University of St.Gallen

Executable-Price-Based Valuation of Flexible Generation Assets in Fragmented Intraday Electricity Markets

Michael Schürle, University of St. Gallen

15th INREC 2026
Essen, 27th August 2026



From insight to impact.

Outline (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

Outline (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 balancing energy (BE) activation
- Focus on Automatic Frequency Restauration Reserve (aFRR)

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 p.m. (D – 1) until 5 minutes before delivery (= "Gate Closure")
- Prices in continuous trading can vary:
  - Bids can be placed at any time
  - They rest in an order book until they are accepted by another trader
  - Each transaction has its own price

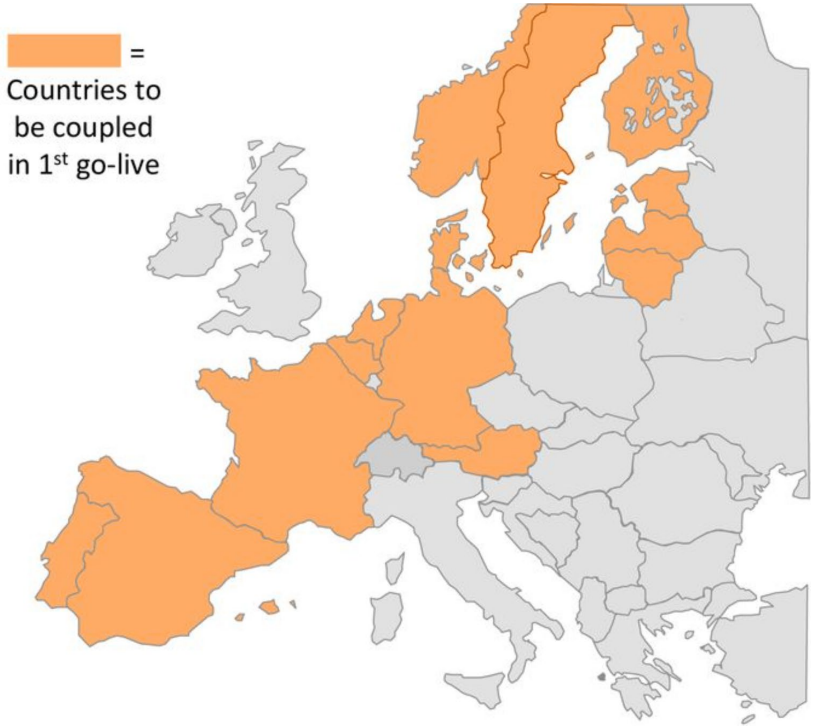
Balancing Energy Market (BEM):

- 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:
  - Cross-border activation after merit order, new signal every 4 seconds
  - Settlement of the delivered energy at the uniform price (CBMP)

Trading phases in the IDM

Three trading phases in the IDM:

- Single Intraday Coupling (SIDC) until T – 60
- Trading within DE until T – 30

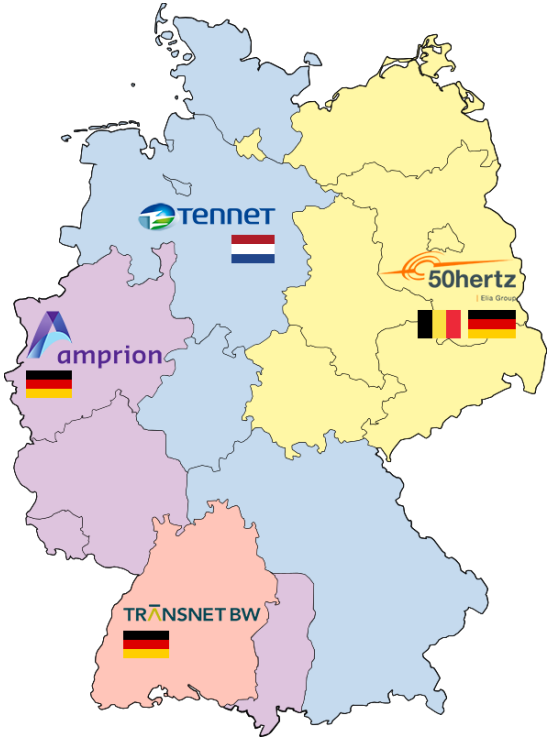


Trading phases in the IDM

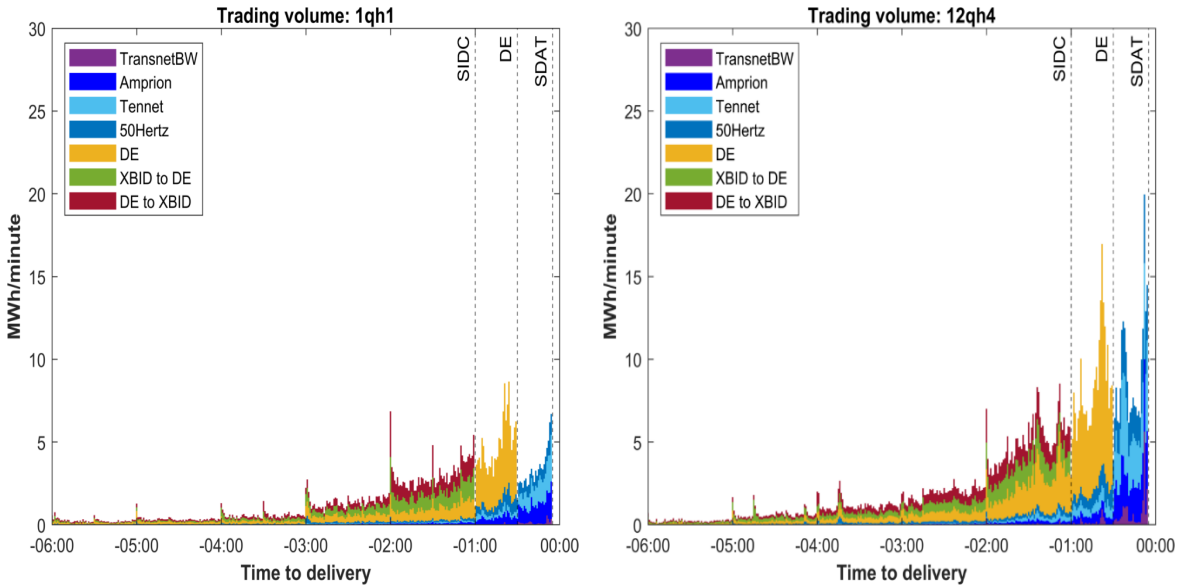
Three trading phases in the IDM:

- Single Intraday Coupling (SIDC) until T – 60
- Trading within DE until T – 30
- Trading within the respective control area (Same Delivery Area Trading, SDAT)

► Significantly different liquidity depending on the control area (trading volume, bid-ask spreads)



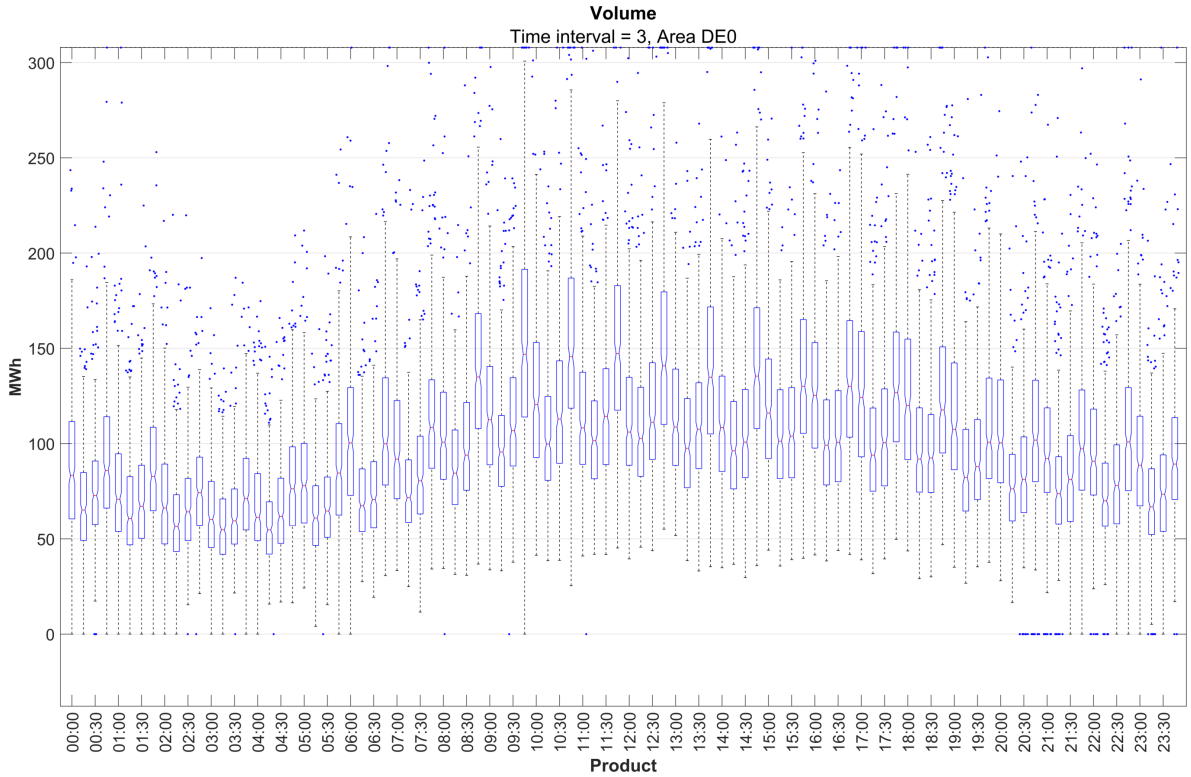
Trading volume by remaining time to Gate Closure



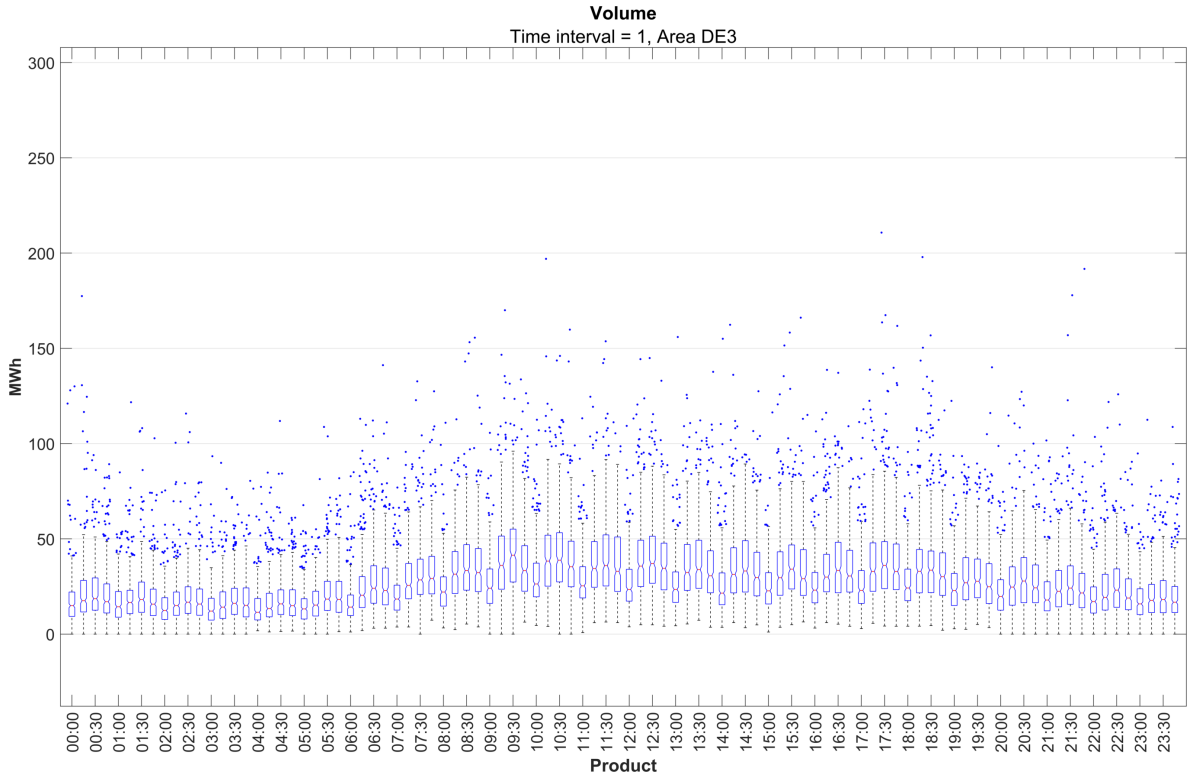
- Trading volume varies depending on the product (time of delivery)
- Tends to increase significantly towards the end of the trading session
- In "illiquid" area possibly no transaction in last 30'

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. Data from 2023.

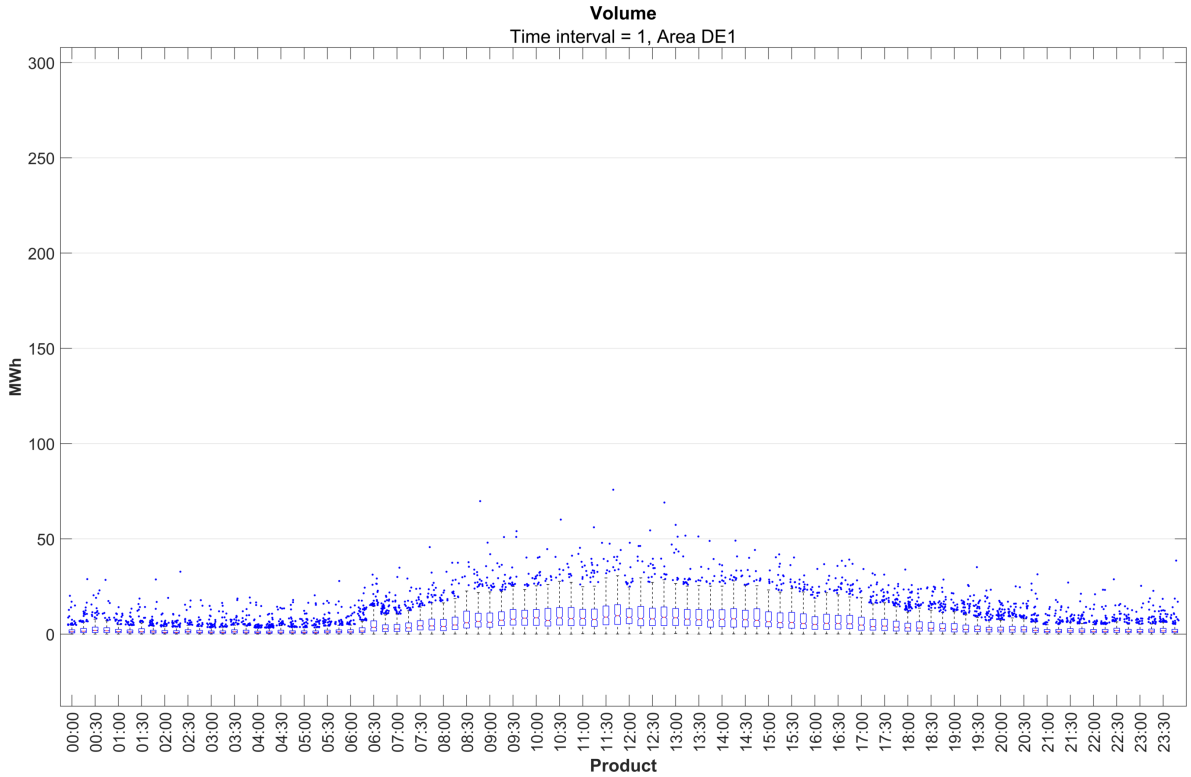
Trading volume 15' products in [T – 45, T – 30): DE



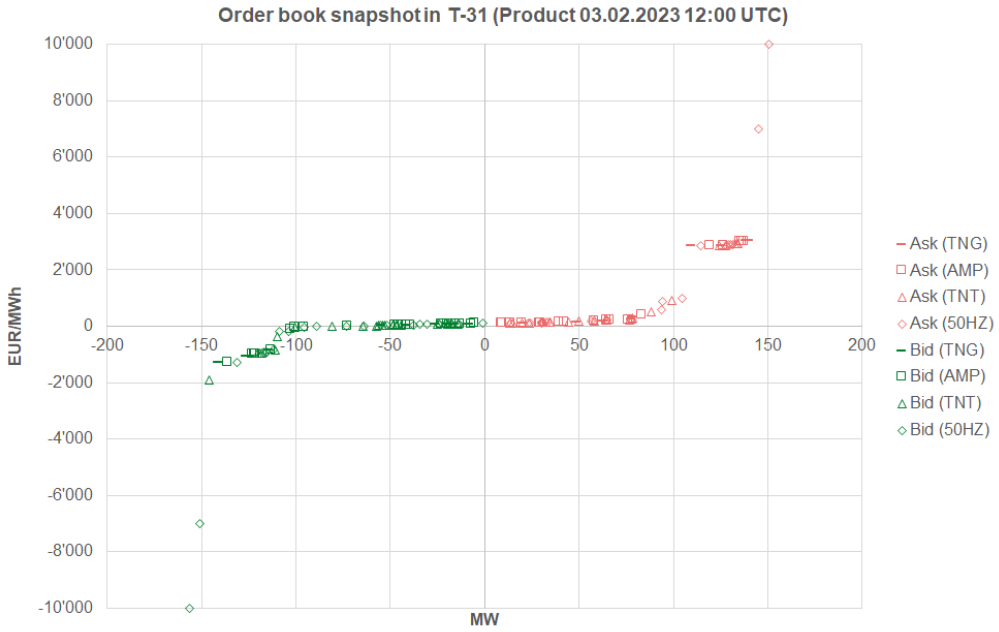
Trading volume 15' products in [T – 15, T – 5): Tennet CA



Trading volume 15' products in [T – 15, T – 5): TransnetBW

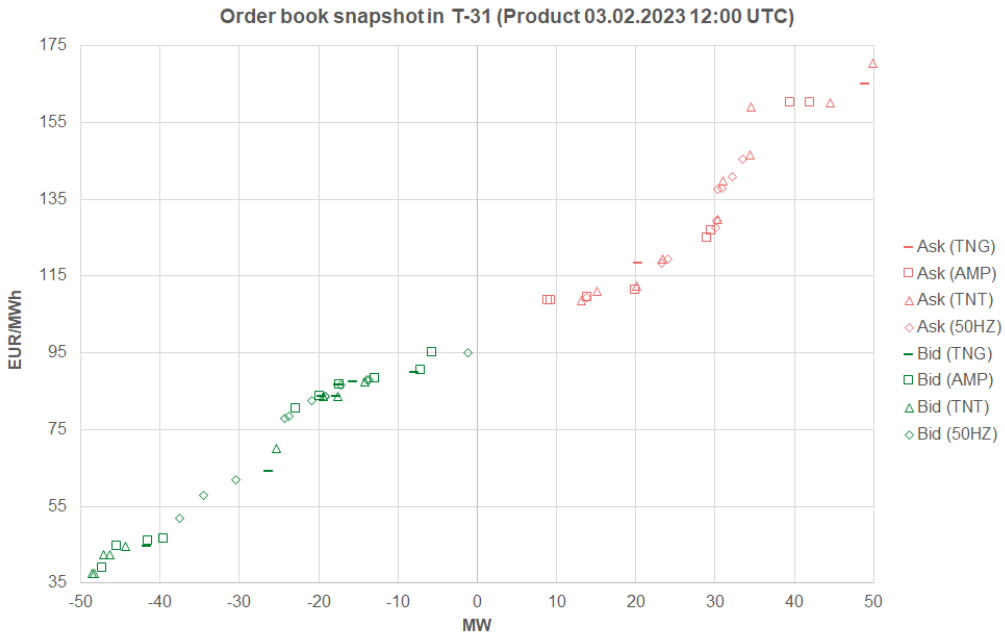


Market liquidity and order book depth: DE



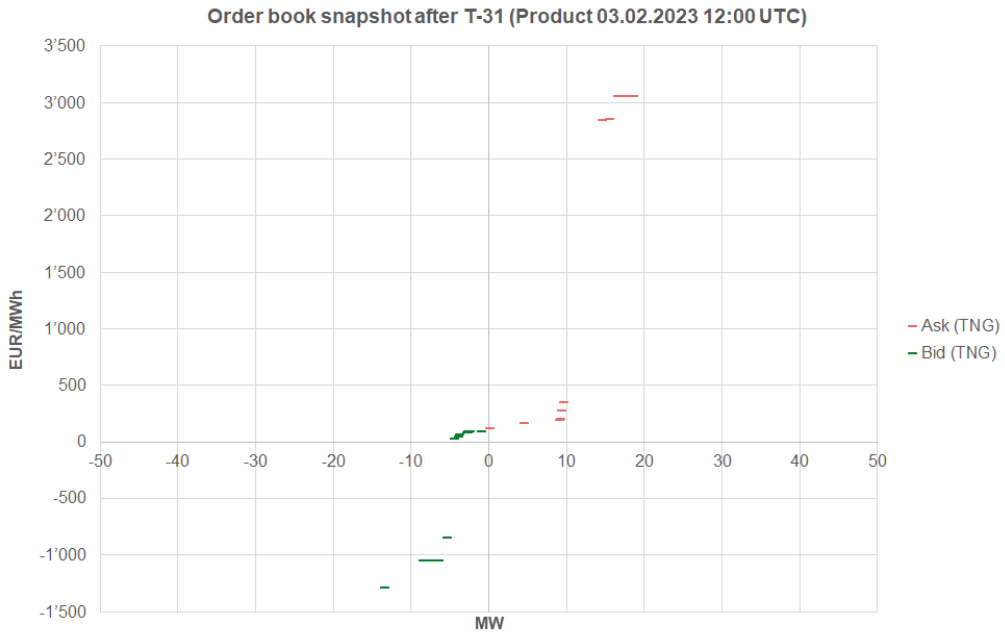
- Order book shapshots in 1' intervals were constructed from all bids in 2023 for the market area DE (42 GB data); this resulted for the SDAT phase in 43 million data points
- Order book depth = cumulated volume of buy or sell orders

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

Market liquidity and order book depth: TransnetBW CA



- 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

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

Tennet CA (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

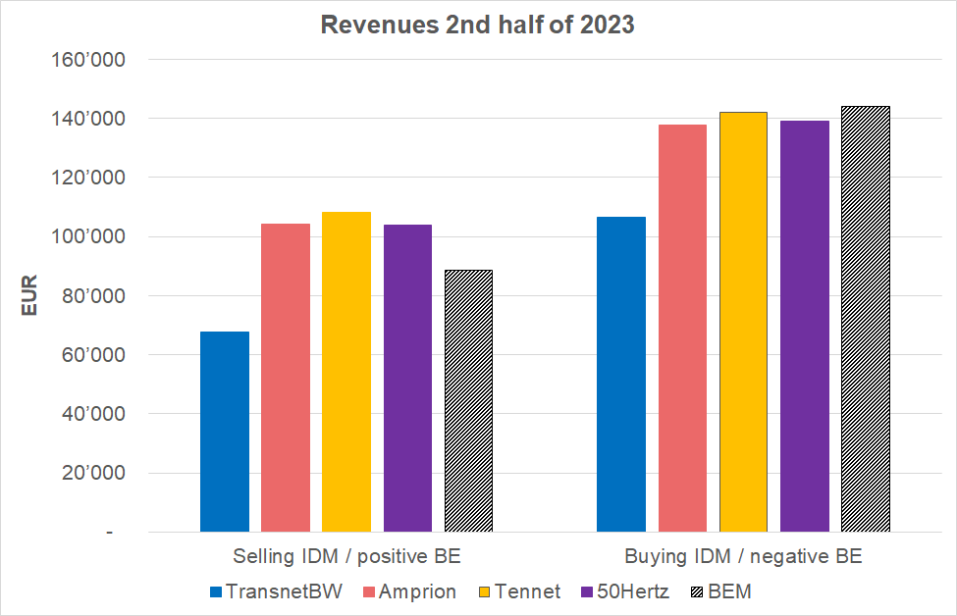
TransnetBW CA (2023)

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

Comparison revenues IDM vs. BEM: Ex-post calculation

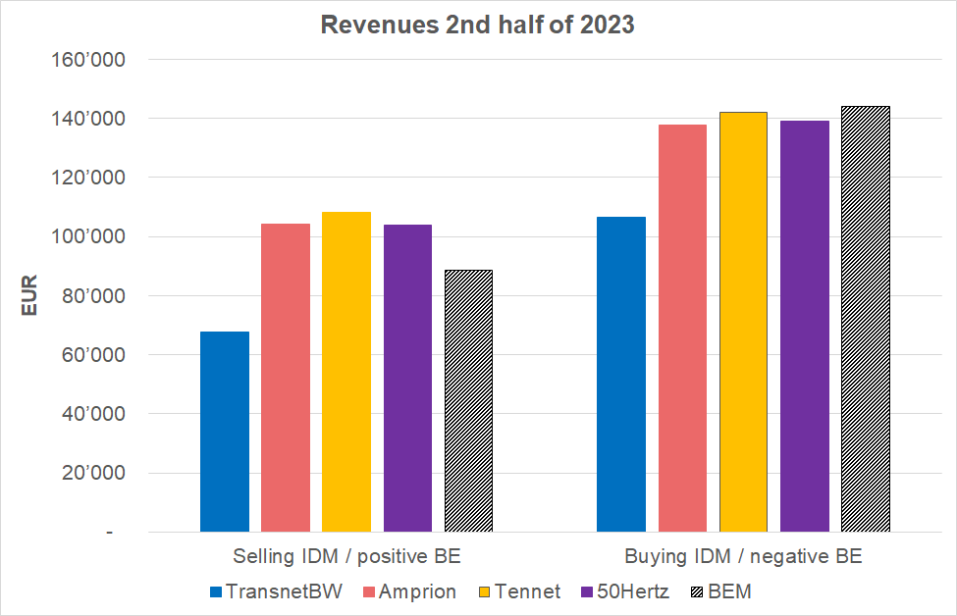
- Flexible capacity offered in the last 30' before delivery at IDM or BEM at variable costs (assumption: gas-fired plant)
- Trading volume 1 MW (increase or decrease of generation)
- Different market liquidity in SDAT phase depending on balancing area implies different revenue potential at IDM
- Ex-post 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

Comparison revenues IDM vs. BEM: Ex-post calculation



- 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 control area)
- IDM and BEM similarly attractive

Comparison revenues IDM vs. BEM: Ex-post calculation



- 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 control area)
- IDM and BEM similarly attractive
- What if a provider bids in the market that appears *currently* more attractive?
- Model-based approach (valuation of both alternatives as financial options)

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 for activation of POS or NEG (publication with a 15-minute delay)
- Offer in the market with the higher option value

Valuation as financial options (for both 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):

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

- $d = \frac{\mu - X}{\sigma}$; 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.

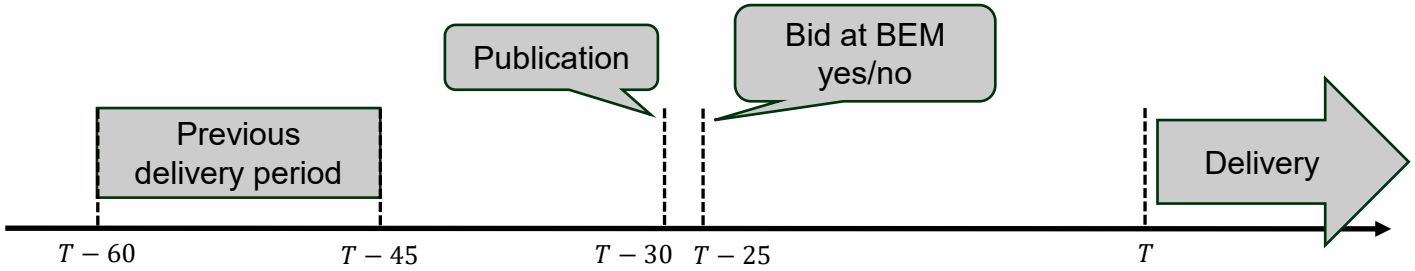
Assumptions for modelling BE option

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

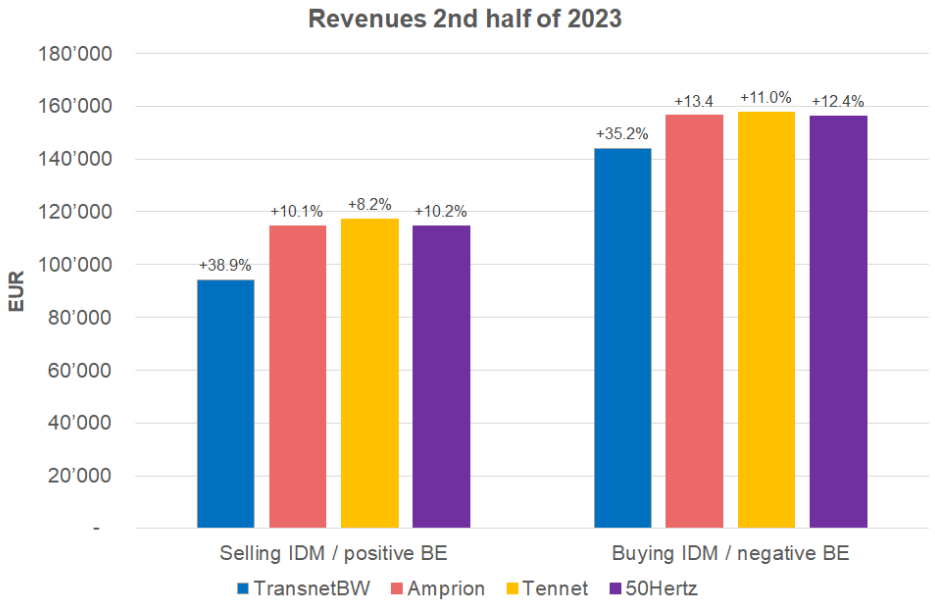
$$P_T^{act,+} = c^+ + a^+ \cdot P_{T-60}^{act,-} + b_1^+ \cdot P_{T-60}^{act,+} + b_2^+ \cdot P_{T-120}^{act,+}$$

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

- Low coefficient of determination (≈12%)

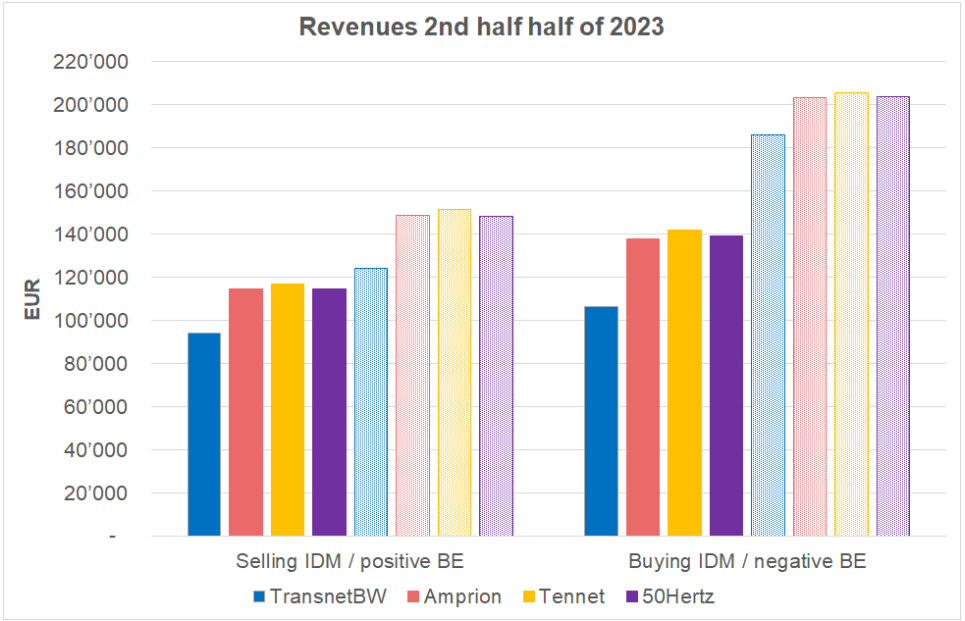


Revenues combined strategy IDM & BEM



- 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 relative change compared to ID trading only
- Improvement in generation (selling at IDM, positive BE) and consumption (buying at IDM, negative BE), the biggest in "illiquid" TransnetBW area

Combined strategy vs. perfect foresight



Model assessment: Comparison with perfect foresight

- How much could a clairvoyant have earned, who is able to anticipate the market with higher revenues?
- Colored bars show revenues of combined strategy per area
- Shaded bars represent revenues of perfect foresight (bid in market with higher revenues, assuming it is known in advance)

Summary

- Model-based approach for deciding in which market to offer capacity
- Value of flexibility is modeled analogously to a financial option
- Bid is placed in market with higher option value (= expected revenue)
- Despite its simplicity, approach leads to higher revenue than bidding only in a single market
- 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

Outlook

- Normality assumption for executable prices as first approximation
- Study order book depth (dependency on transaction volume) and model variation
- Ad-hoc approach for volatility estimation intraday price:
  - For each product, variation of executable prices around adjusted VWAP during calibration period
  - But: Volatility may depend on level of liquidity, fundamental factors, …
- Identify potential common drivers of BE and ID prices
- Extension to longer sample period

Acknowledgement: This research was supported by ERA-Net & the Swiss Federal Office of Energy.