University of St.Gallen

Modelling illiquid intraday electricity markets

Moving from transaction prices to executable prices derived from order books



Michael Schürle, University of St. Gallen

Lillehammer Business Analytics Workshop
29th May 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

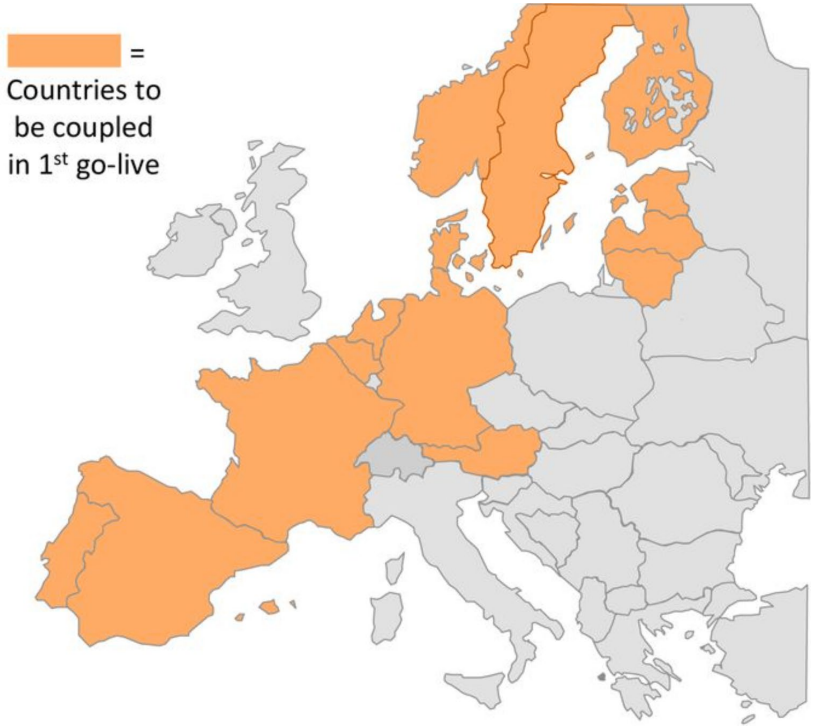
Balancing Energy Market (BEM):

- 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

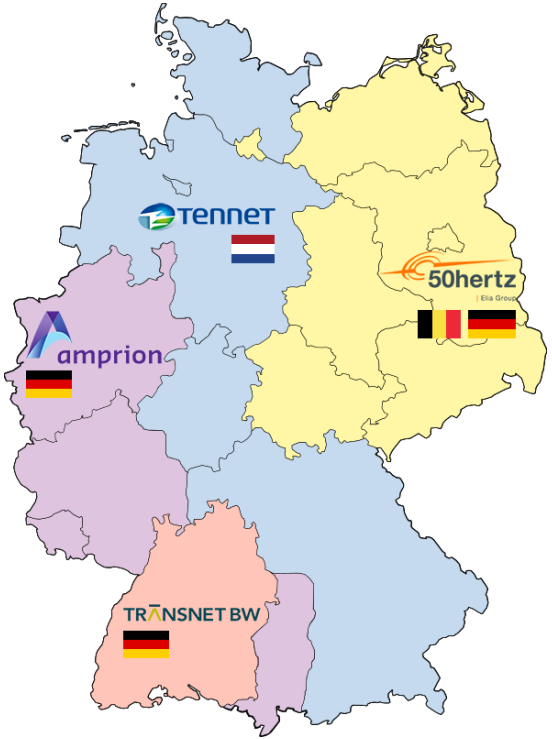


Trading phases in the IDM

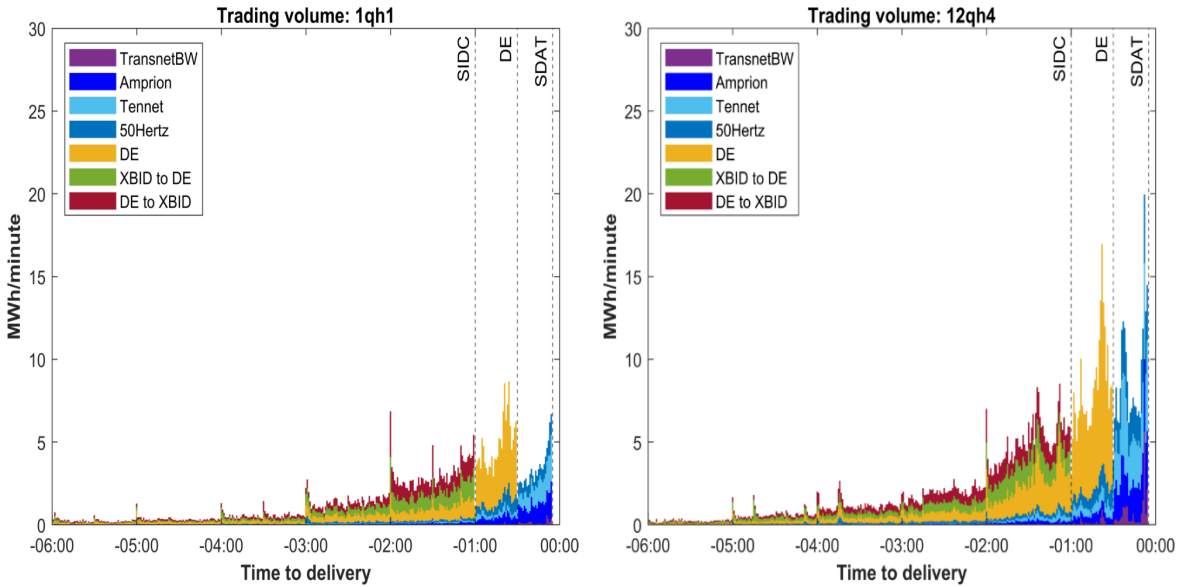
Three trading phases in the IDM:

- 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)



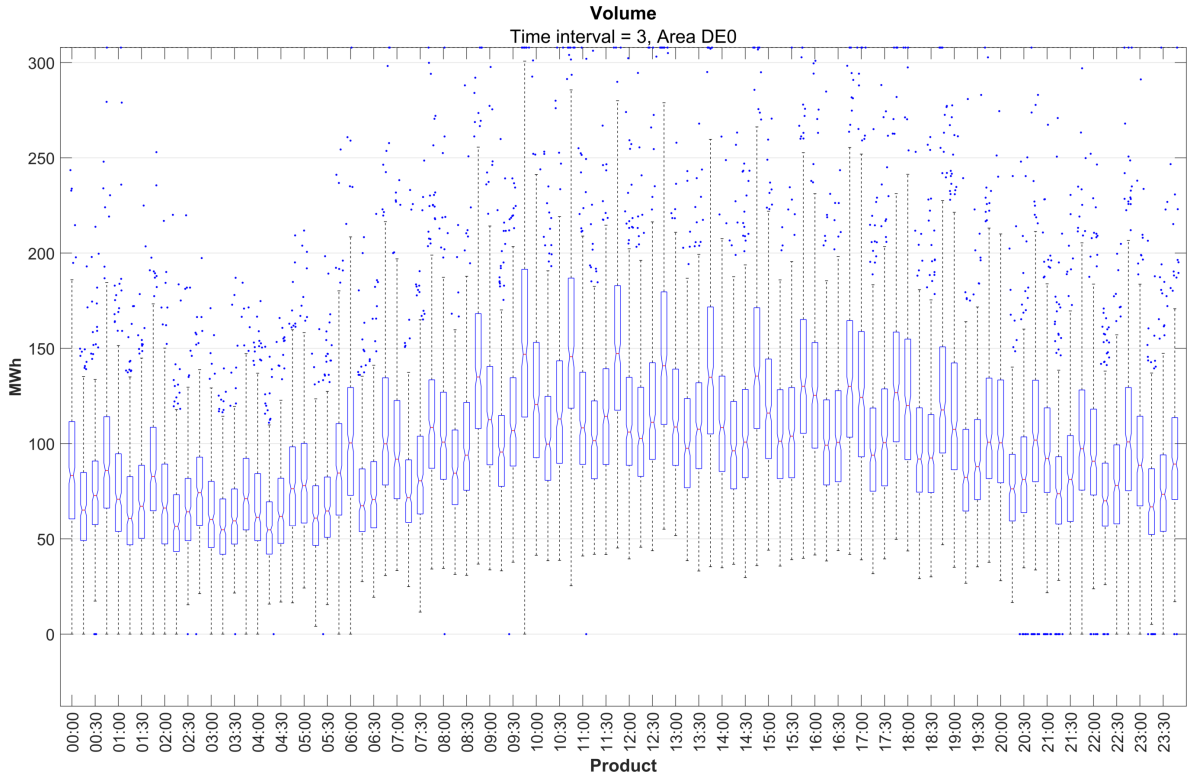
Trading volume by remaining time to Gate Closure



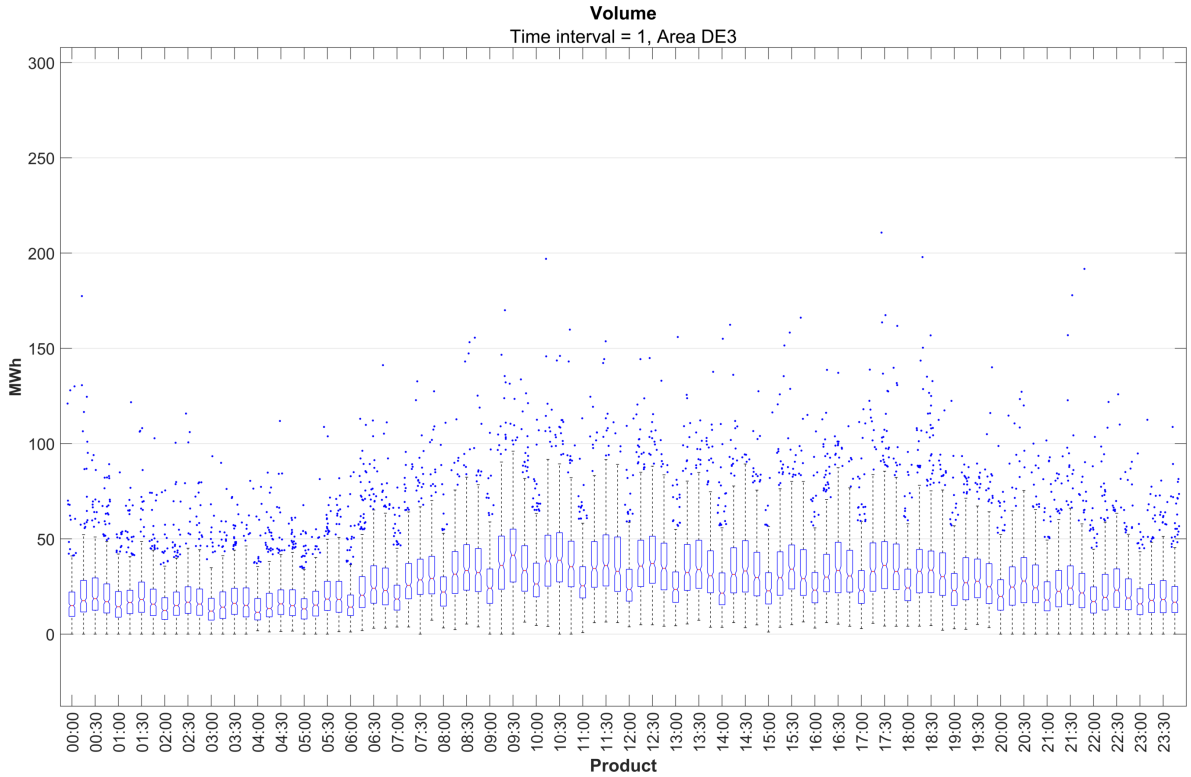
- Trading volume varies depending on the product (time of delivery)
- Tends to increase significantly towards the end of the trading session
- In "illiquid" area possibly no transaction in last 30'

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.

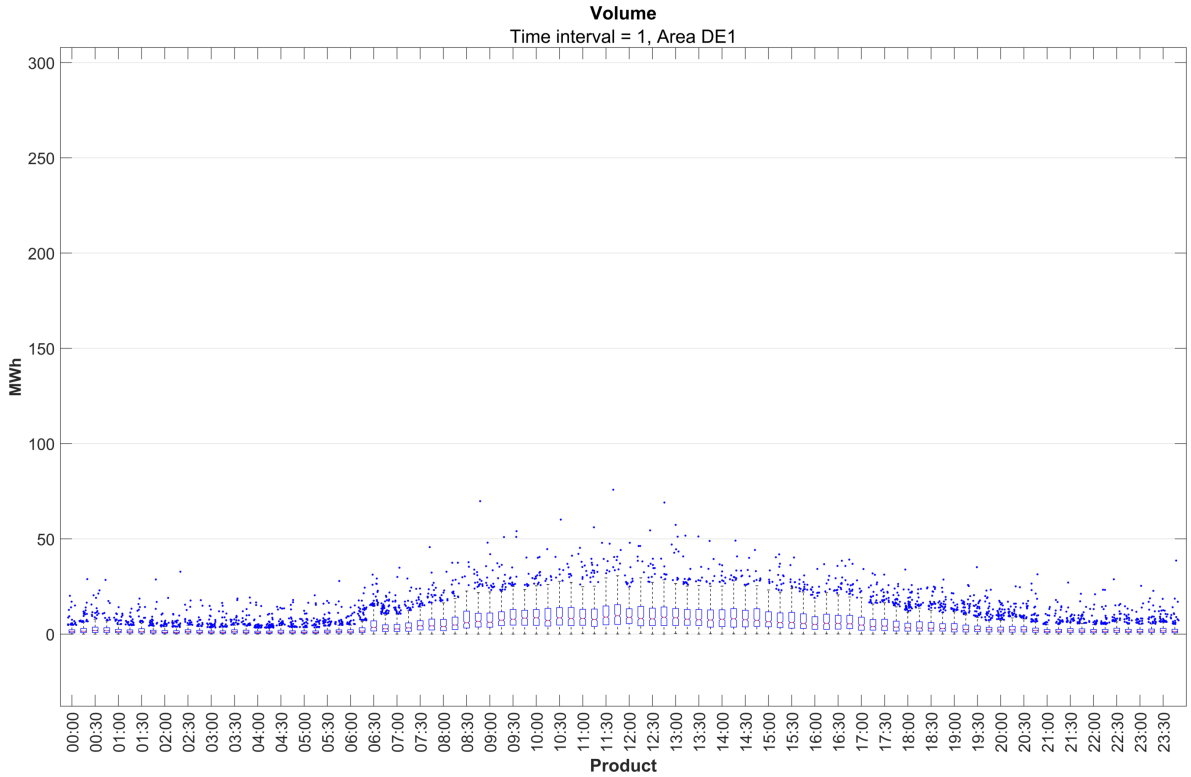
Trading volume 15' products in [T – 45, T – 30): DE



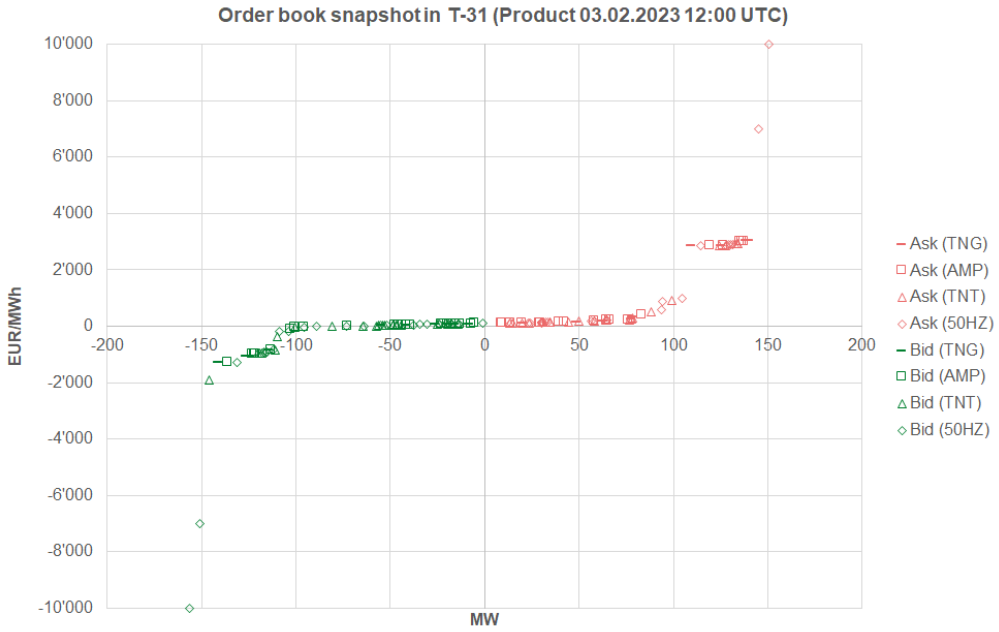
Trading volume 15' products in [T – 15, T – 5): Tennet CA



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

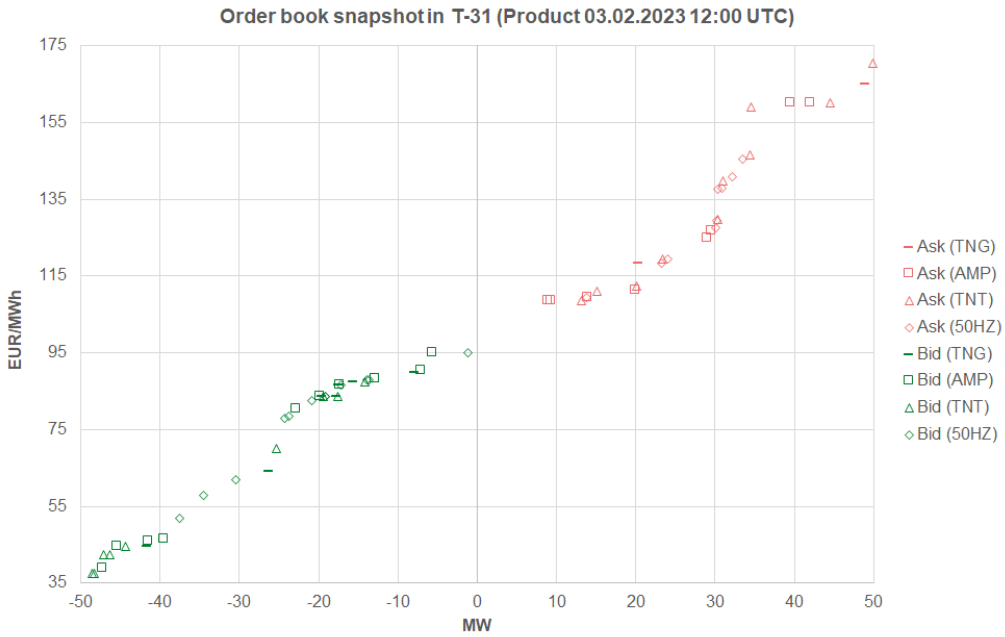


Market liquidity and order book depth: DE



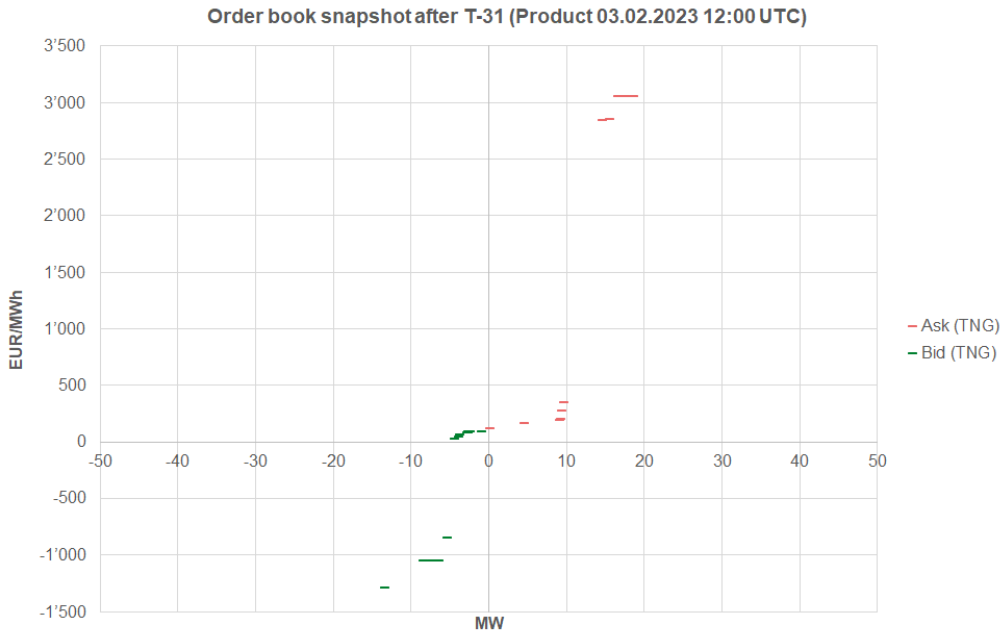
- Order book shapshots in 1' intervals were constructed from all bids in 2023 for the market area DE (42 GB data); this resulted for the SDAT phase in 43 million data points
- Order book depth = cumulated volume of buy or sell orders

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

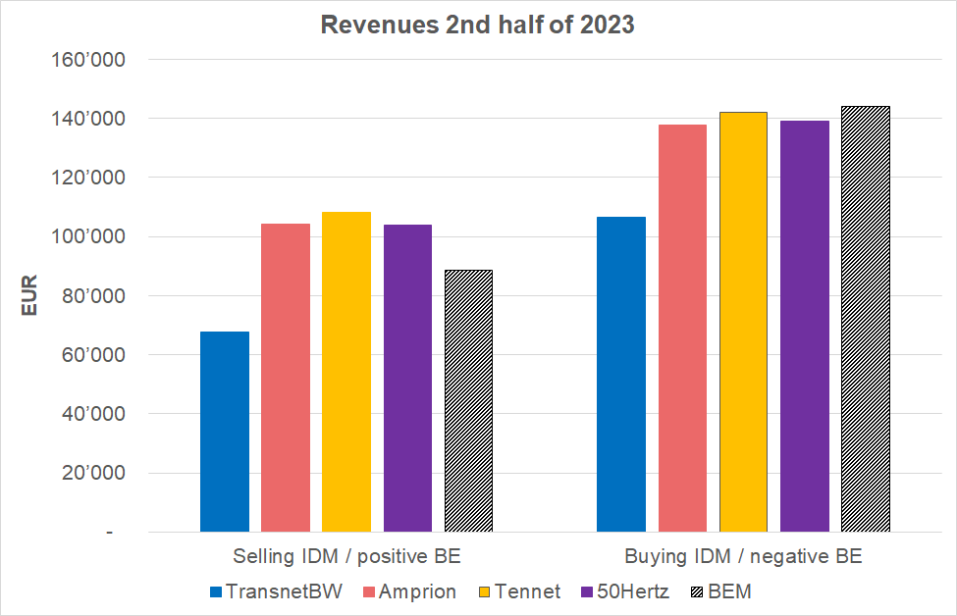
TransnetBW CA(2023)

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

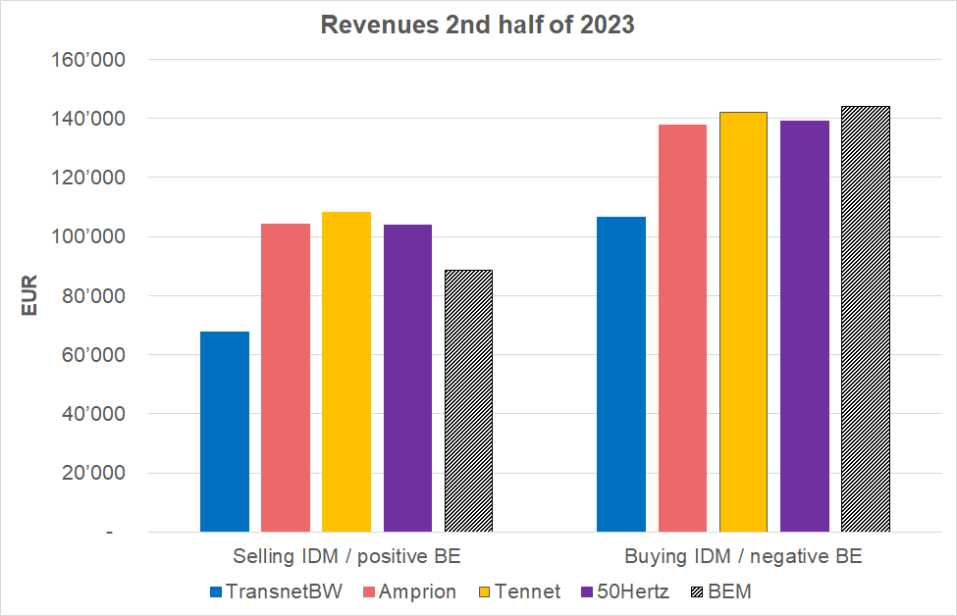
- Flexible capacity offered in the last 25' before delivery at IDM or BEM at variable costs (assumption: gas-fired plant)
- Trading volume 1 MW (increase or decrease of generation)
- Different market liquidity in SDAT phase depending on balancing area implies different revenue potential at IDM
- Ex-post 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

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.

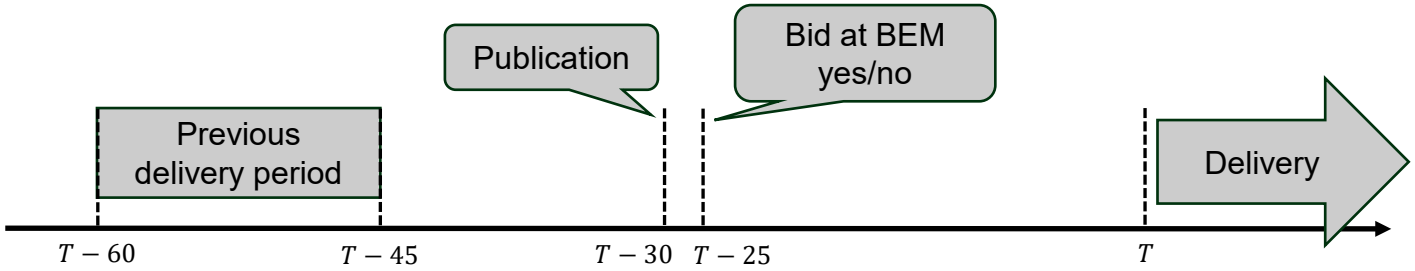
Assumptions for modelling BE option

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

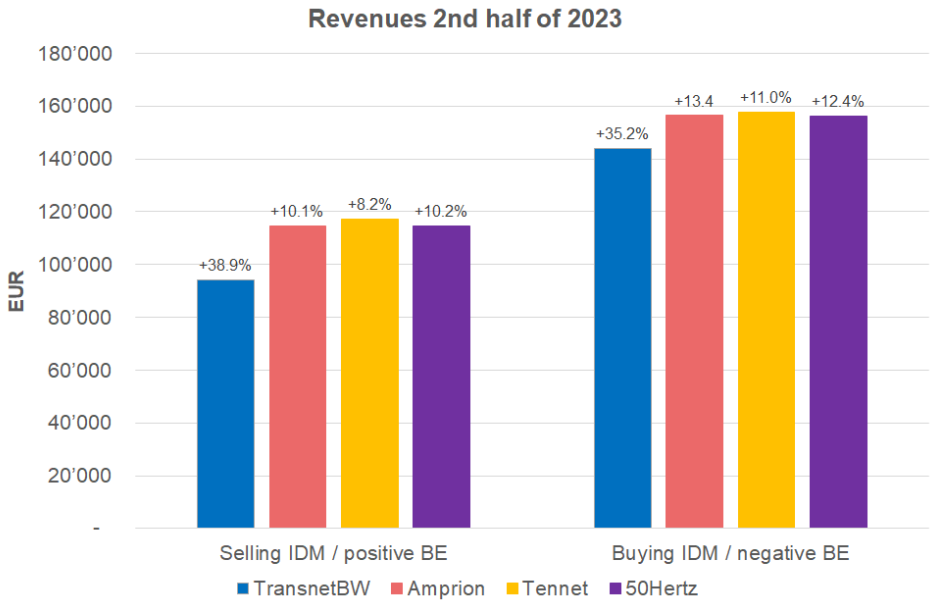
$$P_T^{act,+} = c^+ + a^+ \cdot P_{T-60}^{act,-} + b_1^+ \cdot P_{T-60}^{act,+} + b_2^+ \cdot P_{T-120}^{act,+}$$

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

- 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

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.