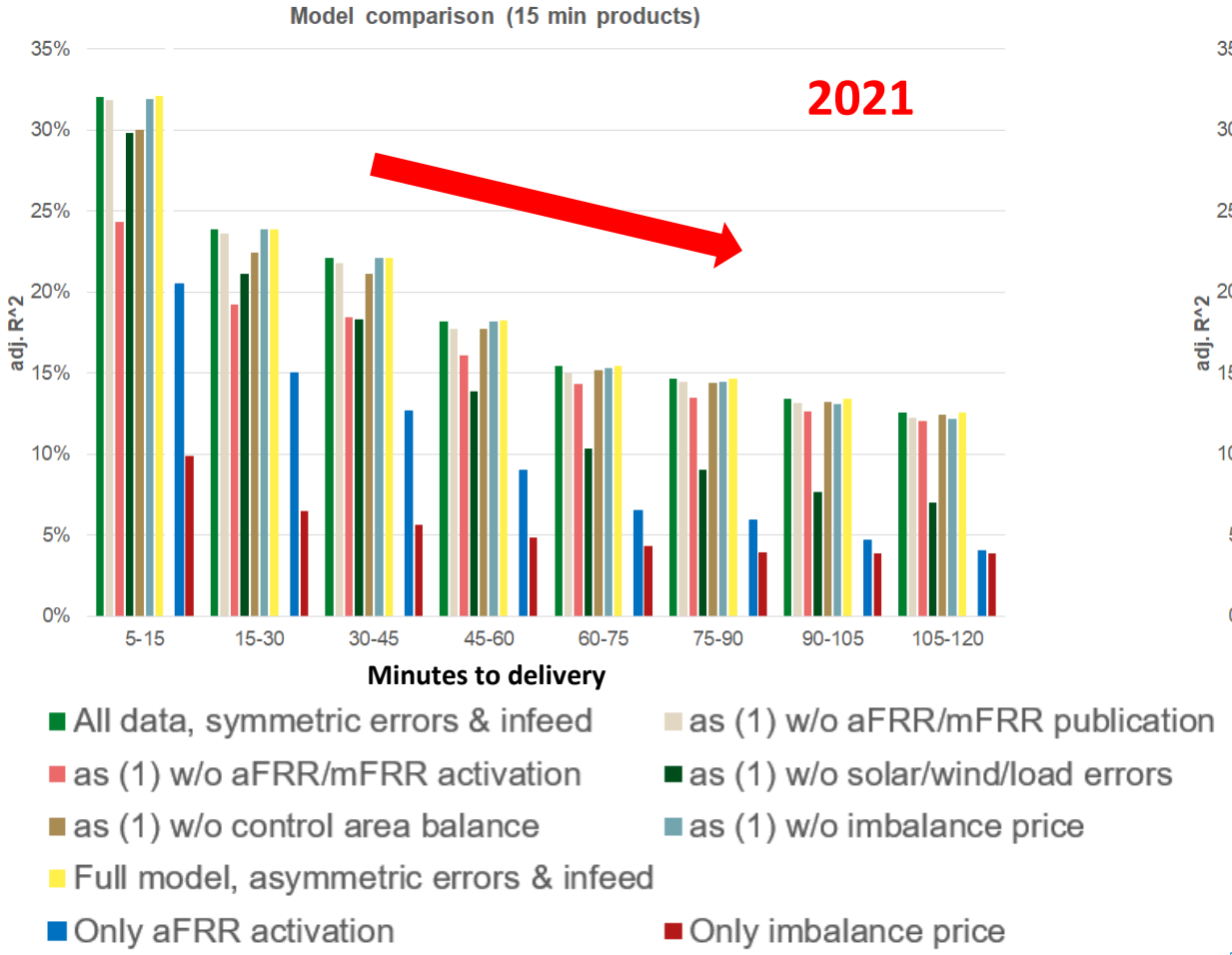
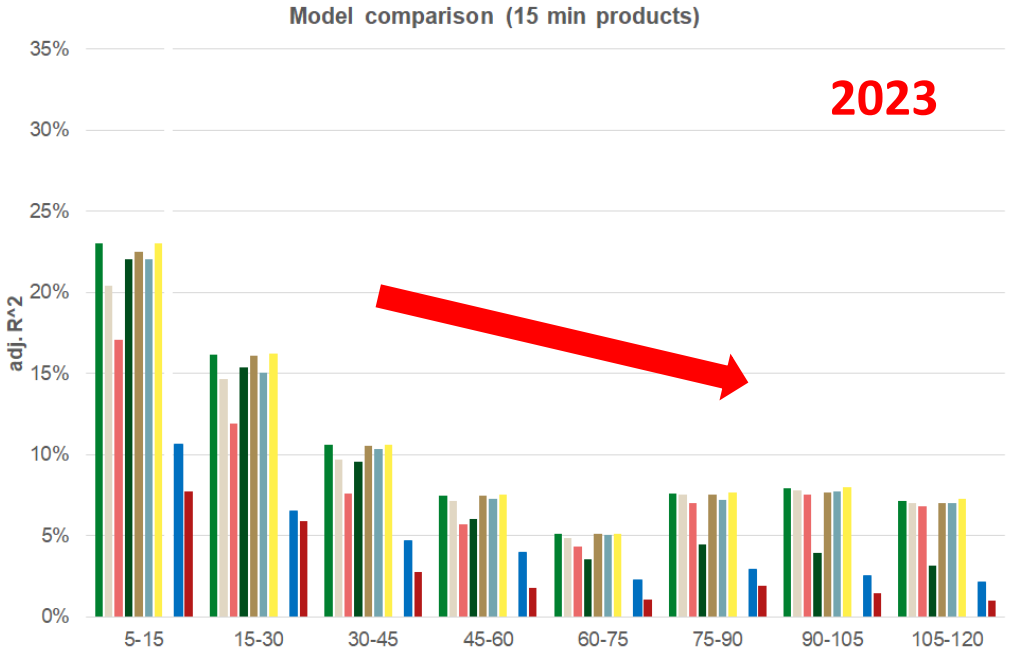
Appendix: Comparison of model specifications





- Overall lower explanatory power in 2023, also for the model versions aFRR activation is left away
- New variable "imbalance price" alone had higher explanatory power in 2021, but it seems to contribute more than control area balance in 2023

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Appendix: Comparison of model specifications

- 15 min products: Higher explanatory power for front products. Their price is more sensitive to new information on the "system state"
- Higher explanatory power in 2021 than 2023, this holds also for model variants where aFRR/mFRR activation are removed and only the publicly available variables are used
- Removing aFRR/mFRR publication does generally not reduce R^2 much
- Removing control area balance reduces R^2 for front products in 2021, but not in 2023. Vice versa for the imbalance price

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Appendix: Background

- 2021 and 2023 show similar control area balance deviations, which can be seen as proxy for reserve energy demand
- However, the activated reserve energy volumes activated reported by German TSOs have decreased significantly

	2021		2023	
	POS	NEG	POS	NEG
Total annual aFRR activation [MWh]	850'715	834'019	624'360	763'708
Tutal annual mFRR activation [MWh]	105'782	54'717	44'483	16'366
Avg. absolute control area balance [MW]	339.64		364.86	

- Effect of more efficient netting and cross-border exchange?
- Given the initial hypotheses, less activations mean also that (large) market participants receive fewer price signals

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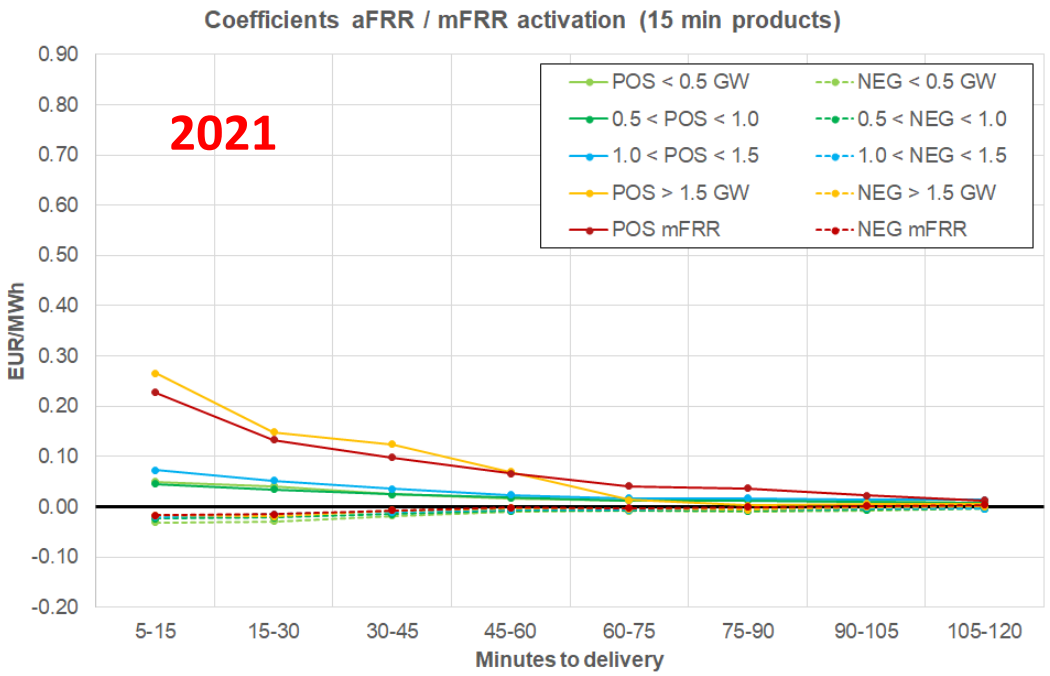
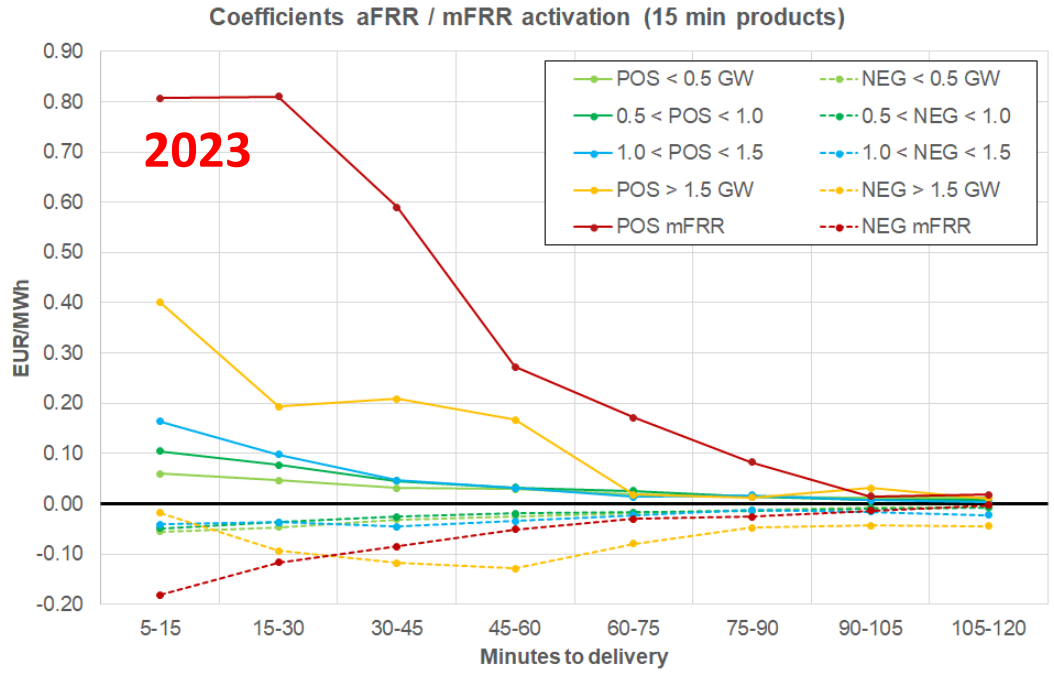
Appendix: Estimated coefficients (15' products)





- Large sensitivity w.r.t. aFRR activation (POS), e.g., a coefficient of 0.27 means that an activation of 1500 MW increases the ID price ≈ 400 EUR/MWh

- Also, large impact for mFRR activation (POS)
- Price sensitivities for NEG activation much smaller
- Note: Coefficients of front product more than twice larger then for hourly products

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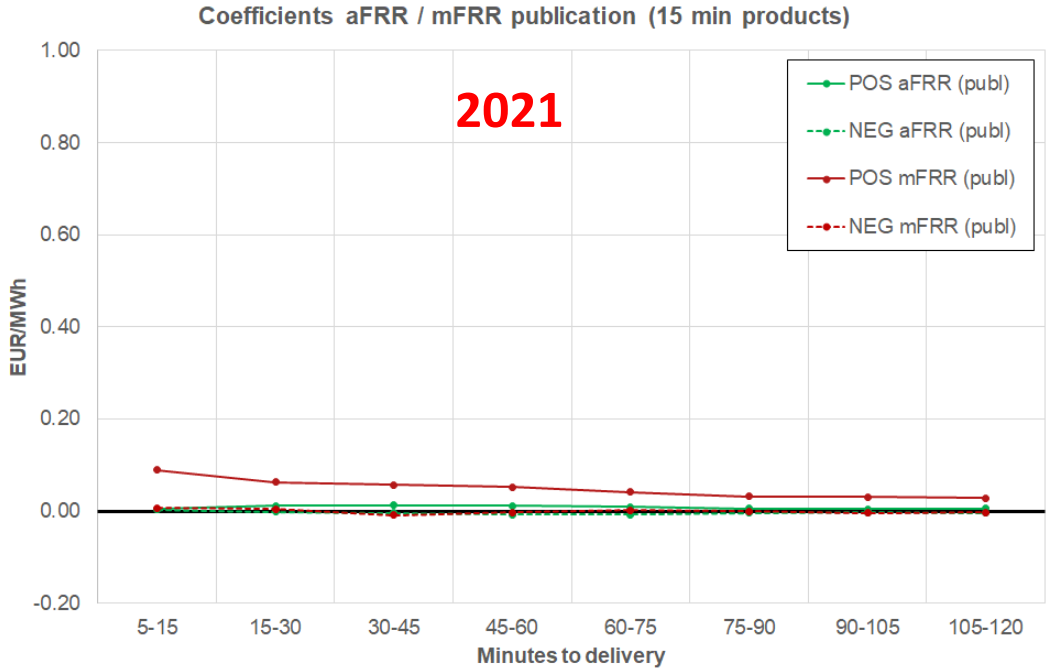

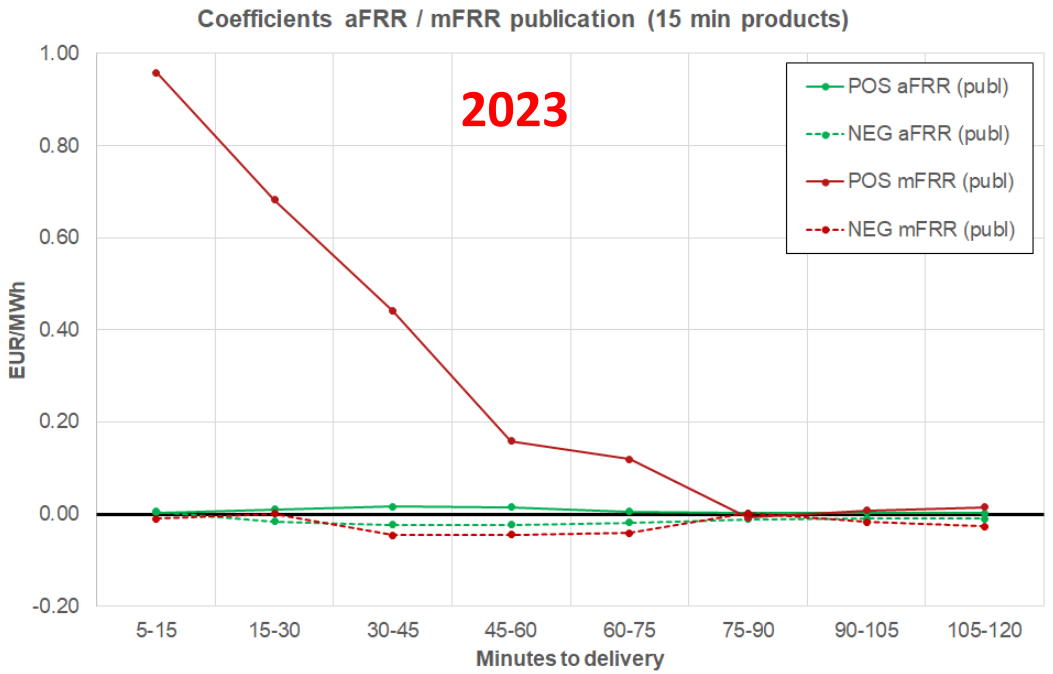

- In 2021 much smaller sensitivities w.r.t. publication of aFRR/mFRR activation (POS)
- NEG activation insignificant (aFRR) or inconclusive sign (mFRR), but large errors!

- In 2023 enormous increase of sensitivity w.r.t. publication of mFRR activation (POS)

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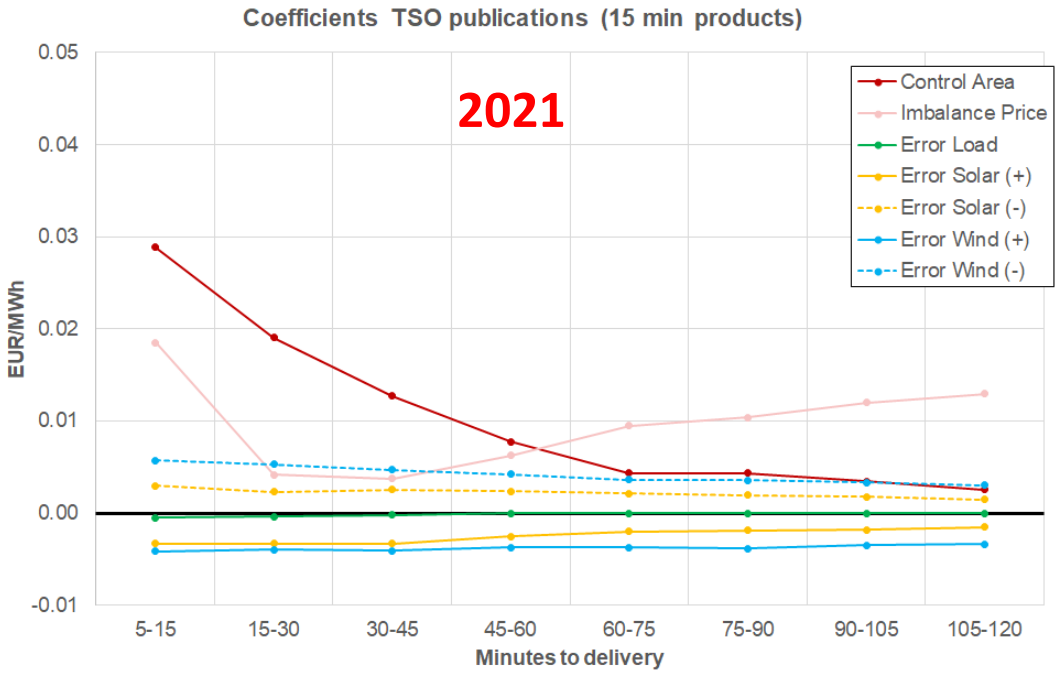

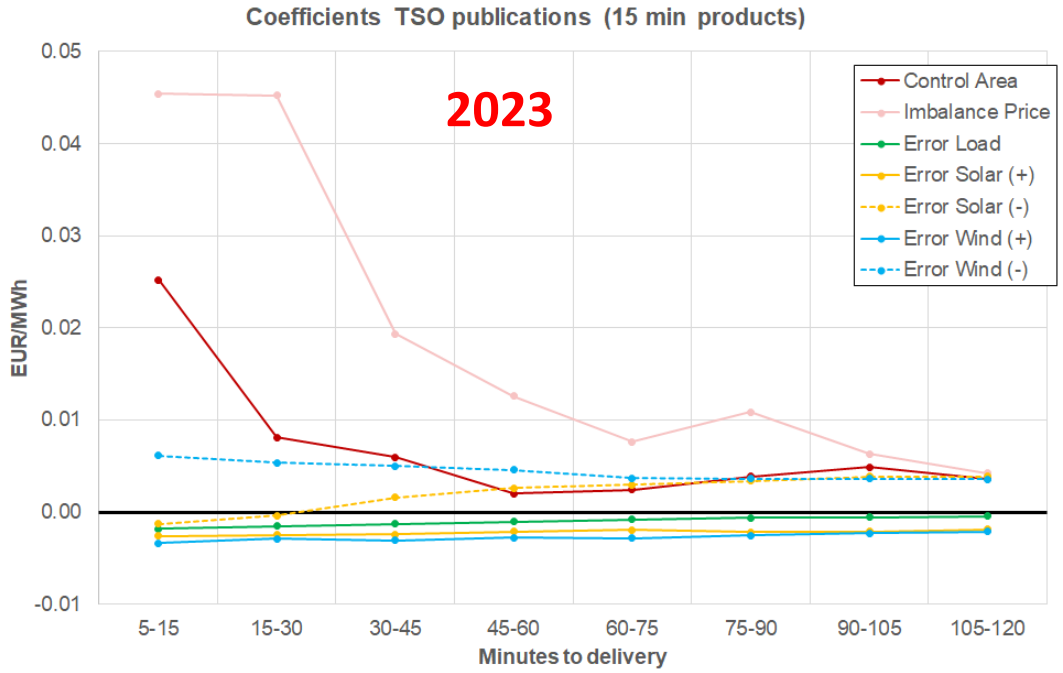

- Overall smaller impact of TSO publications
- Largest for control area balance (no distinction between direction, magnitudes would be similar)
- Behavior of imbalance price coefficient not conclusive in 2021

- Impact of errors of wind and PV infeed not changed, load error insignificant
- In 2023, mut higher sensitivity w.r.t. imbalance price, see also adj. R^2s

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Appendix: First interpretation

- Reduction in R^2 from 2021 to 2023 because considered factors from use of reserve energy contribute less to the explained variation
- After the introduction of PICASSO, German market participants receive less price signals from reserve energy activations as also foreign BSPs entered the market, less reserve energy is activated overall
- The higher sensitivities w.r.t. reserve energy use mean that if there is an activation, then the system is "more unbalanced" in 2023 than it was in 2021 for a comparable activation
- This applies in particular to mFRR, because if less aFRR is needed, then activations of mFRR occur even more rarely and in "more extreme" situations
- The calculation of control area has changed in 2023; possibly therefore the imbalance price provides better signals on deviations in the system

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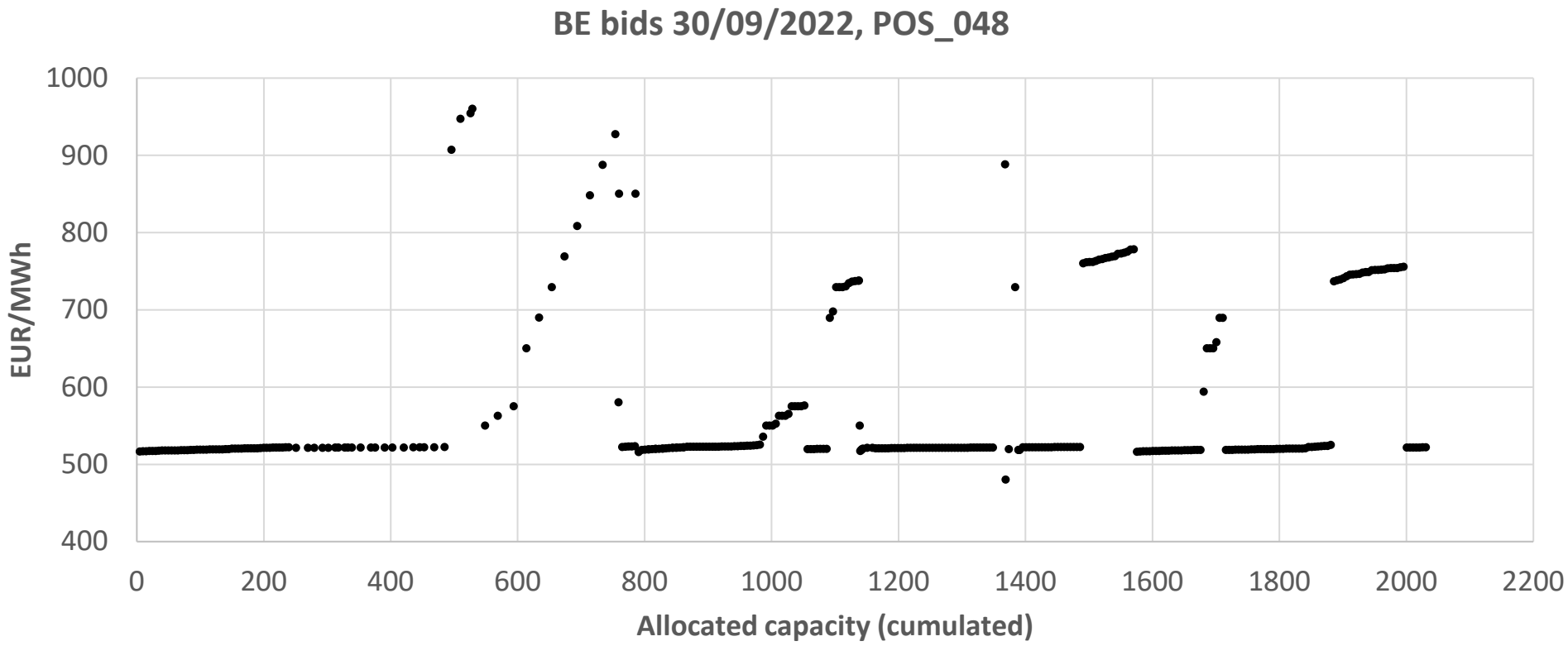
Appendix: Concentration at BEM



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