SAPB

Optimization of battery storage in the context of European short-term markets

SAPB-study 2025

Brandenburg University of Technology Cottbus - Senftenberg

Steinbeis

Disclaimer

50Hertz Scientific Advisory & Project Board

This short study was prepared within the framework of the 50Hertz Scientific Advisory and Project Board (SAPB). The SAPB is an interdisciplinary group of professors who support 50Hertz in developing new approaches to thinking and solving solutions and in transferring findings from research into 50Hertz's practice where appropriate. The short study was supported in particular by experts from TU Berlin, TU Dresden, TU Ilmenau, the Öko-Institut and IKEM.

In the context of the SAPB studies commissioned by 50Hertz, the participating scientists conduct research unrestricted and outcome-neutral. The results of the study and recommendations for action developed are examined and discussed in detail by 50Hertz, but not all of them necessarily correspond to 50Hertz's positions.

SAPB

Agenda

- Motivation (50Hertz & Steinbeis)
- Work Package 1: Scenario development (Steinbeis)
- Work Package 2: Development and Parameterization of the Optimization Model (BTU)
- Work Package 3: Analysis of Battery Schedules (BTU)
- Work Package 4: Analysis of the influence of the continuous trading market (Steinbeis)
- Work Package 5: Outlook and Conclusion (Steinbeis & BTU)

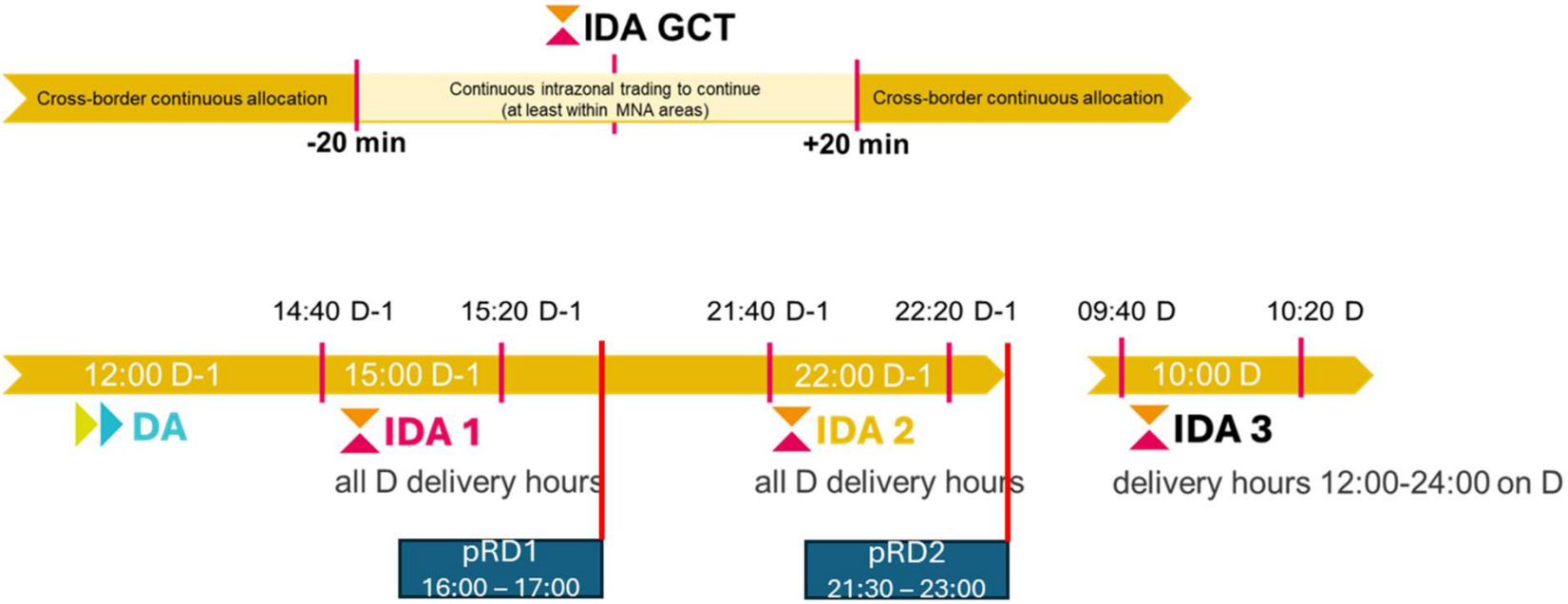
SAPB

Motivation (I)

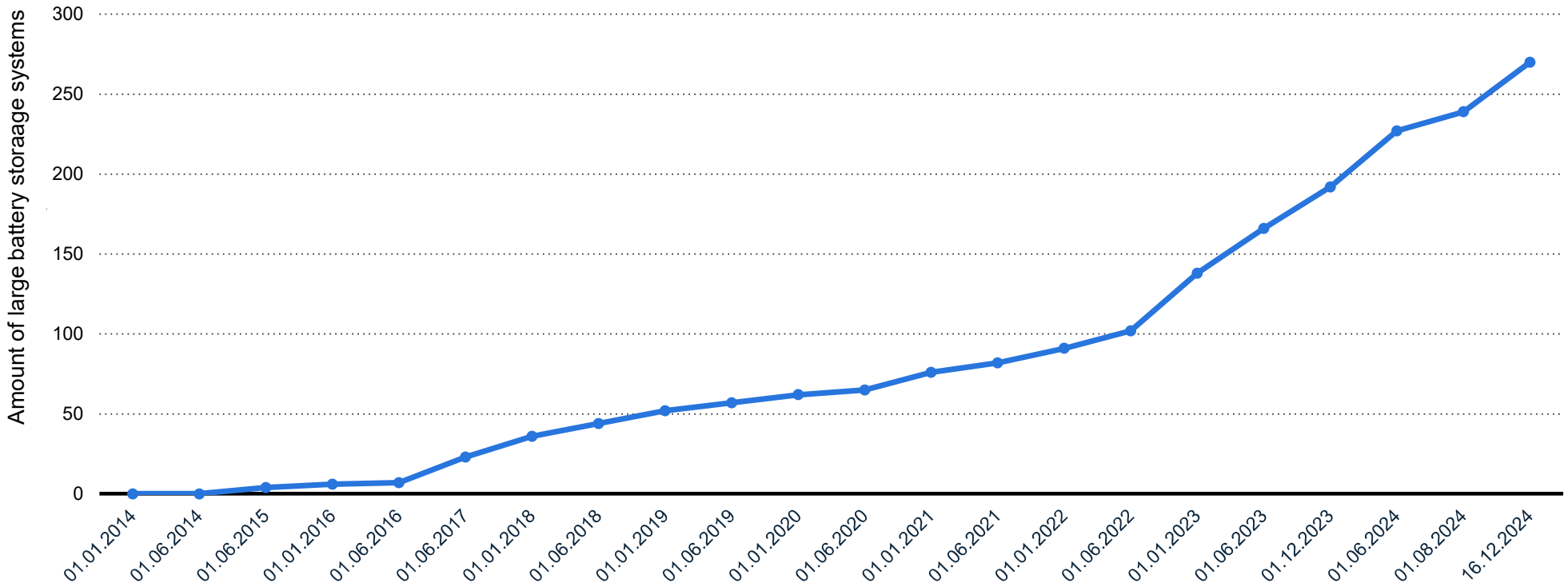
- Historically, grid operators have been able to rely on relatively stable feed-in and load profiles. In addition to the integration of variable renewable energies, battery storage systems in particular will lead to increased volatility in the future.
- At the same time, the European electricity markets are fully integrated in the day-ahead and intraday market time ranges, so that, on the one hand, a larger market leads to greater liquidity and thus lower volatility and, on the other hand, special situations in other European countries could activate battery storage systems in Germany.
- With the introduction of European intraday auctions (IDA) in June 2024 and the Europe-wide introduction of 15-minute products in the day-ahead auction (DAA) market, the European process chain is initially complete. The four German transmission system operators primarily use preventive redispatch processes in D-1 (pRD1, pRD2) for congestion management.
- This raises the question of how battery schedules could develop based on day-ahead and intraday auctions. A battery optimization model for the historical year June 2024 – July 2025 is used for the evaluation.
- Since continuous intraday trading cannot be simulated, this study focuses on a quantitative analysis of the status quo without the addition of bids from battery storage system operators.

Motivation (II)

Overview of the European process chain including the time periods of the preventive redispatch processes.



Number development of large battery storage systems (> 1MWh) in DE



Deutschland; Stand: 17.12.2024 **Quelle(n):** Bundesnetzagentur; RWTH Aachen; ID 1548557

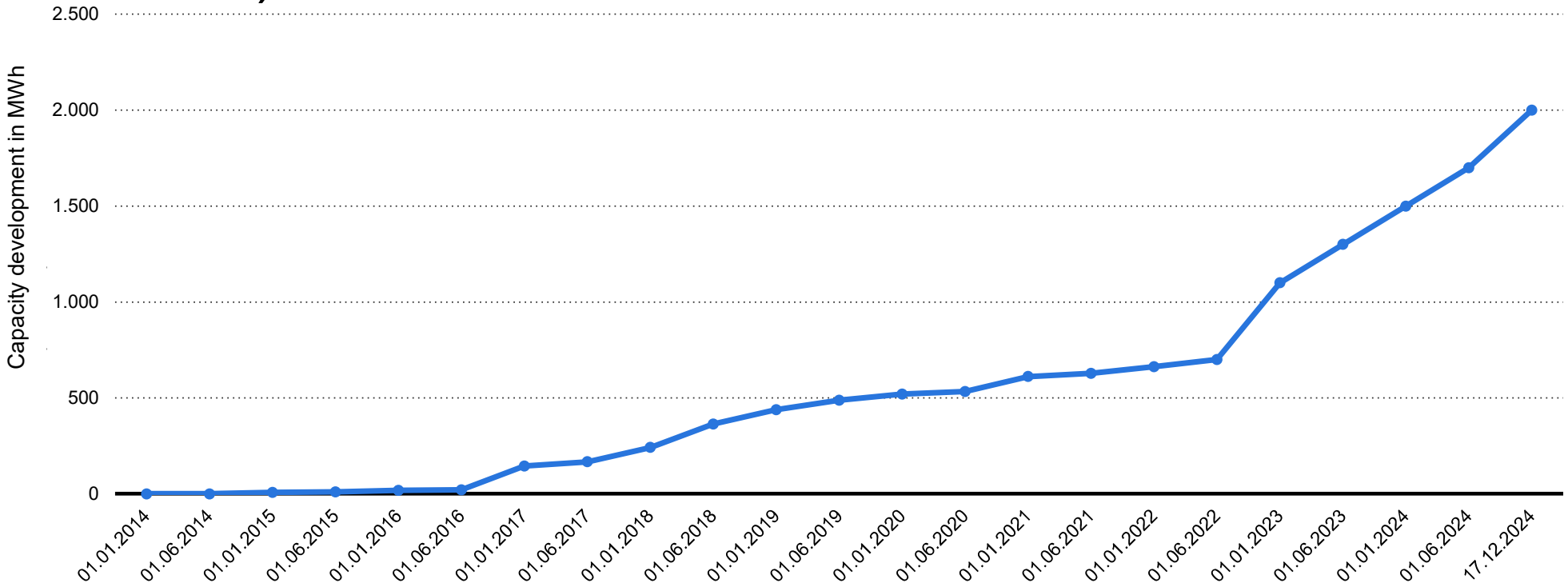
statista

Brandenburg University of Technology Cottbus - Senftenberg

Steinbeis

SAPB

Capacity development of large battery storage systems (> 1MWh) in DE



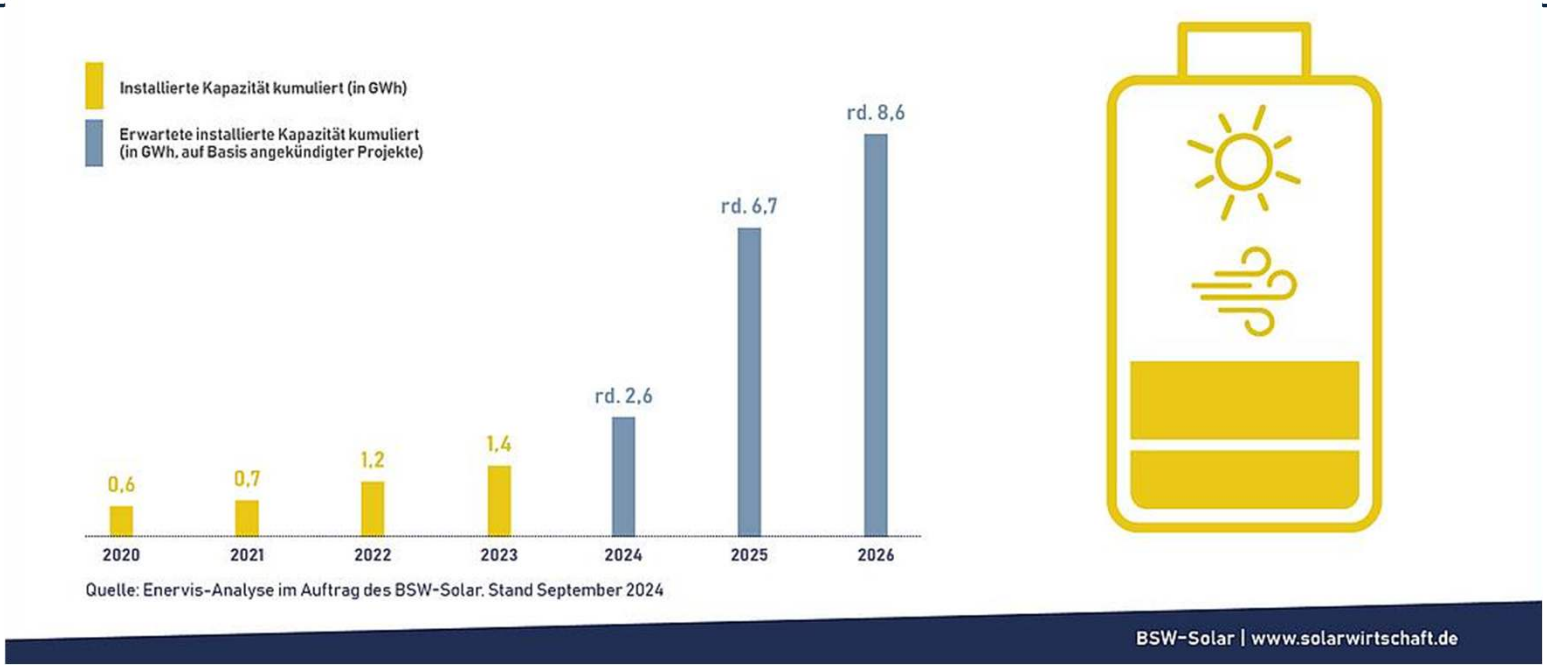
Deutschland; Stand: 17.12.2024 **Quelle(n):** RWTH Aachen; Bundesnetzagentur; ID 1548622

statista

b-tu Brandenburg University of Technology Cottbus - Senftenberg

Steinbeis

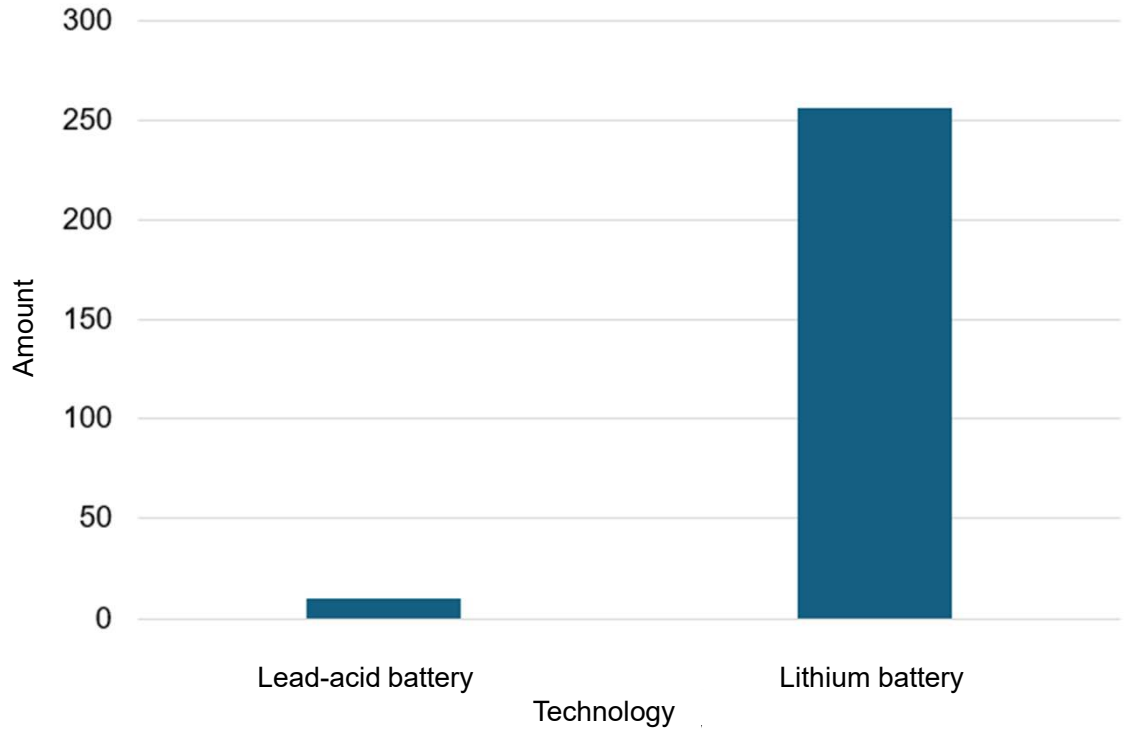
Expected battery capacity in Germany



List of announced stand-alone storage projects until 2026

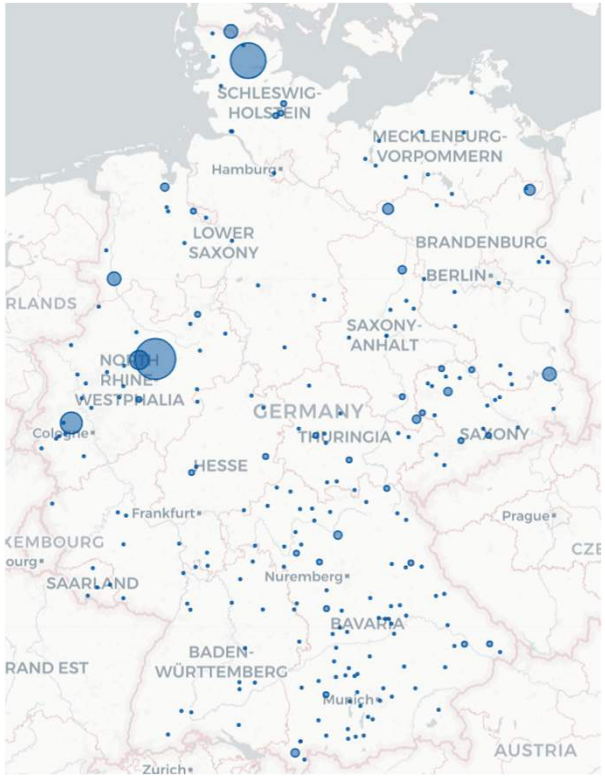
3 GW und 5,676 GWh (Regelleistung-online, Stand 2024)

Technology of large battery systems



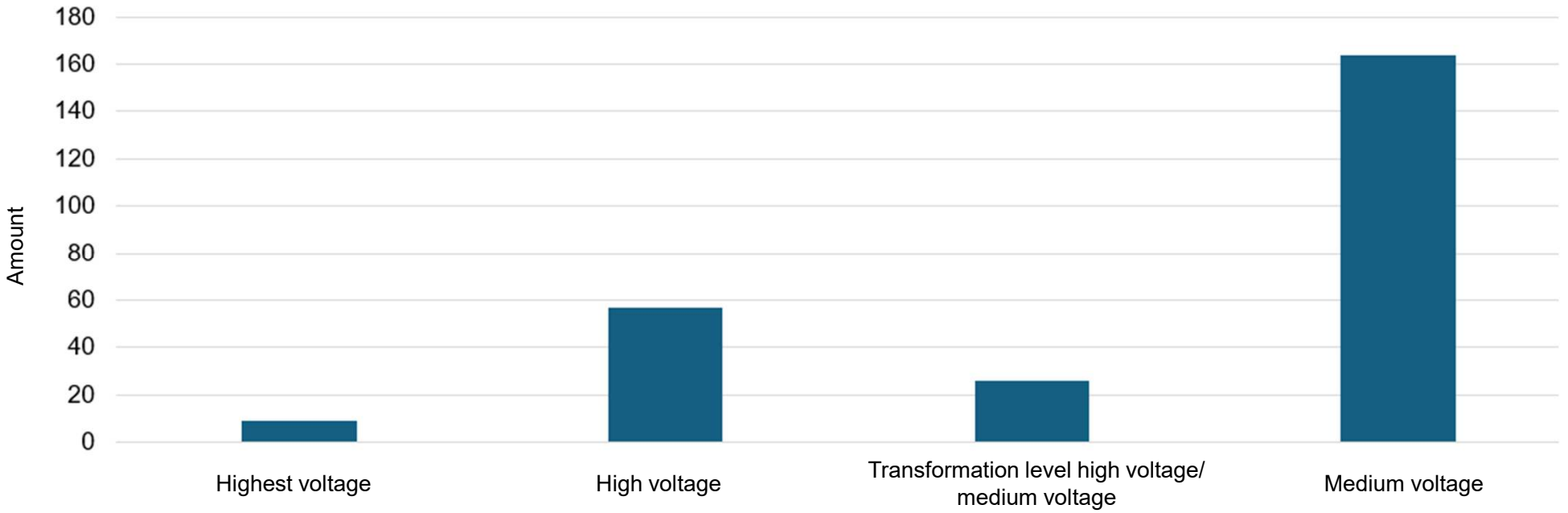
Source: MaStR

Distribution of large battery systems in Germany



Source: www.battery-charts.de/de/battery-charts-de

Connection voltage levels of large battery storages in DE 08.25



	Highest voltage	High voltage	Transformation level high voltage/ medium voltage	Medium voltage
Power:	136,74 MW	731,76 MW	213,89 MW	959,56 MW
Capacity	159,62 MWh	1037,84 MWh	301,80 MWh	1372,03 MWh

Quelle: MaStR

SAPB

Largest battery storage system in Germany

- Bollingstedt (Schleswig-Holstein)
- In operation since spring 2025
- Capacity: 238 MWh
- Power: 103,5 MW
- Storage of surplus solar and wind energy
- Technology: Lithium-ion
- Voltage level: 110 kV

Foto: Frank Molter/dpa

SAPB

Largest battery storage system in Europe

- Blackhillock, Scotland
- operation since March 2025
- Capacity: 400 MWh
- Output: 200 MW
- Reduction of grid bottlenecks
- Voltage level: 275 kV

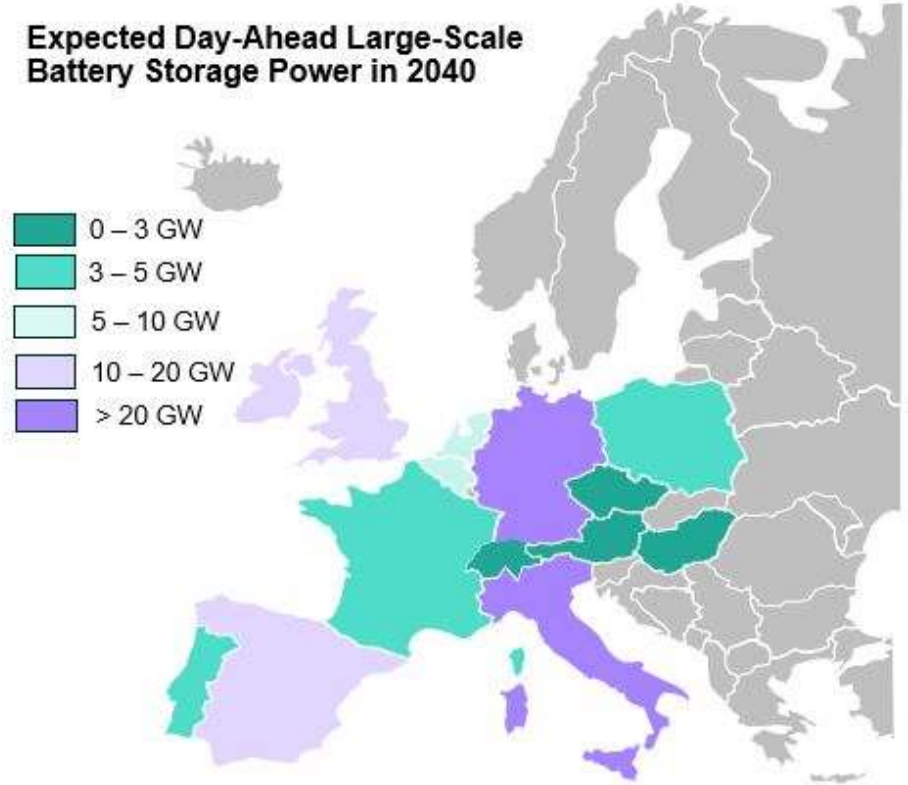
Foto: Zenobe

SAPB

Largest planned battery storage system in Germany

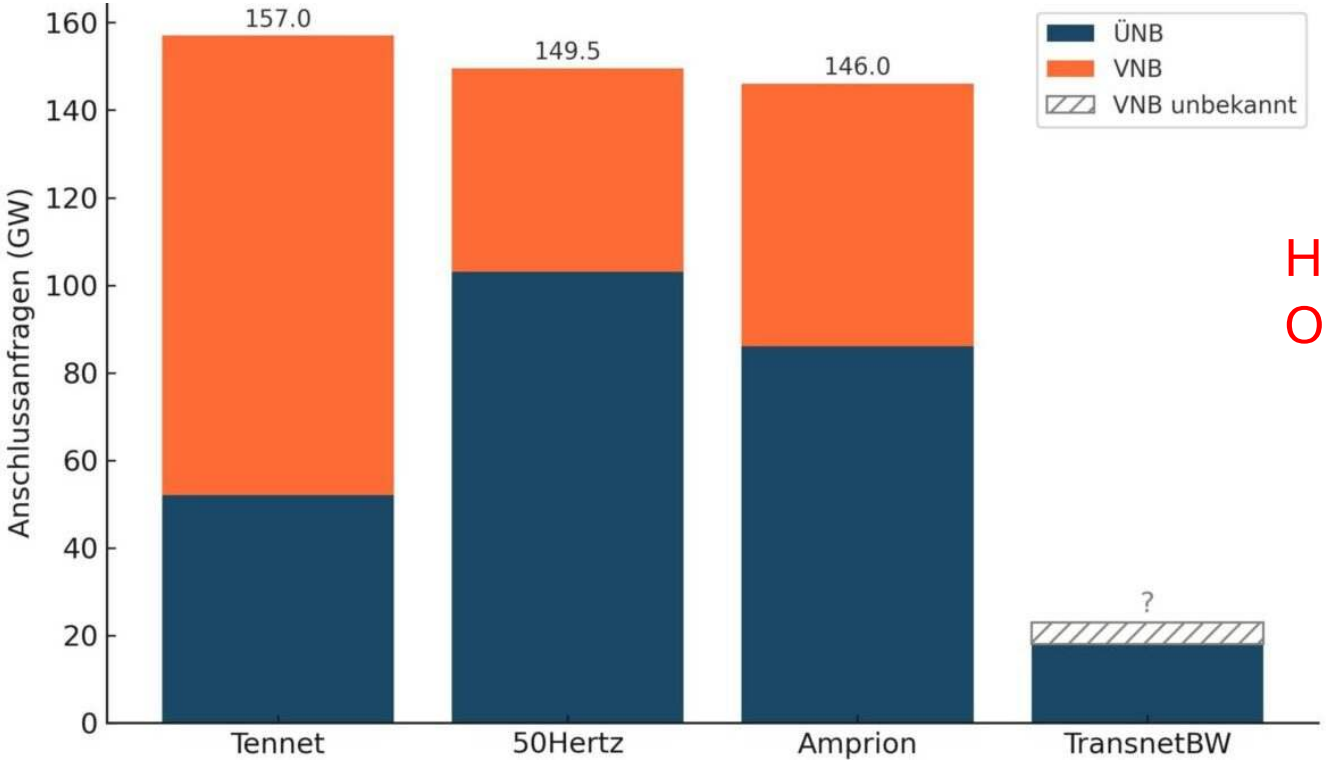
- Waltrop (Nordrhein-Westfalen)
- Connected till 2028
- Capacity: 1800 MWh
- Power: 900 MW

Availability of significant day-ahead large-scale battery storage power in 2040 expected



Quelle: Montel Analytics

Grid connection requests way higher than projections of grid connection plan – but how many will really come?



How many will actually come?
One-fifth?

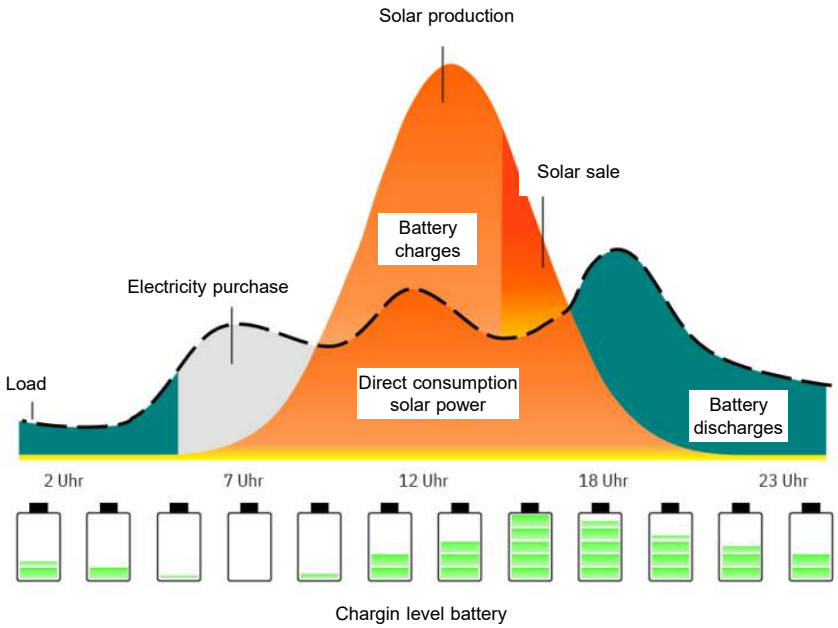
https://www.pv-magazine.de/2025/08/29/mittlerweile-mehr-als-500-gigawatt-netzanschlussfragen-fuer-grosse-batteriespeicher/

SAPB

Business models for battery storage

Market based-utilisation one of a variety of possible business models for battery systems

- System services
- Industry: Peak load capping, own consumption
- Integration of renewable energies: Peak load capping, own consumption
- Market-based utilisation



Source: 42technology AG

Applications for stationary storage systems

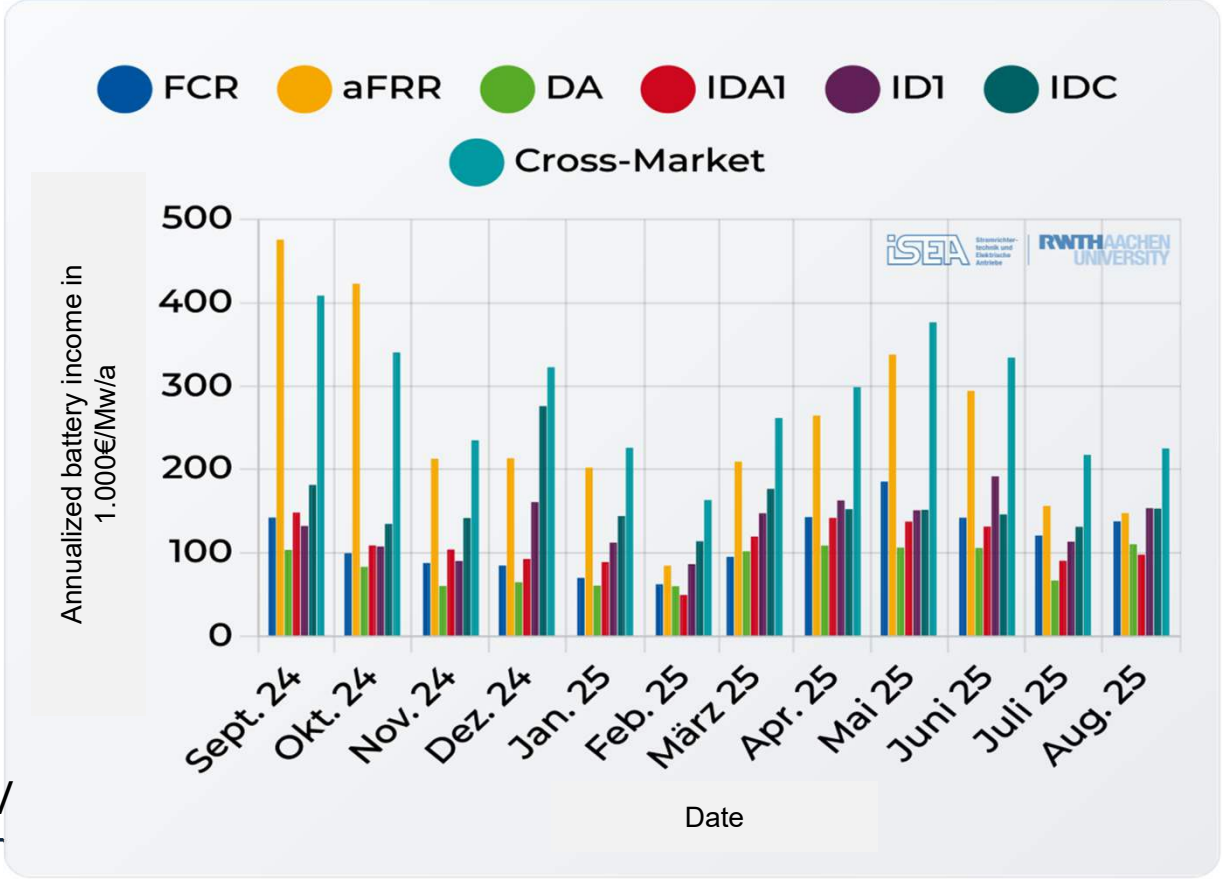
		Applied	Possible	
Frequency Control	Momentanreserve	(✓)		Market, grid connection requirement
	Primary control reserve	✓		Market
	Secondary control reserve	✓		Market
	Tertiary control reserve		✓	Market
	Long-term reserve			-
	Extrem Frequency	✓		Grid connection requirement
Voltage control static and dynamic	Reactive power provision	✓		Market, Grid connection requirement
	Active power provision		✓	Market, Grid connection requirement
	Short-circuit current provision	✓		Grid connection requirement
	Voltage-related redispatch		✓	
	Voltage quality		✓	
	Buffer storage, e.g., DC charging for EVs and ships	✓		Maybe Grid connection requirement.
Restoration of Supply	Uninterruptible power supply	✓		
	Black start capability		✓	Maket
Operational management	Gradient control (ramp rate control)	(✓)	✓	Grid connection requirement
	Grid voltage management / grid booster	(✓)		Redispatch, Grid booster
	Switchable load		✓	No market

Applications for stationary storage systems

		Applied	Possible
Integration EE	PV home storage systems	✓	
	Coverage of own needs	✓	
	Smoothing of the feed-in at the connection point		✓
	Use of potentially regulated energy		✓
Industry	Covering own needs	✓	
	Peak load reduction, load smoothing	✓	
	Lastverschiebung (Demand Side Management)	✓	
Energy Market	Intraday Trading	✓	
	Day Ahead	✓	

Revenue options for large battery storage systems

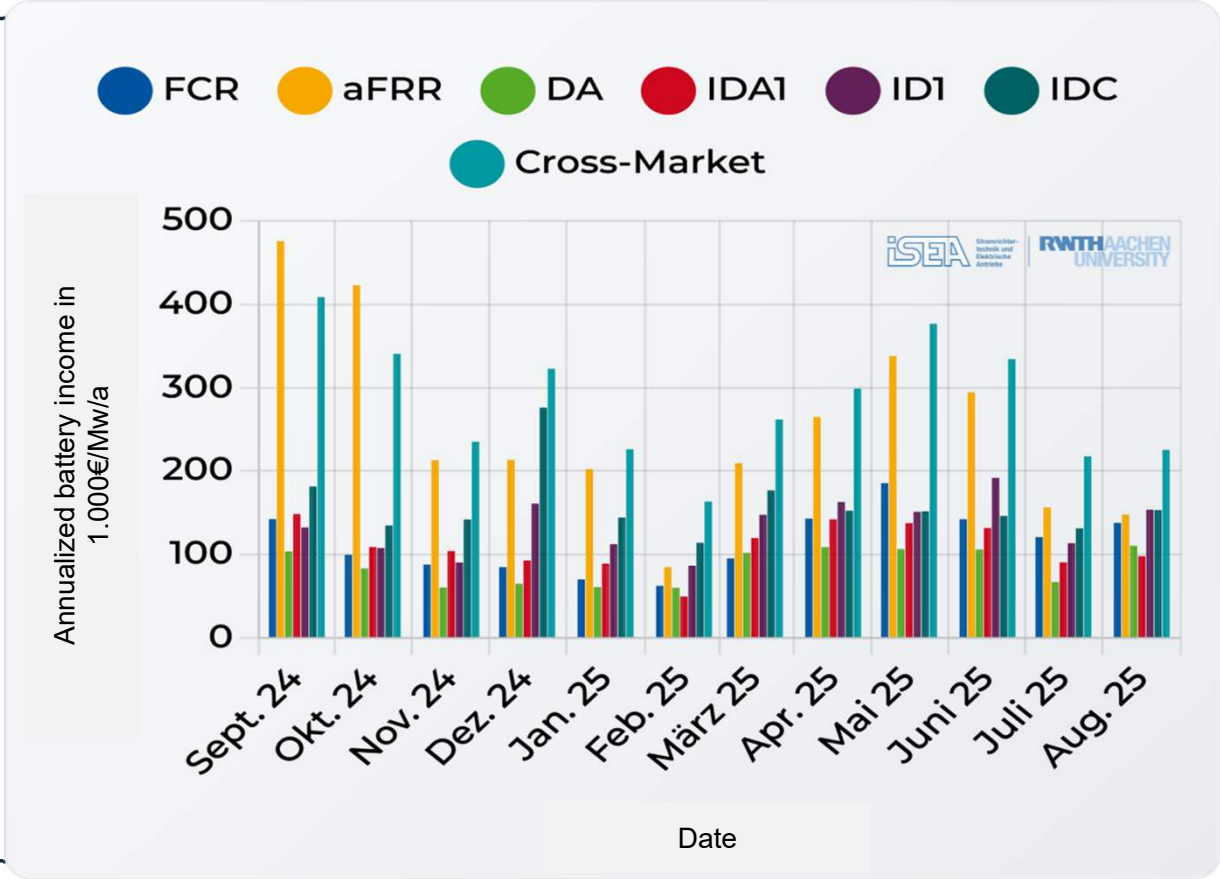
- FCR – Primary control reserve
- aFFR – Secondary control reserve
- DA – Day Ahead
- IDA1 – Intraday auctions
- ID1 – Intraday Trading
- IDC – Continuous Trading



https://battery-charts.de/de/home-de/

Revenue options for large-scale battery storage

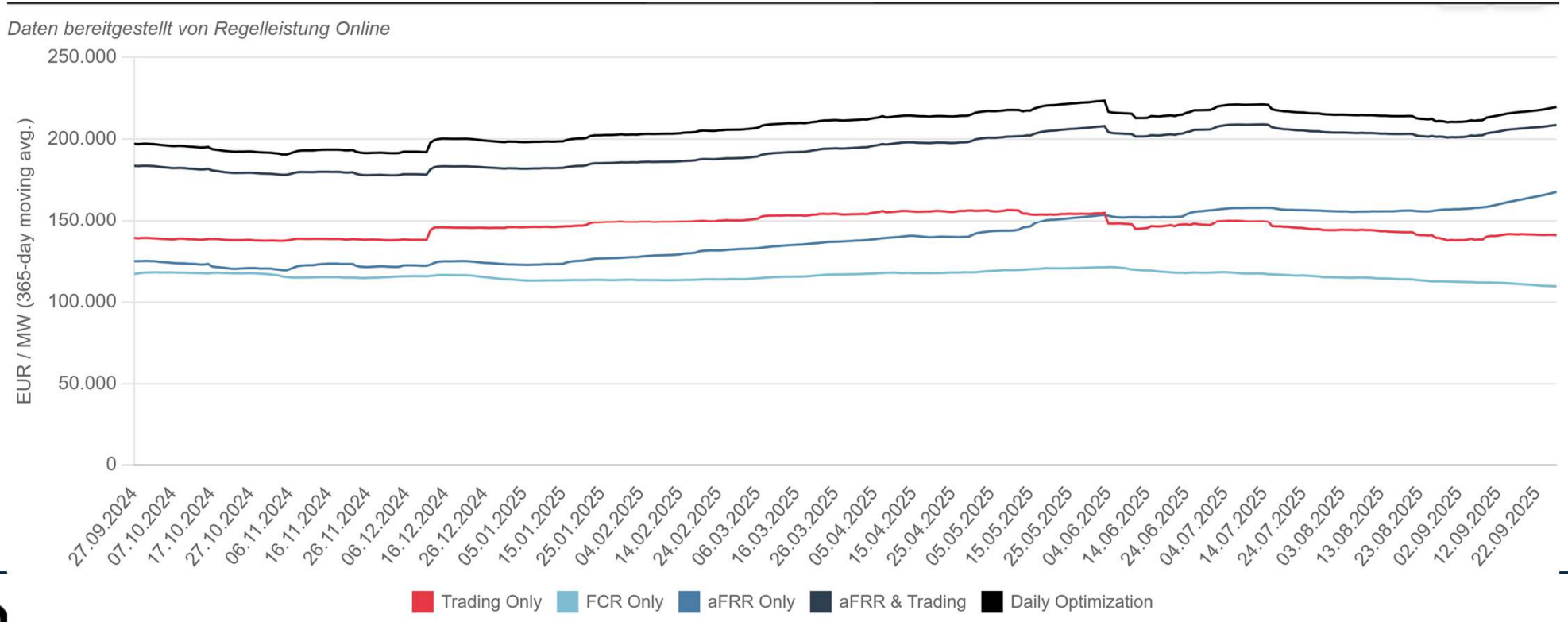
- Largest revenue options in the balancing power market esp. aFRR
- Potential revenues higher in intraday than in day-ahead trading
- Revenues in continuous trading very attractive for BESS



https://battery-charts.de/de/home-de/

Revenue options for large-scale battery storage

- **BESS Revenue Index – 2h (regelleistung-online.de)**



Conclusion

- Strong growth in battery storage is expected by 2030 (11/25 - 51 GW of reserved capacity in the transmission grid).

→See study **storage for system strength**

- Potential for high revenues day-ahead, intraday, and continuous trading

→ Power system-oriented operation and market–oriented operation have to be combined to avoid further grid congestion

SAPB

Scenarios

Boundary conditions

- 100 GW of battery storage capacity requested at 50 Hertz
- Average capacity is 400 MW and P2E ratio 2-4
- Singe and large battery system
  1) 1 MW/ 1-4 MWh Storage
  2) Technical Parameters:
     - Lithium-Ionen Technologie
     - Depth of discharge 90%
     - Efficiency AC/AC 96%
     - Full cycles 6000 at DoD 100%, 1C/1C, EoL 70% (Tesvolt)
     - According to BloombergNEF, €600–800 per kilowatt hour (kWh), approx. €400/MWh in 2030
     - Maximum 2 full cycles per day, entered by max. daily discharge energy

Scenario 1: Operation of the battery storage system currently

- Frequency stability 50% of battery capacity :
  - 25% - 75% SOC
- Dayahead
- Intraday High trades shortly before gate closing,
  - because attractive prices prevail and/or
  - must be reloaded immediately after a primary control power call.

Scenario 2: Operation of the battery storage system in the market

- Classification: Control reserve market has limited capacity
- Primary control reserve (as of 2024)
    - Prequalified: total 4.5 GW; battery storage approx. 800 MW
    - German demand (589 MW) plus maximum export capacity (176 MW
- Secondary control reserve
    - Prequalified: 22.5 GW (POS) and 23.7 GW (NEG)
    - Daily demand fluctuating: around 2 GW, SRL negative and positive

Scenario 2 : Operation of the battery storage system in the market

- Battery projects in Germany are increasingly able to reach the break-even point of 10% on the day-ahead market alone.

→With high installed storage capacity, it is very likely that trading will only take place on the day-ahead and intraday markets in the future.

- Goal: optimisation of storage operation based on market data. Selected strategy

Scenario description and selection

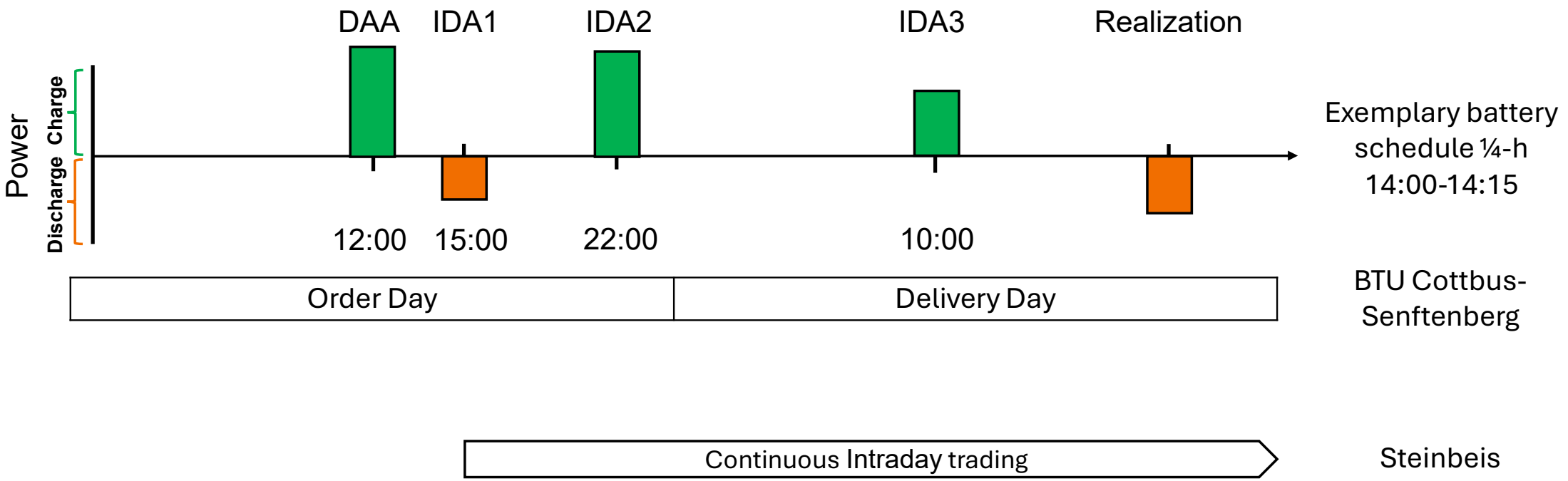
- Szenario 1:
  - Operation in frequency and energy markets
- Szenario 2:
  - Operation in energy market
  - Goal: optimisation of storage operation based on market data. Selected strategy

SAPB

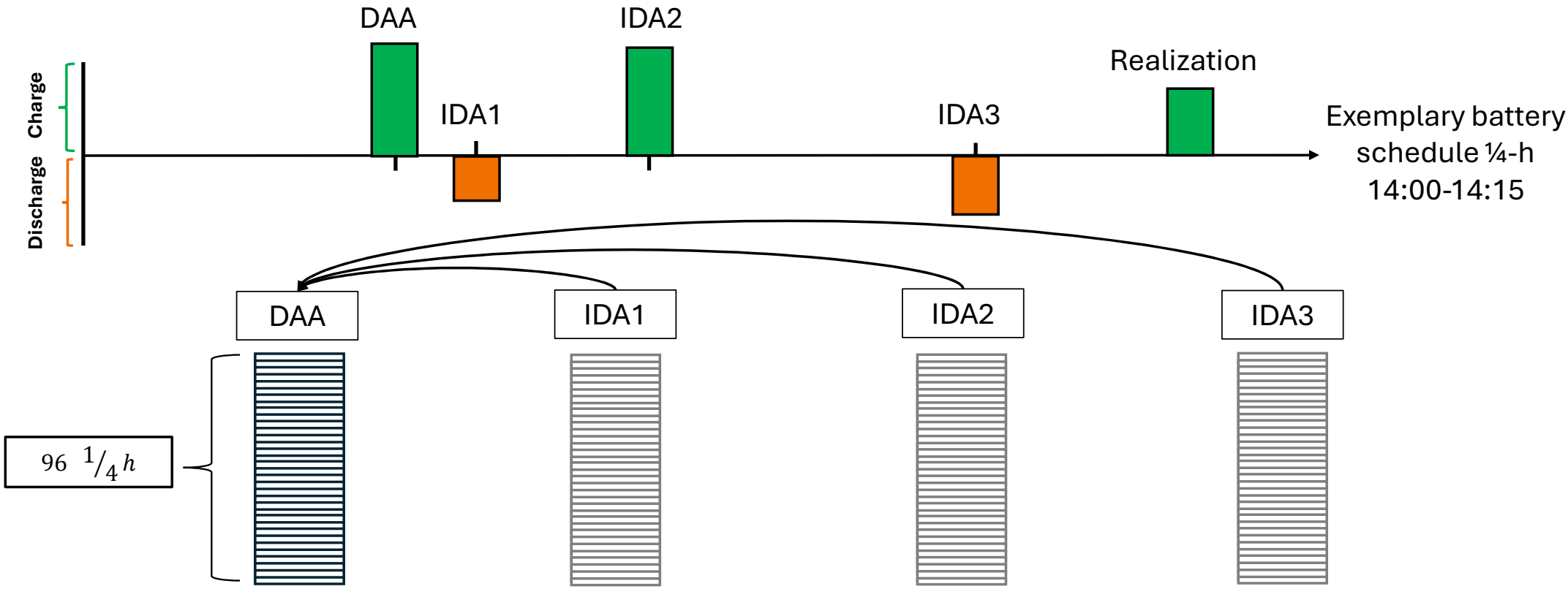
Work Package 2:

Development and Parameterization of the Optimization Model (BTU)

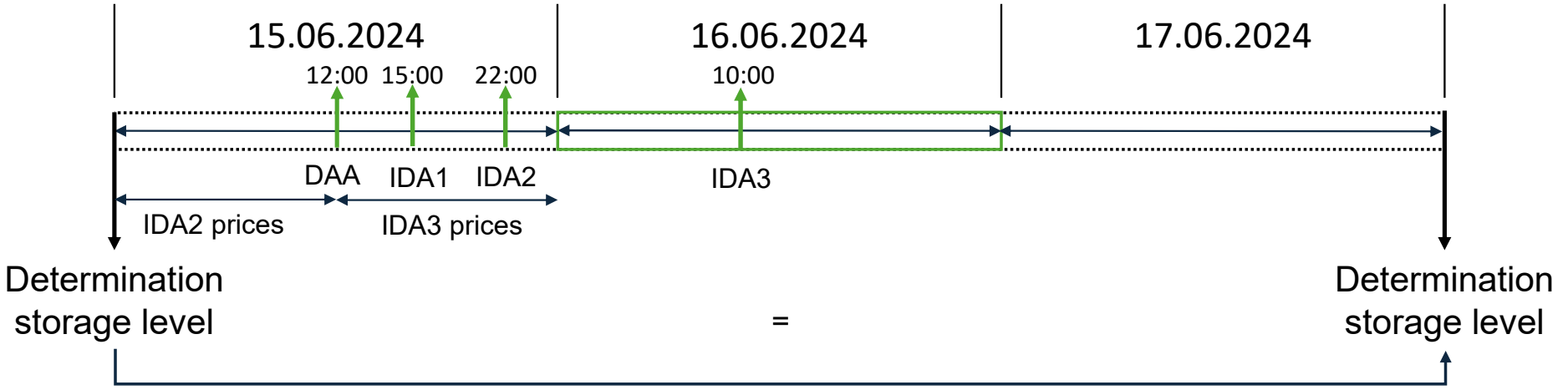
Starting point: Quantification to which extend batteries change their schedule between DAA and IDAs



Starting point: Comparing schedules from IDAs to the reference DAA schedule



Modelling Approach: Treating the Starting Day - Defining Start and End Storage Level

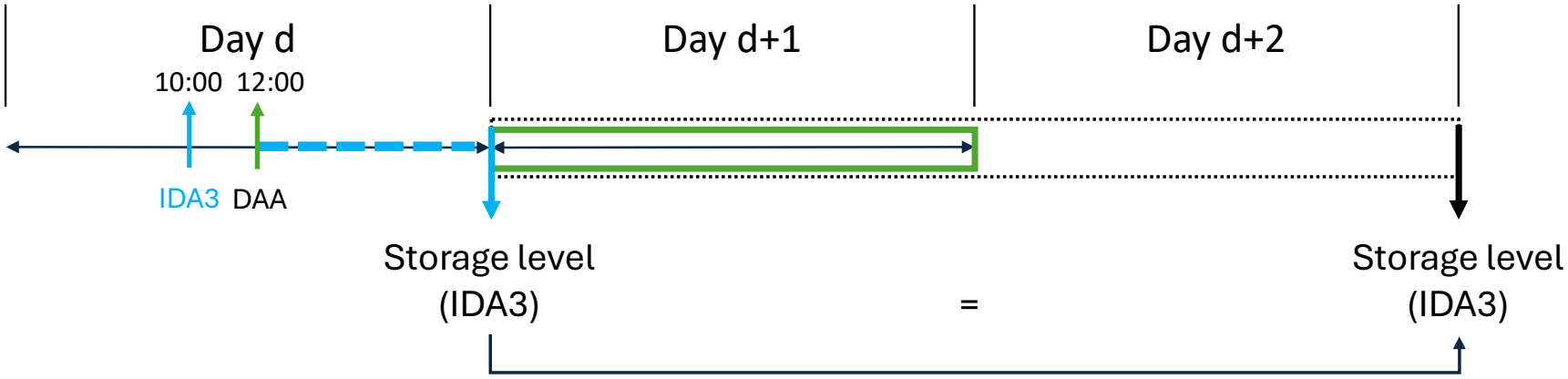


Analysis day of interest

Optimization horizon

We determine the storage level at the start of the observation period. Since this affects dispatch on the first modeled day (15.06.2024), the first day of interest becomes 16.06.2024. To prevent the model from using more energy than initially stored, the starting and ending storage levels must be equal.

Modelling Approach: Daily Optimization (DAA, IDA1, IDA2)

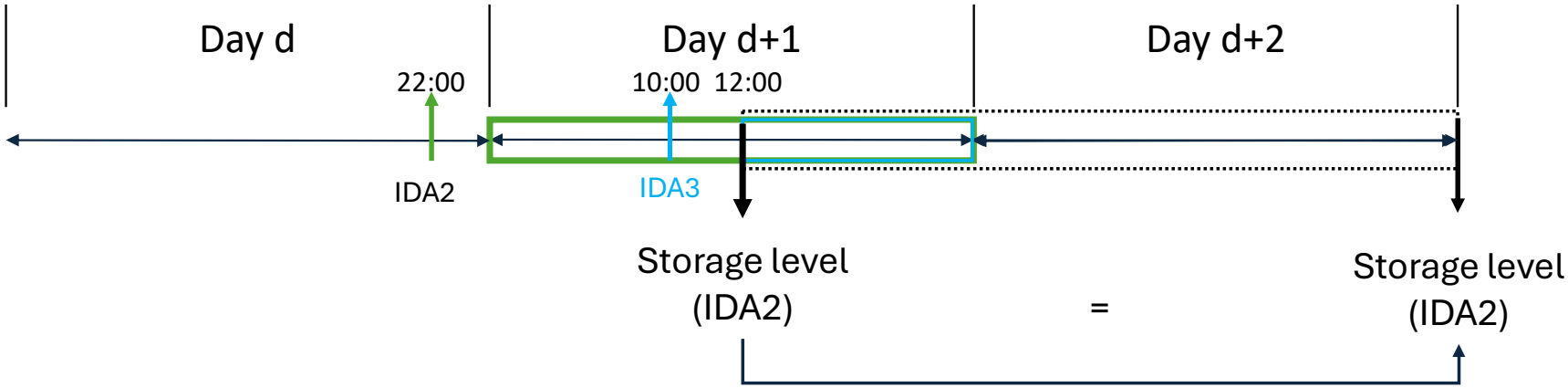


Analysis day of interest

Optimization horizon

The DAA optimization is based on the storage level handed over from day d to day d+1 (the first hour of the day of interest). This level is determined by the previous IDA3 schedule, which includes all hours from 12:00-24:00 in day d.

Modelling Approach: Sequential Optimization IDA3



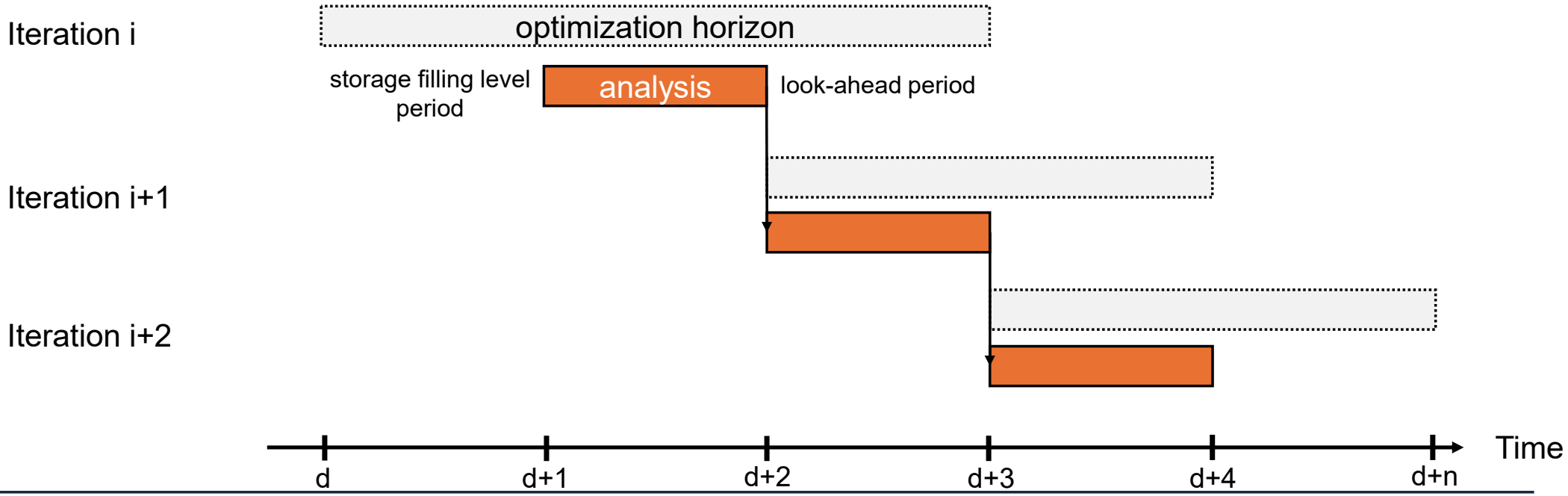
IDA2 | IDA3 Analysis day of interest

Optimization horizon

We always compare the computed schedules of a full day. As IDA3 covers 12:00-24:00 only, 0:00-12:00 contains the fixed IDA2 schedule which automatically sets the storage level for the start of the IDA3 period at 12:00, which is then individually optimized.

Modelling Approach: Rolling Horizon - Daily Iterations

- The optimization model iterates over the whole observation period (15.06.2024 – 31.07.2025).
- The iteration (i) happens daily (d), this implies 410 coupled optimizations for one scenario.



Modelling Approach: Detailed Information

- We are interested in comparing the storage dispatch decisions of the DA-Auction and the three ID-Auctions. We compute schedules for each day (“day of interest”) of the observation period based on the individual auction prices for each time step. But what is the starting filling level of the storage at the day of interest and how to minimize the so called “Horizon Problem”?
- The “Horizon Problem” refers to the challenge of choosing the correct length for a planning period (or "horizon") in optimization problems for energy storage systems. The problem also includes choosing the value for the storage filling level at the beginning and end of the optimization period. Those points are strongly influencing the optimization outcome.
- To reduce the impact of the “Horizon Problem”, we include periods bevor and after the day of interest addressing two issues: 1) What is the correct starting filling level of the storage? and 2) How long is the optimization period?
- Addressing 1), we start the optimization with determining the filling level of the storage in the first time step of the observation period (15.06.’24 - 31.07.’25). As this is directly influencing the dispatch decisions of this day (15.06.’24), we treat the second day (16.06.’24) as the first day of interest. Once the storage schedule for the 16.06.2024 is computed, we automatically have the start storage filling level for the next day (which is equal to the filling level of the last time step in 16.06.’24 $\pm$ charging or discharging actions in the first time step of the 17.06.’24).
- Addressing 2), we include another day, coming after the day of interest. This allows the storage optimization to include potential future signals into the optimization of the schedule of the day of interest. Furthermore, we impose a boundary condition: “the storage filling level at the first time step must equal the filling level at the final time step of the optimization horizon”. This ensures for all iterations, that the storage does not exploit more energy than initially stored (e.g., emptying the storage because the optimization horizon ends). Including the extra day behind the day of interest also reduces the influence of the boundary condition on the dispatch decisions within the day of interest.
- Overall, we run a Rolling Horizon algorithm to compute the schedules of the day of interest in an iterative manner. For the start of the optimization, we consider an optimization horizon of three days in iteration (i) to address the starting storage level issue as described in 1). From then, we compute an optimization horizon of two days as the storage level is transferred from the first day of interest (16.06.’24) in iteration (i) to the next day of interest (17.06.’24) in iteration (i+1). This process continues until the very end of the whole observation period. We exclude the last day of the observation period from our analysis, as issue 2.) cannot be fulfilled for this day.

Data, Assumptions & Simplifications (Caveats)

- **Price data**:
  - Period from 15.06.2024 to 31.07.2025 and 01.10.2025 to 31.10.2025 for all four auctions (DAA, IDA1-3)
- **Assumptions**:
  - 1 MW of battery power is dispatched to maximize revenue
  - Energy to Power Ratio (ETP) = 3 (varied in additional scenarios)
  - 96% charge- and discharge efficiency
  - 5% min. battery filling level
  - 95% max. battery filling level
  - Max. 2 full cycles per day
- **Simplifications**:
  - Modeling the battery as a price taker → neglects large volumes of batteries will influence prices when dispatched
  - All battery capacity is optimized on the spot market → neglects that parts of installed capacity will be dispatched on other markets (e.g. balancing power) or not at all
  - Analysis does not account for battery location → unclear to what extend revised dispatch will stress the grid.
  - On the one hand, redispatch is procured after IDA1 (pRD1). On the other hand, intraday trading continuous after IDA3.

Metrics Used to Measure Dispatch Variations Between Auctions

State Match: the test time series (IDA 1-3) has the same operating state (charging, discharging, or idling) as the reference time series (DAA).

Exact State Match: the test time series has the same operating state and the same power value as the reference time series (exact match).

State Switch: the test time series deviates “moderately” from reference time series, i.e. discharge/charge to idle and idle to discharge/charge.

State Reversal: the test time series shows the opposite operating state to the reference time series (e.g., charging instead of discharging).

Max State Reversal: the test time series shows 200% difference to the reference time series (i.e. either from 100% charging to 100% discharging or vice versa).

Ø-Deviation: Average absolute deviation of power values (in MW) between test and reference time series over the entire observation period. Corresponds to the mean absolute error (MAE).

SAPB

Work Package 3:
Analysis of Battery Schedules (BTU)

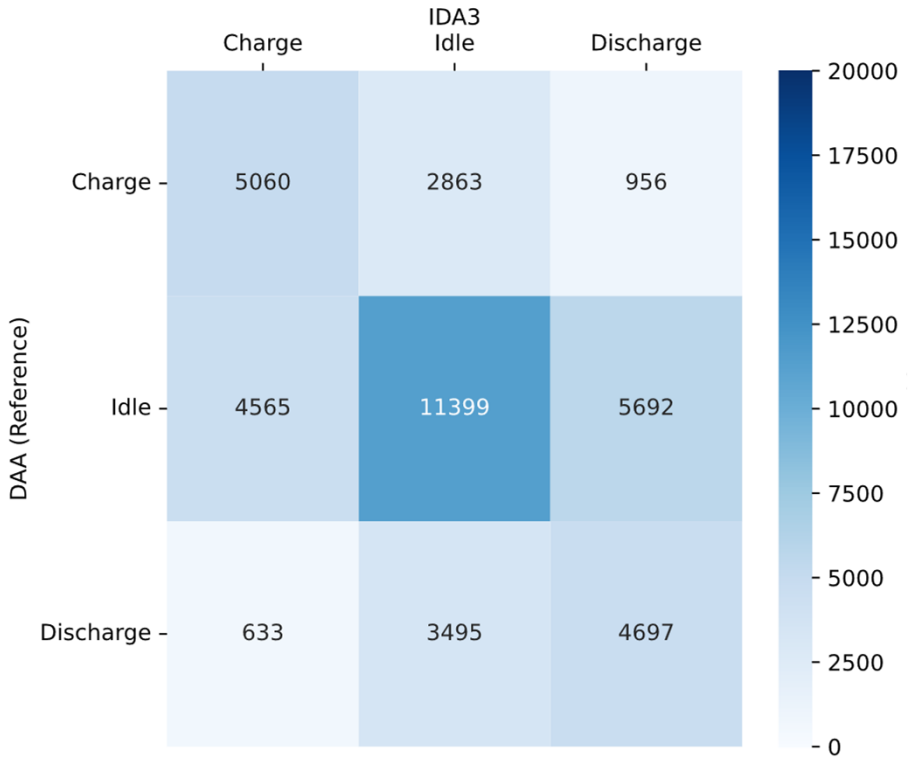
Results & Analysis – Presentation

- Results will be shown for DAA-IDA3* comparison with an Energy-to-Power (ETP) of 3 for the time horizon 15.06.2024 - 31.07.2025 and results for time horizon 01.10.2025 – 31.10.2025 (newly introduced ¼-hourly DAA), complemented by selected key aspects for additional analysis.

- Further results are presented in the Appendix.
  - Detailed results for IDA1 and IDA2
  - Detailed results for ETP 2, 4 and 6

* Note that our IDA3 results are a combination of IDA2 (0:00 – 12:00) and IDA3 (12:00 – 24:00), as the IDA3 auction covers the second half of the day only.

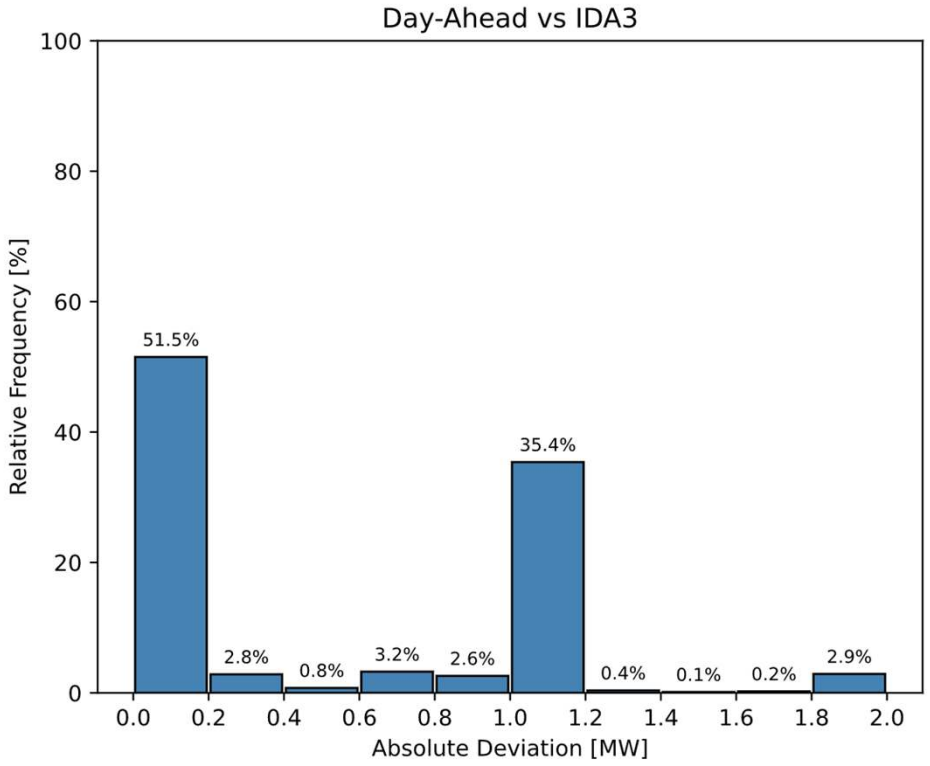
Comparison DAA vs. IDA3: Behavior Changes in 46,25% of all Hours



- Time steps in optimization period: 39.360
- State Match in 21.156 time steps - about half the time (53,75%)
- State Switch (from idle to charge/discharge or from charge/discharge to idle) in 16.615 time steps (42,21% of the time)
- State Reversal in 1.589 time steps (4,04% of the time)

Check „Detailed Information on the Visualizations"

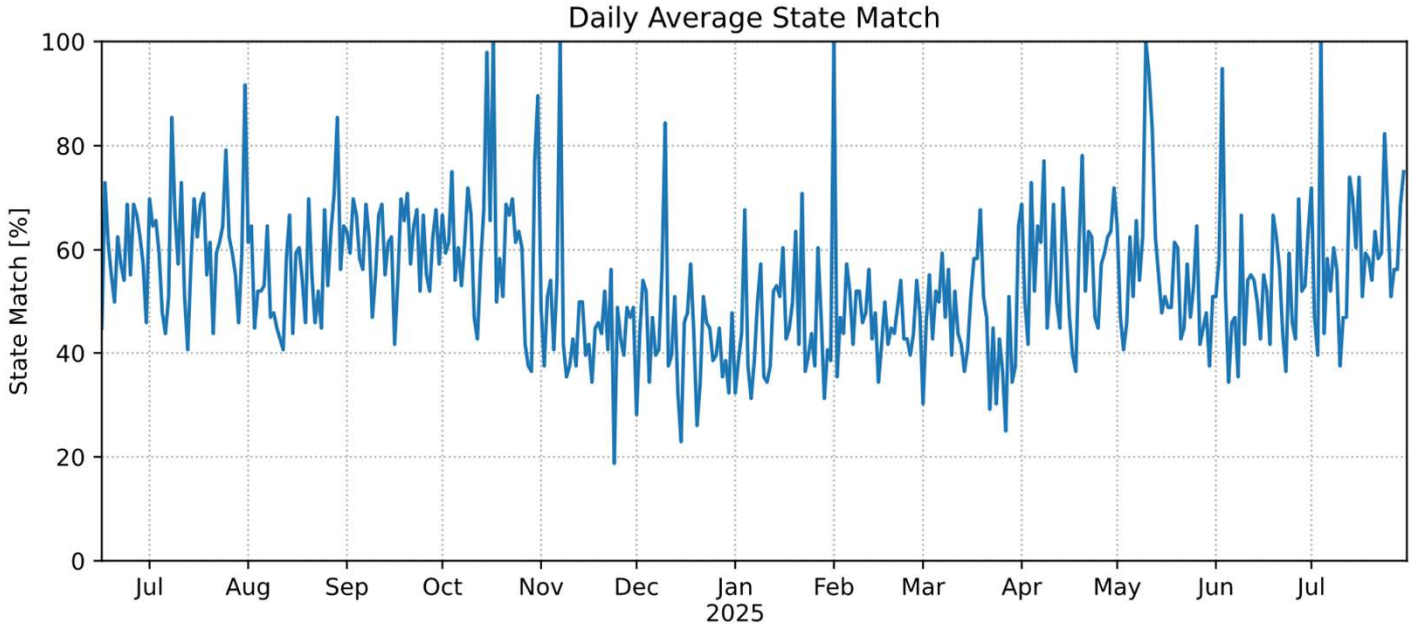
Comparison DAA vs. IDA3: 3% of all Hours Show a Complete Switch



- No deviation about half the time
- 100% inst. cap. shift happens frequently (35.4%)
- Max State Reversal (200% inst. cap. shift) rarely happens (2.9%)

Check „Detailed Information on the Visualizations"

Comparison DAA vs. IDA3: There are Less State Matches in Winter Hours

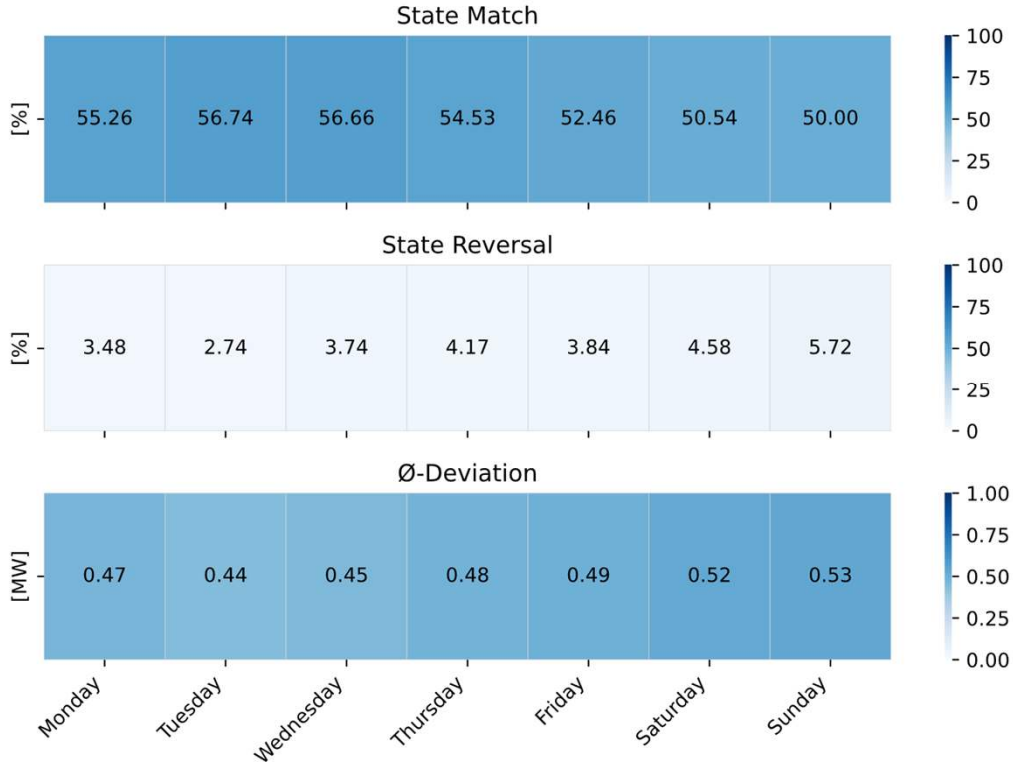


Min. State Match (day)	Max. State Match (day)
24.11.2024	17.10.2024

- Strong variations of daily average State Match over time
- Few days with 100% State Match
- No days with 0% State Match
- In general, winter has lower State Matches than summer

Check „Detailed Information on the Visualizations”

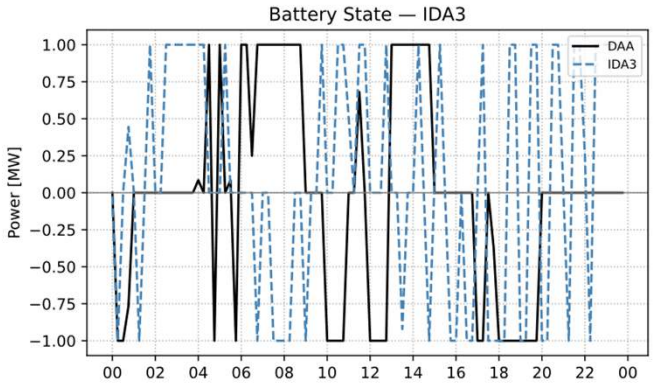
Comparison Weekday Metrics DAA vs. IDA3: Most Changes Occur on Sundays

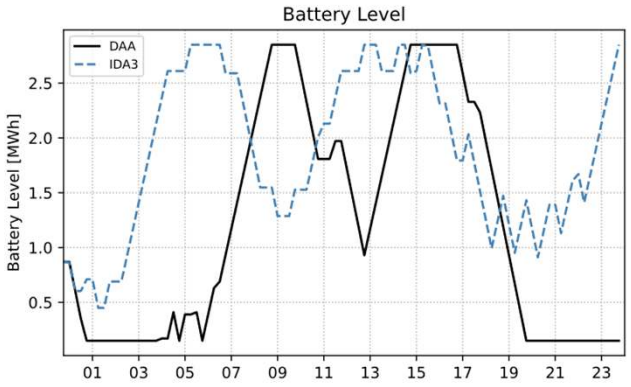


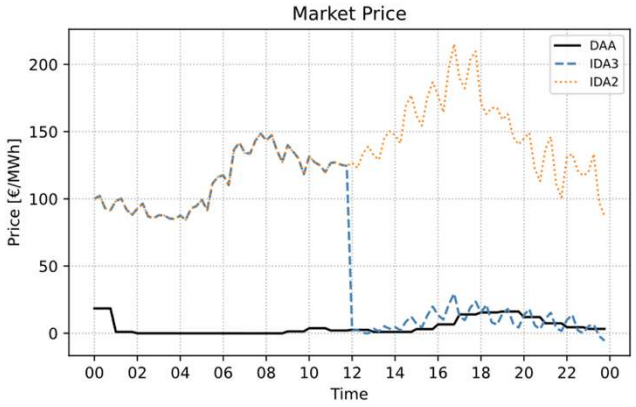
- Difference between workdays and weekend
- Lower State Match, more State Reversal and higher Ø-Deviation on weekends
- Tuesday has least deviations
- Sunday has most deviations

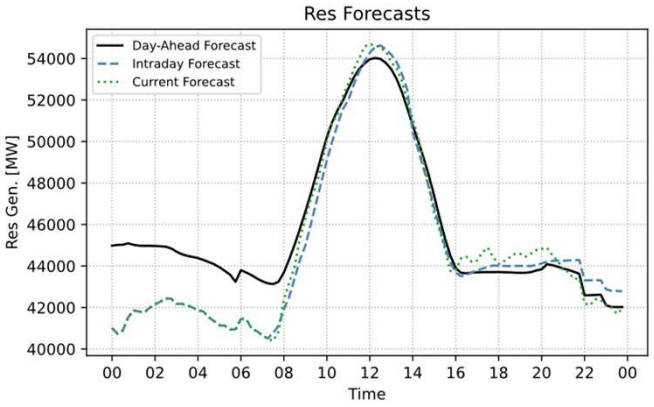
Check „Detailed Information on the Visualizations"

Extreme Day 24.11.2024 DAA vs. IDA3: Deviations Result from Updated RES Forecasts









- Extreme day = day with highest number of **Max State Reversal** (here a Sunday)
- Very different battery state pattern
- Shift of battery filling level
- Strong market price deviation between auctions
- Strong renewable forecast deviation between Day-Ahead and Intraday/ Realization
- Batteries react to updated RES forecasts, not „speculation“.

Check „Detailed Information on the Visualizations”

General Comparison to DAA: IDA 2&3 with Most Deviations - State Reversal Increases with Higher ETP Ratio

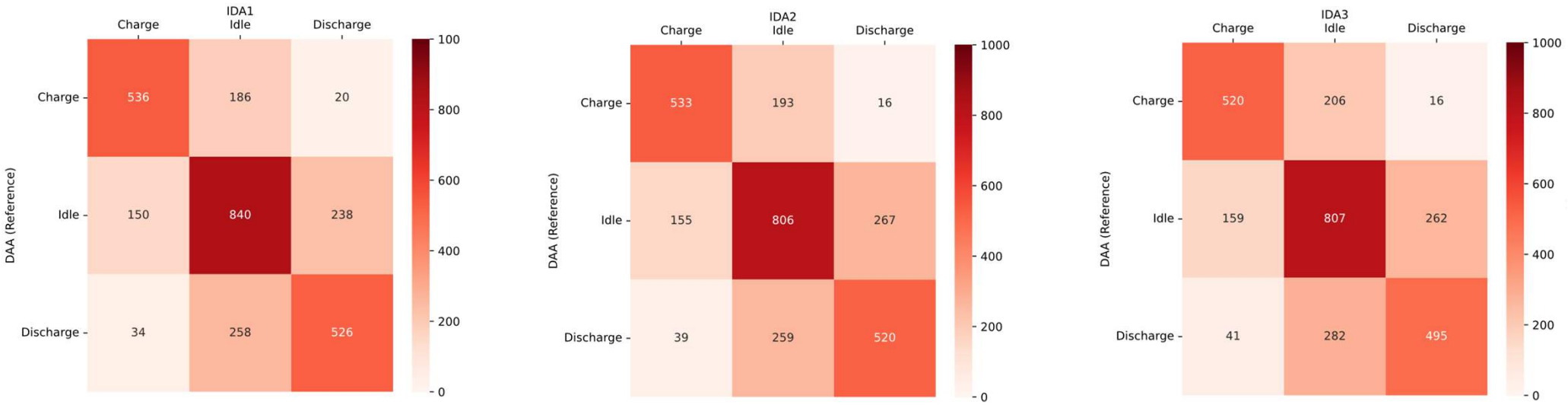
ETP	Auction	State Match [%]	Exact State Match [%]	State Reversal [%]	Ø-Deviation [MW]
2	IDA1	60.76	57.73	1.85	0.39
	IDA2	58.48	55.60	2.04	0.41
	IDA3	58.68	55.74	2.09	0.41
3	IDA1	57.48	53.78	3.56	0.44
	IDA2	53.10	49.53	4.01	0.49
	IDA3	53.75	50.11	4.04	0.48
4	IDA1	56.68	54.29	5.35	0.46
	IDA2	51.97	49.58	6.24	0.52
	IDA3	52.26	49.89	6.19	0.52
6	IDA1	63.91	61.51	7.41	0.42
	IDA2	57.72	55.24	9.10	0.50
	IDA3	57.87	55.31	8.93	0.50

Detailed Information on the Visualizations

- **Visualization – Confusion Matrix:** This matrix is a special table that allows to compare our reference DAA schedule with the IDA schedules. Each row represents the operating status of the DAA schedule and each column the operating status of the respective IDA schedule. The diagonal therefore counts the number of time steps where both schedules have a State Match. The other fields count the number of timesteps, where the DAA schedule was in a specific state and the IDA3 schedule in a different state. E.g. first row, second column, in 2863 time steps the DAA schedule was charging while the IDA3 schedule was in idle.
- **Visualization – Deviation Histogram:** This figure represents the frequency distribution of state deviations of the IDA from the DAA. It is used to visually analyze the distribution, shape, and dispersion of these deviations, showing that most measurements fall into two classes: No or very small deviations (0.0-0.2 MW) or deviations in the order of the installed power (1.0-1.2 MW).
- **Visualization – Average State Match:** This diagram shows the average State Match for each day of the whole observation period. The graphic visualizes the seasonal pattern and helps to identify specific days where on average the State Match of all 96 time steps is low of high.
- **Visualization – Comparison Weekdays:** This figure depicts the average values of the three metrics for each day in the observation period. It is useful to visualize patterns between the days. It becomes clear, that the match between working days is higher compared to weekend days.
- **Visualization – Extreme Day Analysis:** The four diagrams are depicting different time series data of a specific (extreme) day. On this specific day we measured the highest number of Maximum State Reversals between DAA and IDA3 of the whole observation period. The top left visualizes, the battery operating state of the DAA and the IDA3 schedule. The top right shows the battery filling level of both schedules as a result of the operating state. The lower left diagram visualizes the electricity market prices of the DAA and the IDA3 (we included also the IDA2 as the IDA3 schedule is based on the IDA2 dispatch). The lower right visualizes the renewable infeed forecast, taken form Entso-e, showing the changes in the forecast values as time progresses. This arrangement makes it possible to gain insights on what drives deviations in the battery schedule like the Maximum State Reversal. We can see, that the renewable infeed forecast in the beginning hours of the day of interest deviates strongly. First the DAA forecast assumes a high wind infeed, keeping prices low. The new forecast data became known for the IDA2, showing significantly less wind infeed, driving prices up. For the IDA3, forecast remains within expectations with slightly more wind infeed, leading to lower prices. The battery optimization is adopting the schedule to the varying auction prices, leading also to a different storage filling level.

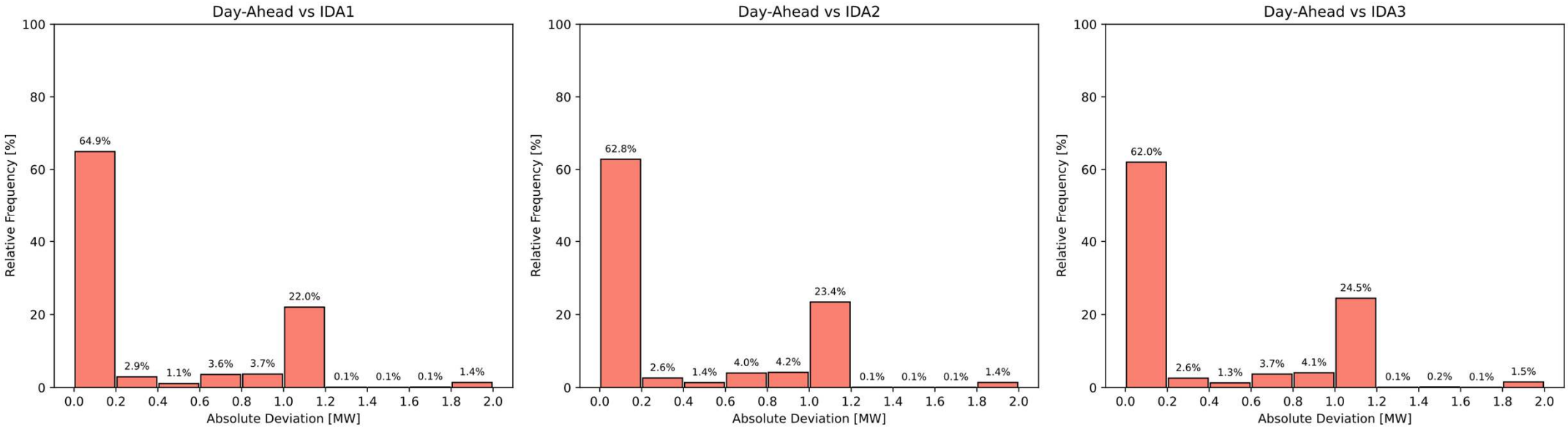
Work Package 3:
Analysis of Battery Schedules (BTU)
Results October 2025

October 2025: Start of 15 Minute DAA - Analysis of Schedule Variations Between Auctions with Battery ETP3



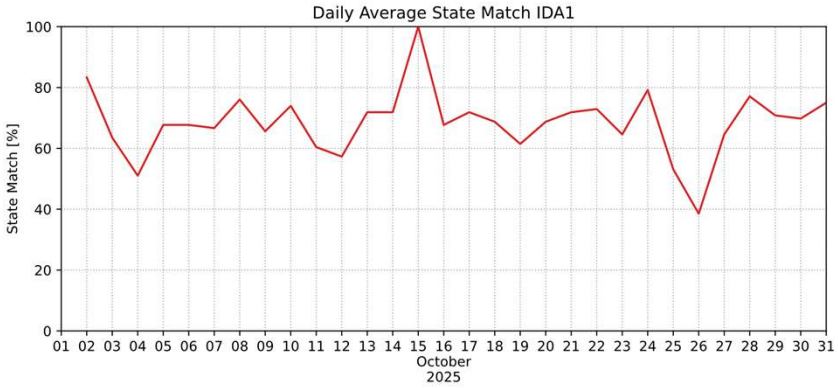
- State Match in around 68 % of the time steps for all DAA to IDA comparisons (before 50%)
- State Switch (from idle to charge/discharge or from charge/discharge to idle) around 30% of ¼-hours (before 40%)
- State reversal around 2% of ¼-hours (before 10%)

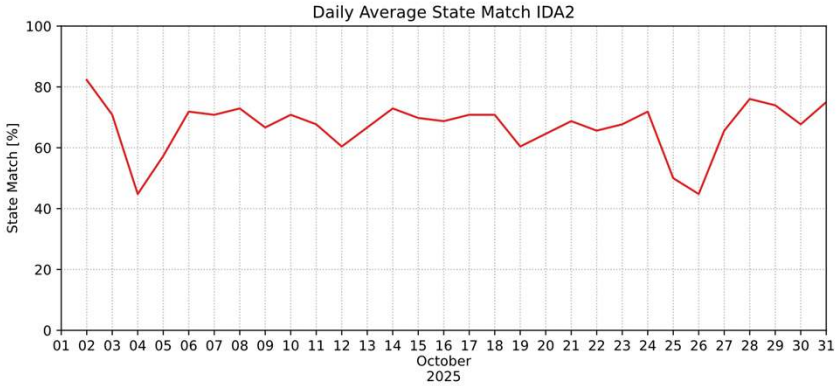
October 2025: Histograms of IDA Schedule Deviations from DAA

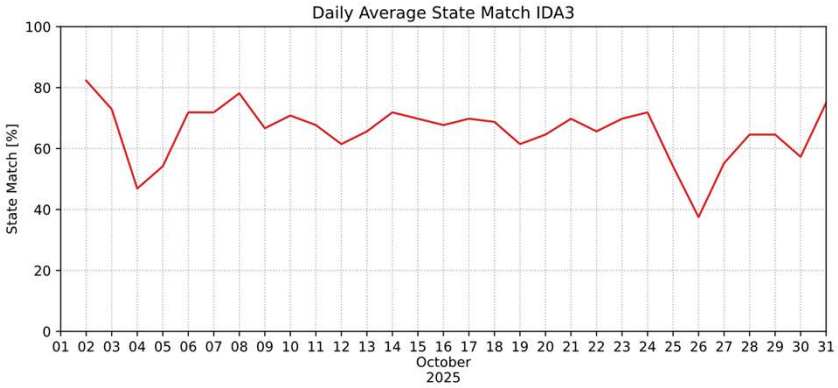


- Timesteps without deviation happen more often (63.7%)
- 100% inst. cap. shift happens less frequently (23.3%)
- Max. State Reversal (200% inst. cap. shift) rarely happens (1.4%)

October 2025: Average Daily State Match of DAA with IDA Schedules

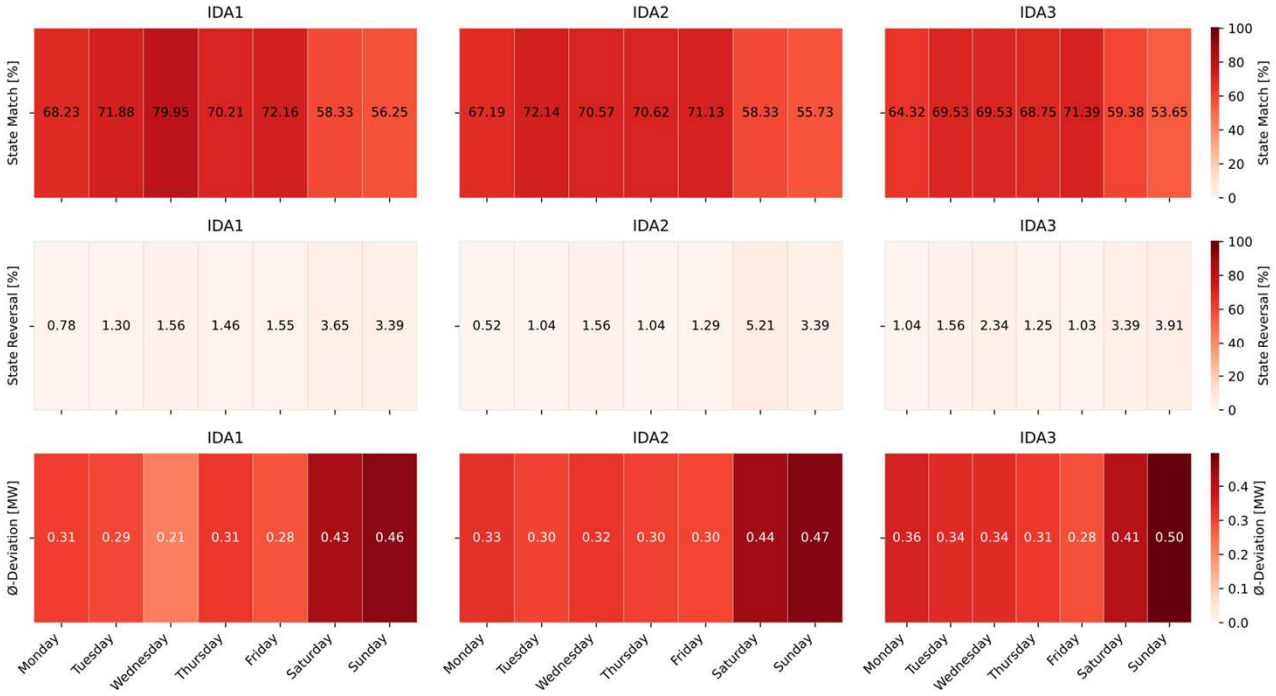






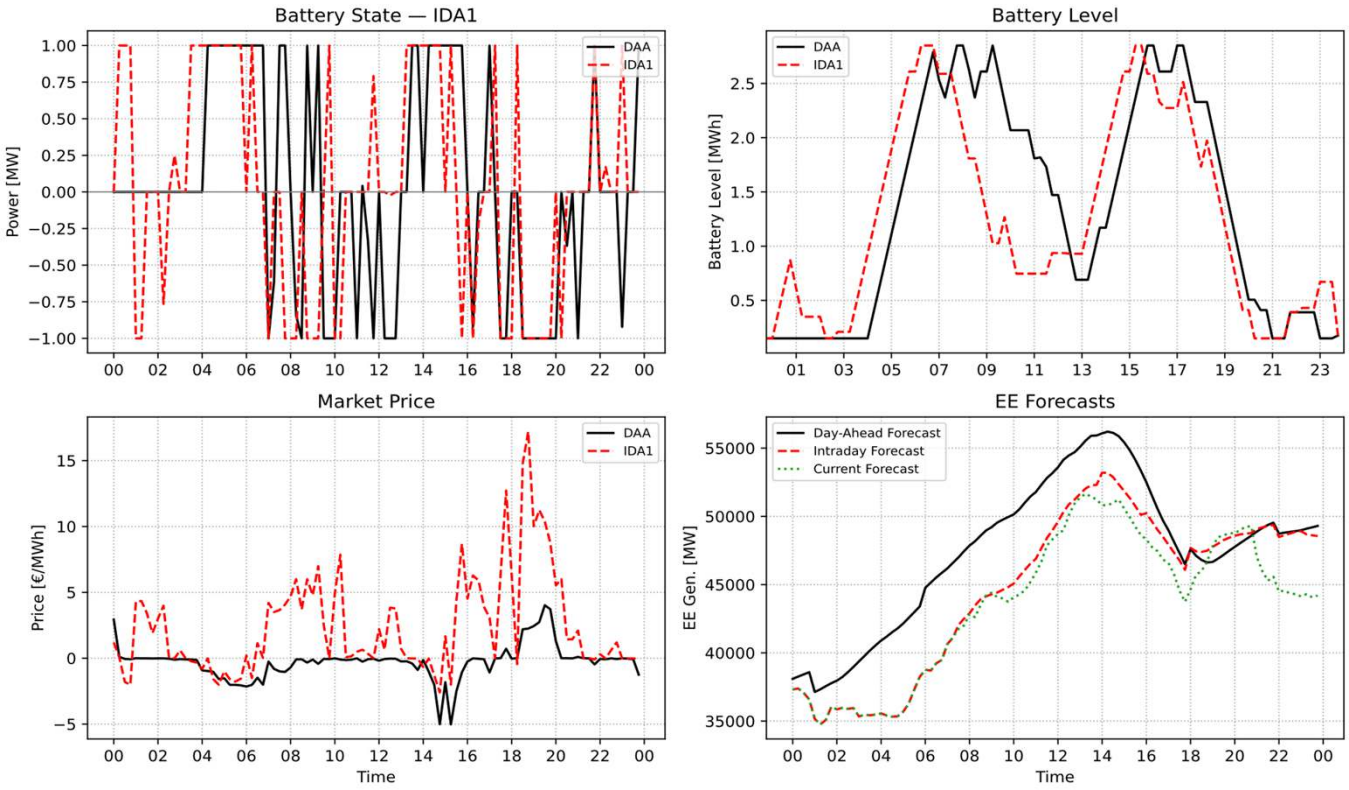
- Similar State Match pattern among all diagramms
- IDA1 has higher State Match and one day with 100%
- 04.10 and 26.10 are days with lowest State Match

October 2025: Analysis of Weekday Patterns in Schedule Deviations Reveals Weekends to be More Challenging



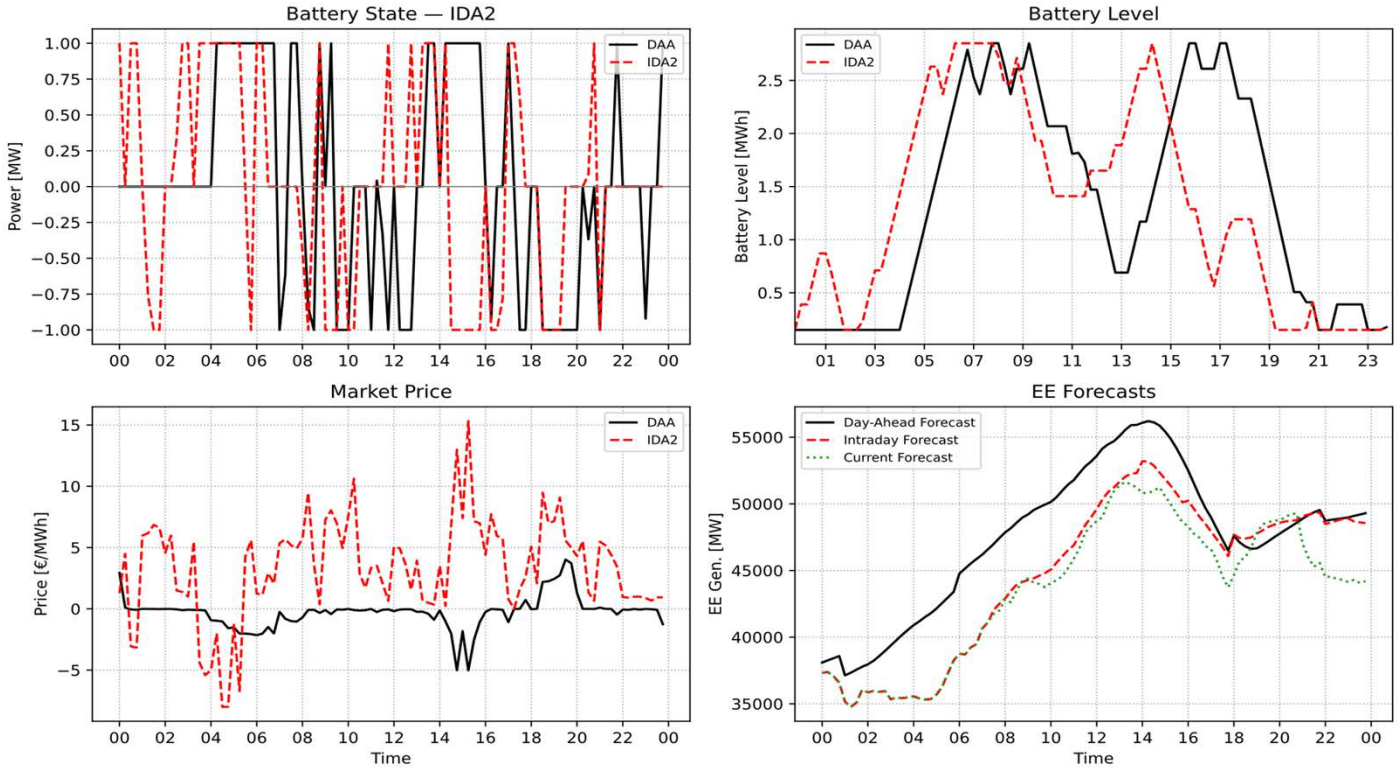
- More pronounced difference between workdays and weekends (lower State Match, more State Reversal and higher Ø-Deviation on weekends)
- Best State Match day differs between auctions
- Monday tend to have least State Reversal
- Sunday has most deviations

Extreme Deviation Day 04. October 2025: Comparison DAA to IDA1 - Low RES Forecast Accuracy



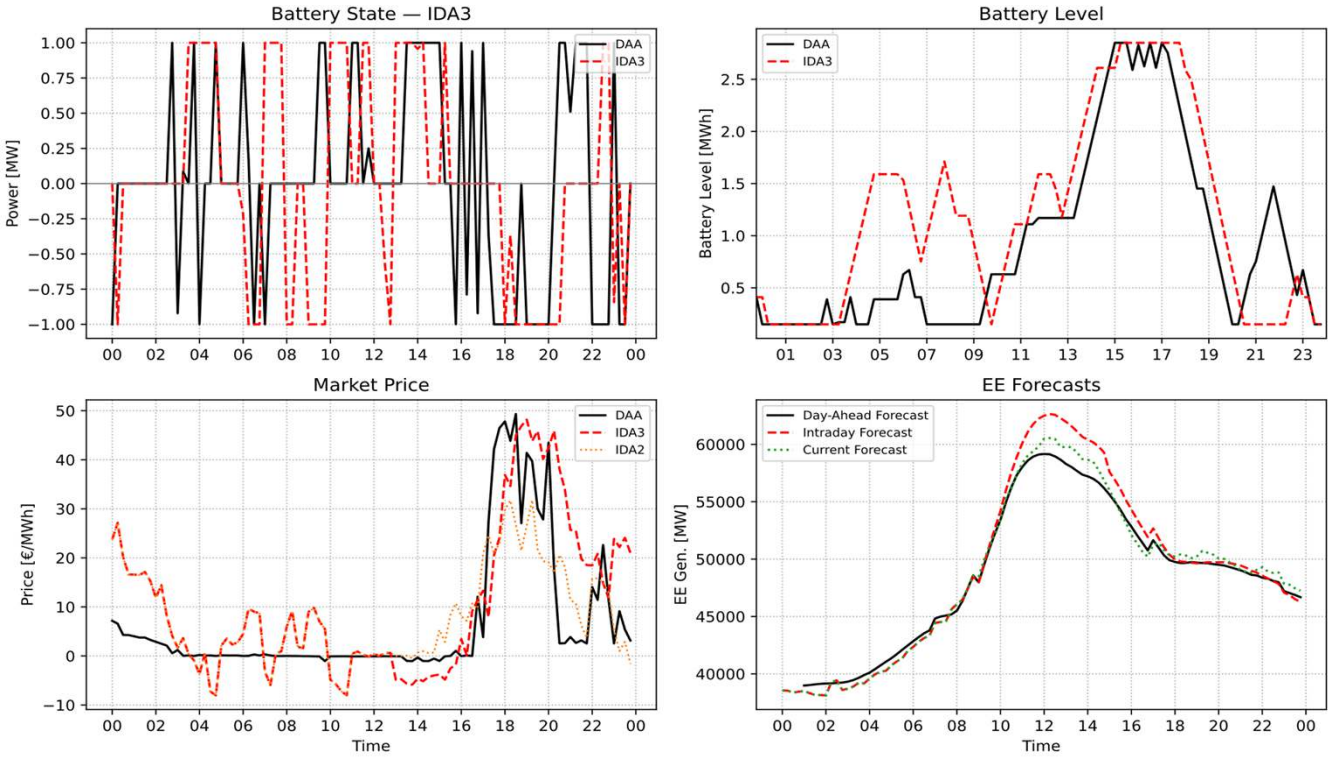
- Extreme day = Saturday
- Very different battery state pattern
- Shift of battery filling level in IDA1
- Strong market price deviation between auctions
- Strong renewable forecast deviation between Day-Ahead and Intraday

Extreme Deviation Day 04. October 2025: Comparison DAA to IDA2 - Low RES Forecast Accuracy



- Extreme day = Saturday
- Very different battery state pattern
- Shift of battery filling level in IDA2
- Strong market price deviation between auctions
- Strong renewable forecast deviation between Day-Ahead and Intraday

Extreme Deviation Day 26. October 2025: Comparison DAA to IDA3 - Low RES Forecast Accuracy



- Extreme day = Sunday
- Very different battery state pattern
- Additional forenoon ramp up of battery filling level in IDA3
- Strong market price deviation between auctions
- Strong renewable forecast deviation between Day-Ahead and Intraday

General Comparison to DAA: IDA 2&3 With More Deviations - State Reversal Increases with Higher ETP Ratio

ETP	Auction	State Match [%]	Exact State Match [%]	State Reversal [%]	Ø-Deviation [MW]
2	IDA1	69.80	65.78	0.97	0.29
	IDA2	67.54	63.49	0.90	0.31
	IDA3	67.14	63.13	1.08	0.32
3	IDA1	68.22	63.31	1.94	0.33
	IDA2	66.68	60.98	1.97	0.35
	IDA3	65.35	60.11	2.04	0.36
4	IDA1	69.30	65.67	3.91	0.33
	IDA2	68.94	64.99	4.27	0.34
	IDA3	67.72	64.13	4.56	0.35
6	IDA1	74.93	71.70	5.67	0.31
	IDA2	74.39	71.31	5.95	0.31
	IDA3	73.99	70.84	6.21	0.32

Work package 4: Analysis of the influence of the continuous trading market (Steinbeis)

- Goal: Overview continious trading behavior

- Intraday Data Analysis 2024 to select interesting dates
- Results of continuous trading outcomes

Intraday Data Analysis 2024 - Volume Analysis

Volume Metric	Value
Mean	0.64 MWh
Std. Dev.	1.22 MWh
Min	0.025 MWh
25% Quartile	0.05 MWh
Median	0.20 MWh
75% Quartile	0.675 MWh
Max	100 MWh

- Most trades are small in size (median = 0.2 MWh).
- A few huge block trades exist (up to 100 MWh).
- Distribution is right-skewed: many small trades, few large ones.

Intraday Data Analysis 2024 - Price Analysis

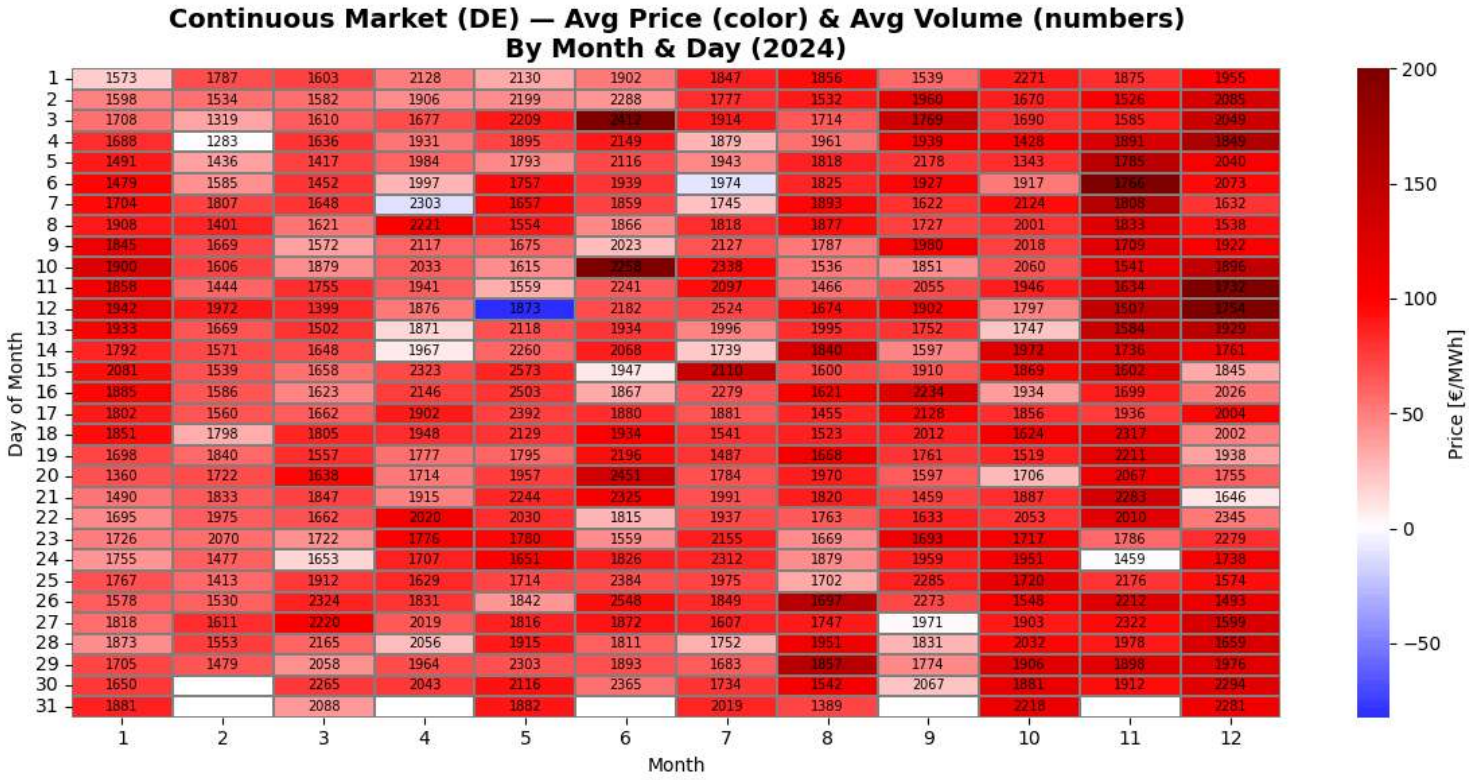
Price Metric	Value
Mean	95.60 €/MWh
Std. Dev σ.	29.50 €/MWh
Min	–663 €/MWh
25% Quartile	78.95 €/MWh
Median	92.60 €/MWh
75% Quartile	111.60 €/MWh
Max	1500 €/MWh

Interpretation:

- Average price ≈ 96 €/MWh.
- Prices are spread with σ ≈ 30 €/MWh
- **Extreme outliers exist:**
  - Negative prices (–663 €/MWh) market oversupply situations.
  - Very high prices (1500 €/MWh), scarcity or last-minute balancing needs.

Methodology: analysis of trading behaviour shortly before gate closure in continuous trading

- 11th May – Normal Day
- 12th May – Lowest Price
- 10th June – High Price
- 6th July – Low Price
- 1st Sep (Normal Day)
- 12th Dec (High Price)



Methodology

Analysis of trader behavior in continuous trading, especially shortly before gate close.

Each trade i is assigned to the Time Before Delivery Δt_i.

For each trade:

$$\Delta t_i = (T_i^{delivery} - T_i^{execution}) \quad \text{in minutes}$$

- $T_i^{execution}$ = timestamp of trade execution
- $T_i^{delivery}$ = start of delivery block (e.g., 15-minute period)

Price Analysis

- The trades sorted acording to the Δt_i
- Calculation of Average Price Pr_{average} for every minute before delivery m

$$Pr_{\text{average}}(\text{m}) = \frac{1}{N_{\text{m}}} \sum_{i=1}^{N_{\text{m}}} Pr_i$$

N_{m}- Number of trades with the same interval before delivery

Pr_i - prices for the trades *i*

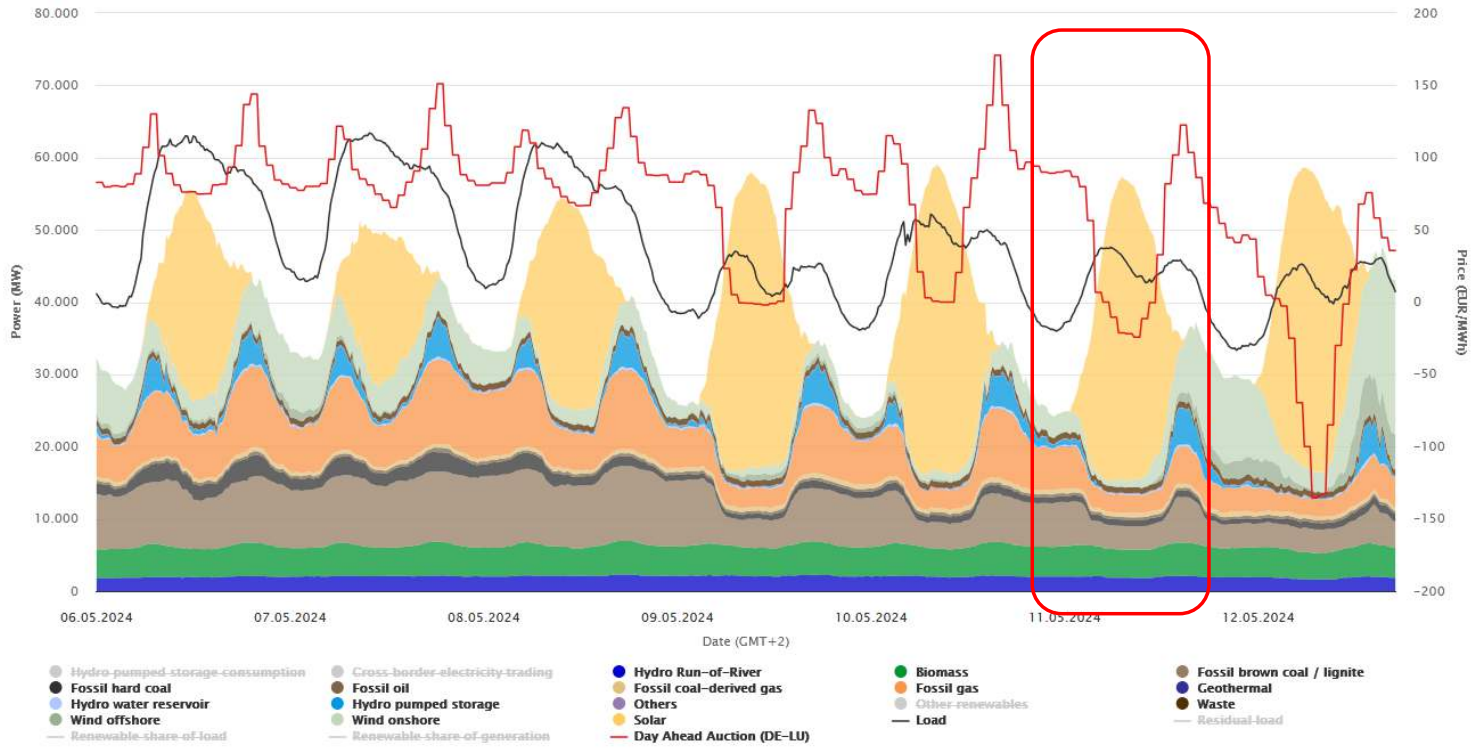
m - time interval before delivery (m=1 minute or m= 30 minutes)

- VWAP(Volume-Weighted Average Price):

V_i - traded volume

$$VWAP\ (\text{m}) = \frac{1 \sum_{i=1}^{N_{\text{m}}} Pr_i \cdot V_i}{\sum_{i=1}^{N_{\text{m}}} V_i}$$

11th May – Normal Day



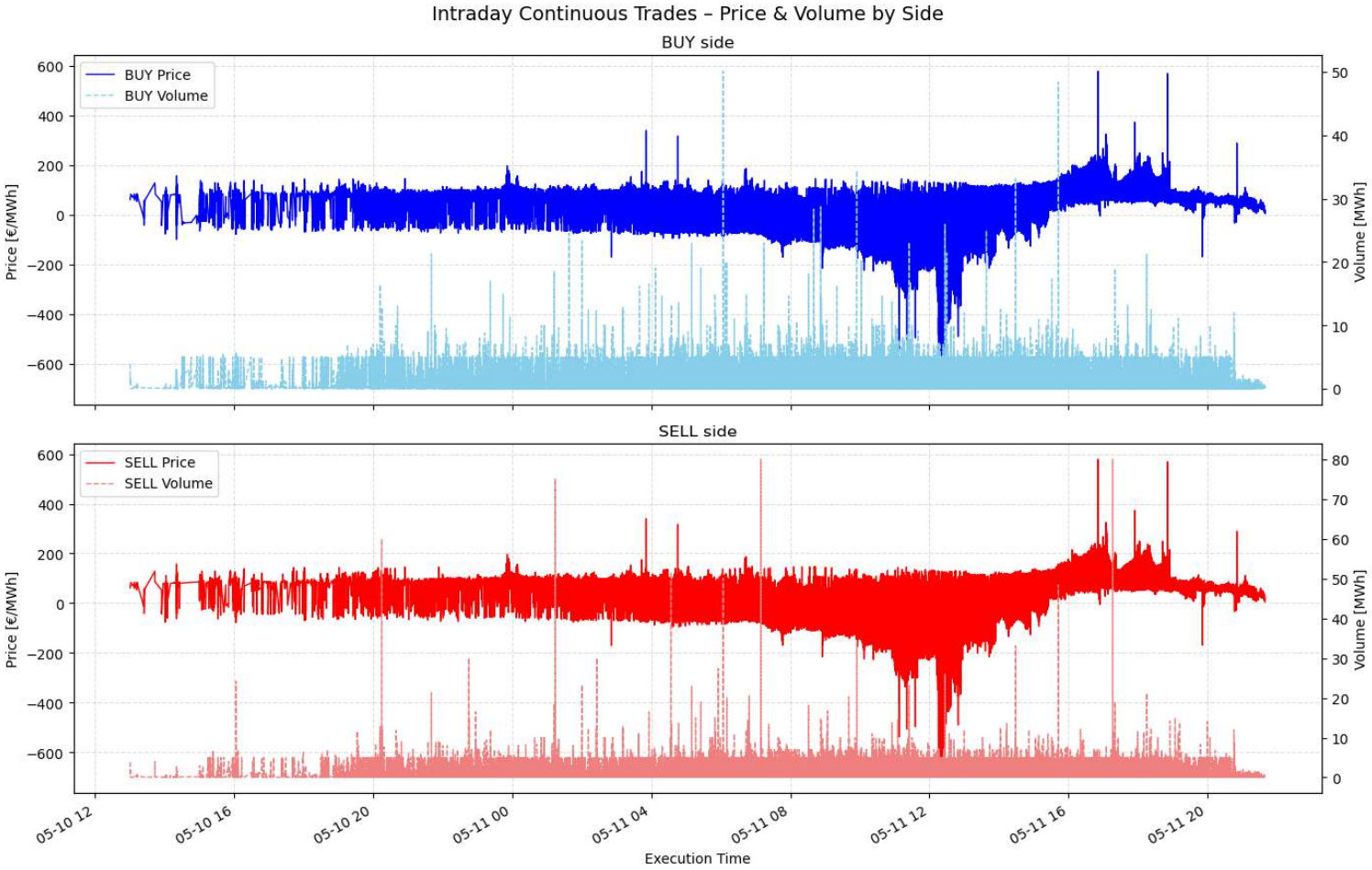
https://www.energy-charts.info/charts/power/chart.htm?l=de&c=DE&year=2024&week=19&source=total

11 May: no direct relation between price level and trading volume is recognisable

- National trade: each trade consists of a sell and a buy ID with the same volume and price
- Cross-border trades have only a sell or a buy trade; the cross-border ID is not known

Findings

- no direct relation between price level and trading volume is recognisable
- High individual prices up to -600 €/MWh at lunch time

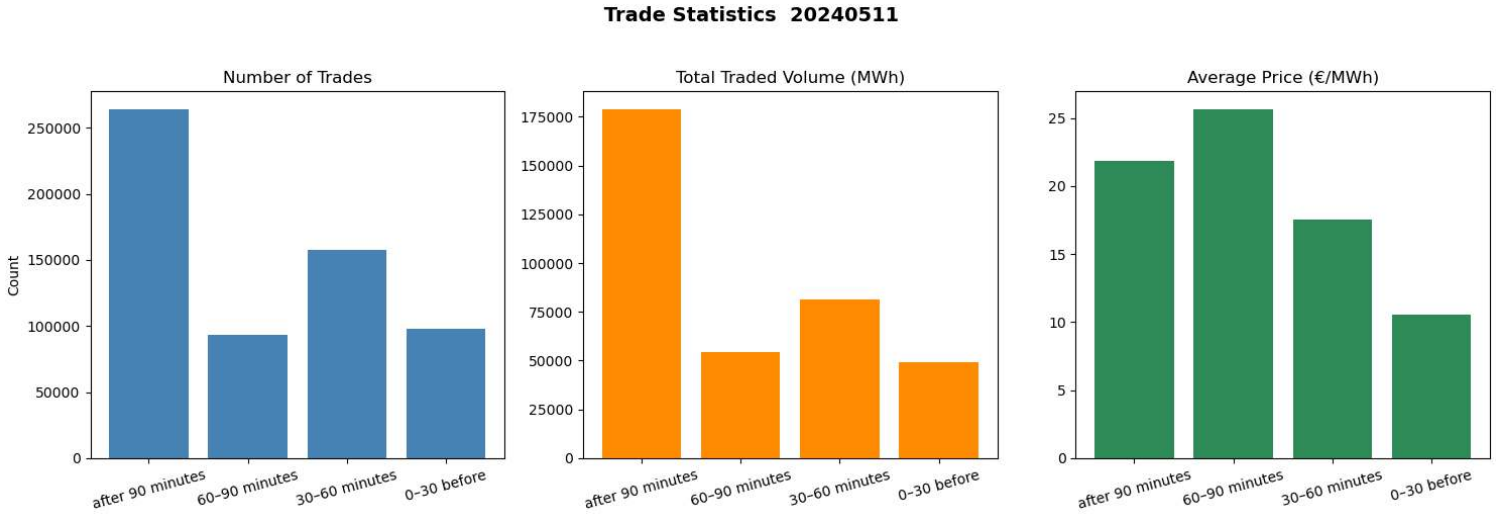


Brandenburg University of Technology Cottbus - Senftenberg

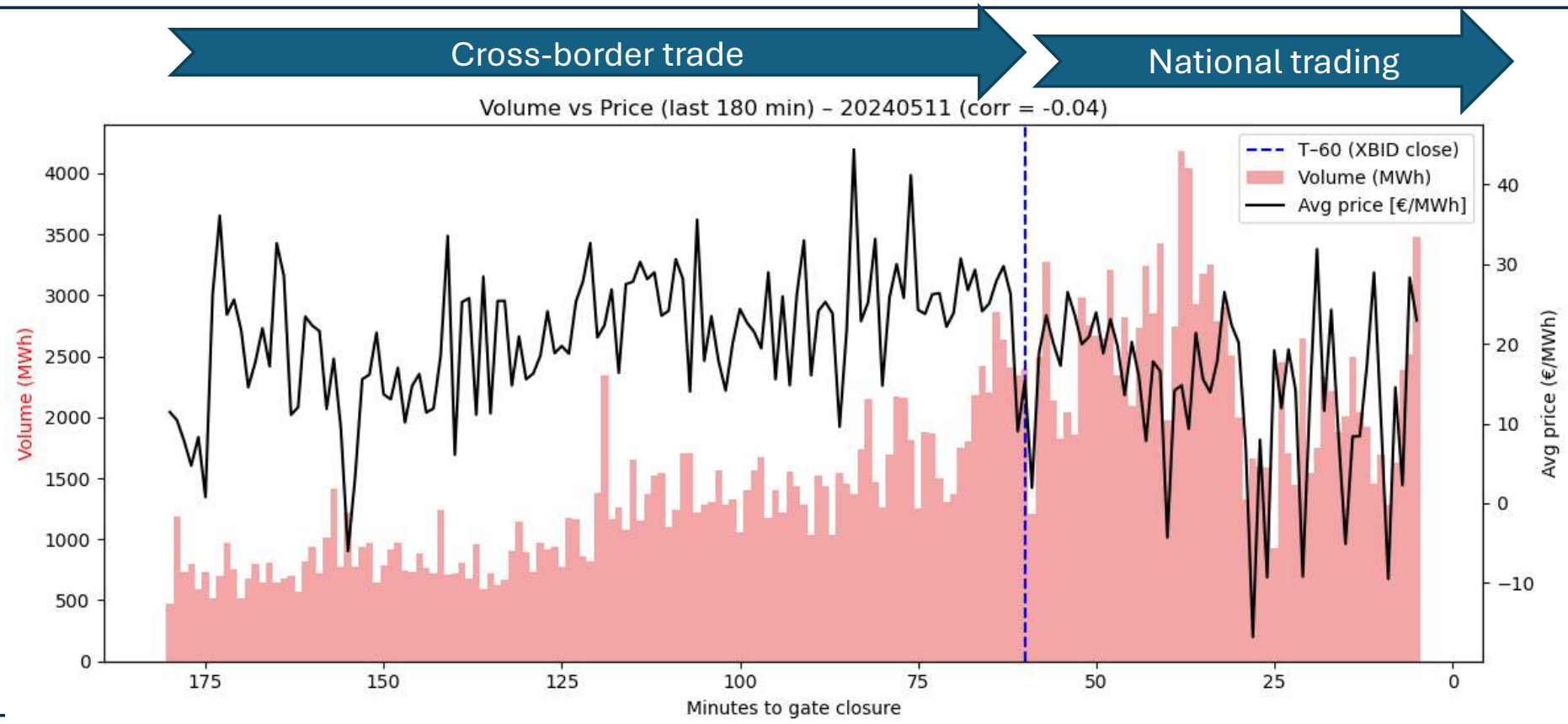
Steinbeis

11 May: high number of trades in the last hours before gate closure

- Trades concentrated in the last 3h before gate closure (≈ 76% of daily volume).
- Within the last 1h, around 36% of trades took place.



11 May: Trades increase before cross-border trade gate closure and in last 60 minutes –with volatile prices



Brandenburg University of Technology Cottbus - Senftenberg

Steinbeis

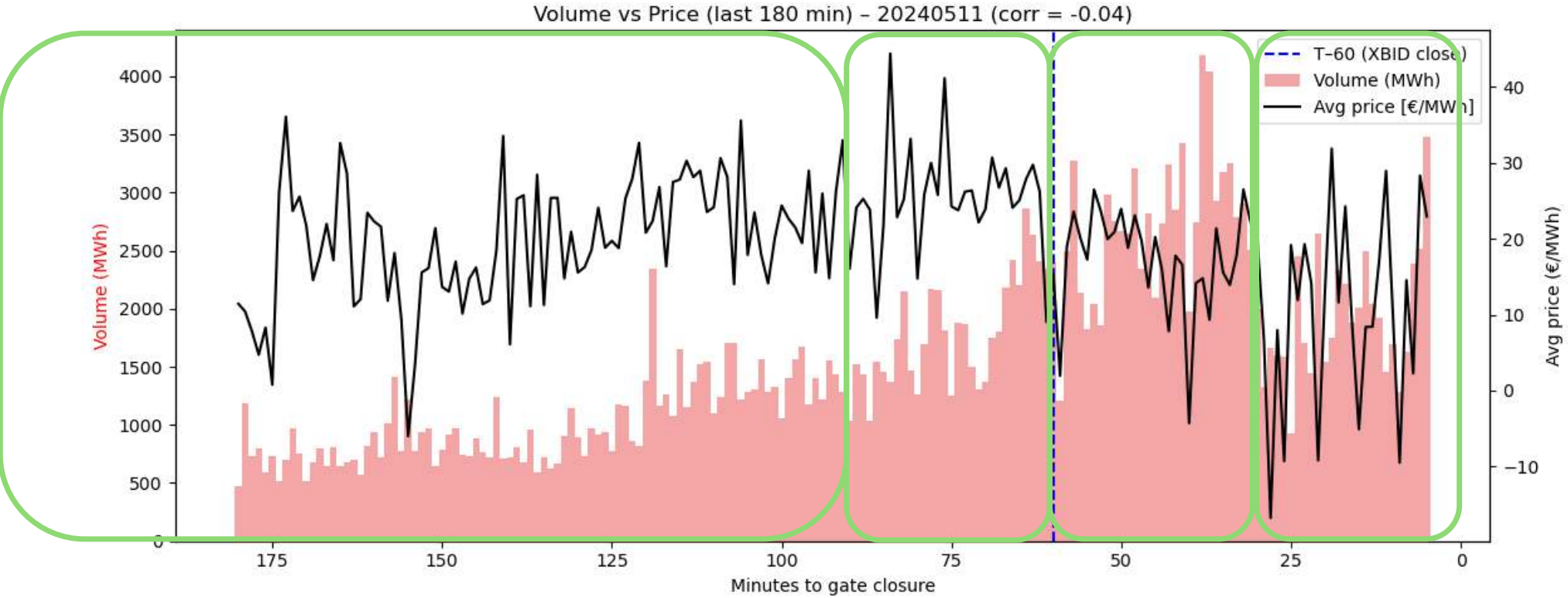
Key Insights 11 May

- Analysis of volume and average prices:
  - Increase in traded volume shortly before gate close time for cross-border trading (60 minutes before delivery)
  - High trading volume in the period between 30 and 60 minutes before delivery (trading between German control areas permitted up to 30 minutes before delivery)
  - High price volatility visible in the last 30 minutes (trading only possible within the control area)

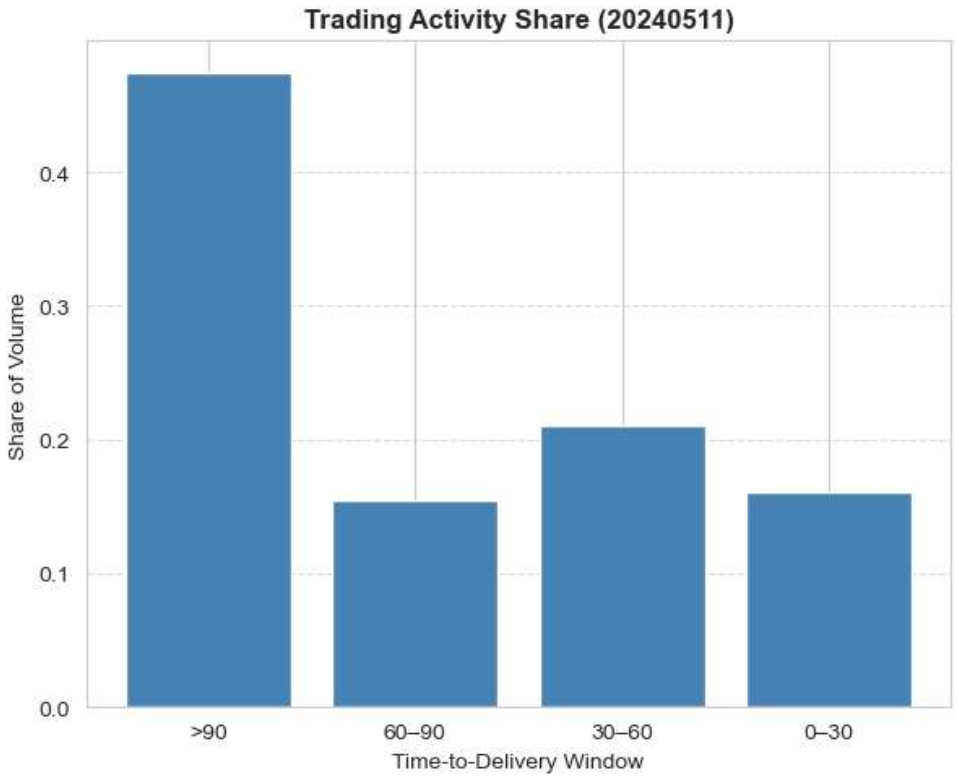
  → Definition of for Analysis Areas

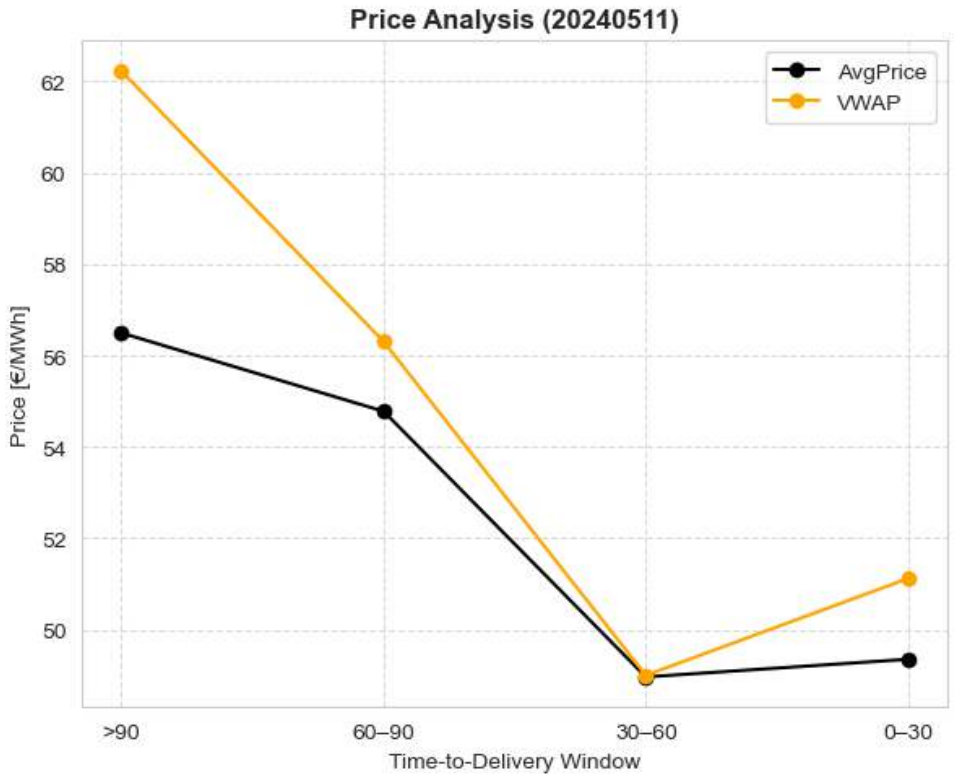
Key Insights 11 May

Within four marked time windows, analysis of:
- Share of total trade volume
- Determination of average prices
- Volatility
- Deviation to Day Ahead prices



Analysis results: volumes and prices





Analysis results - Price volatility

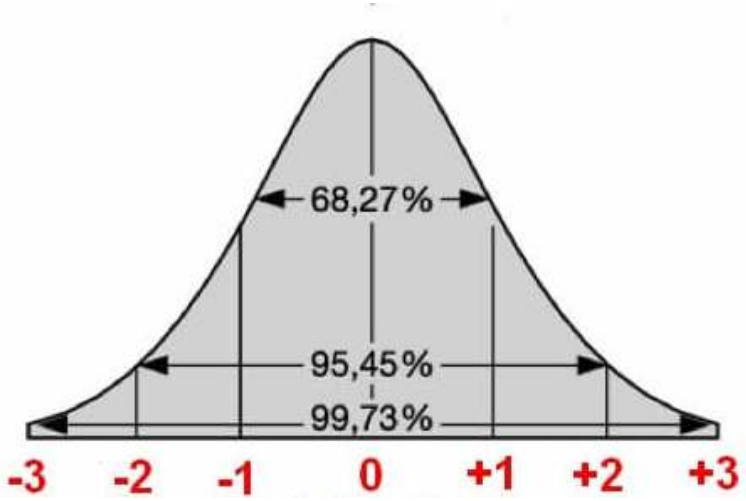
- Mean

$$\overline{x} = \frac{1}{n}(x_1 + x_2 + \ldots + x_n) = \frac{1}{n}\sum_{i=1}^{n} x_i$$

- Standard deviation s for a sample: Measure of the dispersion of prices around an average price

$$s = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2}$$

- In a normal distribution, any value in the population lies:
- with a 68.3% probability in the range $\overline{x} \pm s$
- with a 95.5% probability in the range $\overline{x} \pm 2s$
- with a 99.7% probability in the range $\overline{x} \pm 3s$

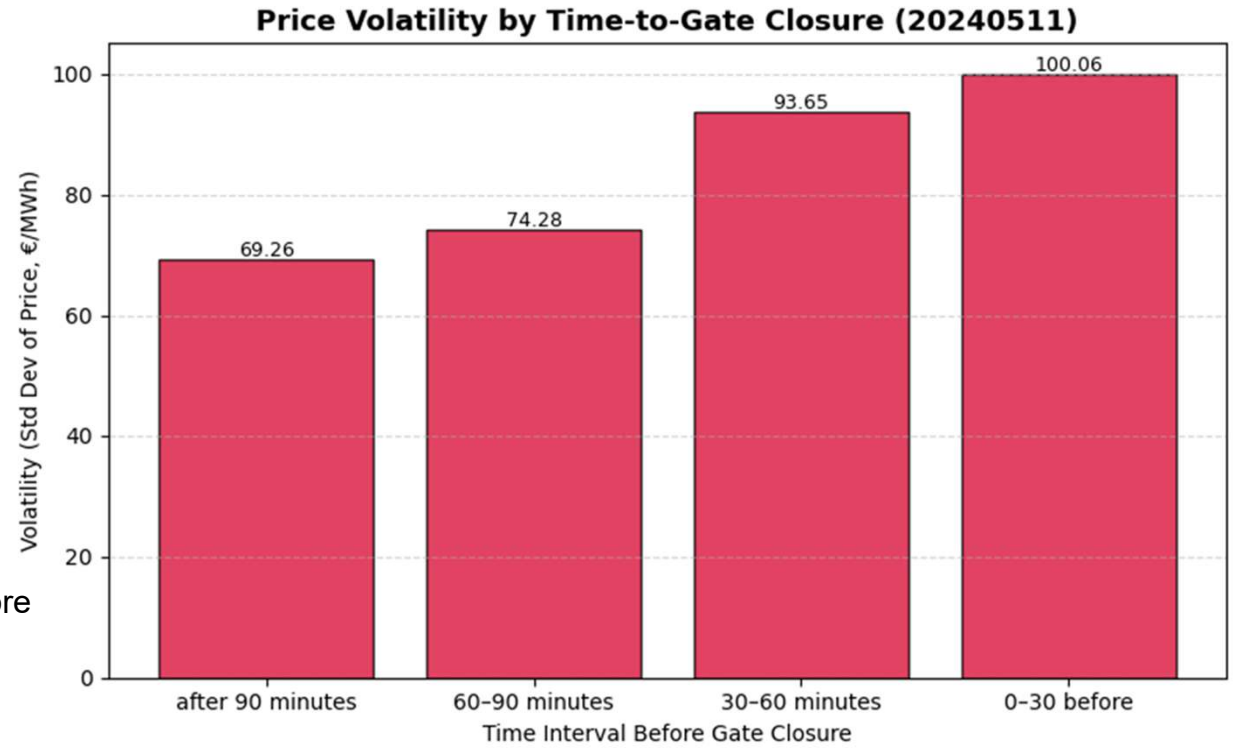


Analysis results - Price volatility

The closer the delivery time, the higher the volatility of the price

$$s_{\mathrm{m}} = \sqrt{\frac{1}{N_{\mathrm{m}} - 1} \sum_{i=1}^{N_{\mathrm{m}}} \left(Pr_i - Pr_{\mathrm{average(m)}}\right)^2}$$

s_{m} - Standard deviation in interval m
N_{m}- Number of trades with the same interval before delivery
Pr_i - price for the trade *i*
m - time interval before delivery



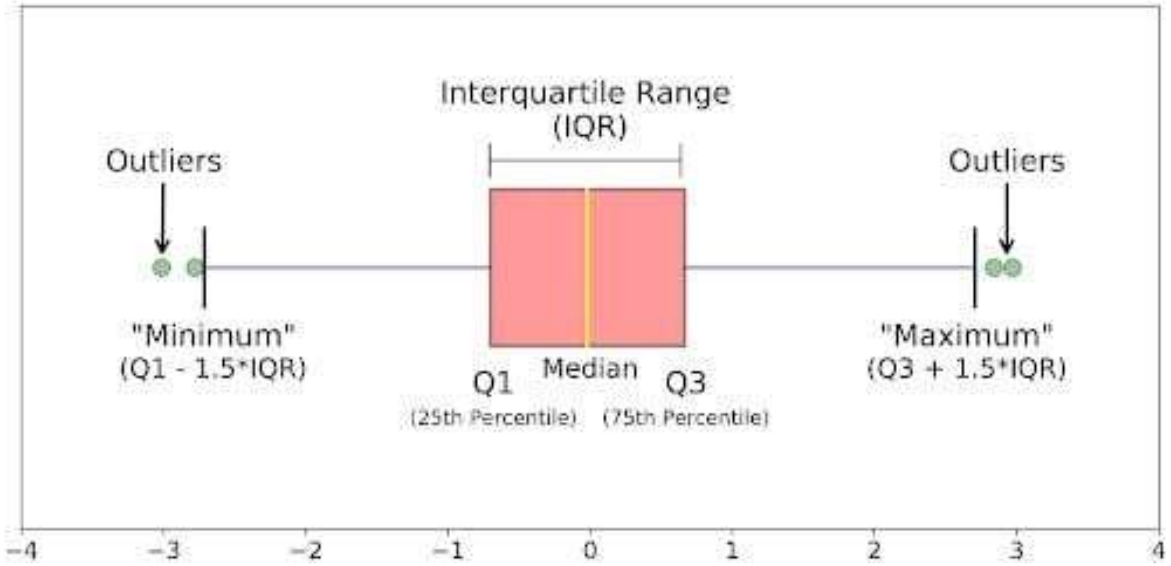
Analysis Method: Deviation to Day Ahead prices

Data Analysis with boxplot:

Box length IQR:
corresponds to the interquartile range (middle 50% of the data), a measure of the dispersion of the data

Median: divides the entire diagram into two areas, each containing 50% of the data.Measure of skewness of the distribution

Whisker: Approximately 1.5 times the interquartile range or the most distant outlier (minimum/maximum)



https://builtin.com/sites/www.builtin.com/files/styles/ckeditor_optimize/public/inline-images/1_boxplots.jpg

SAPB

Intraday vs Day-Ahead Price Spread Analysis

Analysis on how **Intraday Market (ID)** prices deviate from **Day-Ahead (DA)** prices as trading approaches the delivery start.

Methodology:

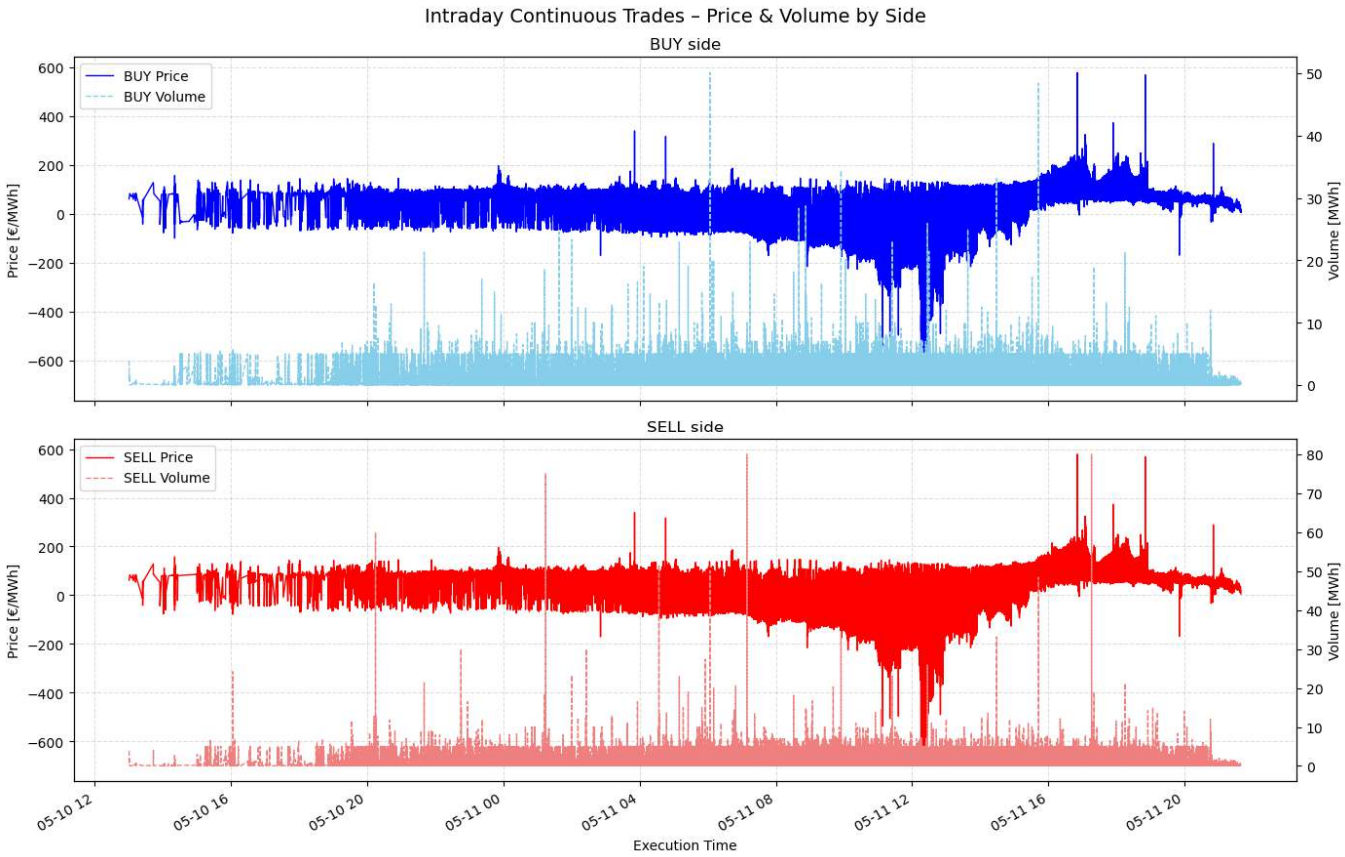
Analysis approach: **Box plot analysis**
Day ahead price : **SMARD.de** – Market Data, **Bundesnetzagentur (Germany)**

For each time step i:

$$\Delta P_i = P_{ID,i} - P_{DA}(t)$$

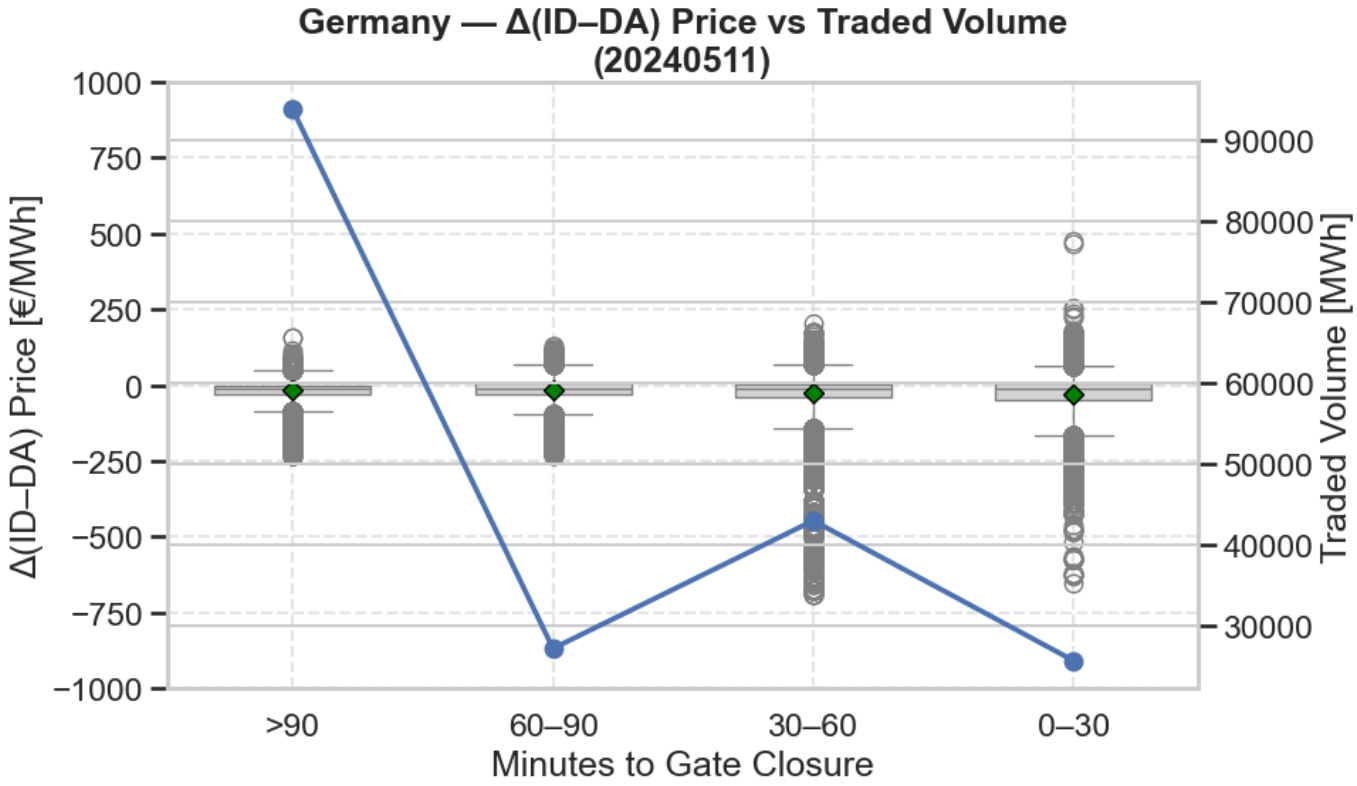
- **$\Delta P_i > 0$:** Intraday price higher than Day-Ahead → *Shortage / Up-balancing*
- **$\Delta P_i < 0$:** Intraday price lower than Day-Ahead → *Surplus / Down-balancing*

Analysis result: Deviation to Day Ahead prices



Analysis result: Deviation to Day Ahead prices

- The closer the delivery time, the larger the deviations from the day-ahead prices
- Outliers with high individual price differences are increasing in particular.



Cross-border vs. internal Trades

Definition per `TradeId`:

$$\text{TradeType}(j) = \begin{cases} \text{Internal}, & \text{if } n_{\text{unique Sides}}(\texttt{TradeId}_j) = 2 \\ \text{Cross-Border}, & \text{if } n_{\text{unique Sides}}(\texttt{TradeId}_j) = 1 \end{cases}$$

- Internal trades: both **BUY** & **SELL** visible in DE.
- Cross-Border trades: only one side visible in DE (counterparty abroad).

Cross-border vs. internal Trades

BUY side:

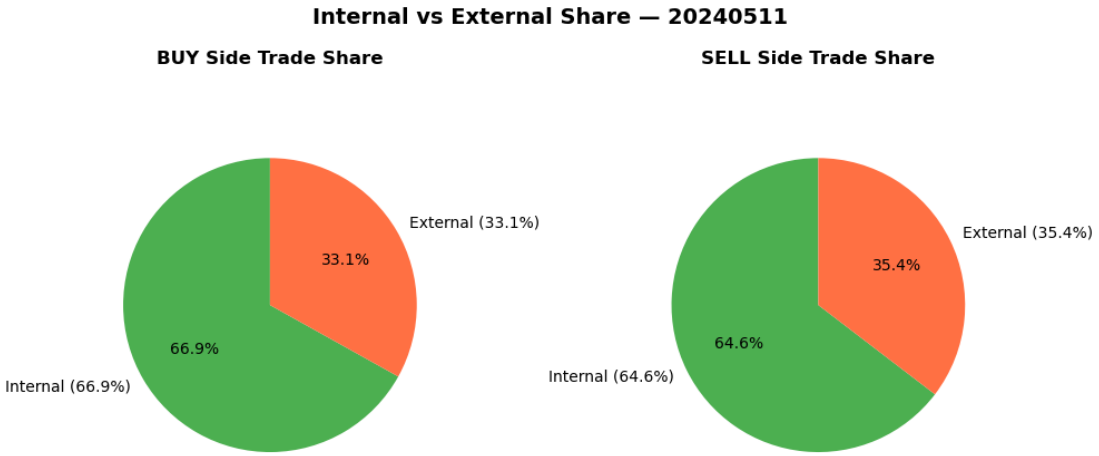
$$\text{External Share}_{\text{BUY}} = \frac{V_{\text{Cross-Border, BUY}}}{V_{\text{All, BUY}}} \times 100$$

SELL side:

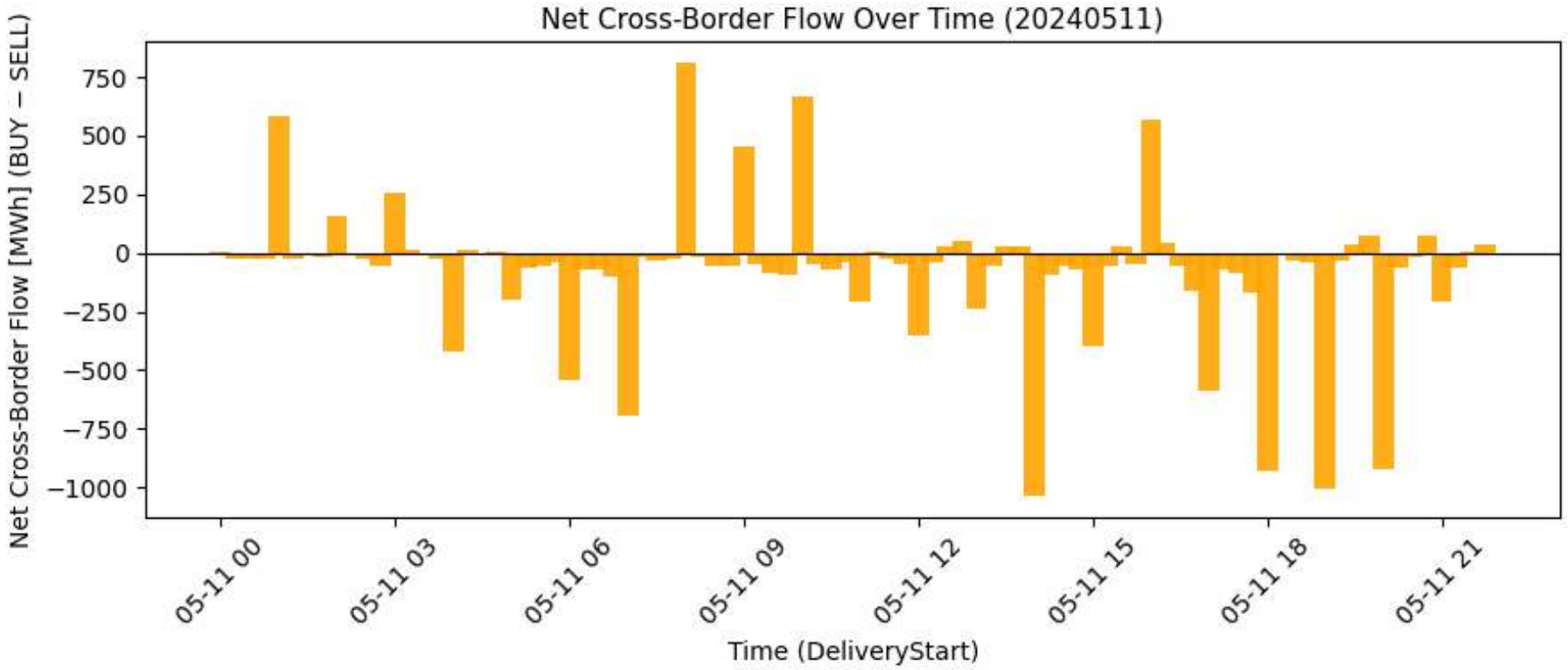
$$\text{External Share}_{\text{SELL}} = \frac{V_{\text{Cross-Border, SELL}}}{V_{\text{All, SELL}}} \times 100$$

Internal shares are complements:

$$\text{Internal Share}_s = 100 - \text{External Share}_s, \quad s \in \{\text{BUY}, \text{SELL}\}.$$

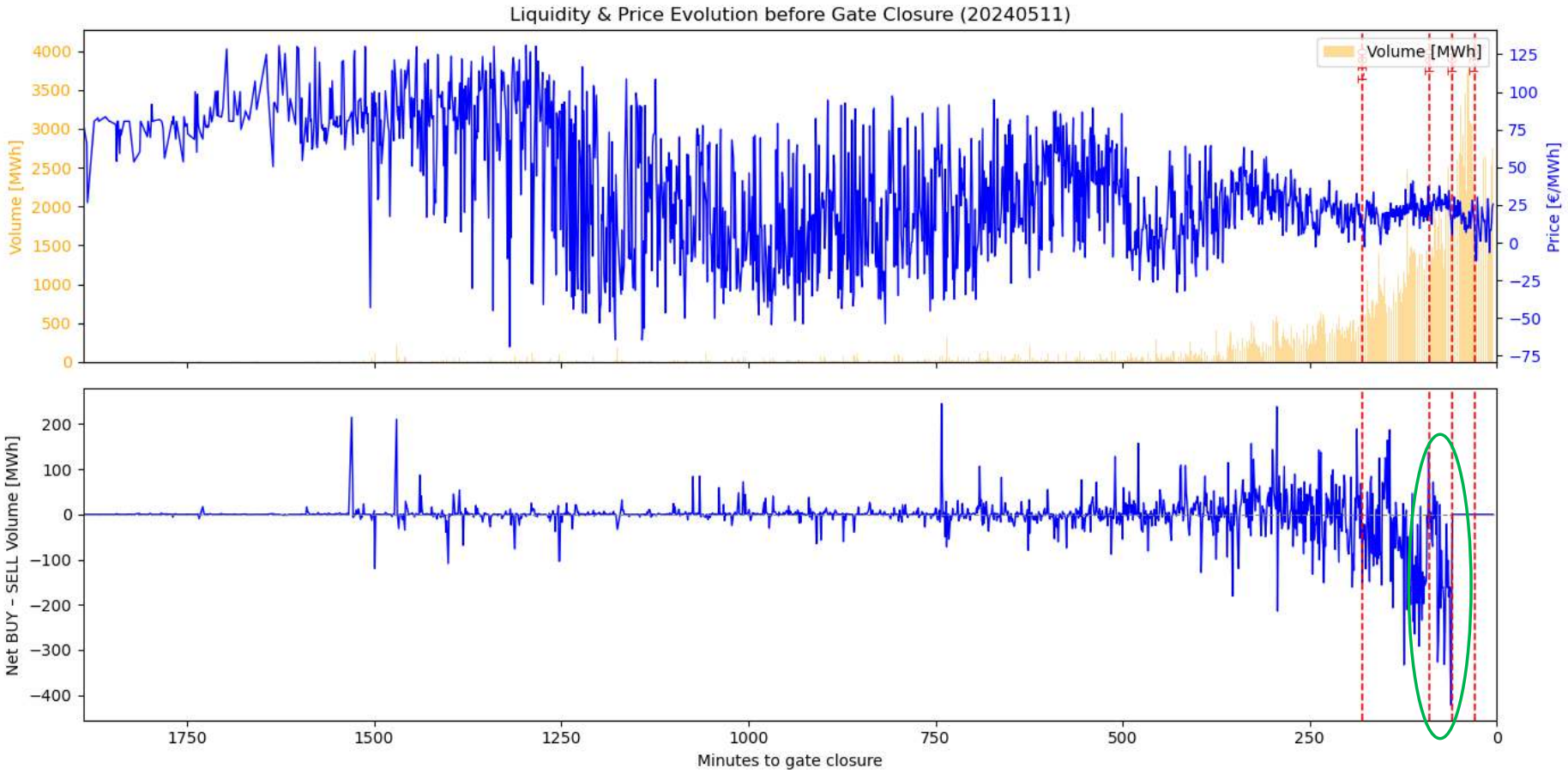


Results: Cross-border vs. internal Trades



Results: Cross-border vs. internal Trades

The closer the delivery time, the higher the volume of external trades, reaching a peak at gate-close time (60 Minuten before delivery.

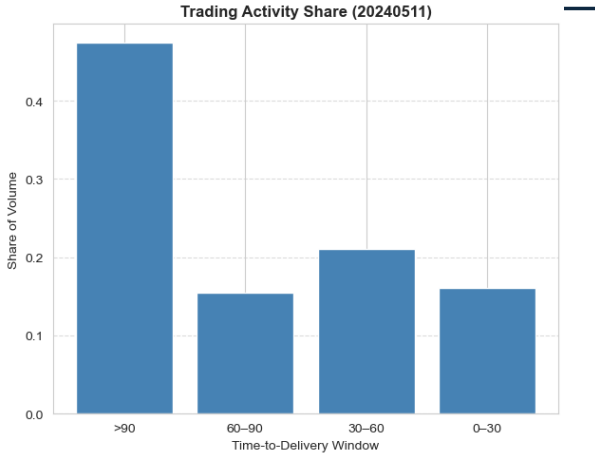


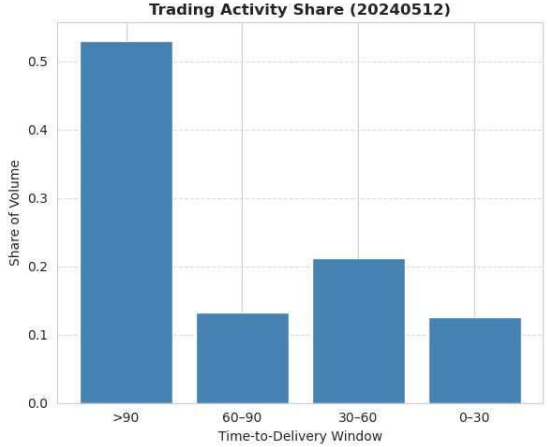
SAPB

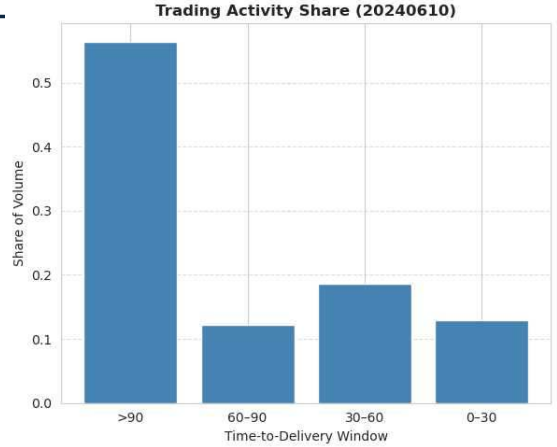
Summary

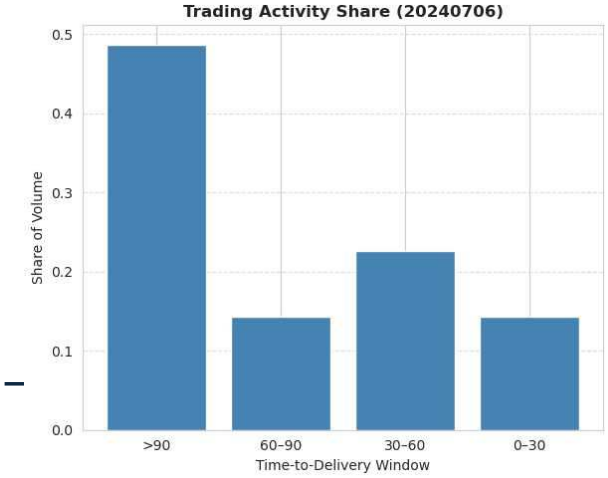
- 43-55% of intraday trades within 90 minutes before delivery
- High price volatility in the last 90 Minutes compared to earlier times
  - no clear tendency within these time windows
- Price jumps after gate-close of european market
  - mostly to lower prices
- Concentration of european trades 60 minutes before delivery, dominant is the selling
- 22 - 44 % volume of cross border trades

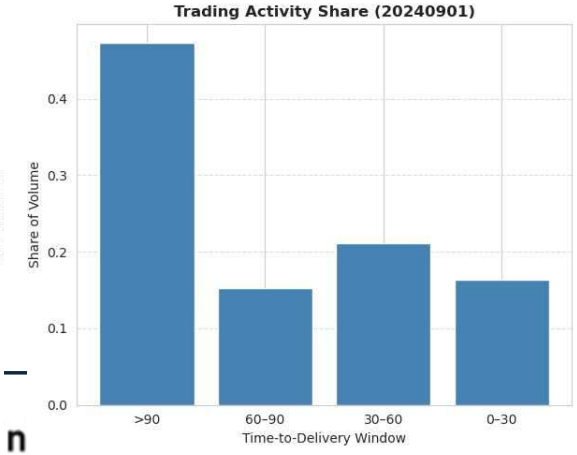
Trading shares: 43-55% of volume within 90 minutes before delivery



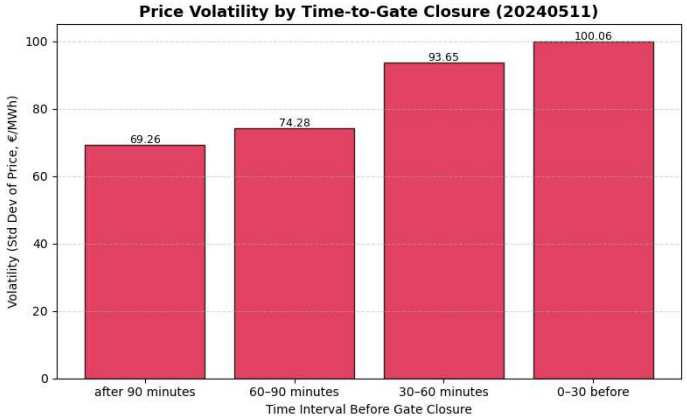


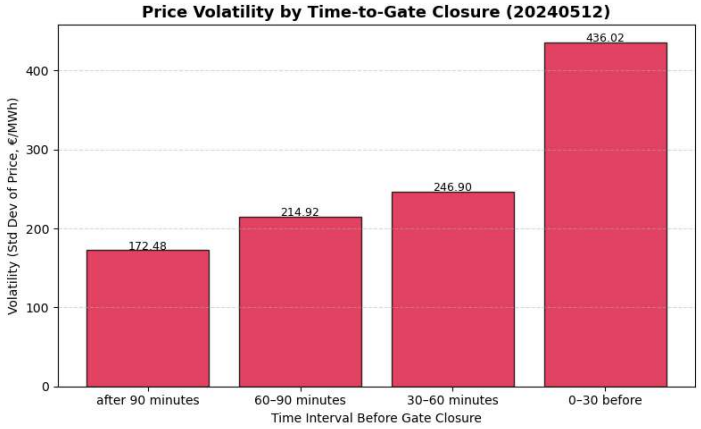


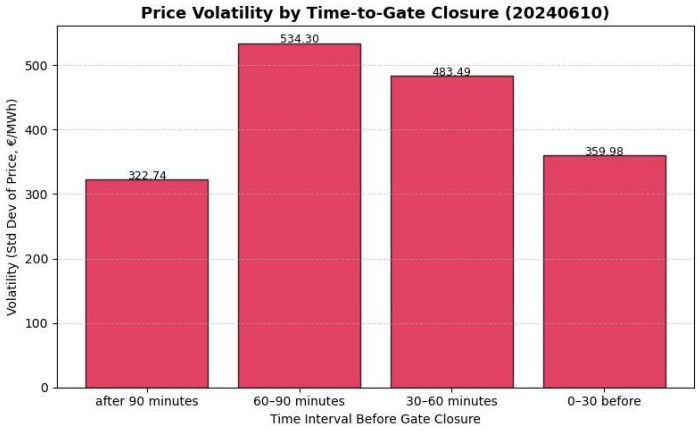




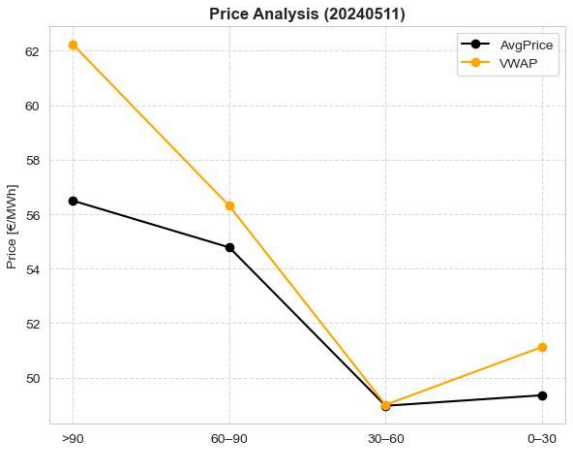
High price volatility in the last 90 minutes compared to earlier times. But, no clear tendency within these time windows.

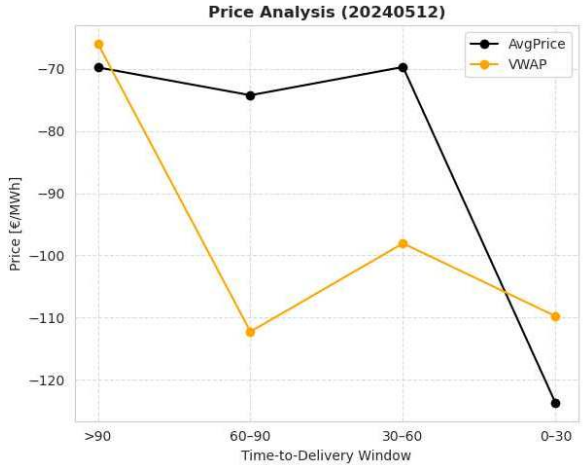


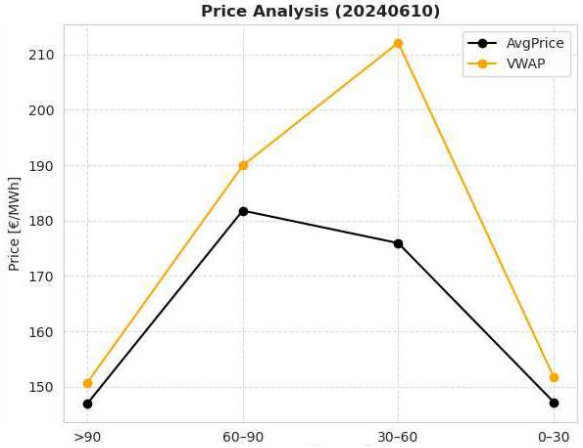


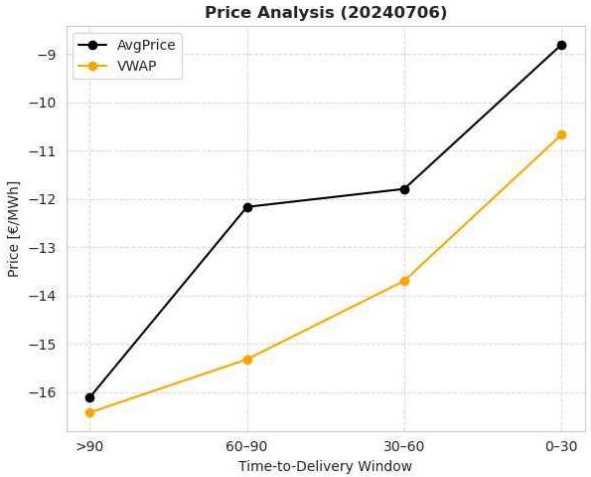


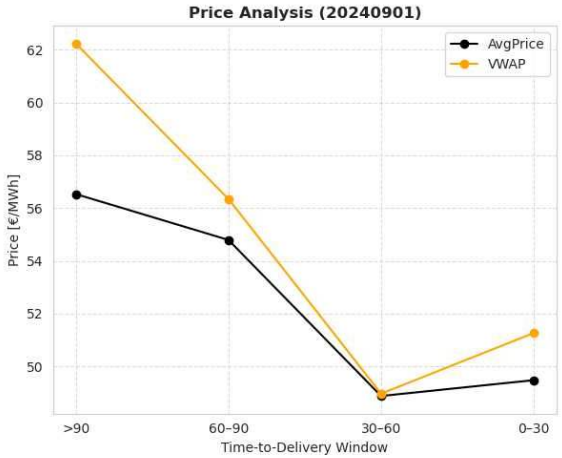
Price analysis. Price jumps after gate-close of European market , mostly to lower prices



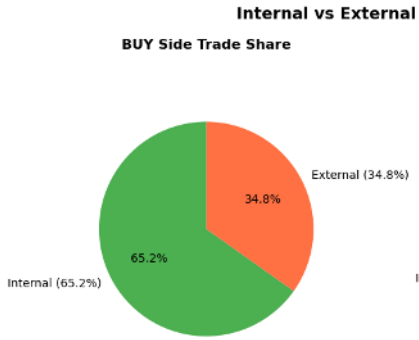


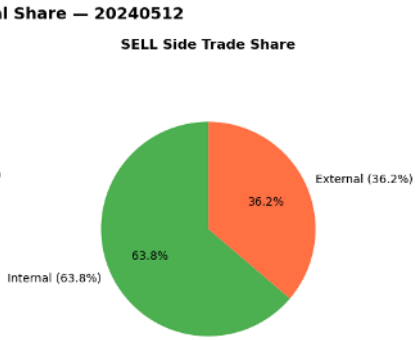


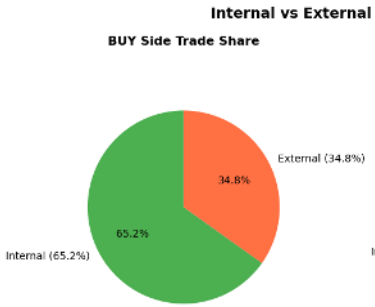


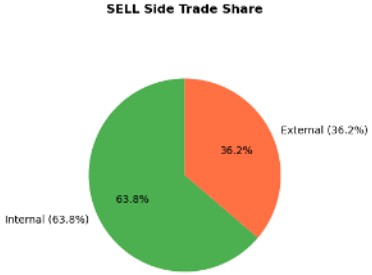


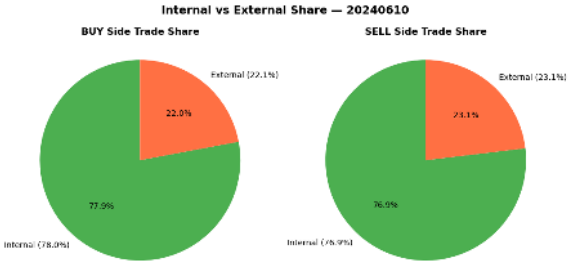
Share of cross-border trades: 22 - 44 % volume of cross border trades

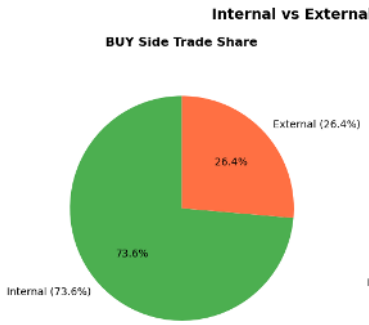


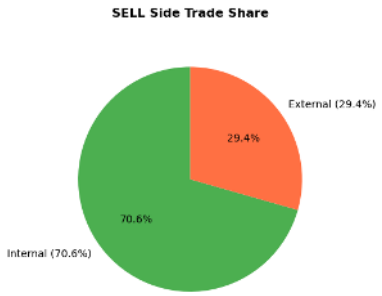


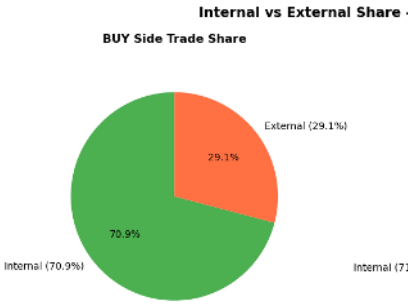


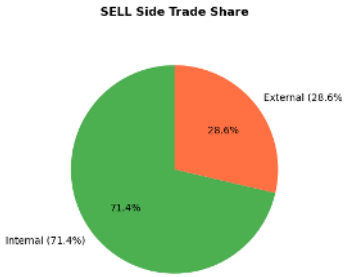


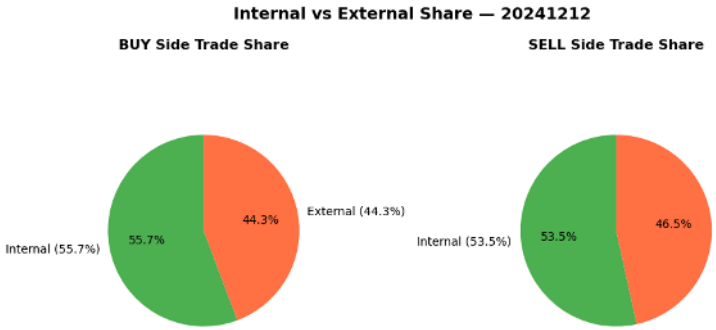












Influence on short term forecast

- The shifting of European gate-close time may shift a high part of the trade amount of the 60-90 window to the 30-60 window
- Higher trade volumes 30 Minutes before gate-close
- High single prices (12.12.24 up to 4000€/MWh) are identified
- High price volatility in extreme scenarios as a reaction to surplus or shortage
  - High neg. prices with high renewable shares (12.5.25)
  - High pos. prices with a low amount of renewable generation (12.12.)

SAPB

Work Package 5:
Outlook and Conclusion (Steinbeis & BTU)

Conclusion

- Short-term Battery trades have to be expected and will highly influence the short-term forecast, but these trades are necessary to balance the system in surplus or shortage scenarios
- Particularly critical is the observation that the schedules set at the day-ahead time are sometimes inverted at the time of implementation. This finding poses considerable operational challenges for grid operation. For grid operators, this results in significantly increased requirements in terms of flexibility management, short-term responsiveness, and monitoring of grid operation.
- The study also highlights the need for a clear definition of the role of the grid operator in the context of the new regulatory framework to avoid grid congestion
- With the right specifications for BESS, load forecasting should become easier; at least, that should be the political goal

Conclusion

- Prices signal scarcity (high price) and abundance (low prices). Batteries reacting to prices thus help the system. However, TSO's redispatch becomes more challenging when batteries change their production or consumption on short notice.
- Nearly 50% of all quarter hours in the IDAs deviate from the DAA schedule.
- Maximum change (200% of inst. cap.) is rare (approx. 3%).
- IDA2&IDA3 tend to have the most deviations compared to DAA.
- State Match is lower in winter than in summer.
- State Match is lower on weekends than on working days.
- State Reversal increases with increasing ETP.

SAPB

Work Package 5: Recommendations

- Strong growth in battery storage is expected by 2030 (currently 51 GW of reserved capacity in the transmission grid).
- Short-term Battery trades (< 30 Minutes before gate close) have to be expected and will highly influence the short-term forecast, but **these trades are necessary to balance the system in surplus or shortage scenarios**
- Particularly critical is the observation that the schedules set at the day-ahead time are sometimes inverted at the time of implementation. This finding poses considerable operational challenges for grid operation.
- The study also highlights the need for **a clear definition of the role of the grid operator in the context of the new regulatory framework to avoid an increase in grid congestion by battery trades e.g., FCA.** But be careful, the storage facilities are needed: the business case for the operators must not be destroyed.

SAPB

Work Package 5: Further Work

- Right specifications for storage facilities has to be developed, that load forecasting can become better
- Development of a forecast methodology for high price volatility
- To derive concrete statements or operational requirements from the results from the perspective of network operators, the metric should therefore be expanded in cooperation with network operators. Only through a network operation-oriented supplement – for example, by taking into account regional network bottlenecks, critical time windows, or system-relevant power fluctuations, the analysis provides a reliable basis for grid-side assessments and recommendations for action.

Work Package 5: Outlook

- Enhance EE forecasting quality (→ lower price changes between DAA and IDA → lower incentive for batteries to vary output).
- Harmonize scheduling times for IDA and preventive Redispatch.
- Optimize Redispatch processes.
- New local tariff components.
- Lender of last resort: restrict batteries' flexibility?
- Results are only scalable to a limited extent, as large battery capacities would violate the assumptions (no grid bottlenecks, batteries as price takers).

Appendix Work Package 3

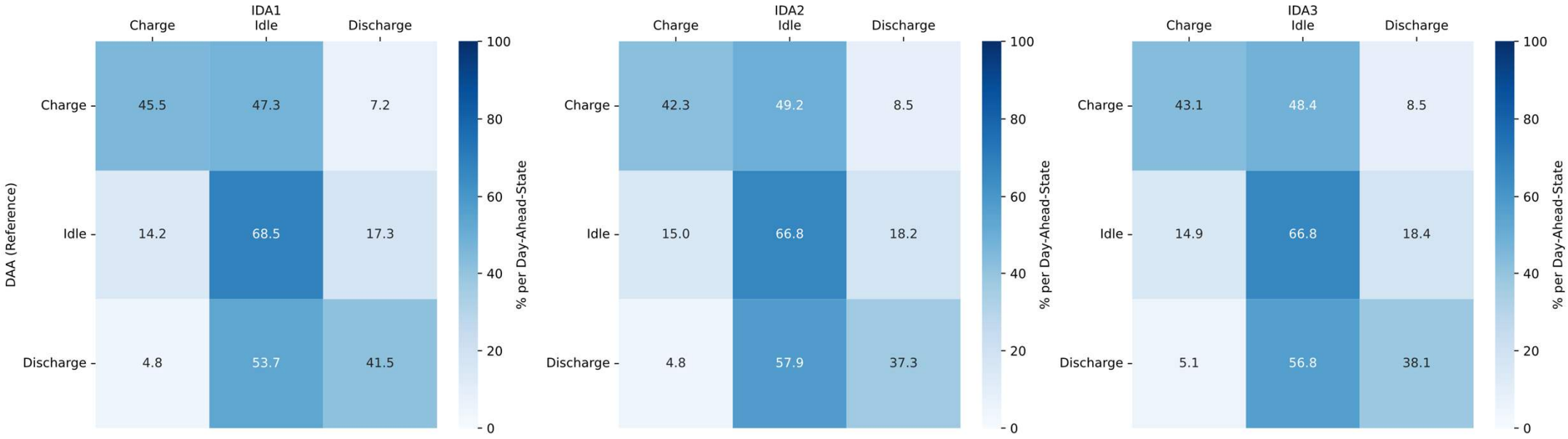
Extended comparison of battery schedules including DAA vs. IDA1, DAA vs. IDA2 and DAA vs. IDA3 with different ETP-Ratios:

- ETP2
- ETP3
- ETP4
- ETP6

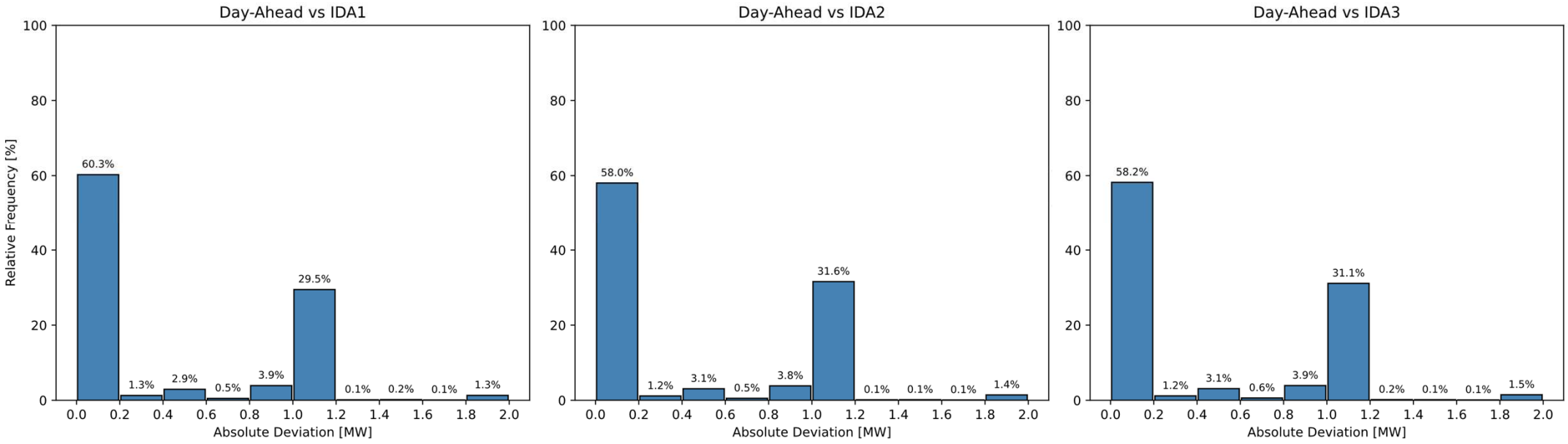
Appendix Work Package 3

ETP2

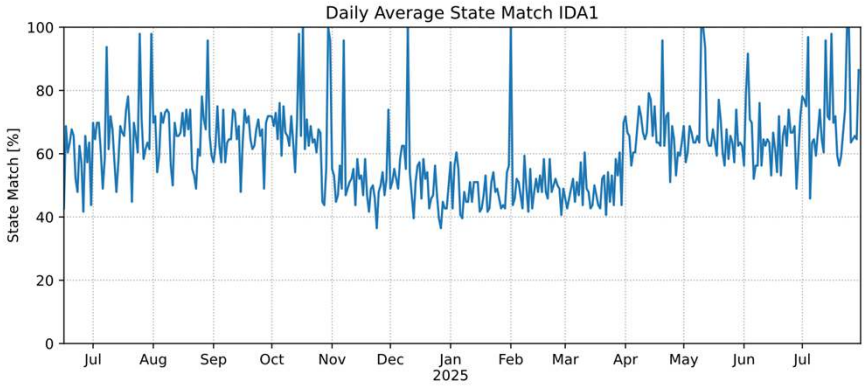
Comparison Percentual Confusion Matrix: DAA vs. Intraday Auctions – ETP2

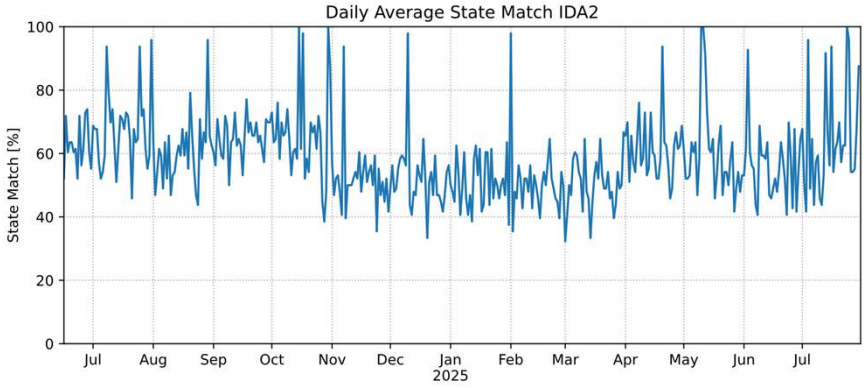


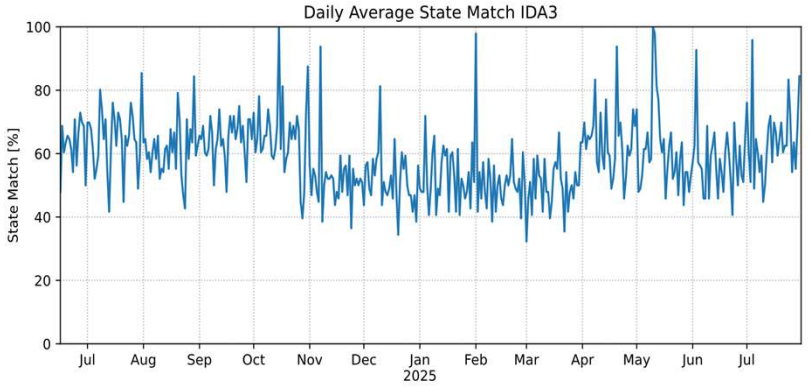
Comparison Histogram DAA vs. Intraday Auctions – ETP2



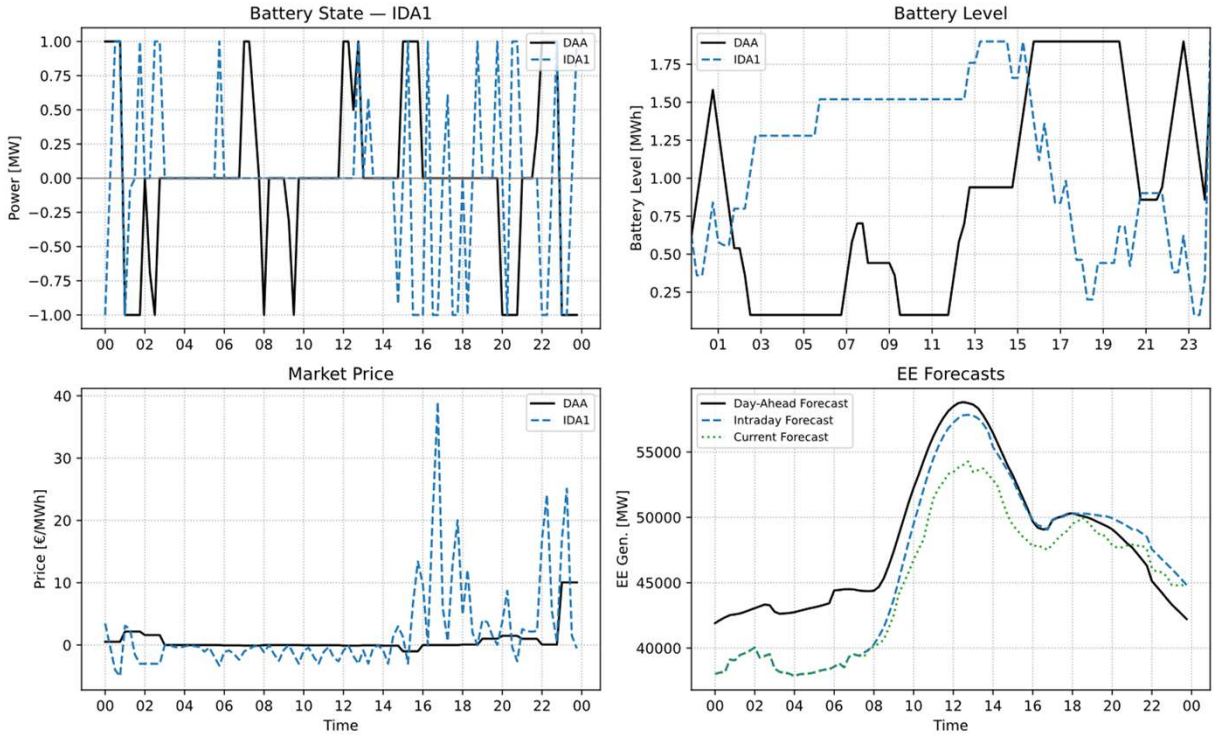
Comparison Daily State Match: DAA vs. Intraday Auctions – ETP2



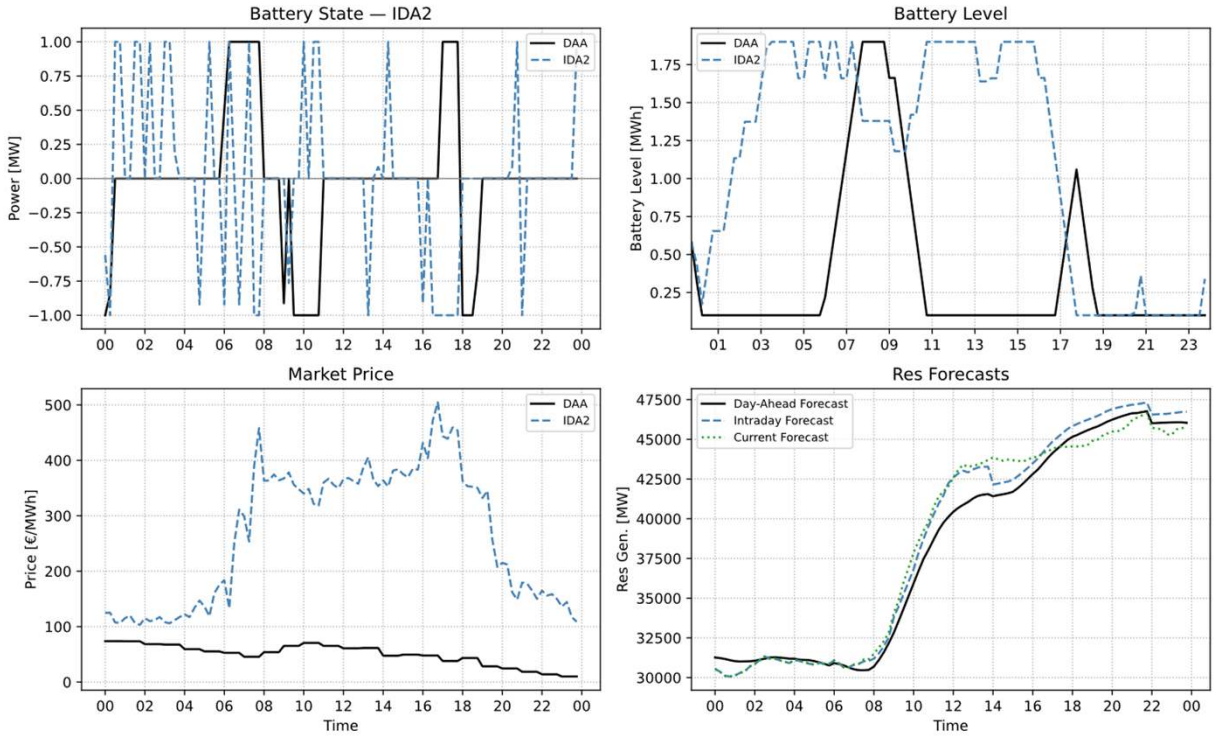




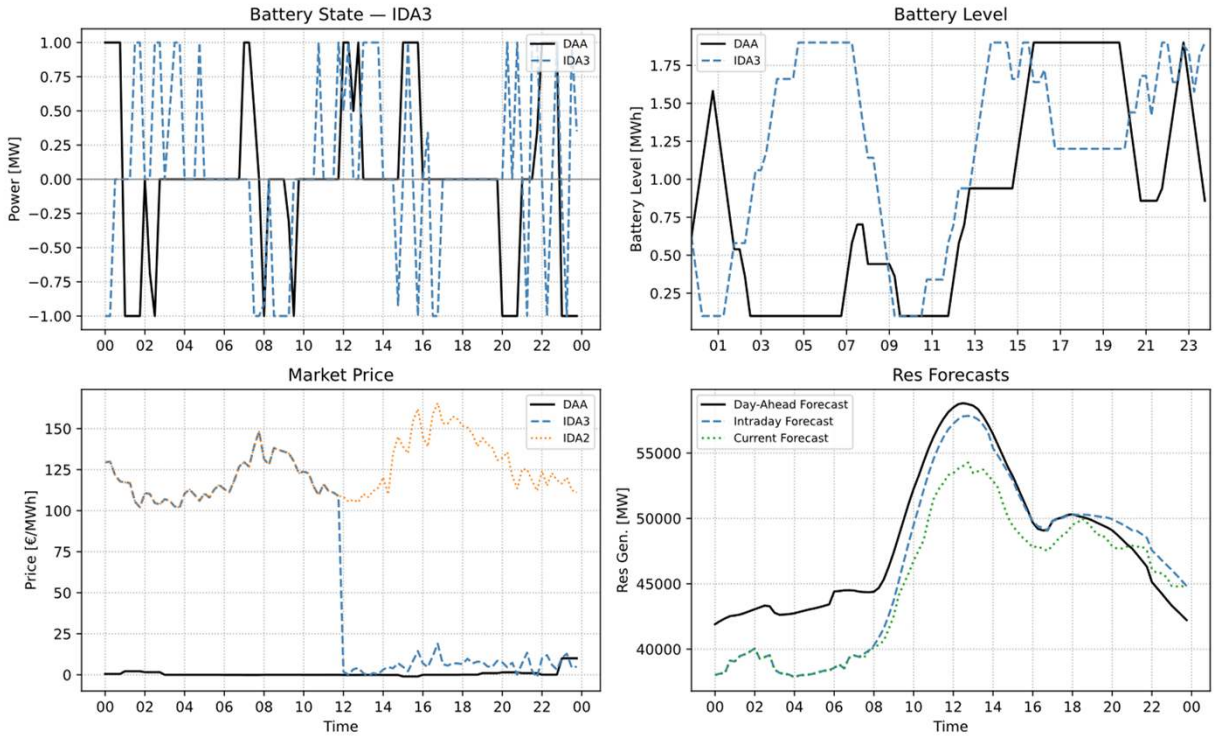
Extreme Day Analysis: DAA vs. IDA1 – 01.01.2025 – ETP2



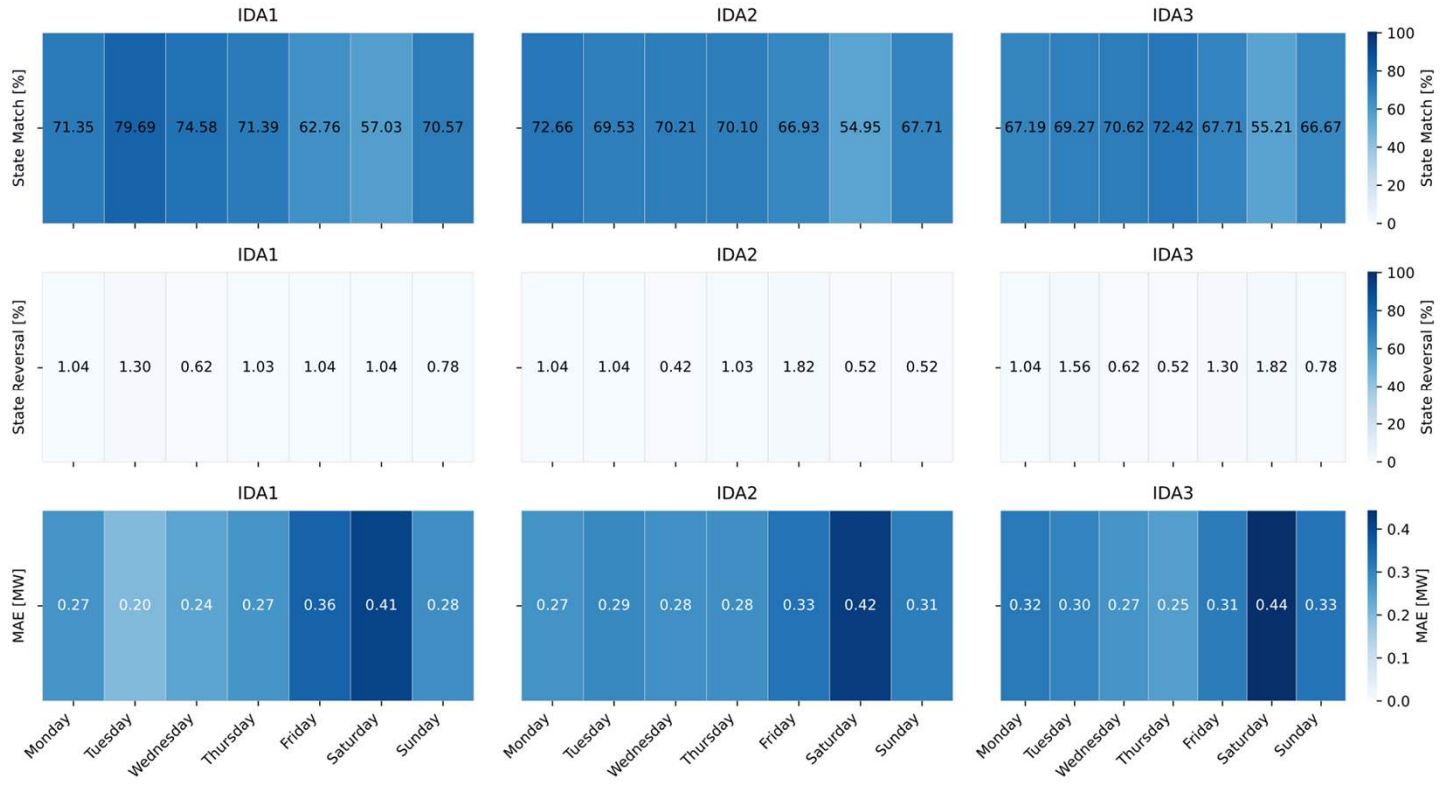
Extreme Day Analysis: DAA vs. IDA2 – 15.12.2024 – ETP2



Extreme Day Analysis: DAA vs. IDA3 – 01.01.2025 – ETP2



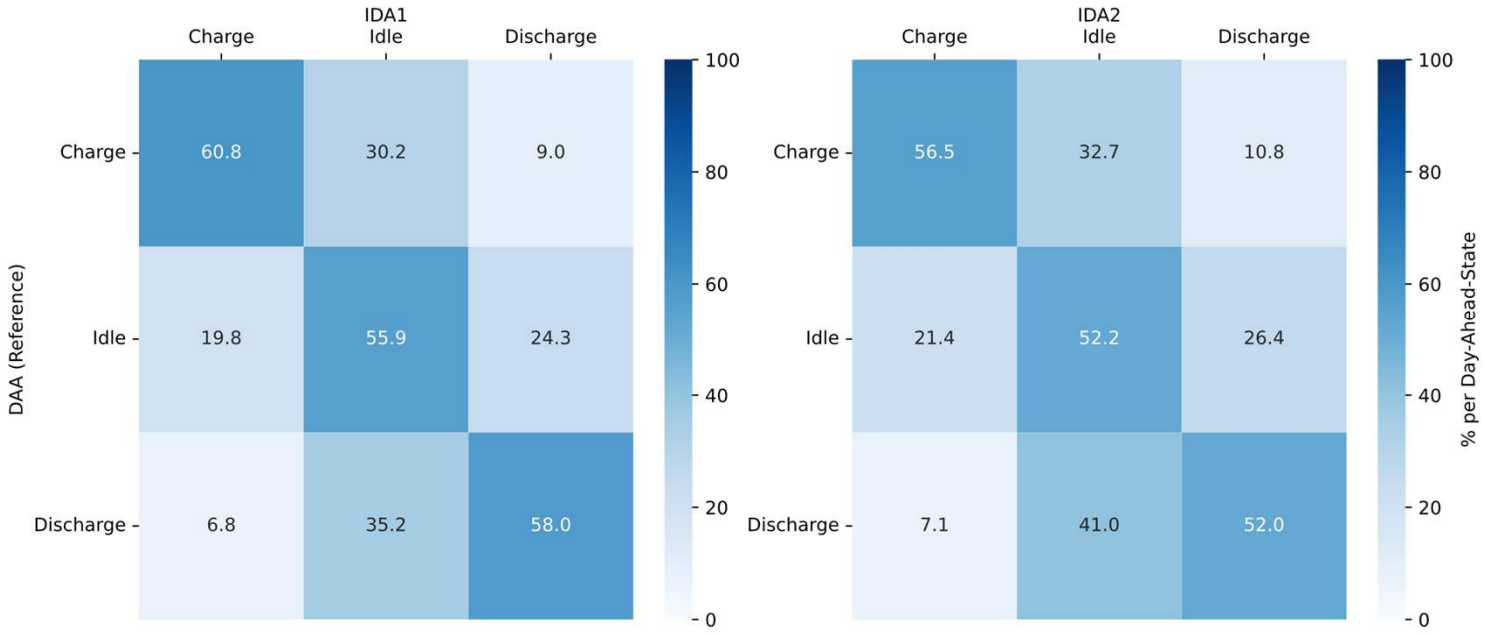
Comparison Weekday Metrics: DAA vs. Intraday Auctions – ETP2



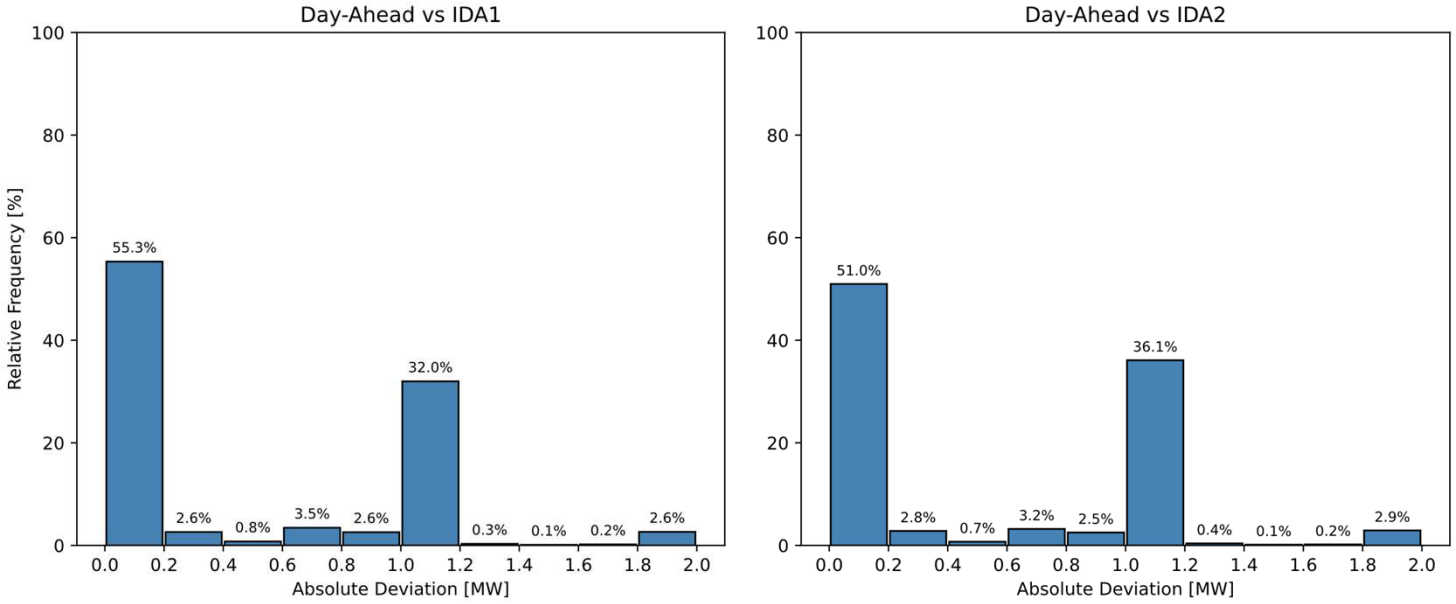
Appendix Work Package 3

ETP3

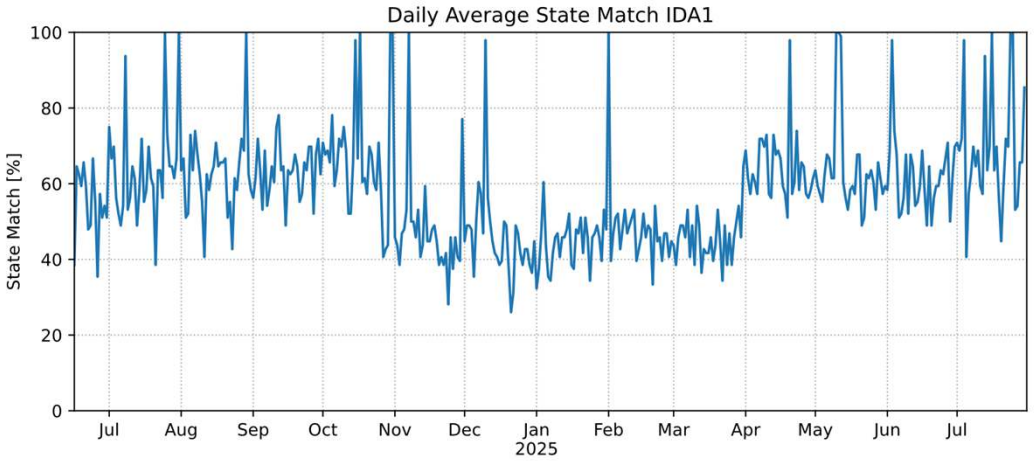
Comparison Percentual Confusion Matrix: DAA vs. Intraday Auctions – ETP3

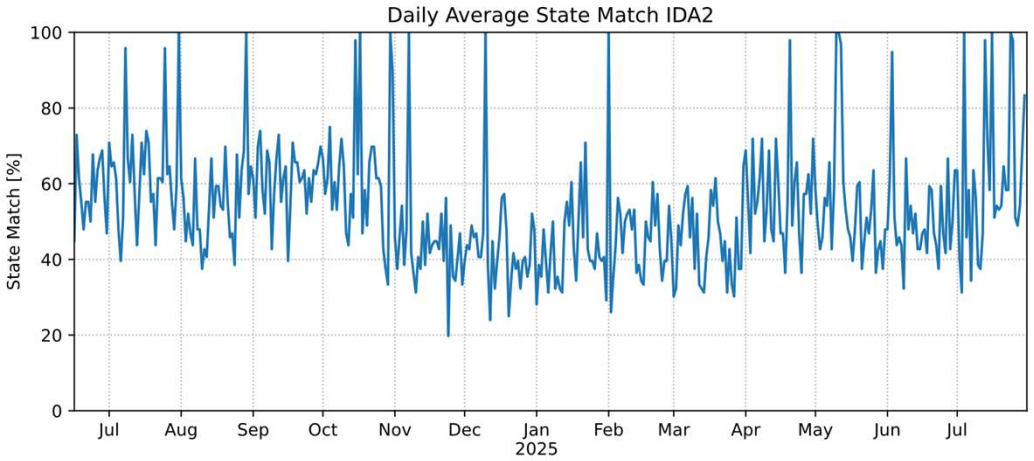


Comparison Histogram: DAA vs. Intraday Auctions – ETP3

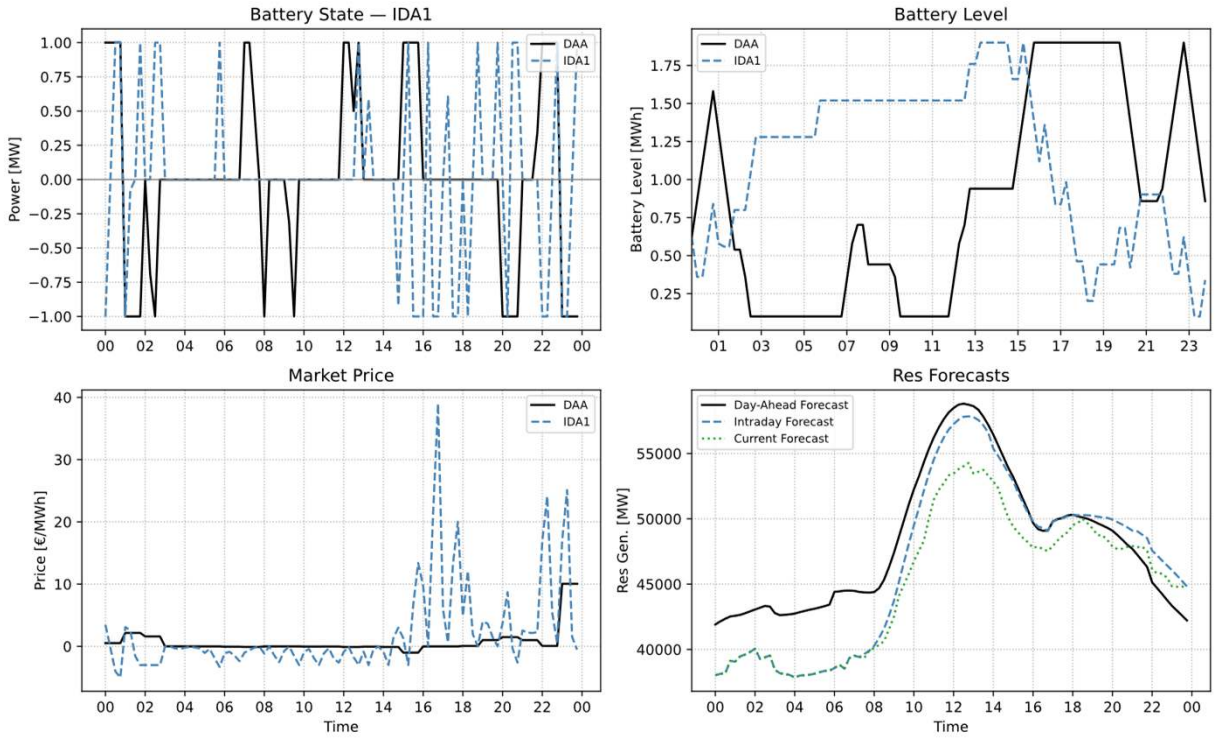


Comparison Daily State Match: DAA vs. Intraday Auctions – ETP3

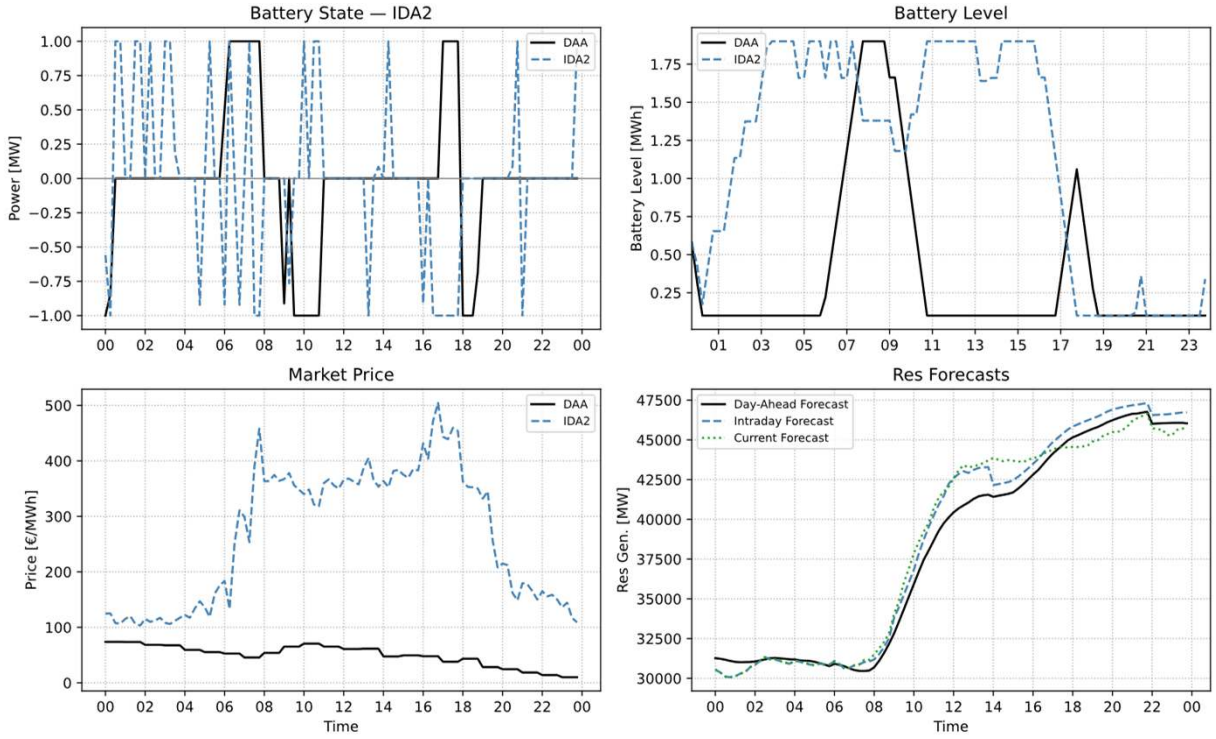




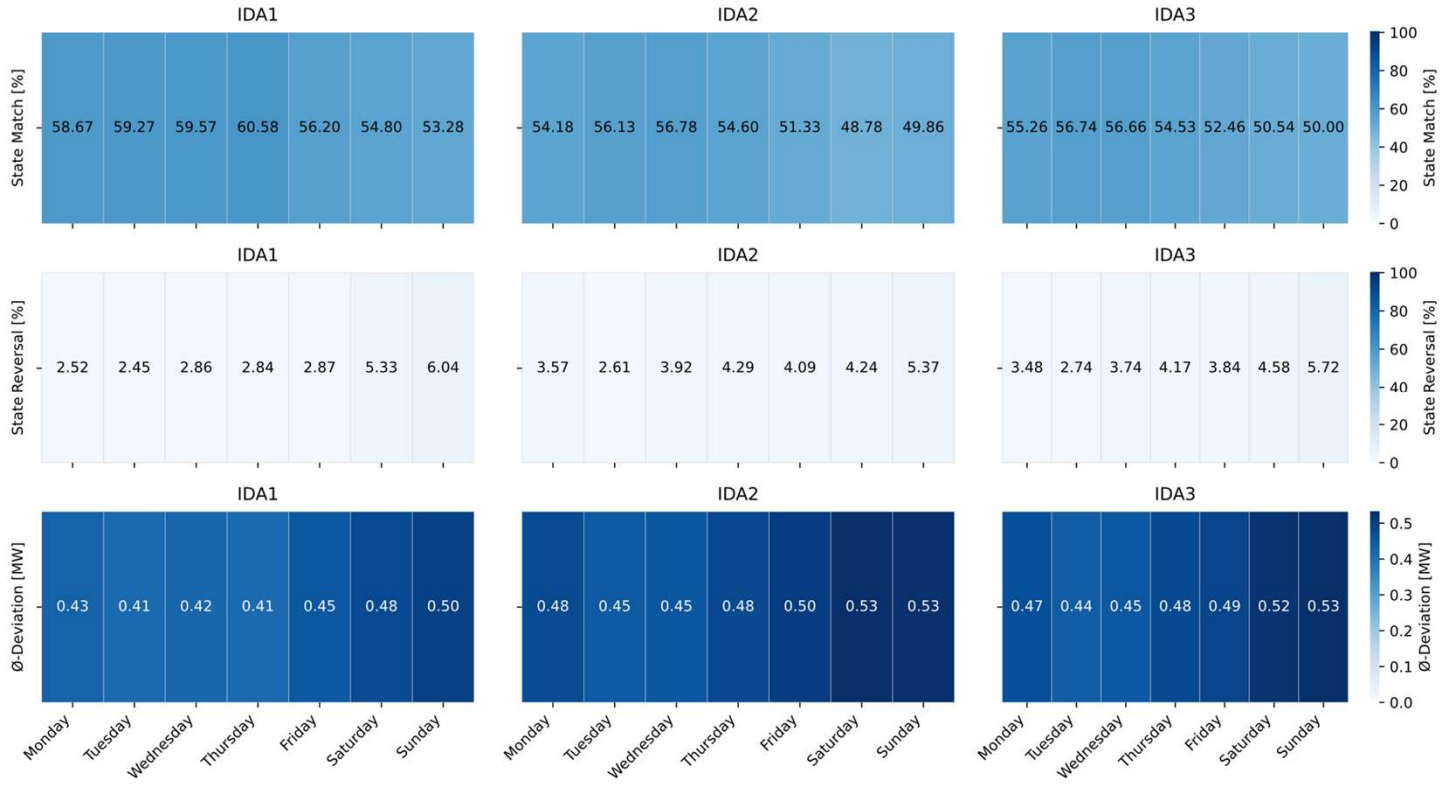
Extreme Day Analysis: DAA vs. IDA1 – 01.01.2025 – ETP3



Extreme Day Analysis: DAA vs. IDA2 – 15.12.2024 – ETP3



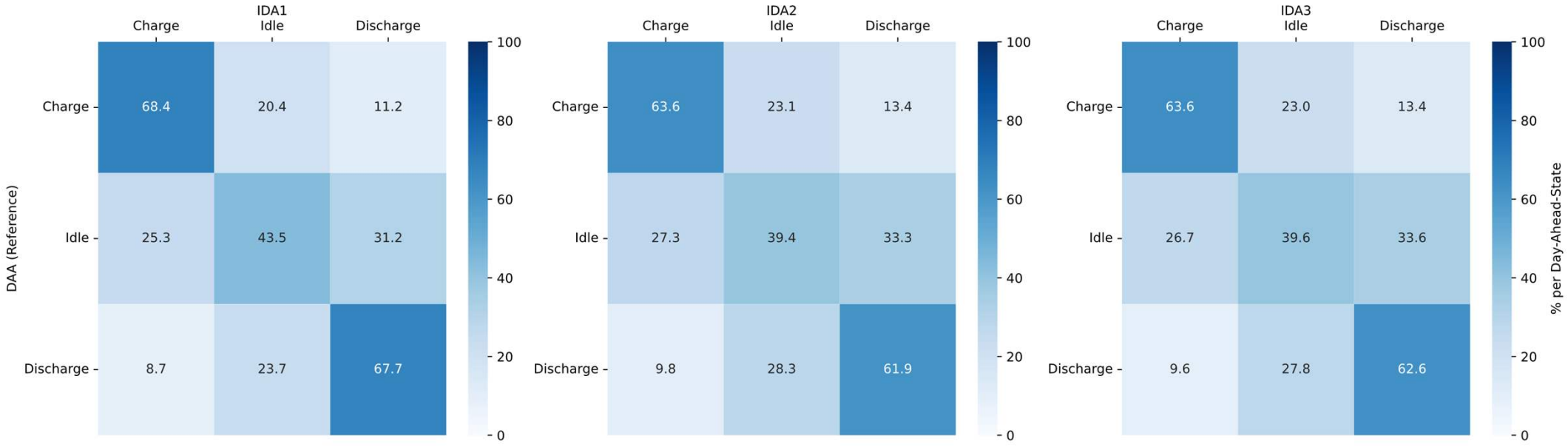
Comparison Weekday Metrics: DAA vs. Intraday Auctions – ETP3



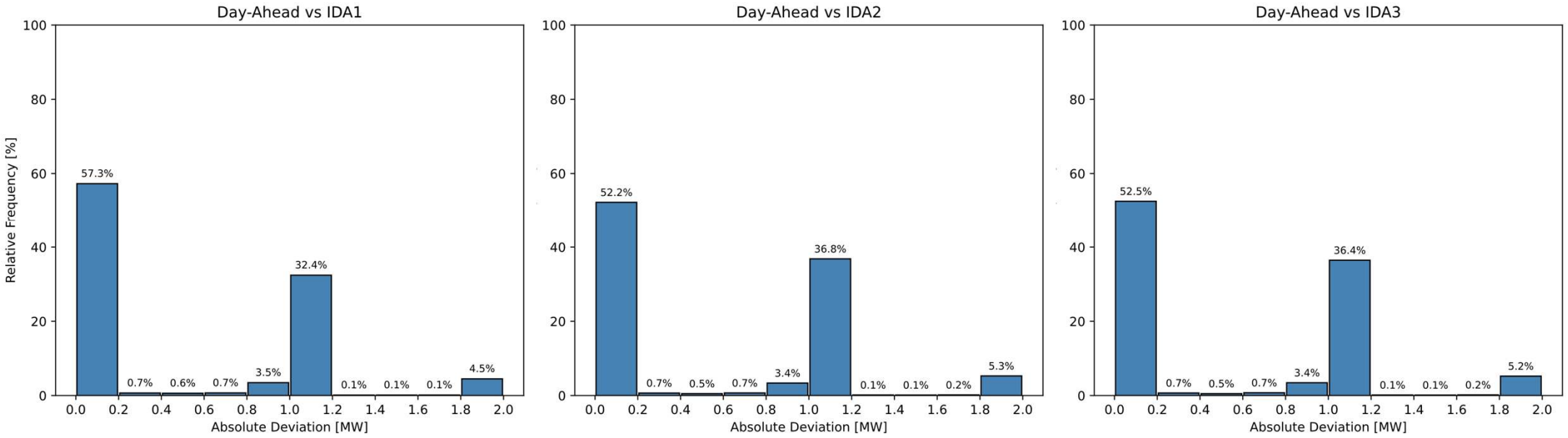
Appendix Work Package 3

ETP4

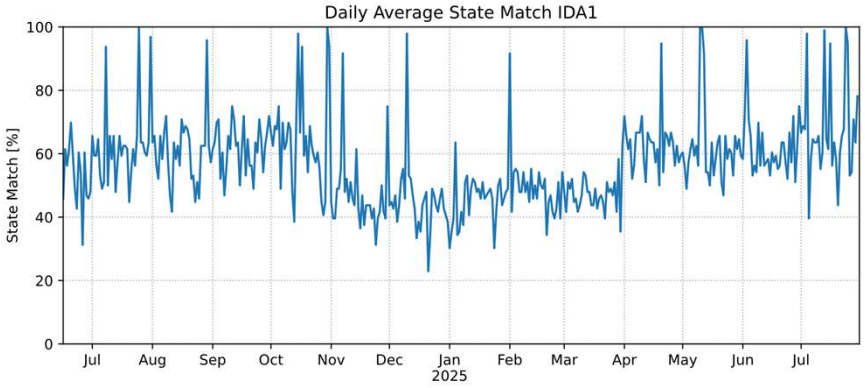
Comparison Percentual Confusion Matrix: DAA vs. Intraday Auctions – ETP4

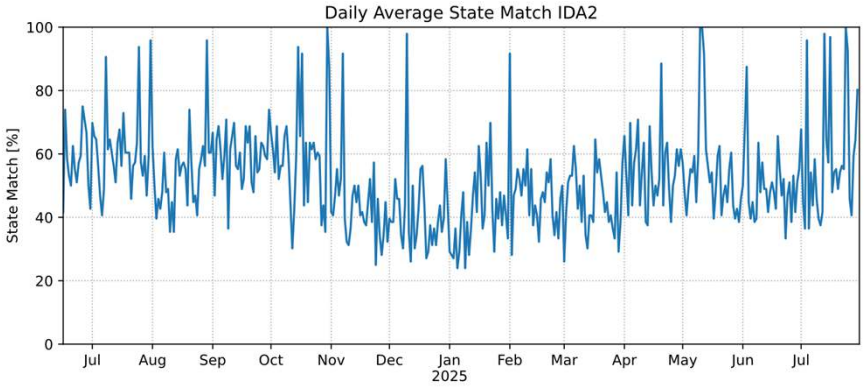


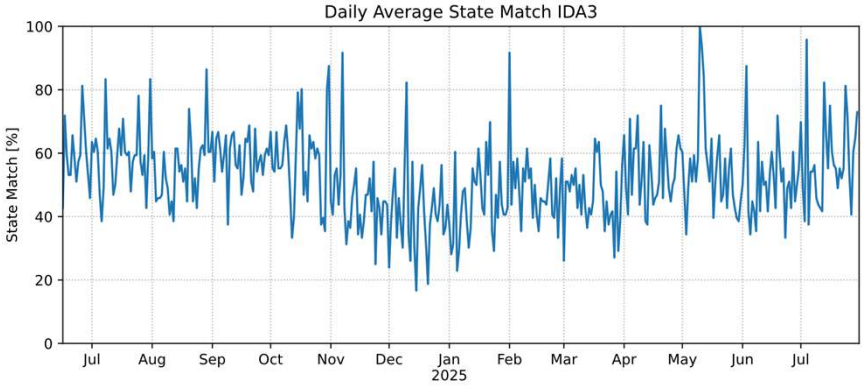
Comparison Histogram: DAA vs. Intraday Auctions – ETP4



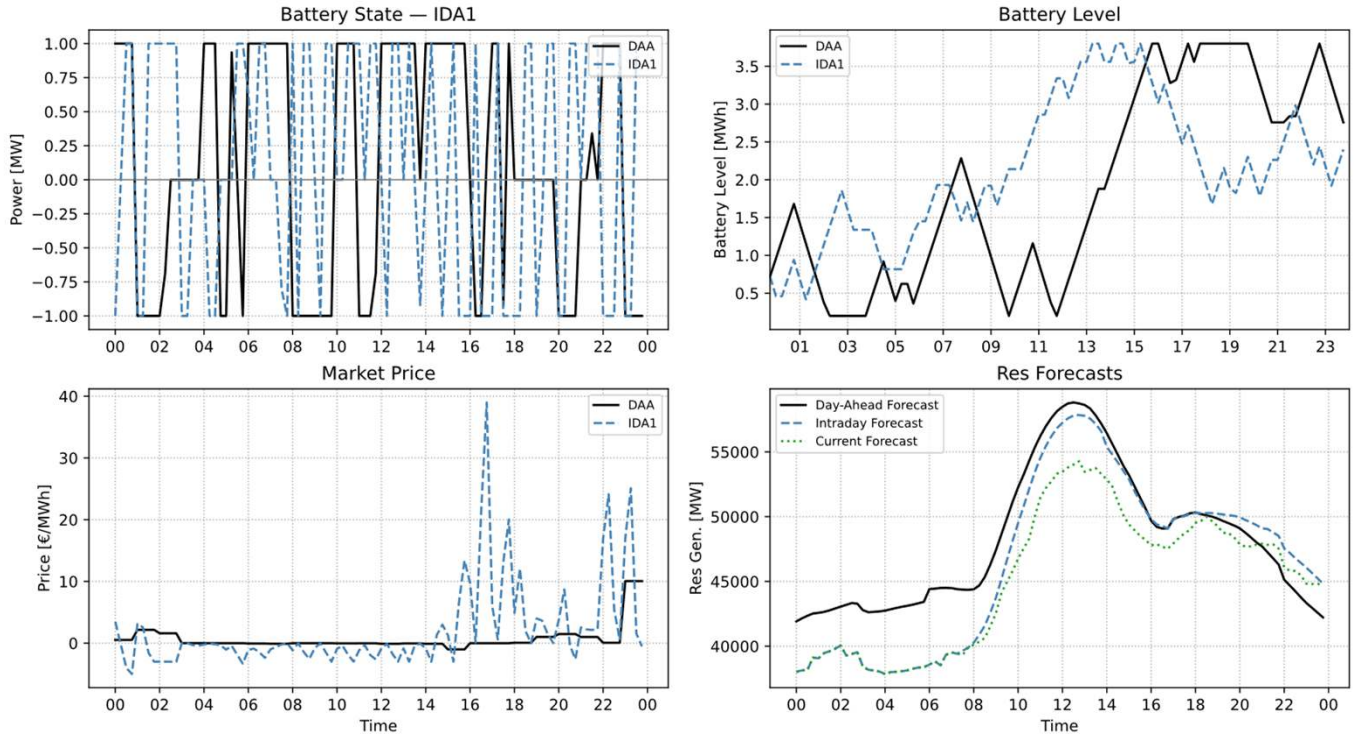
Comparison Daily State Match: DAA vs. Intraday Auctions – ETP4



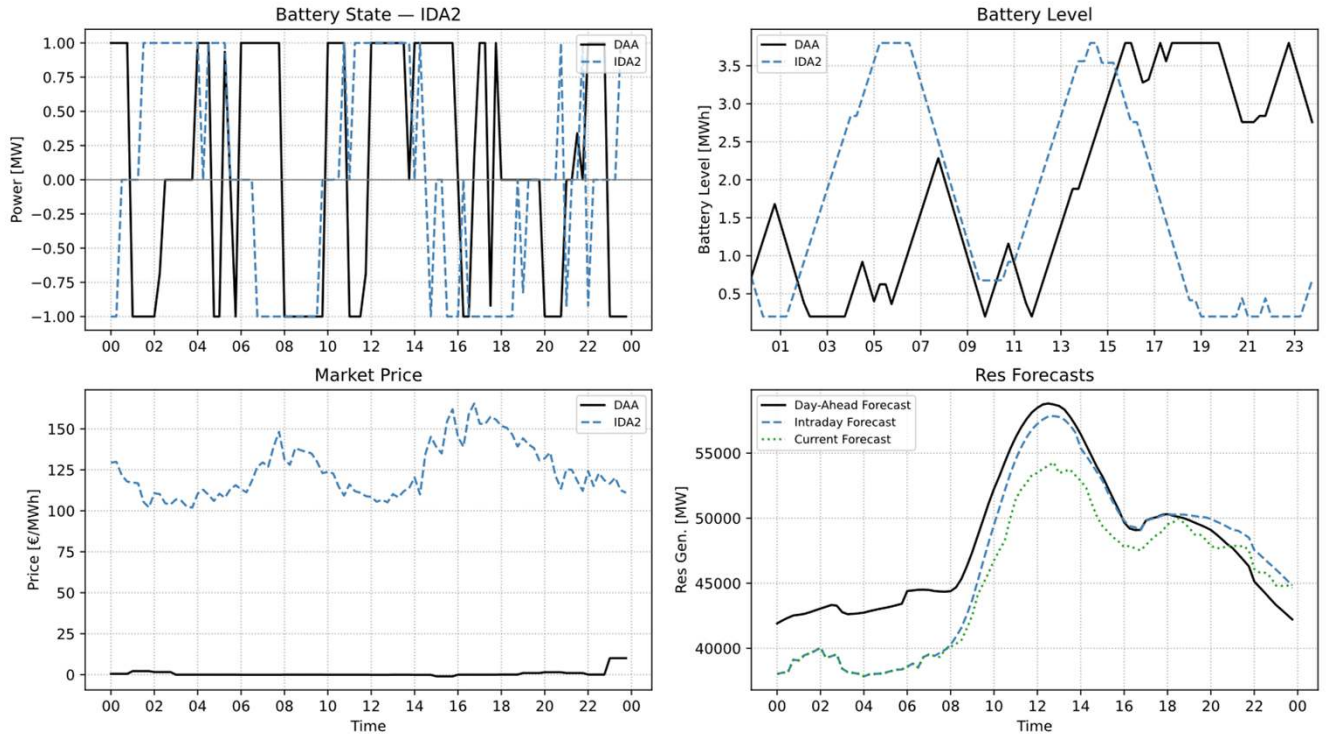




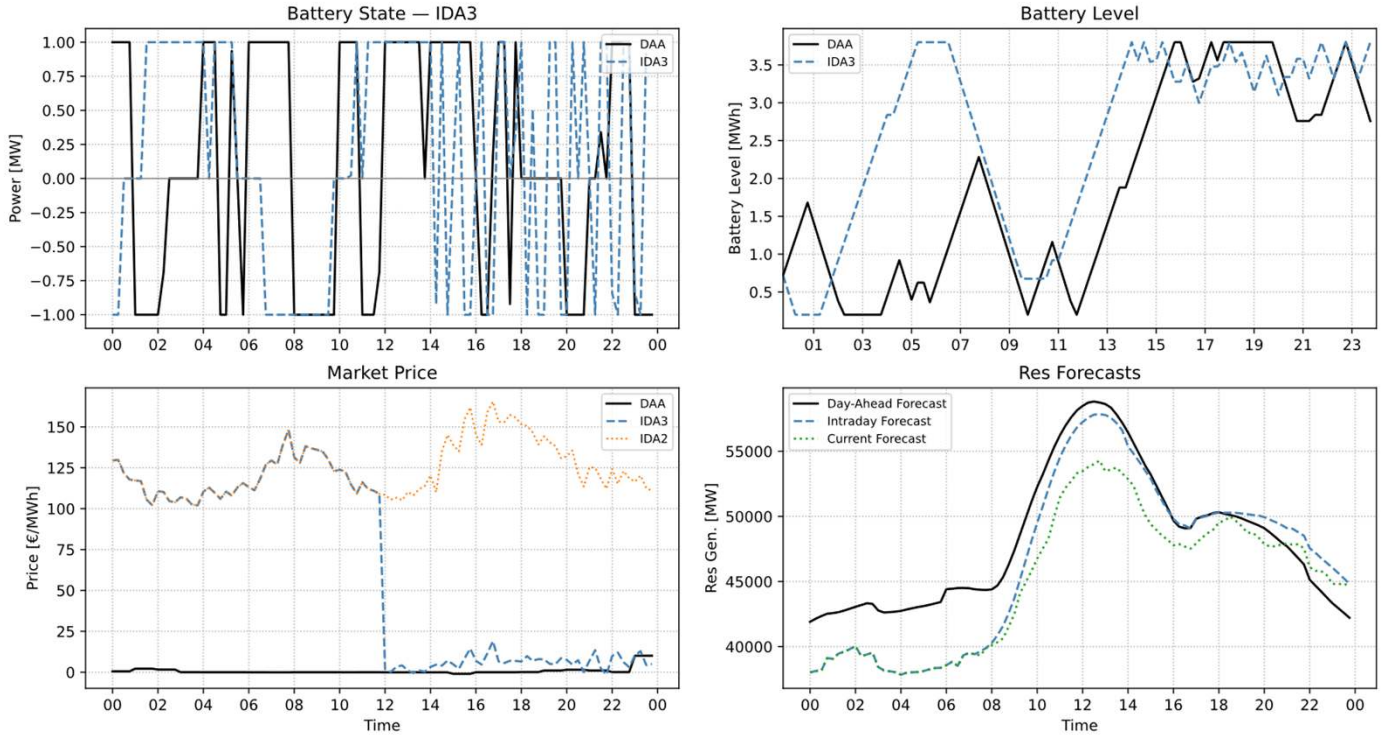
Extreme Day Analysis: DAA vs. IDA1 – 01.01.2025 – ETP4



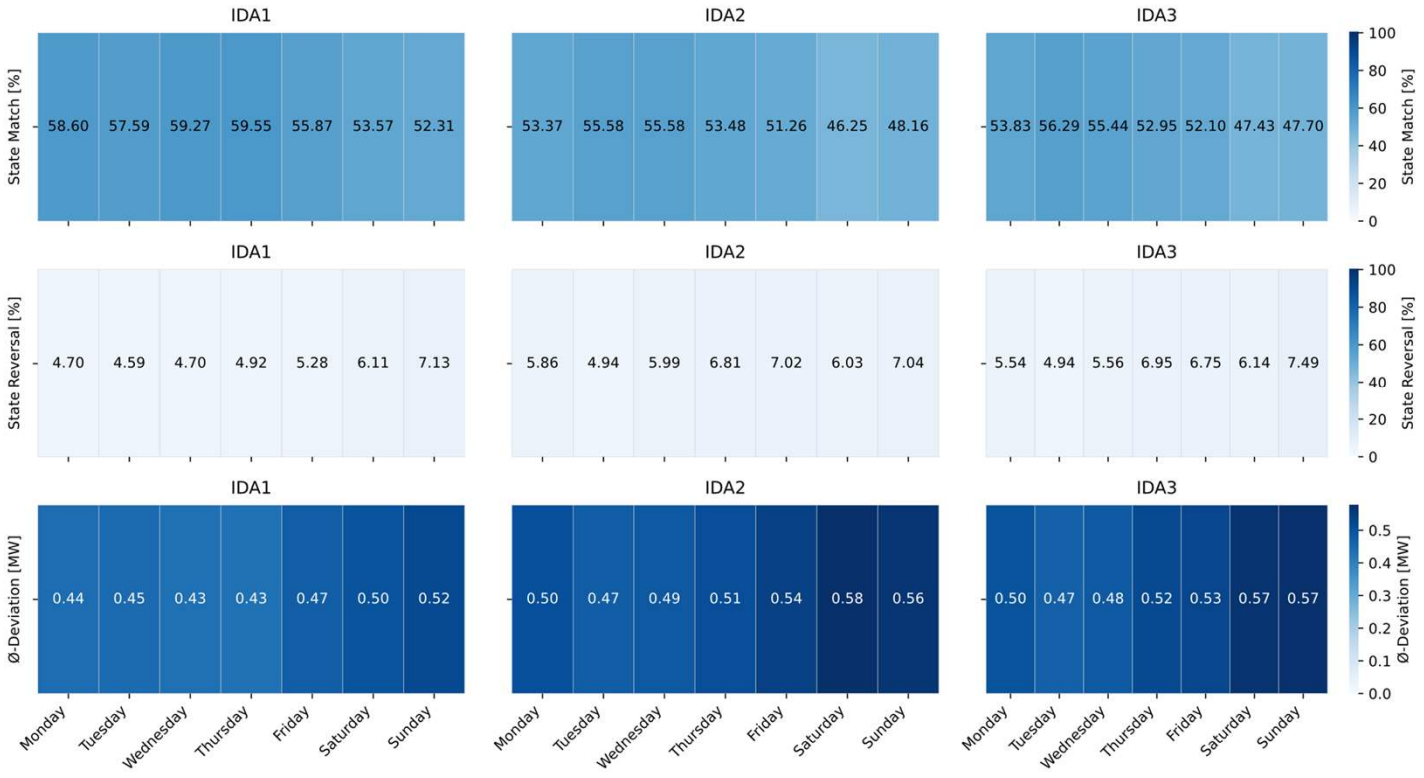
Extreme Day Analysis: DAA vs. IDA2 – 01.01.2025 – ETP4



Extreme Day Analysis: DAA vs. IDA3 – 01.01.2025 – ETP4



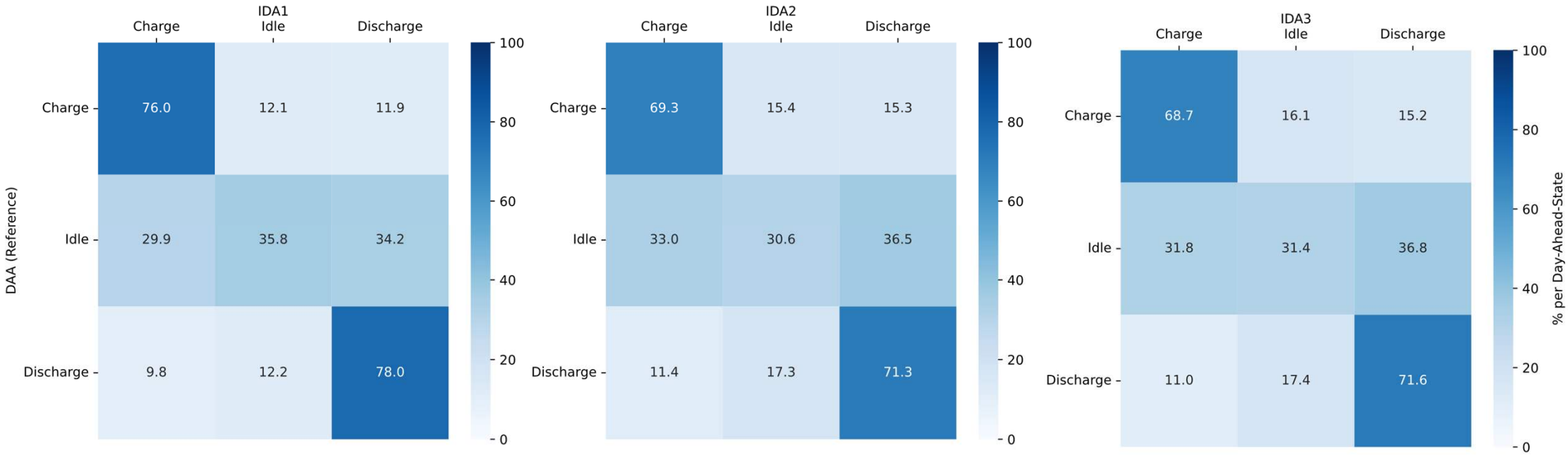
Comparison Weekday Metrics: DAA vs. Intraday Auctions – ETP4



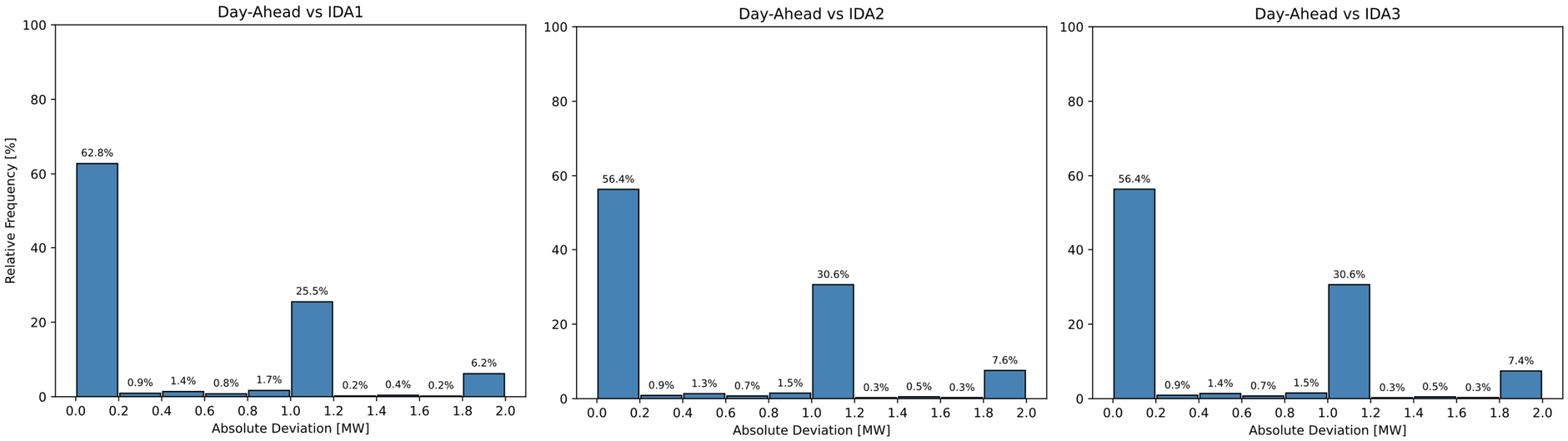
Appendix Work Package 3

ETP6

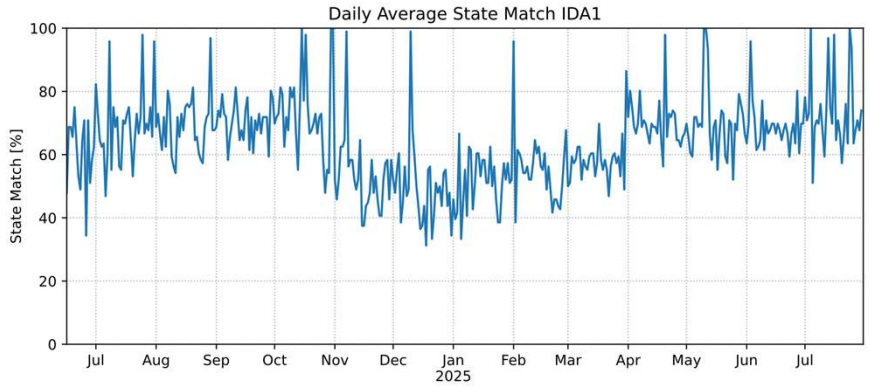
Comparison Percentual Confusion Matrix: DAA vs. Intraday Auctions – ETP6

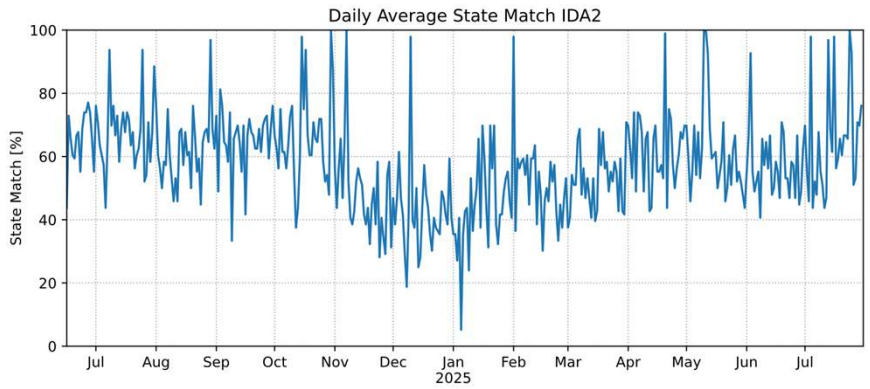


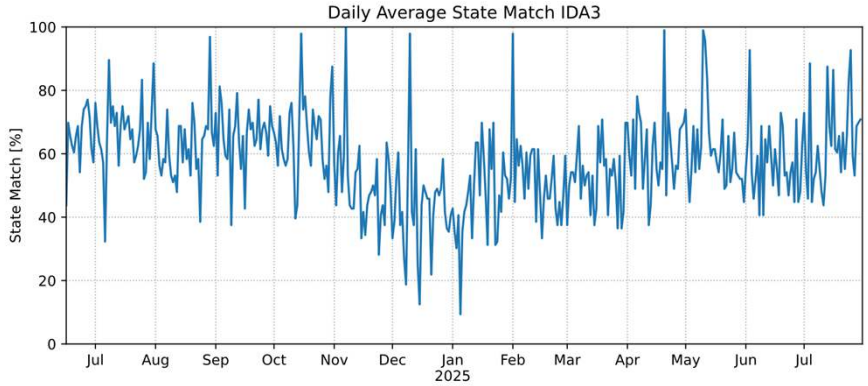
Comparison Histogram DAA vs. Intraday Auctions – ETP6



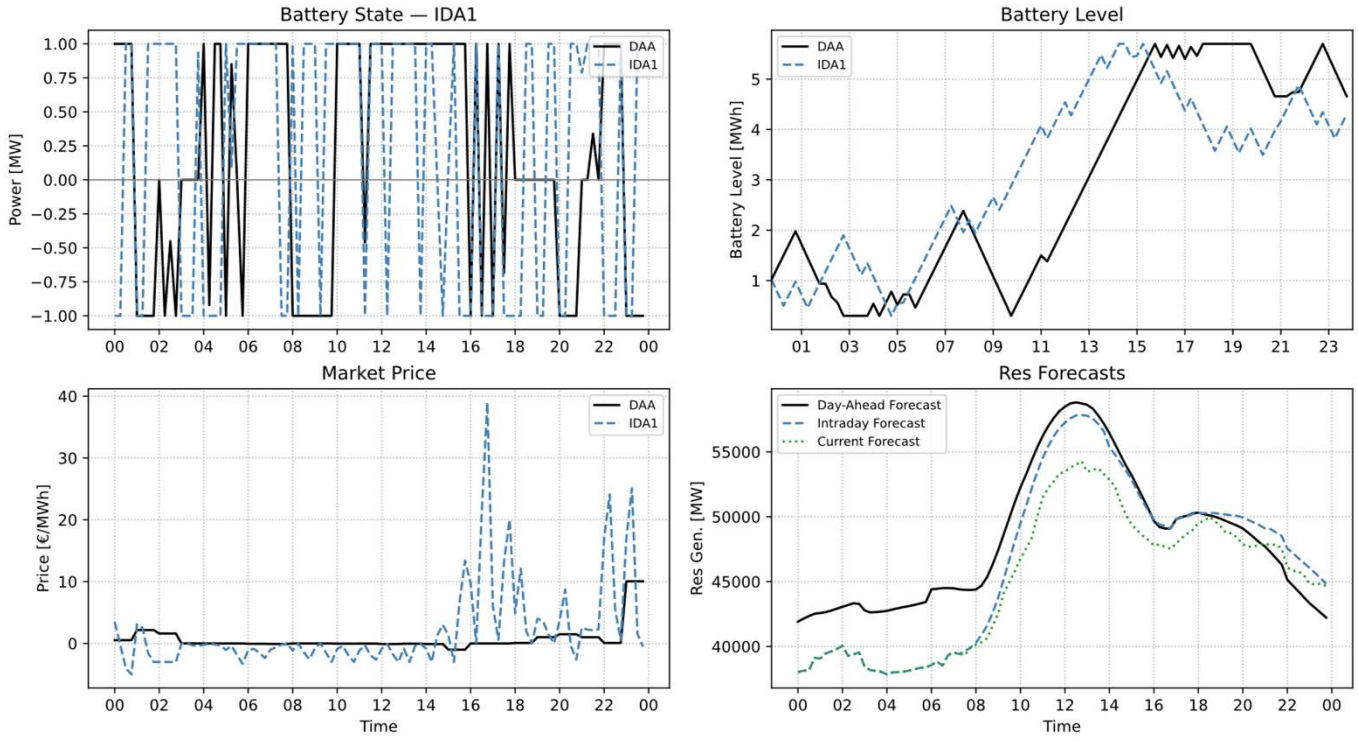
Comparison Daily State Match: DAA vs. Intraday Auctions – ETP6



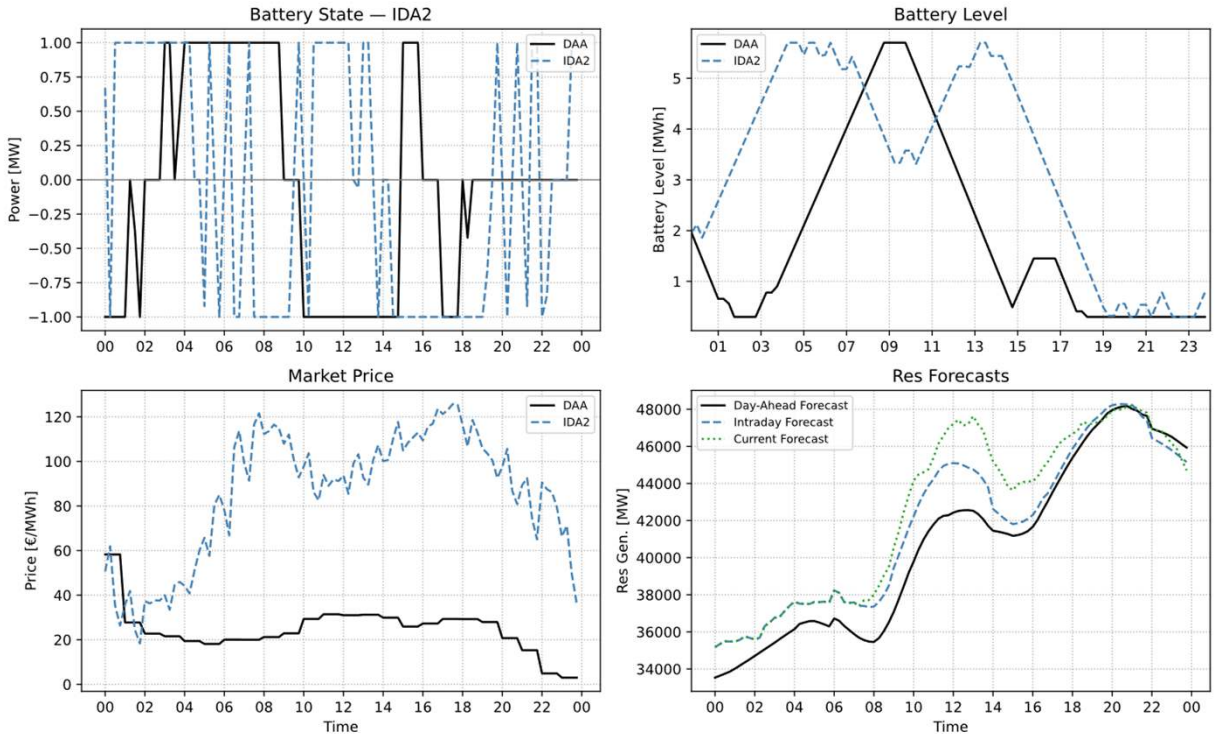




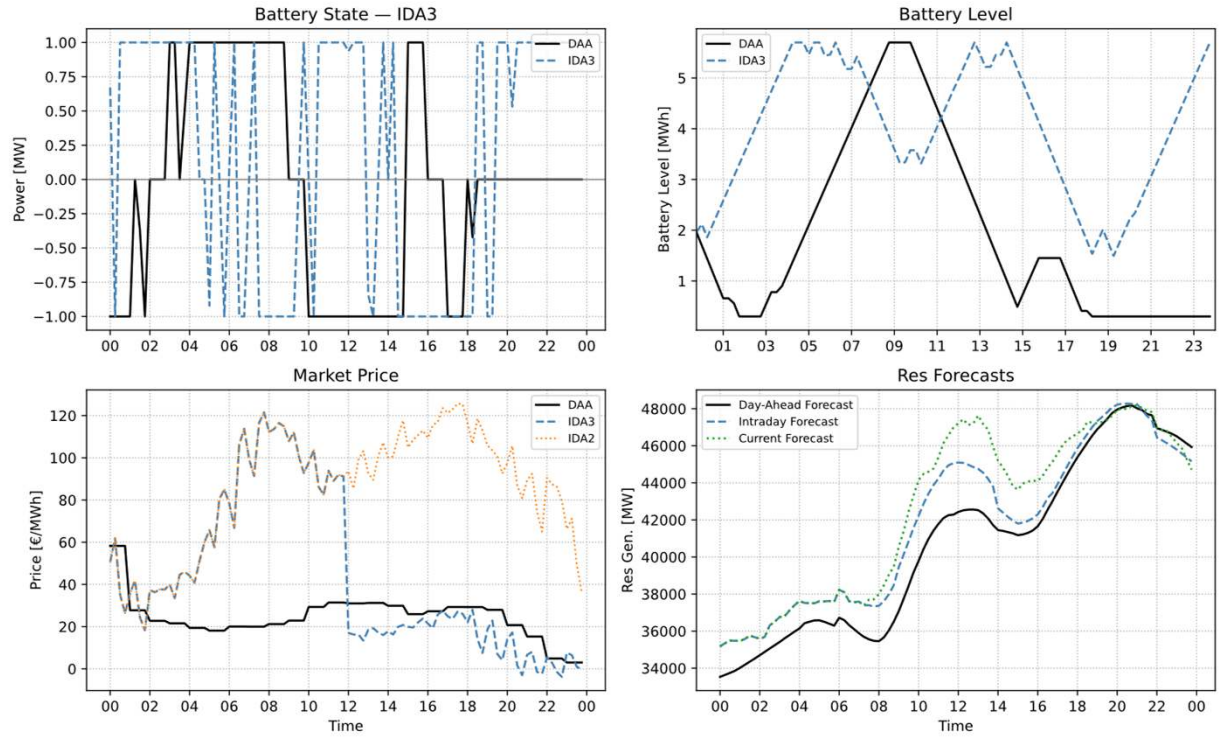
Extreme Day Analysis: DAA vs. IDA1 – 01.01.2025 – ETP6



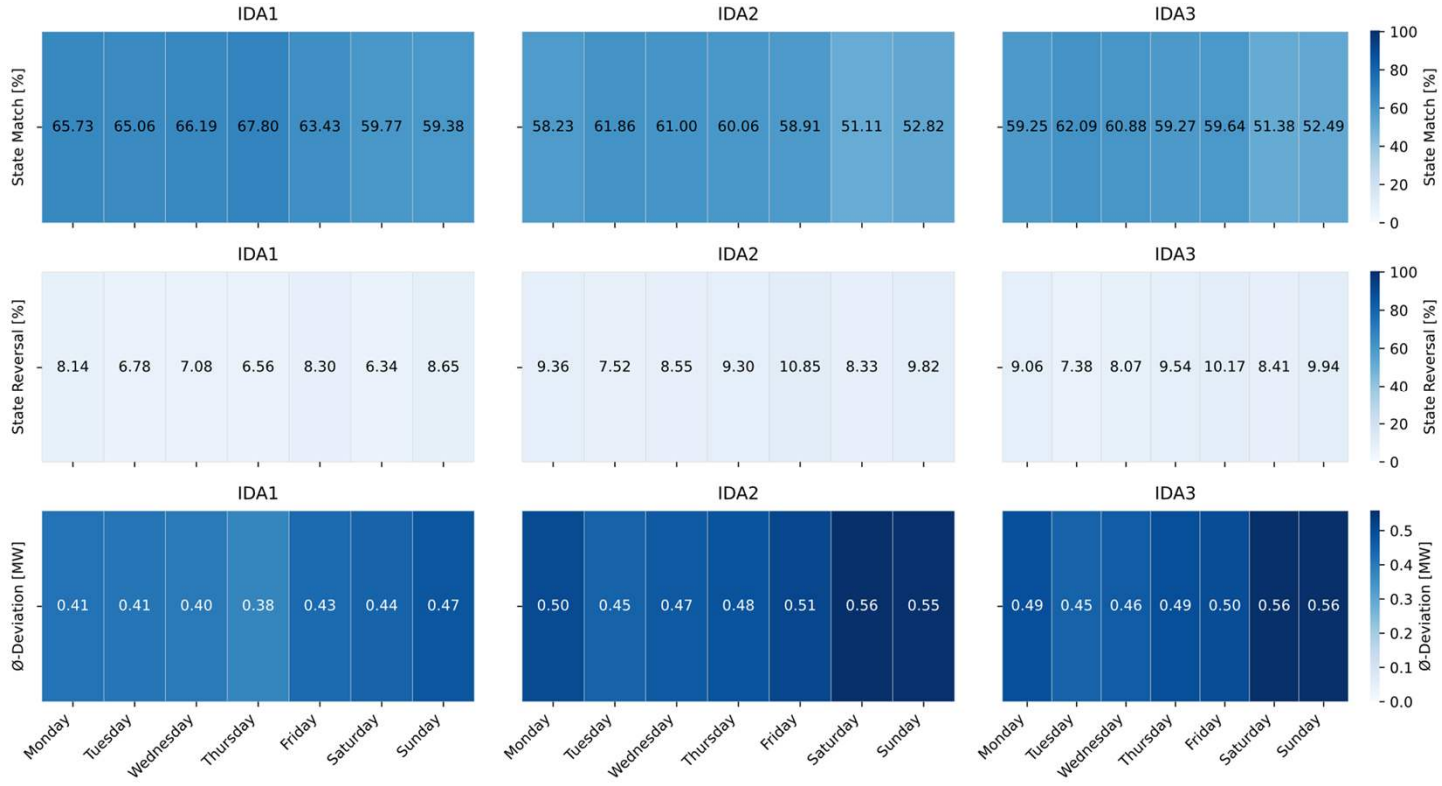
Extreme Day Analysis: DAA vs. IDA2 – 21.12.2024 – ETP6



Extreme Day Analysis: DAA vs. IDA3 – 21.12.2024 – ETP6



Comparison Weekday Metrics: DAA vs. Intraday Auctions – ETP6

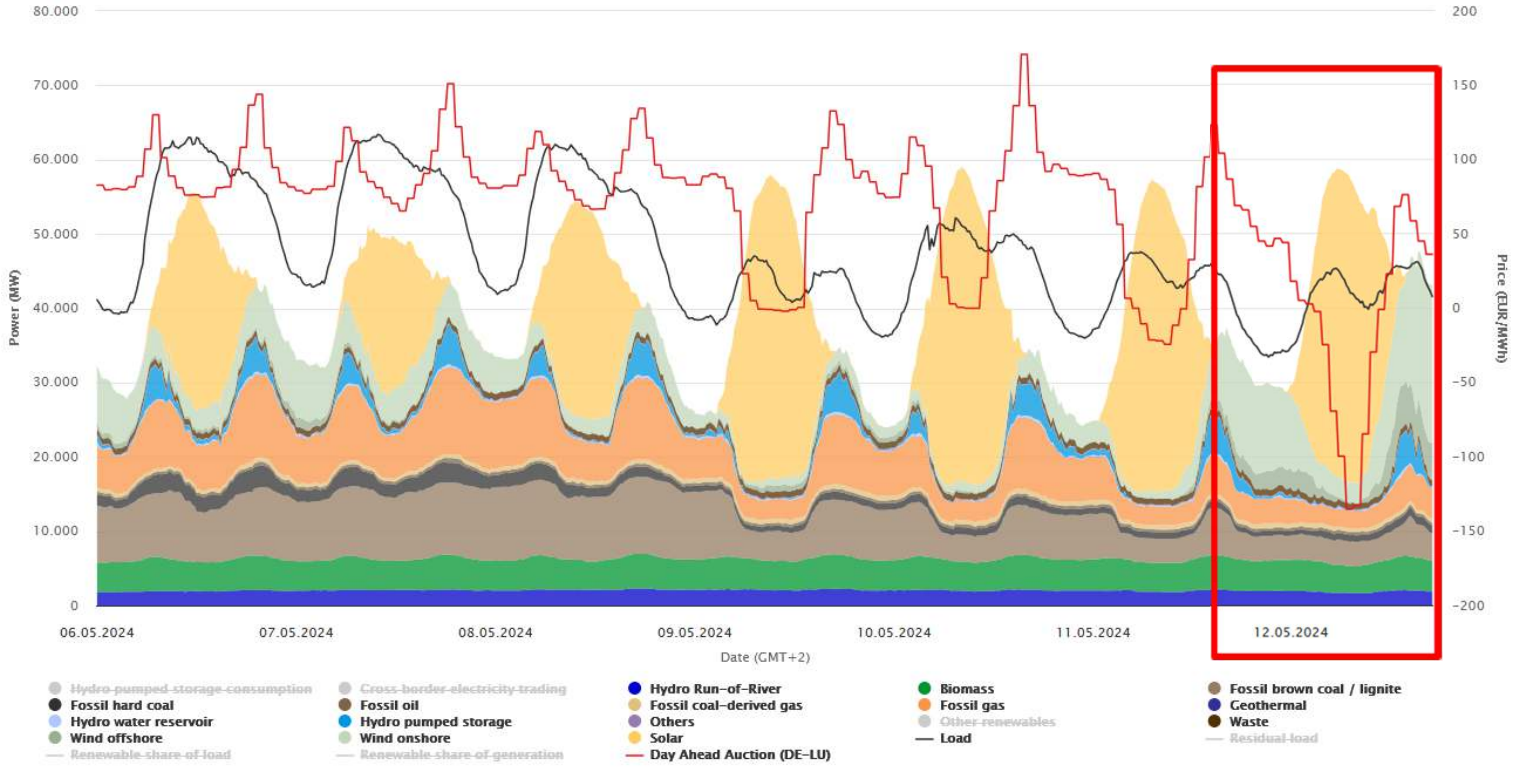


Appendix work package 4

SAPB

Analysis for 12th May
- High share of renewable generation -

12th May – negative prices

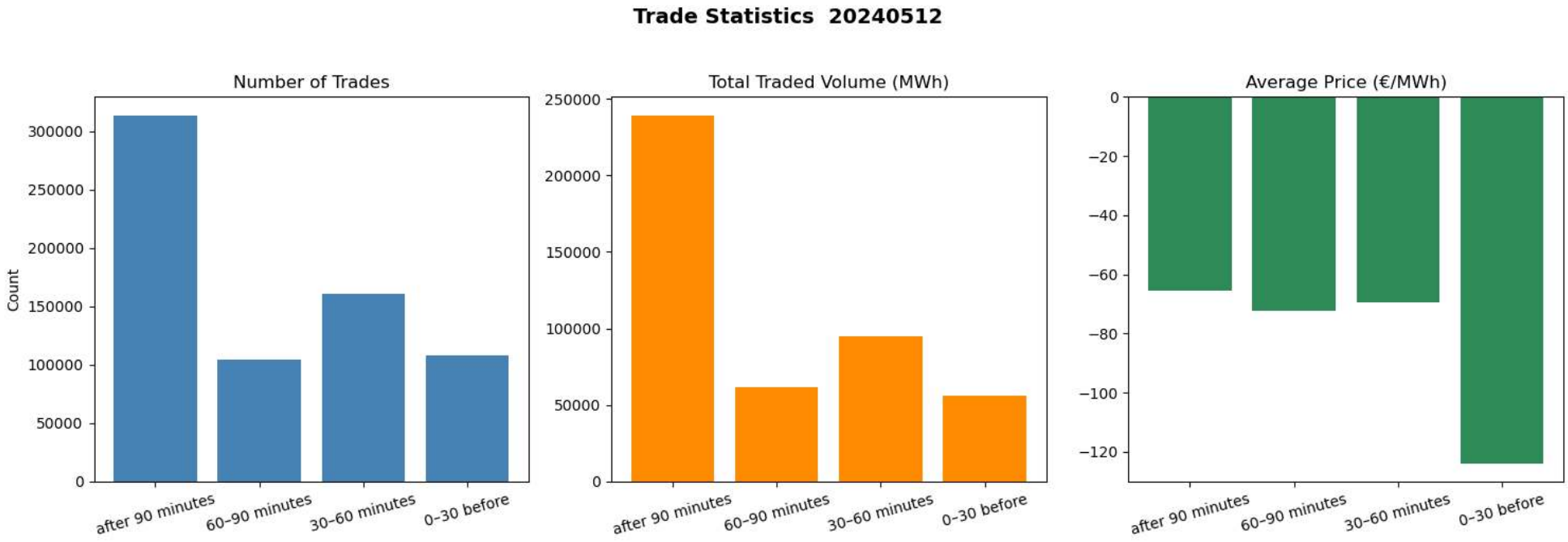


https://www.energy-charts.info/

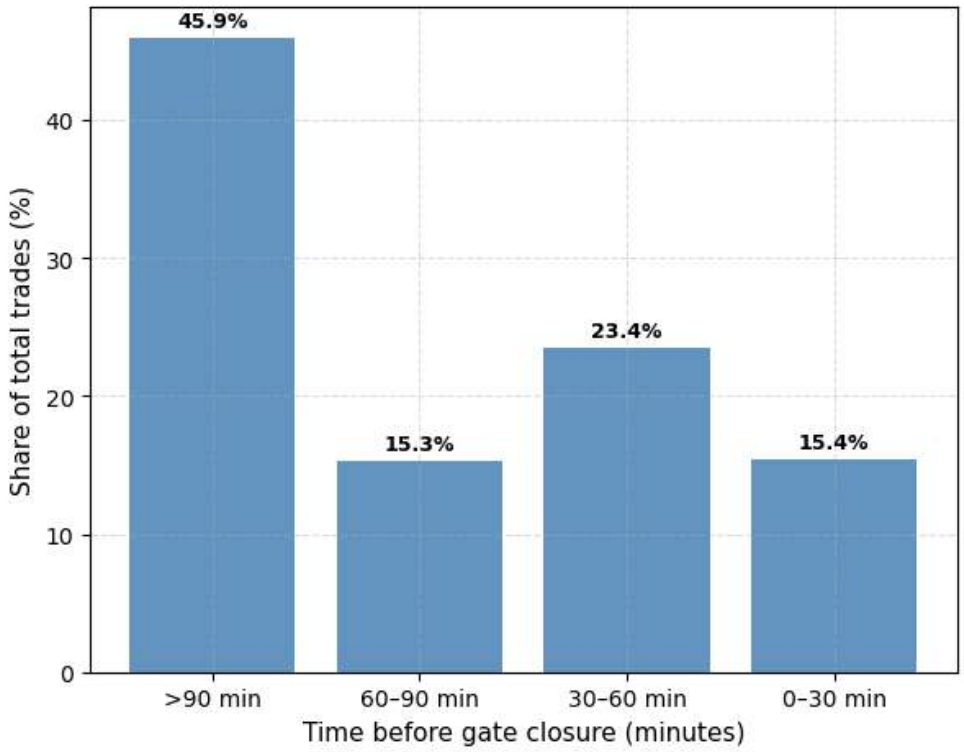
Brandenburg University of Technology Cottbus - Senftenberg

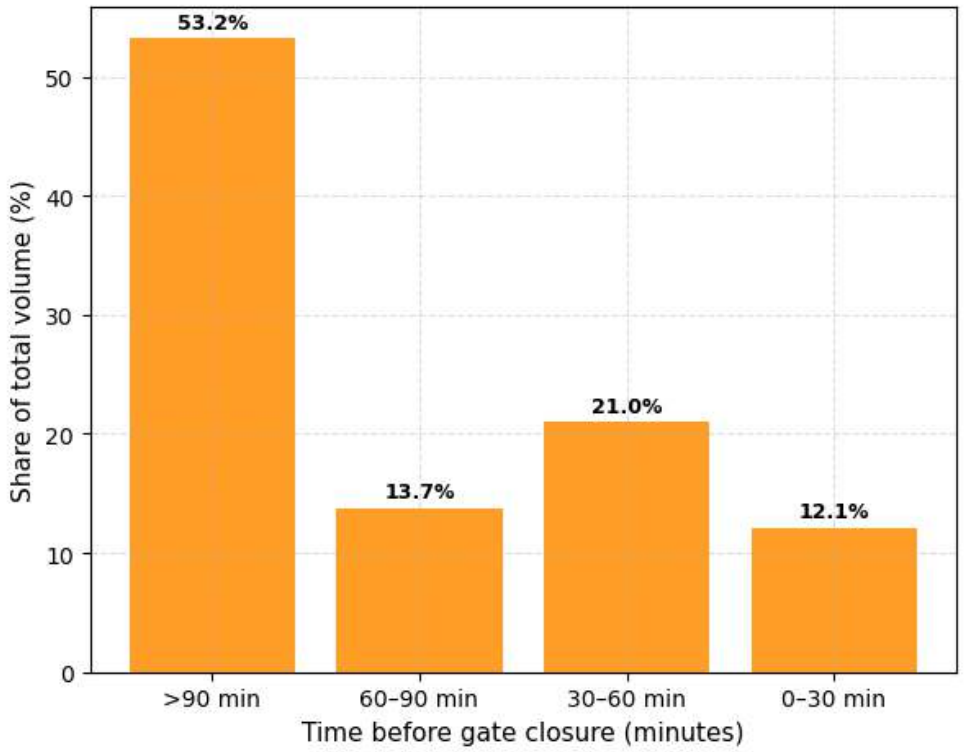
Steinbeis

Trade statistics high number of trades in the last hours before gate closure

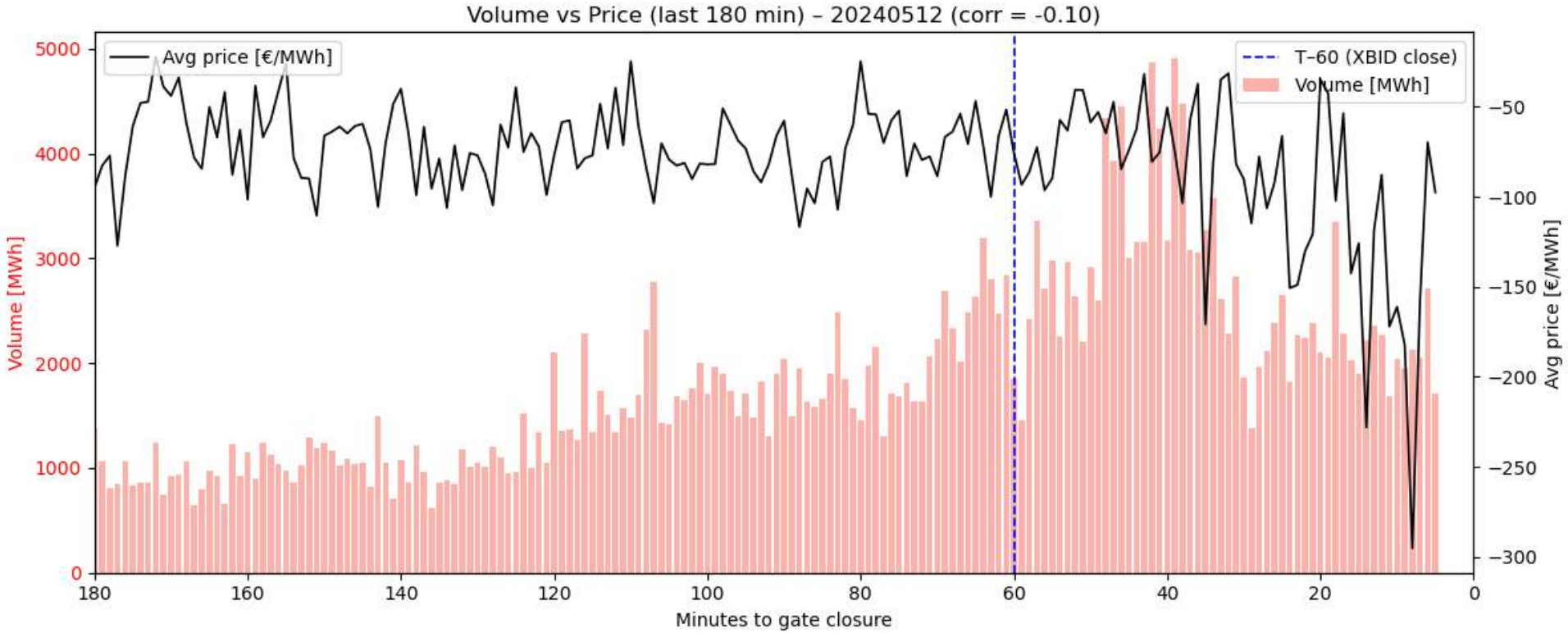


Number of trades and traded volume per gate-closure interval





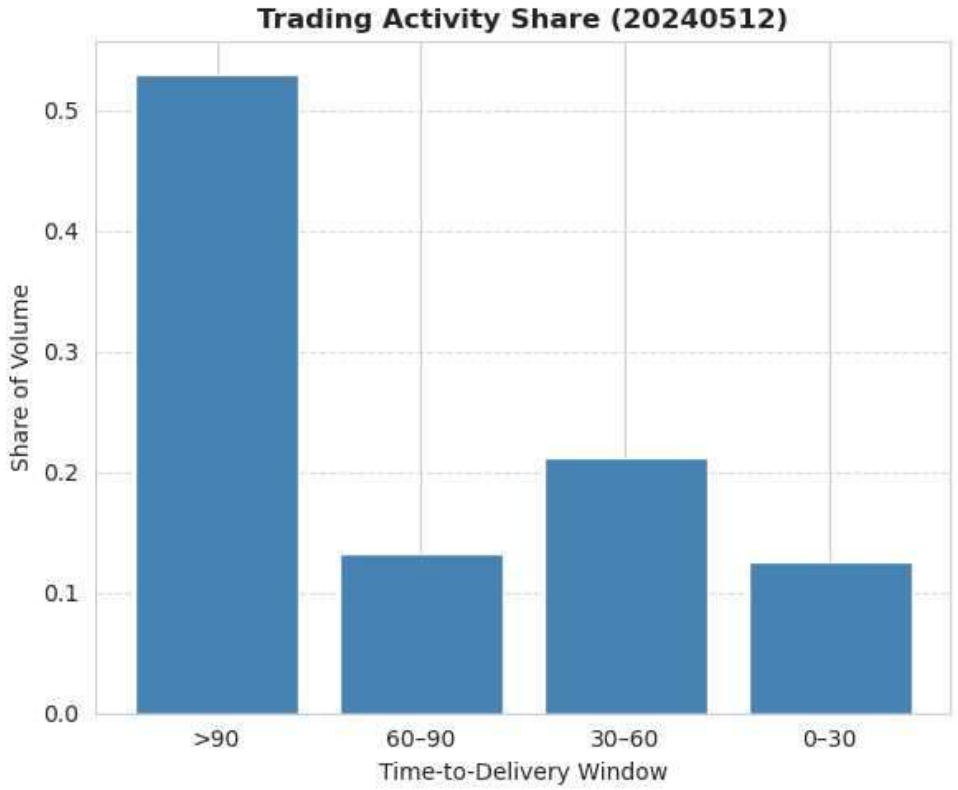
Trades increase before cross-border trade gate closure and in last 60 minutes –with volatile prices

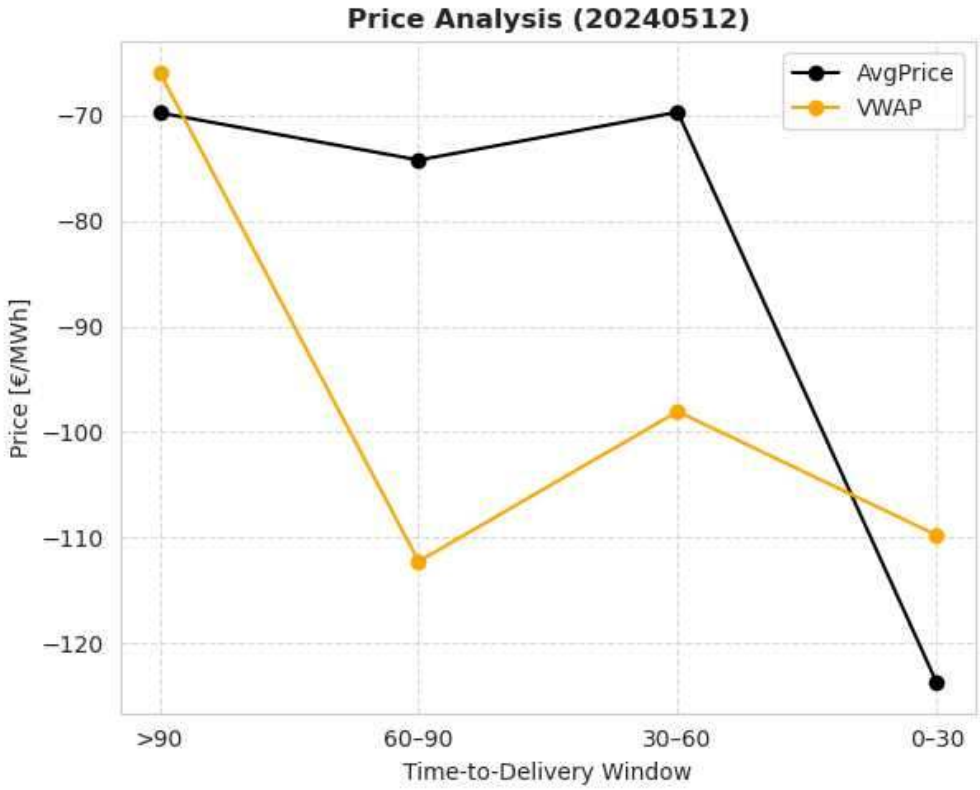


IH0

SAPB

Analysis results: volumes and prices





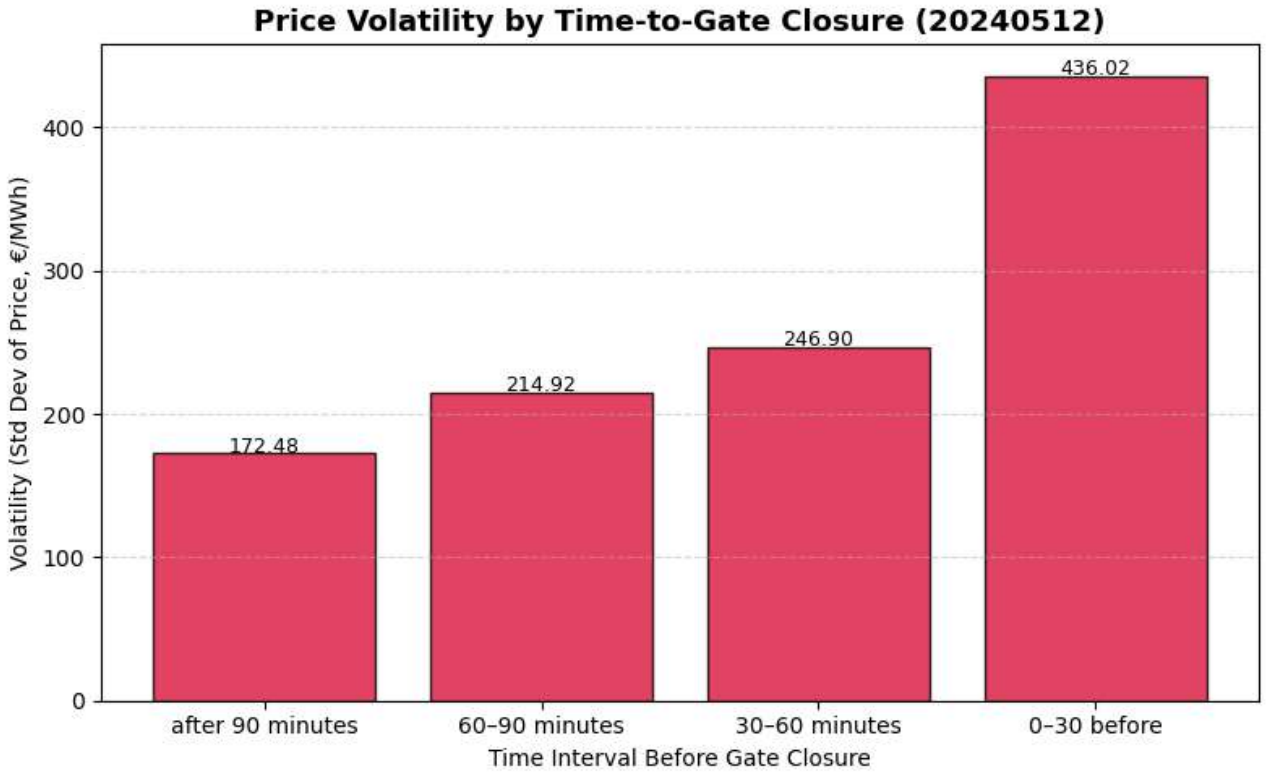
Folie 132

IH0 Die x- Achse muss hier anders herum, wie bei den anderen Bildern

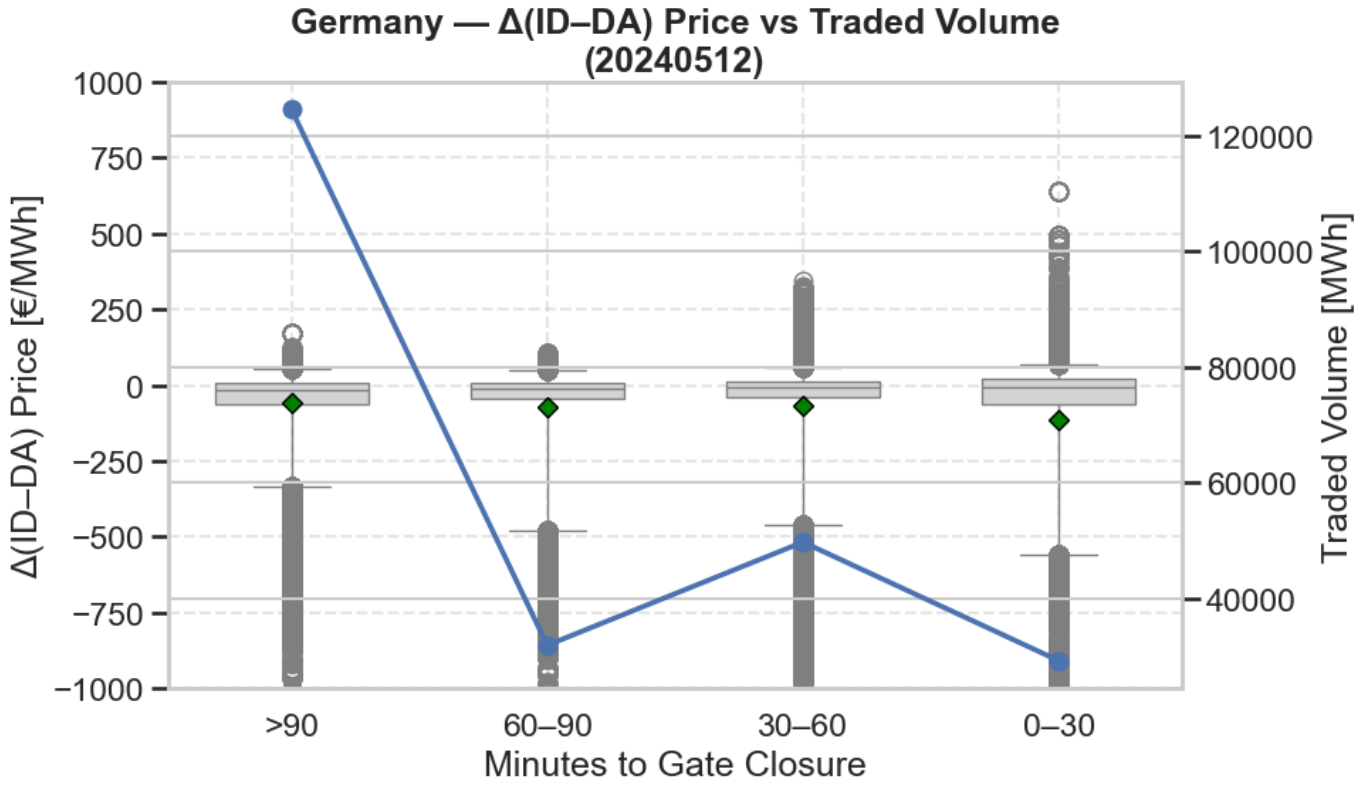
Ines Hauer; 2025-11-07T07:36:35.532

Price volatility (standard deviation) per time interval

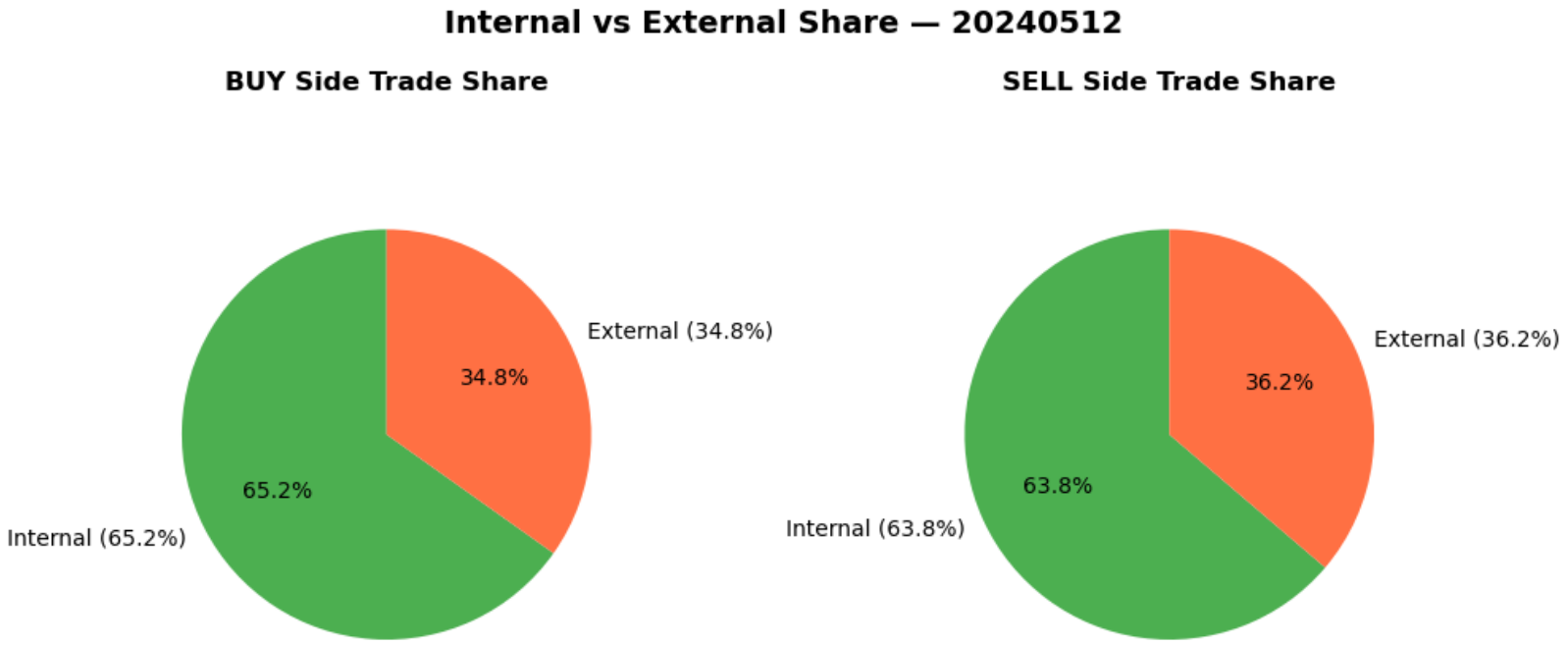
The closer the delivery time, the higher the volatility of the price



Analysis result: Deviation to Day Ahead prices

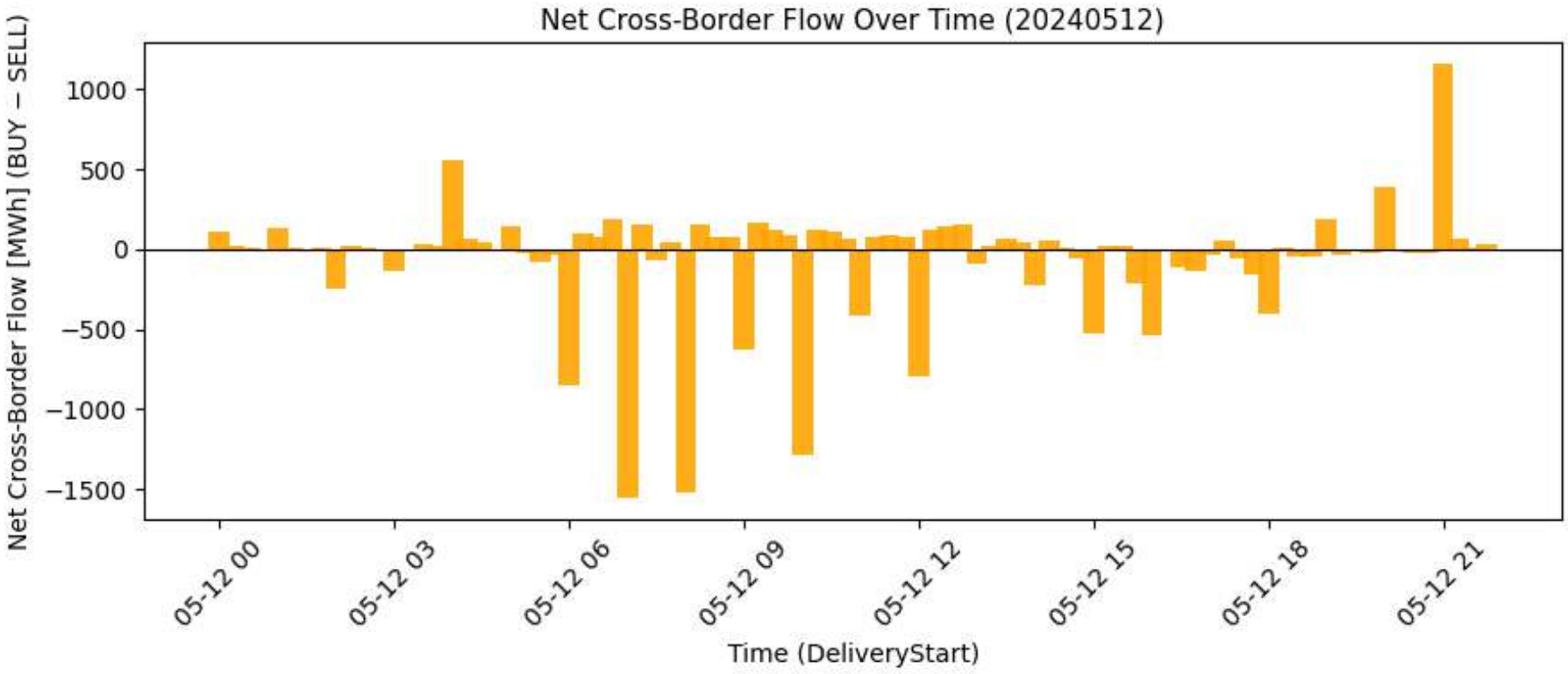


Share of External Trade



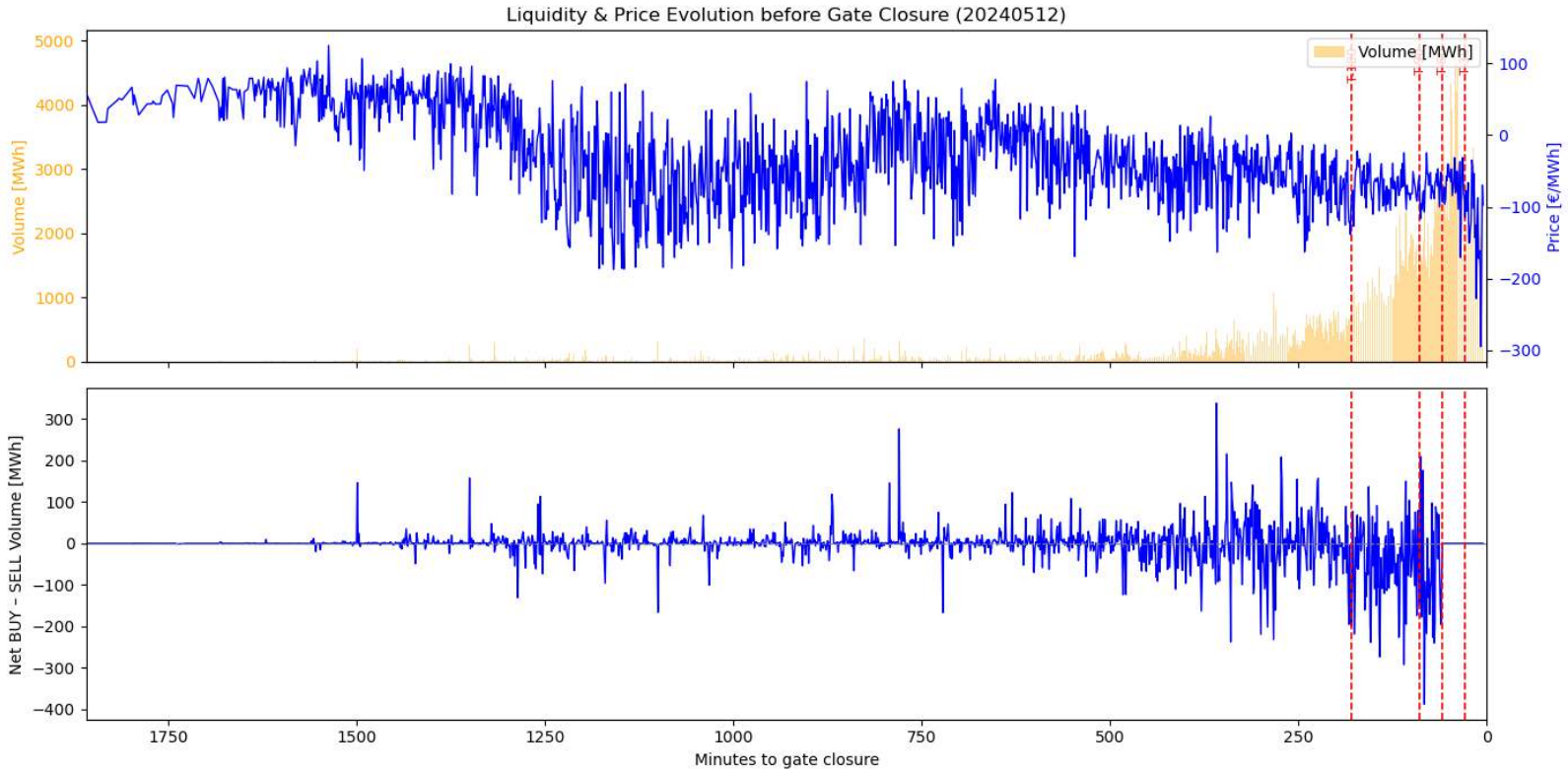
SAPB

Net Cross Border



Results: Cross-border vs. internal Trades

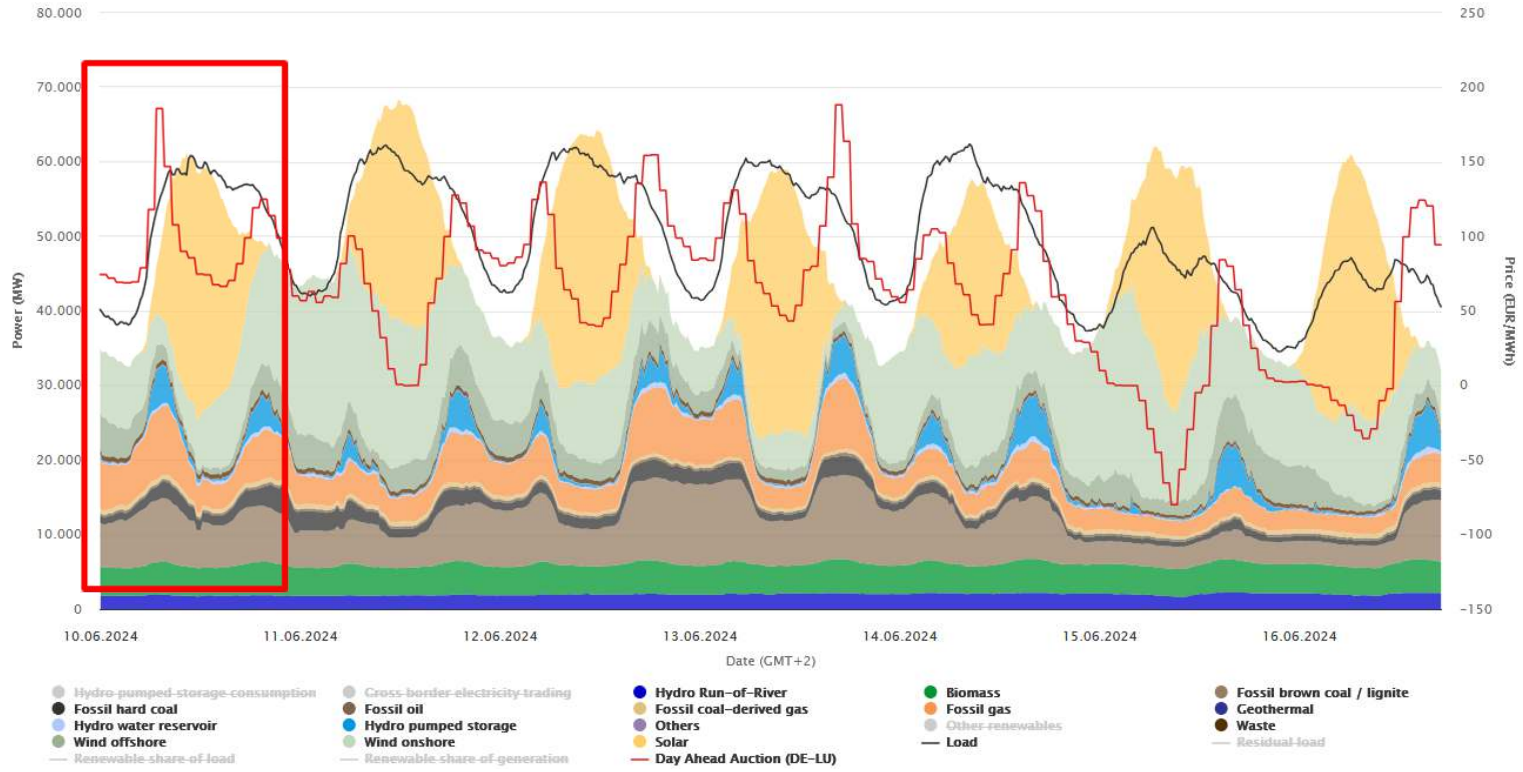
The closer the delivery time, the higher the volume of external trades, reaching a peak at gate-close time (60 Minuten before delivery.



SAPB

Analysis 10th June

10th June

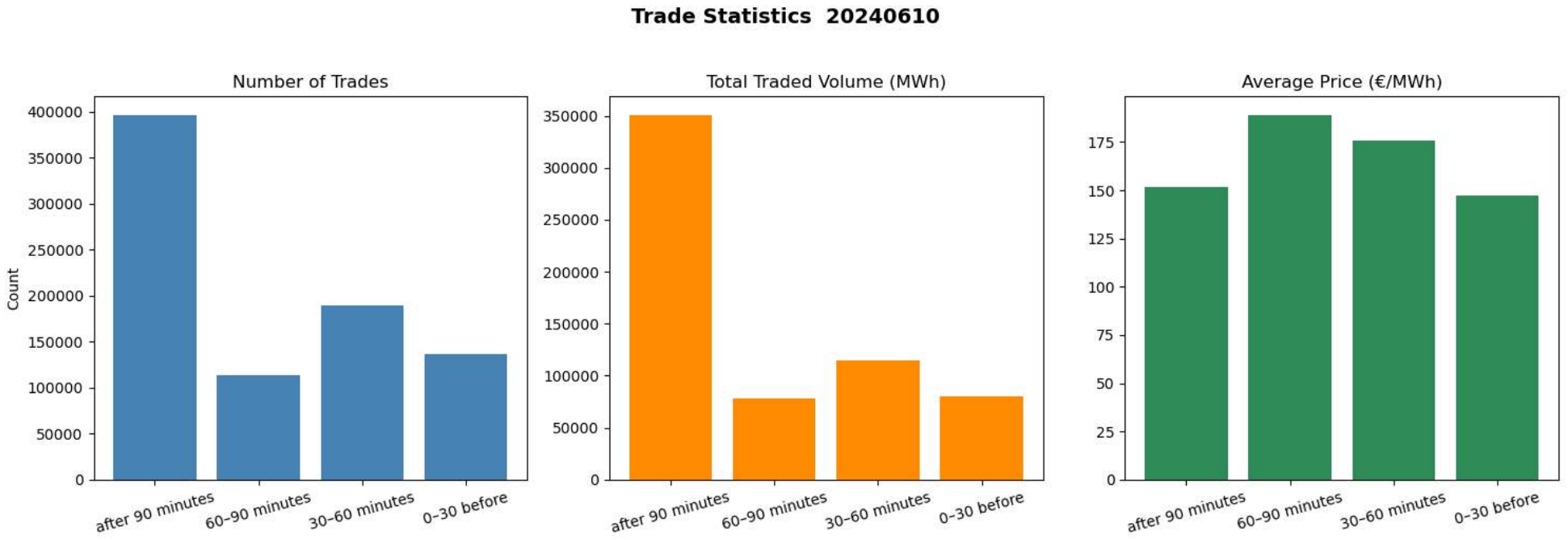


Brandenburg University of Technology Cottbus - Senftenberg

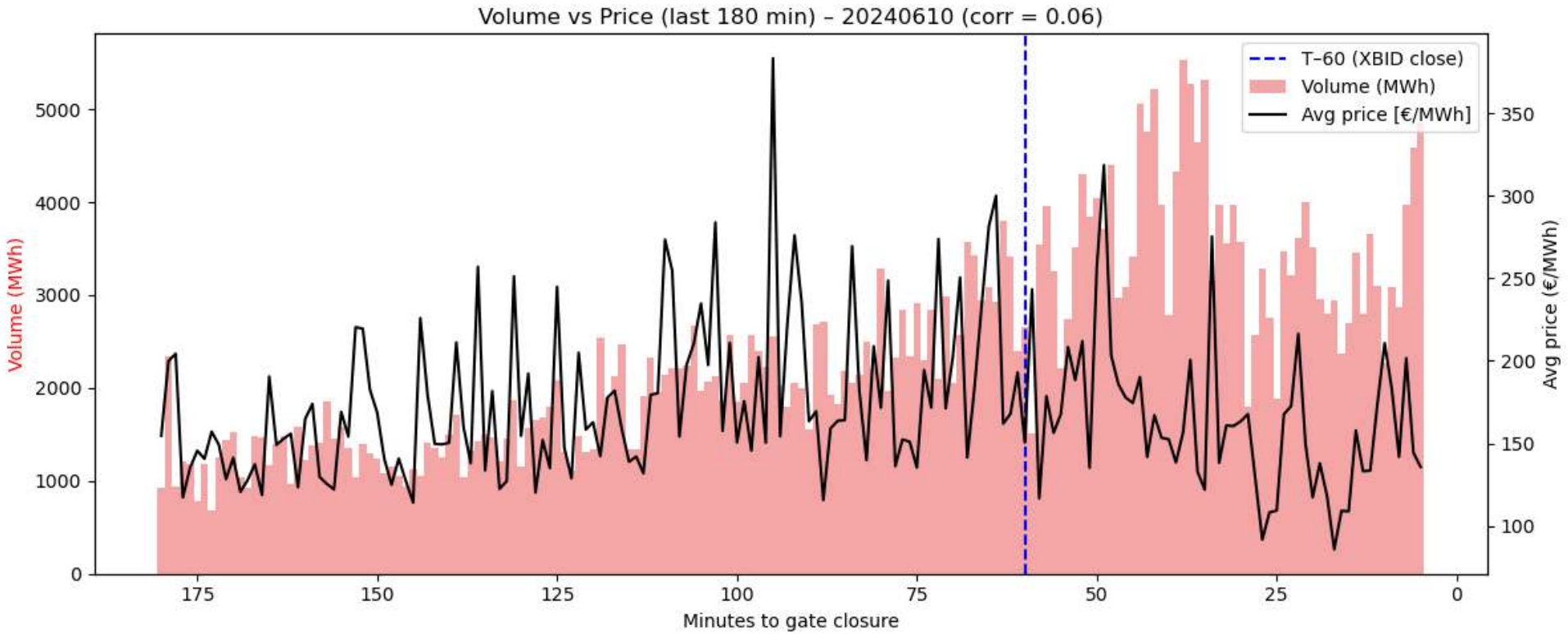
Steinbeis

https://www.energy-charts.info/

Trade Statistics



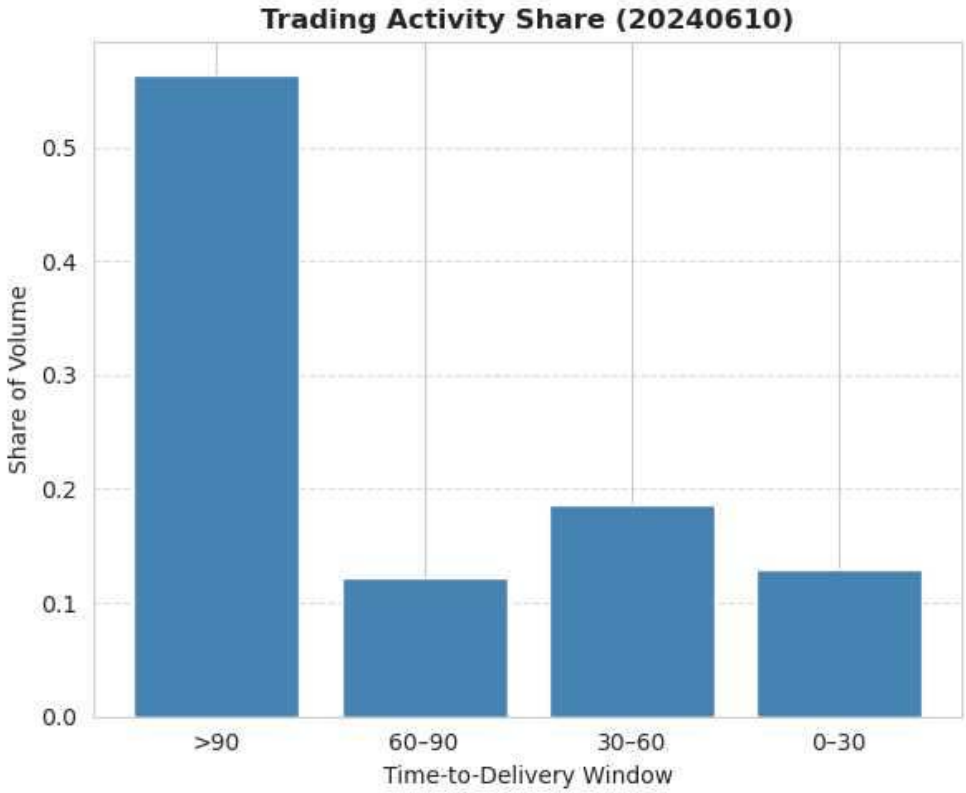
10th June – High Price



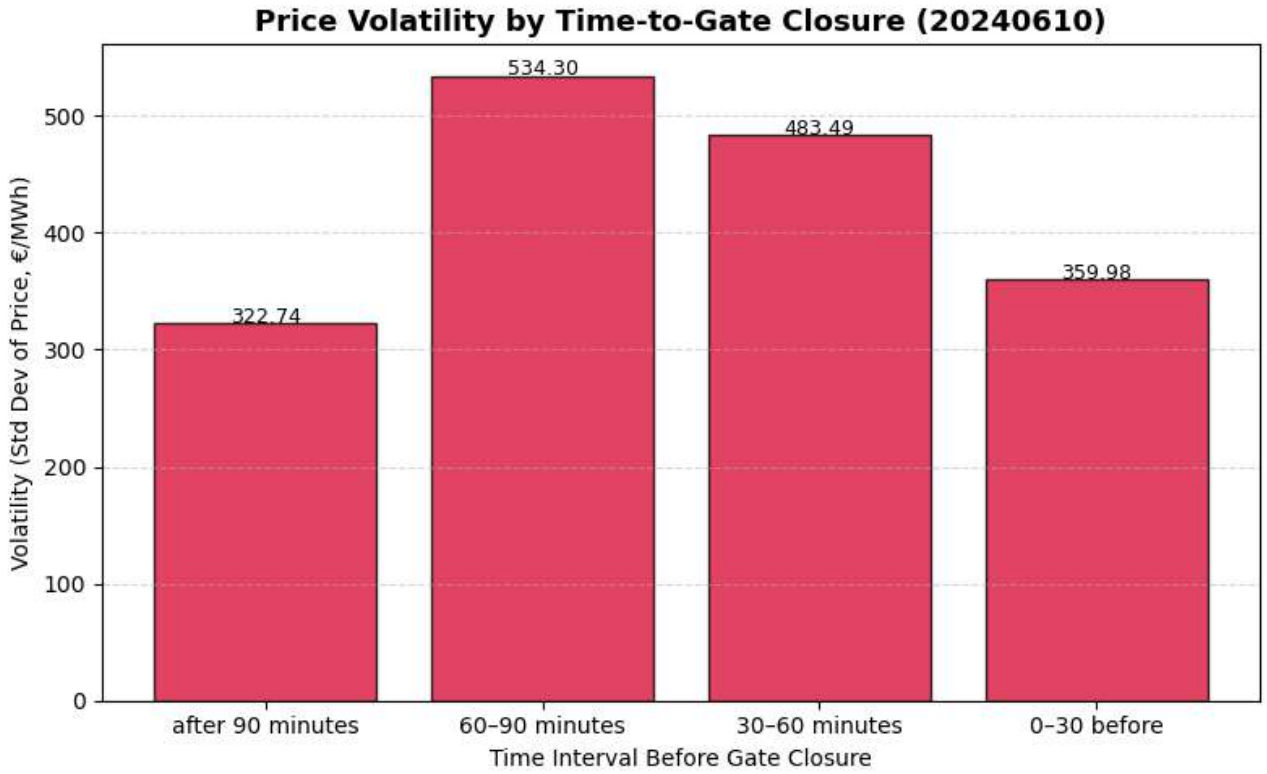
Brandenburg University of Technology Cottbus - Senftenberg

Steinbeis

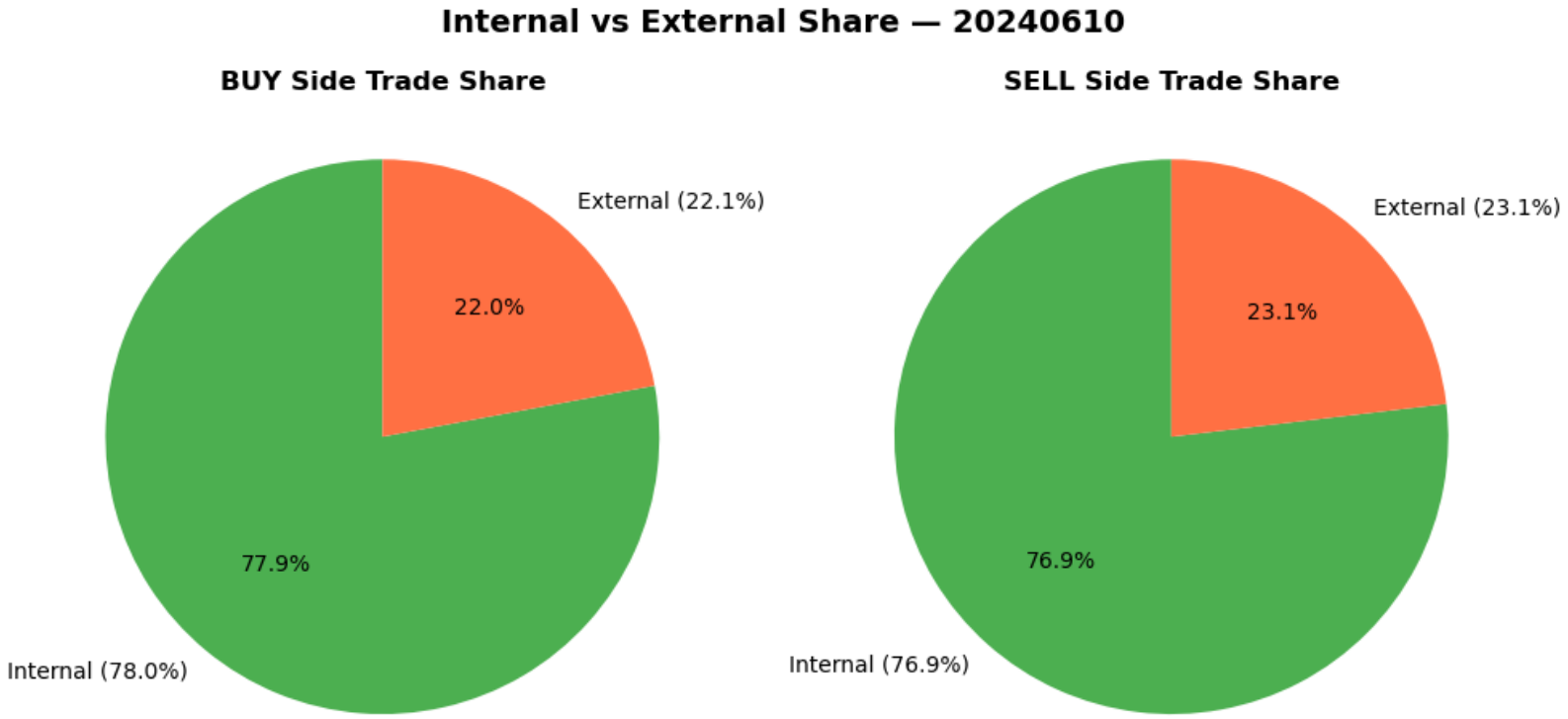
Analysis results: volumes and prices



Price volatility (standard deviation) per time interval

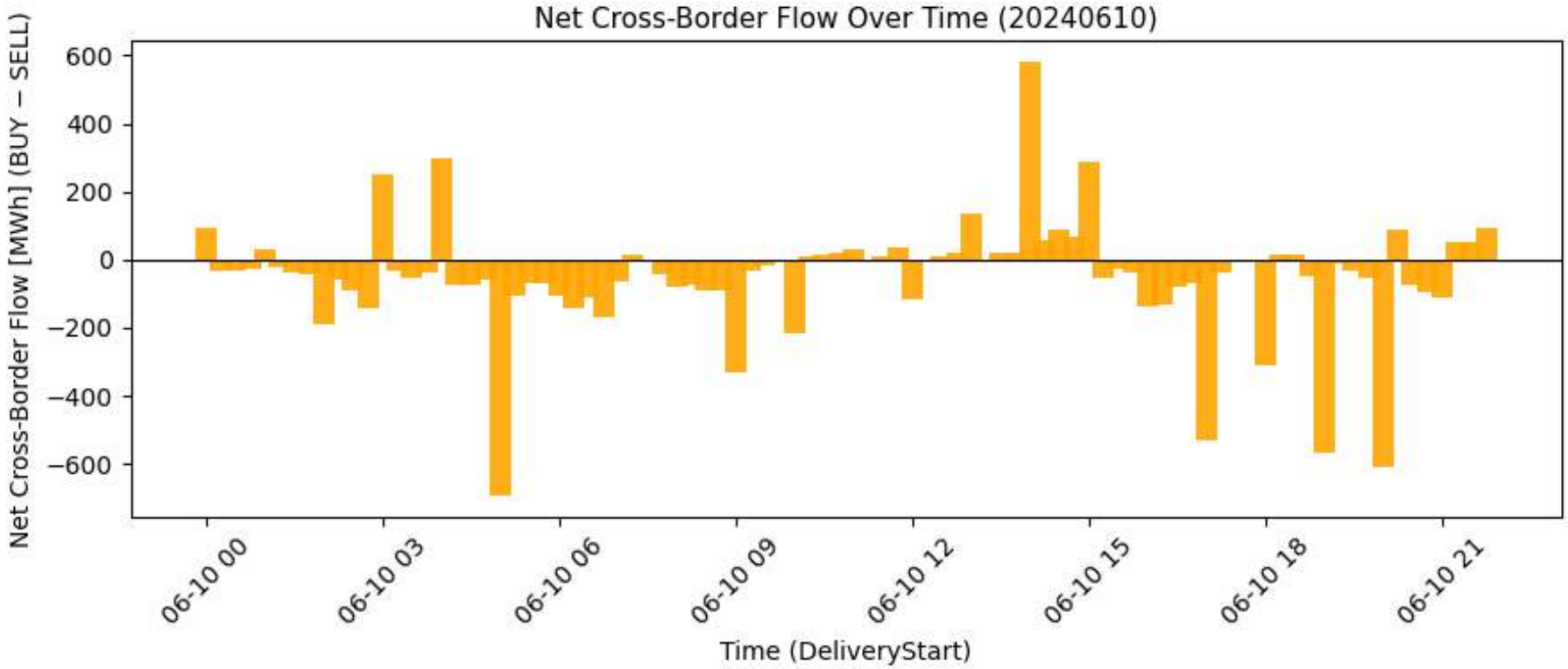


Share of External Trade

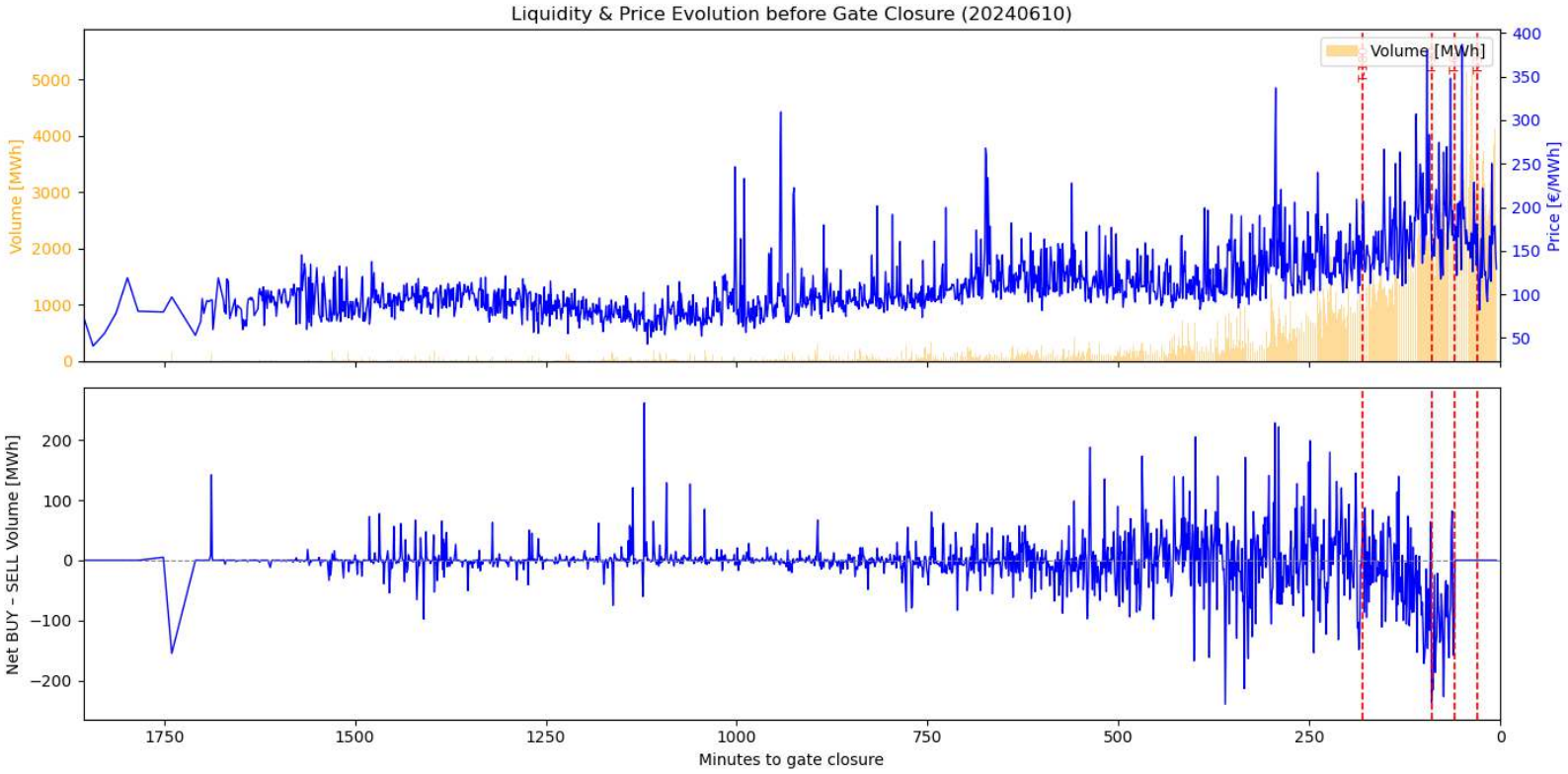


SAPB

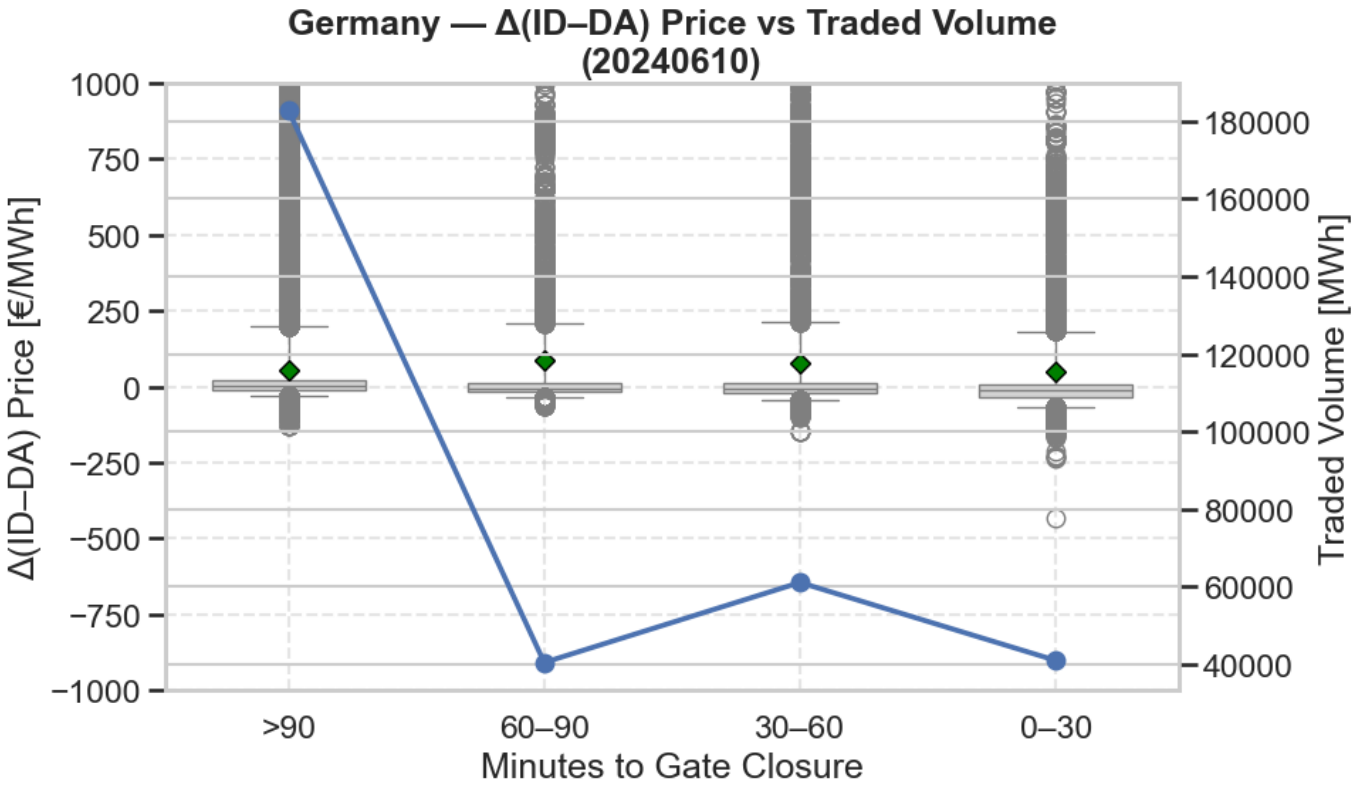
Cross-Border Flow (BUY − SELL)



Results: Cross-border vs. internal Trades



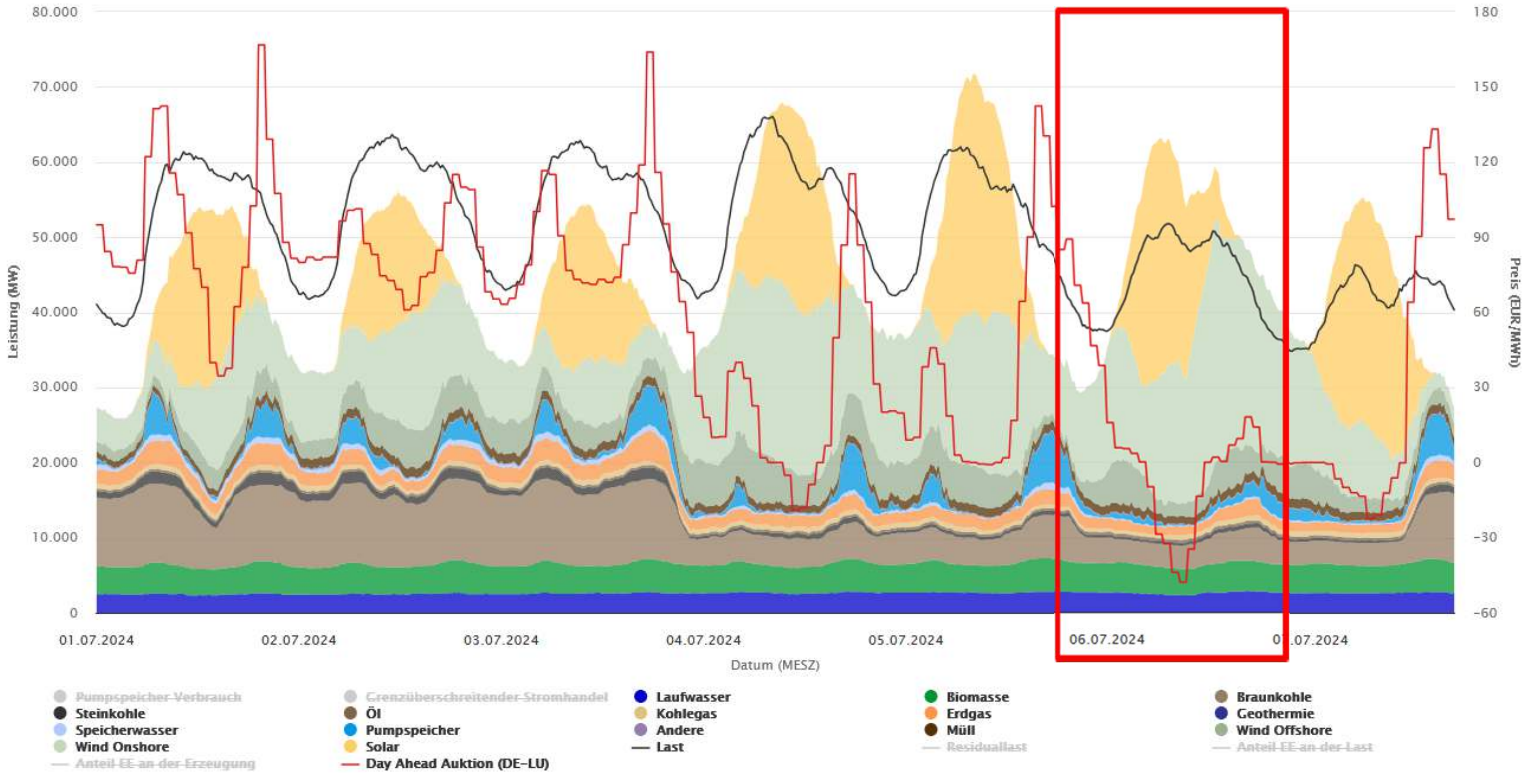
Analysis result: Deviation to Day Ahead prices



SAPB

Analysis 6th July (Lower Price)

SAPB

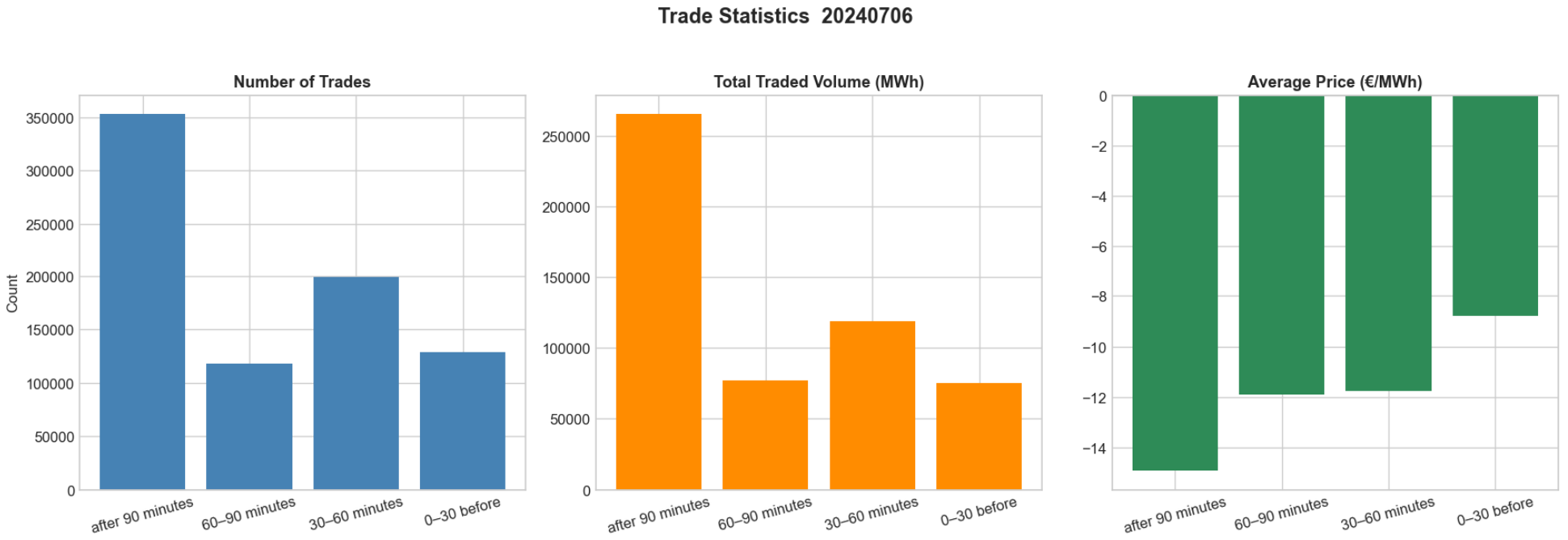


Brandenburg University of Technology Cottbus - Senftenberg

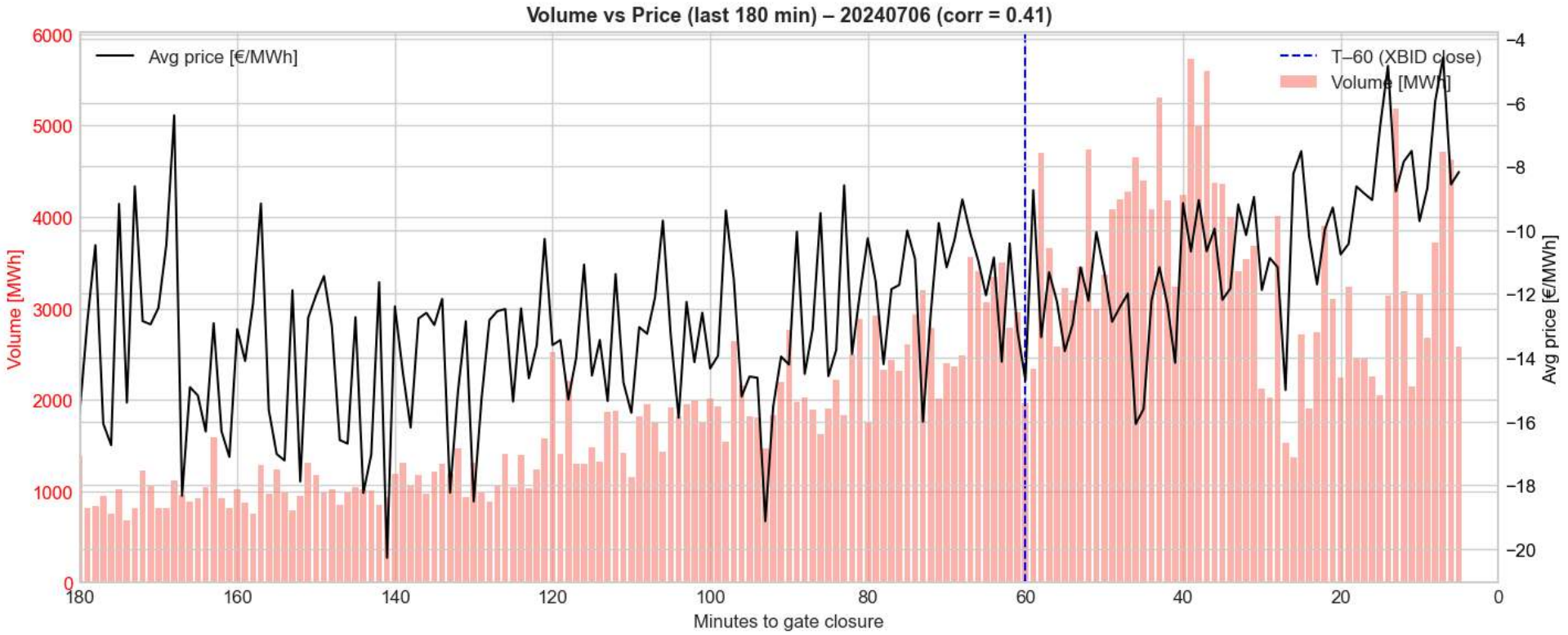
Steinbeis

https://www.energy-charts.info/

Trade Statistics



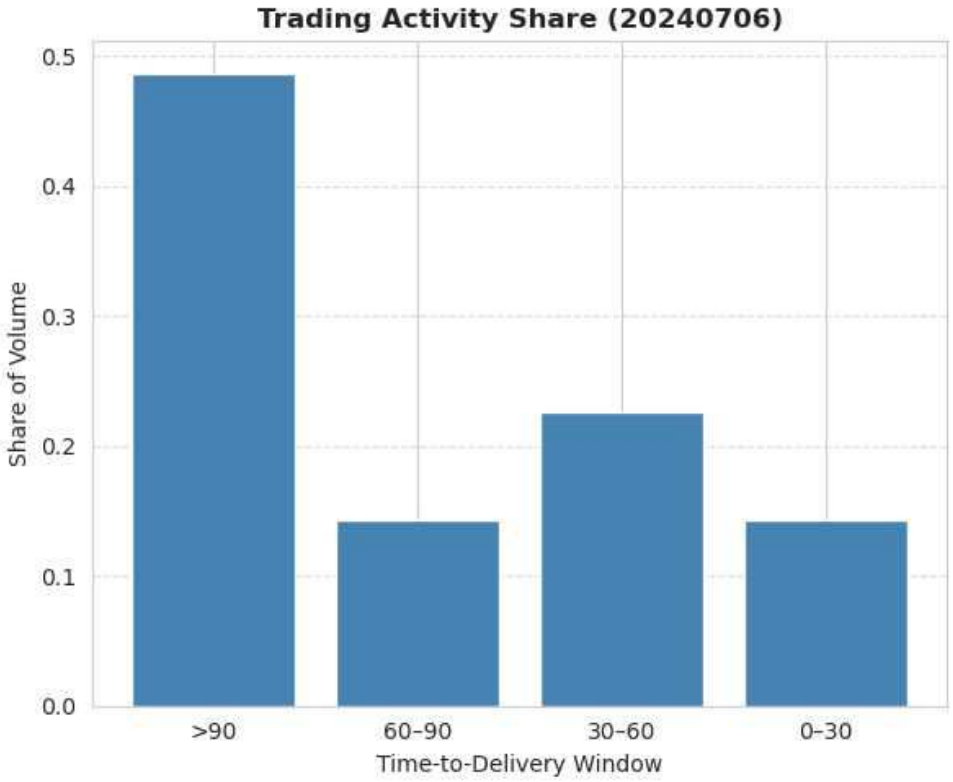
Trades increase before cross-border trade gate closure and in last 60 minutes –with volatile prices



Brandenburg University of Technology Cottbus - Senftenberg

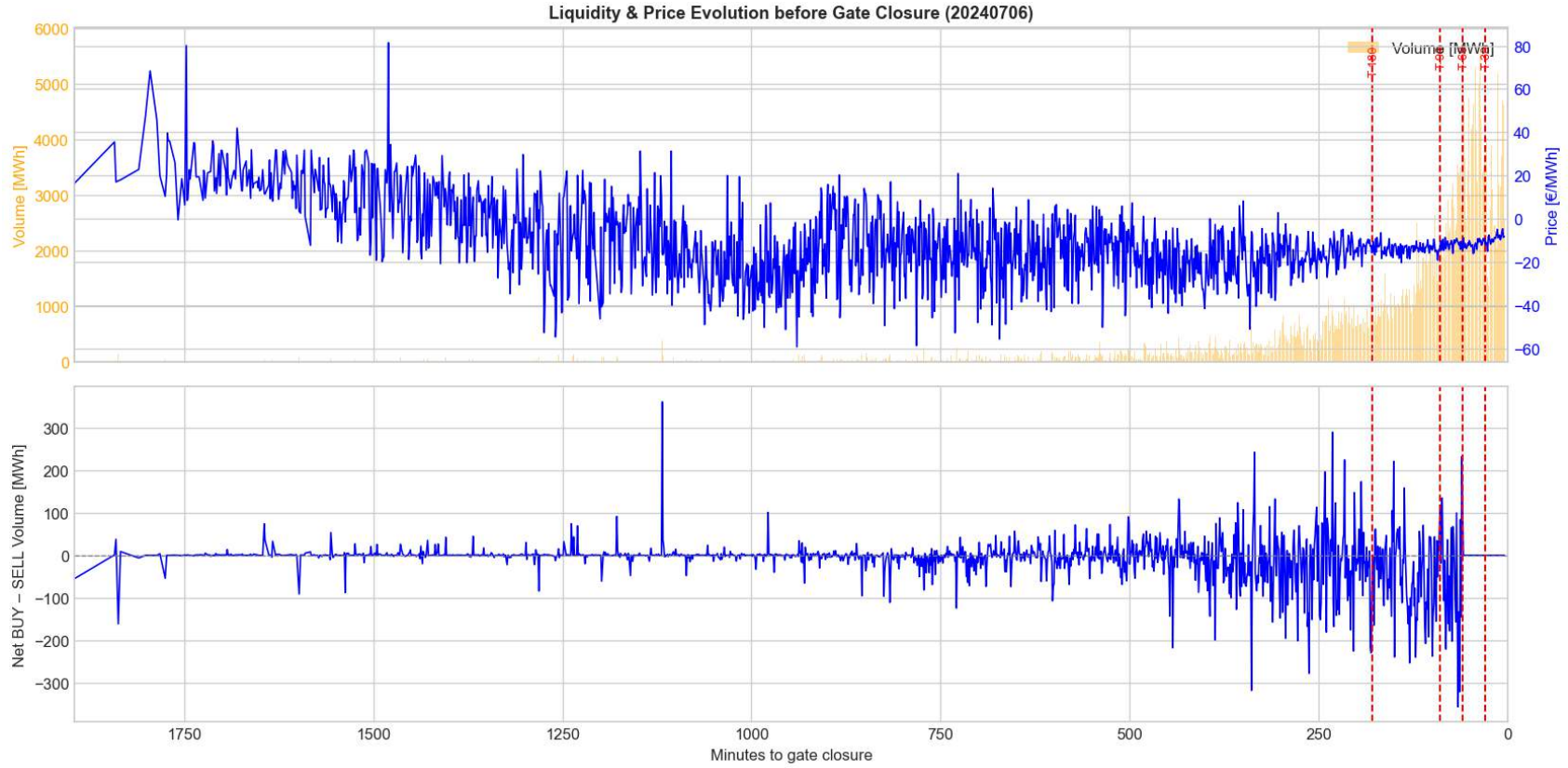
Steinbeis

Analysis results: volumes and prices

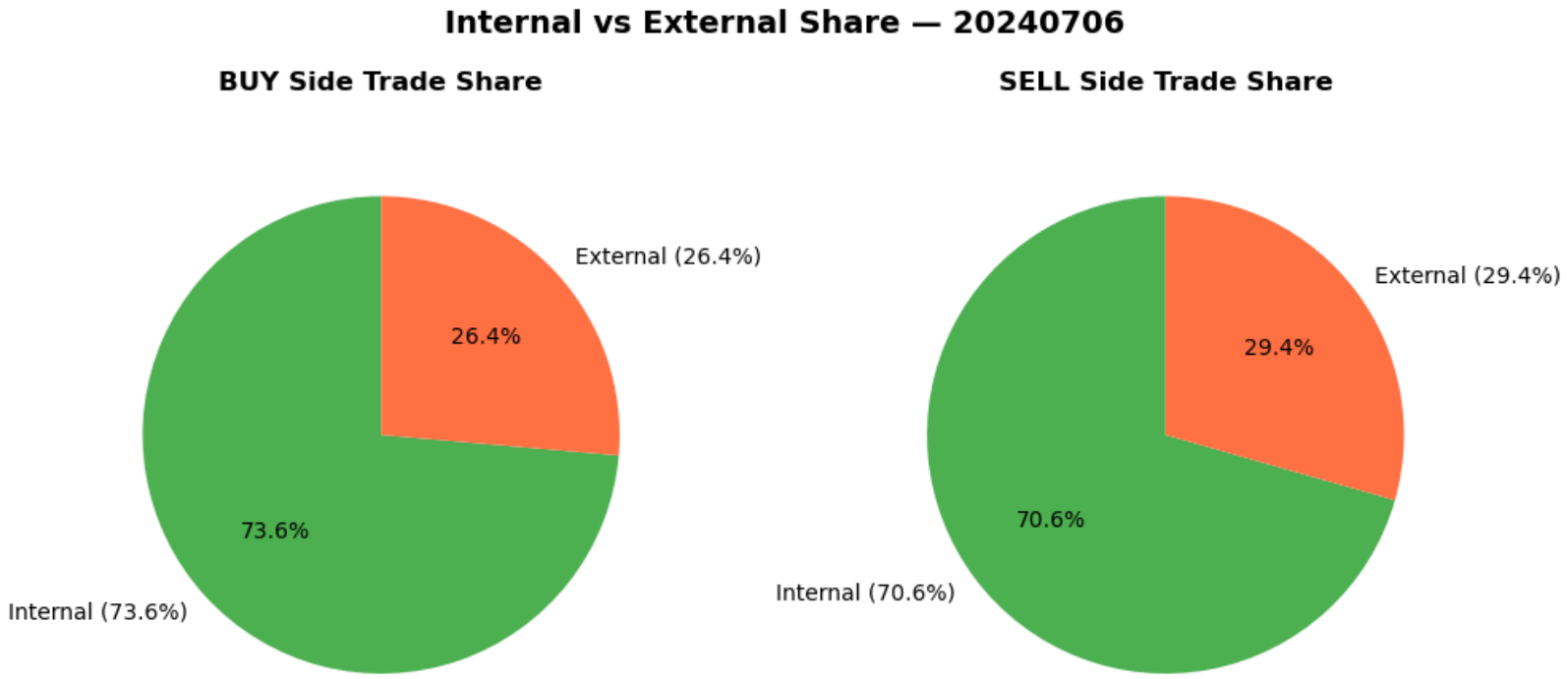


Price volatility (standard deviation) per time interval

Results: Cross-border vs. internal Trades

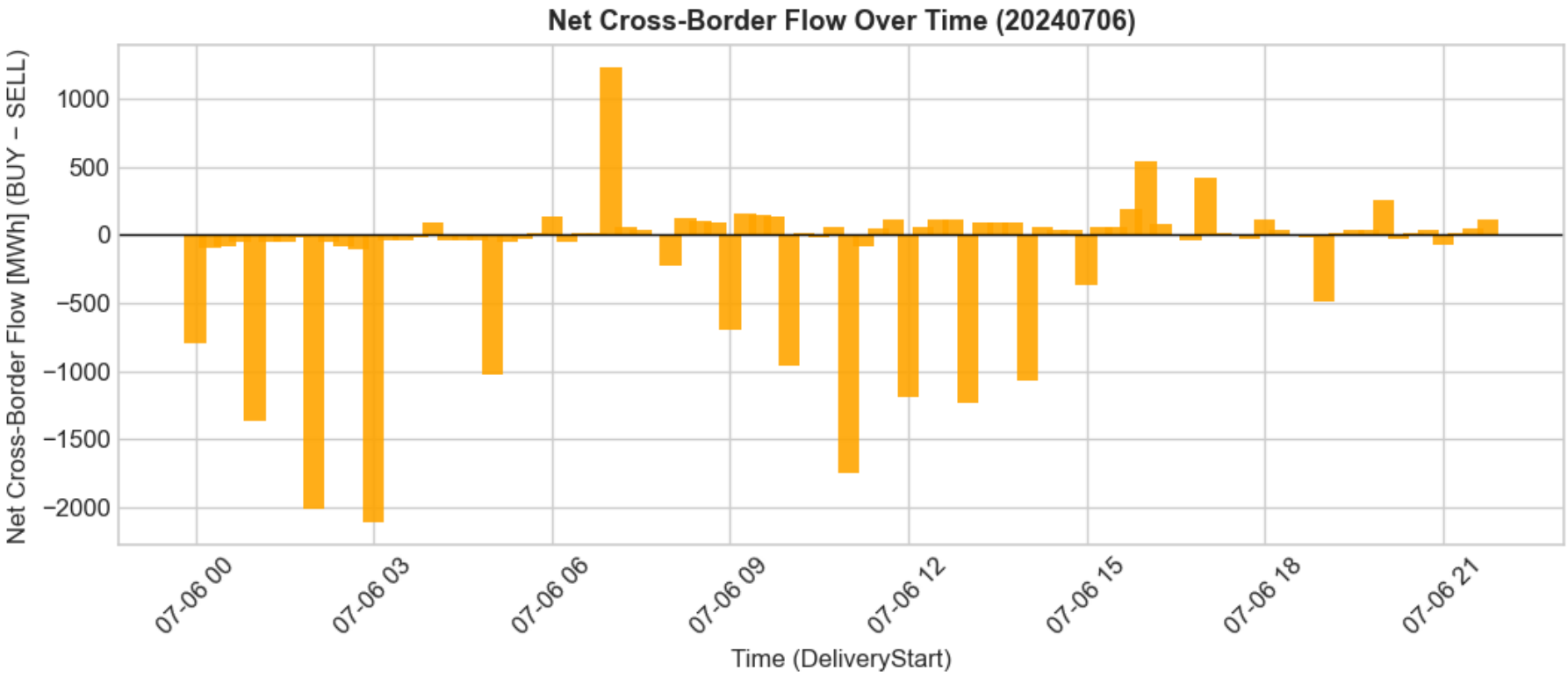


Share of External Trade

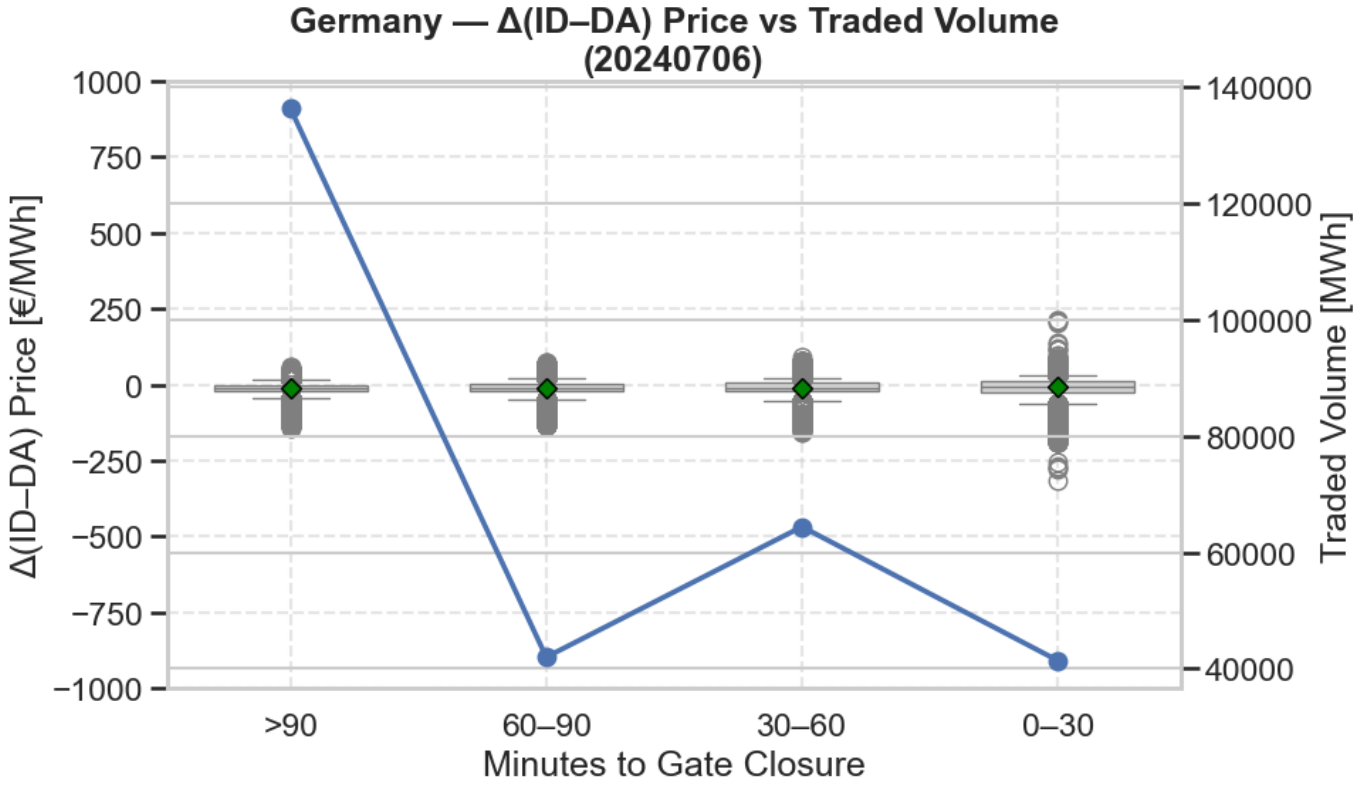


SAPB

Cross-Border Flow (BUY − SELL)



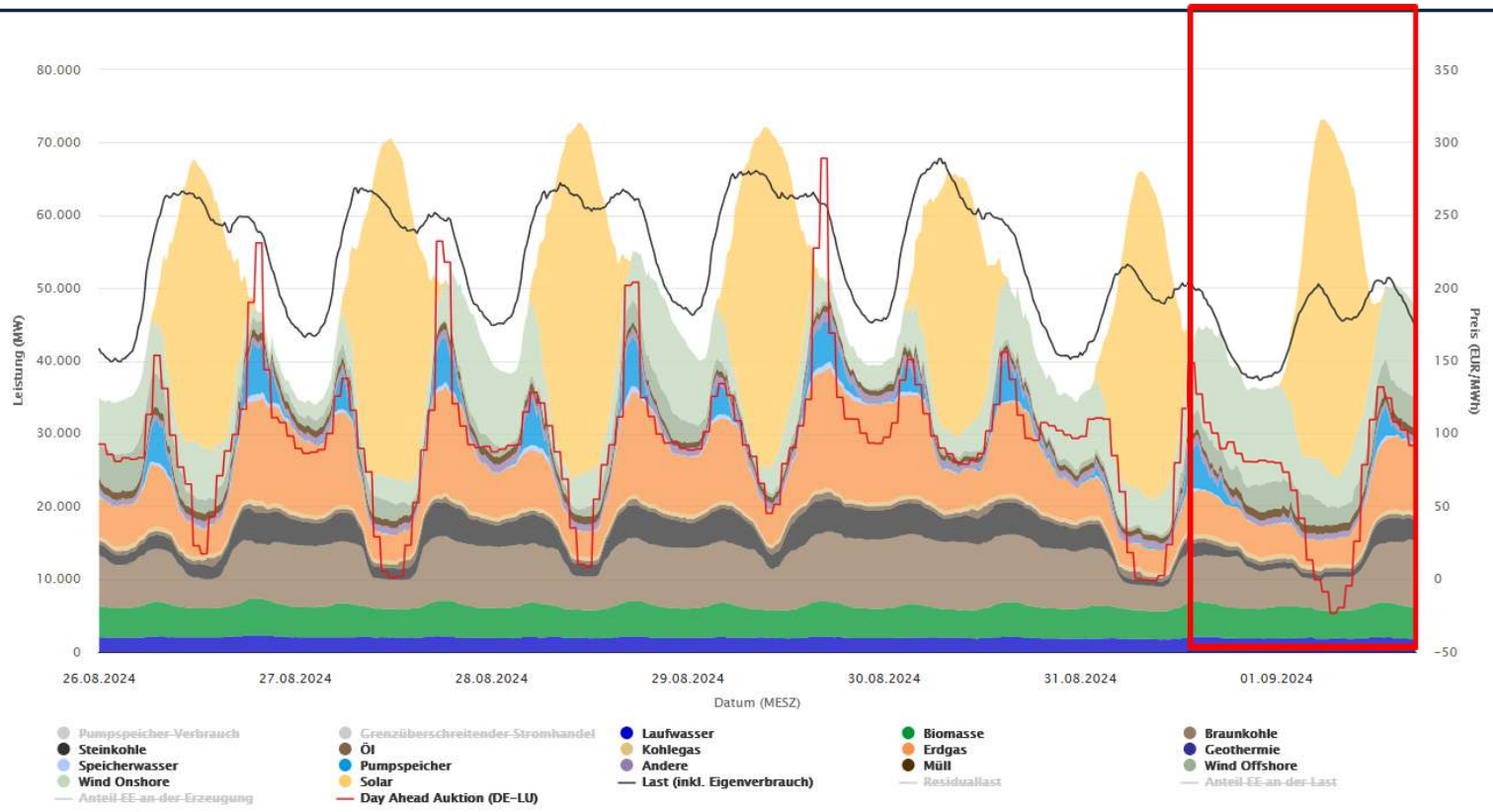
Analysis result: Deviation to Day Ahead prices



SAPB

1st Sep (Normal Day)

1st Sep (Normal Day)

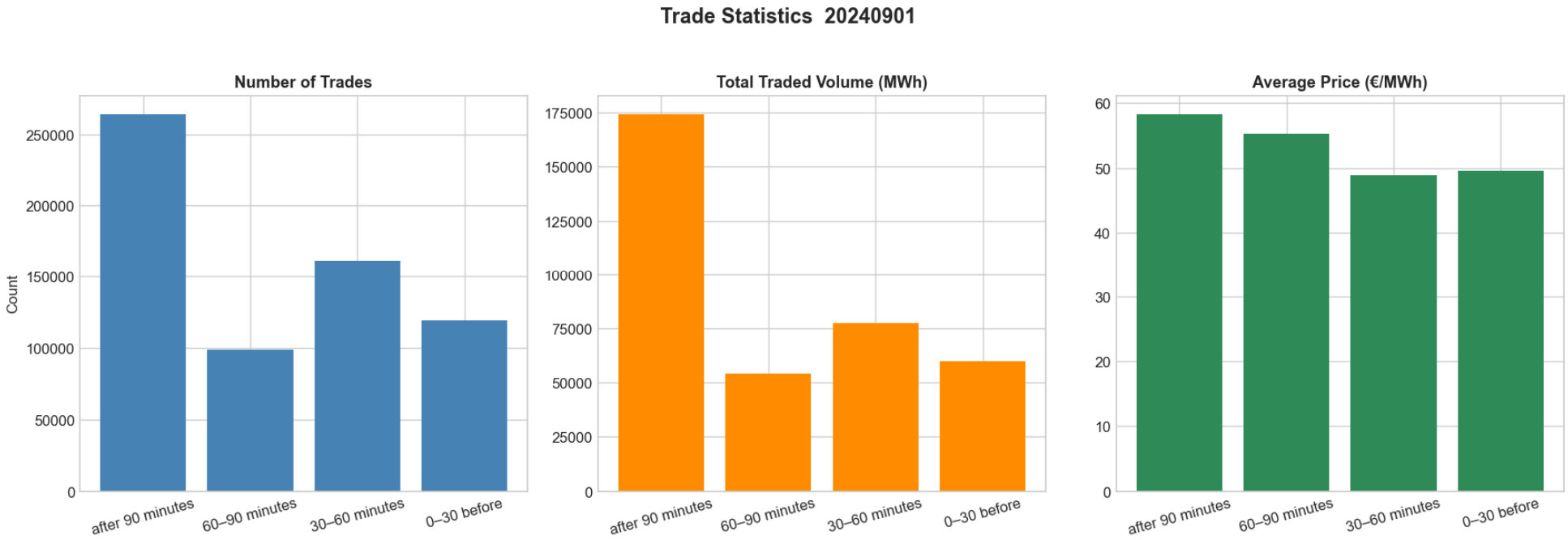


Brandenburg University of Technology Cottbus - Senftenberg

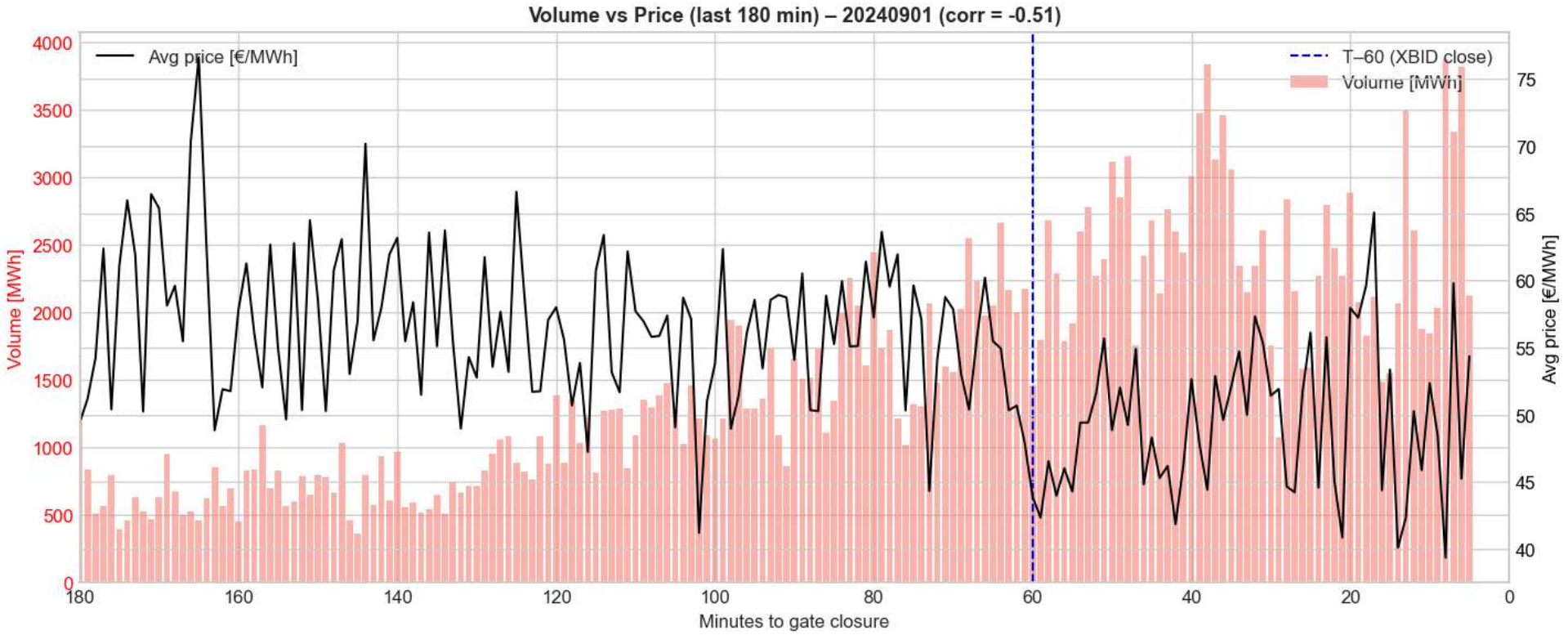
Steinbeis

https://www.energy-charts.info/

Trade Statistics



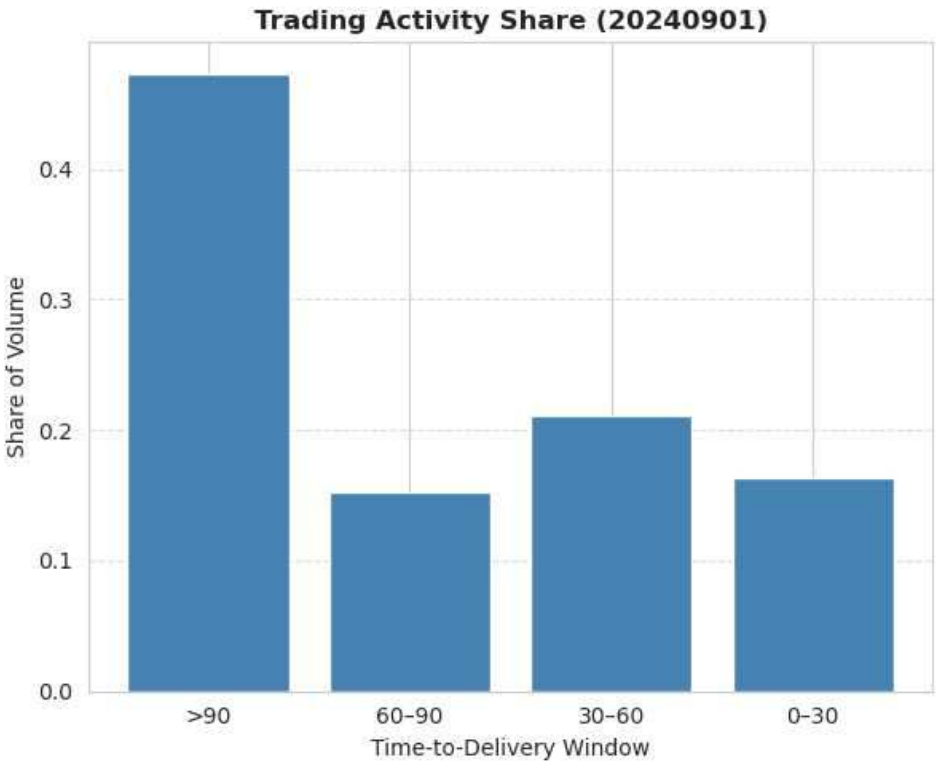
Trades increase before cross-border trade gate closure and in last 60 minutes –with volatile prices

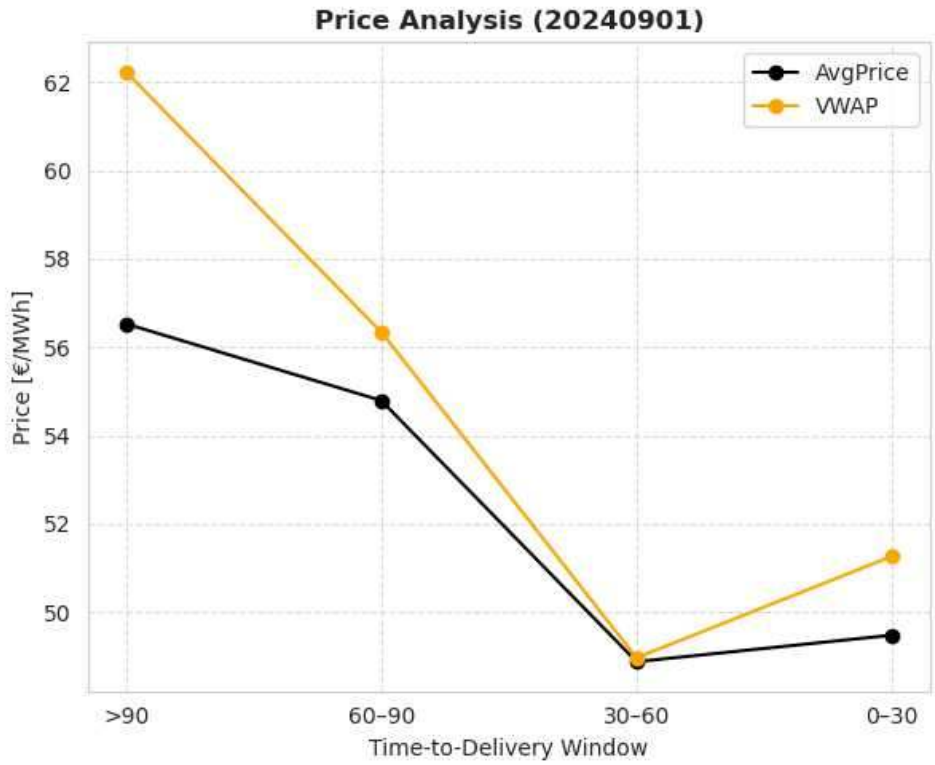


Brandenburg University of Technology Cottbus - Senftenberg

Steinbeis

Analysis results: volumes and prices

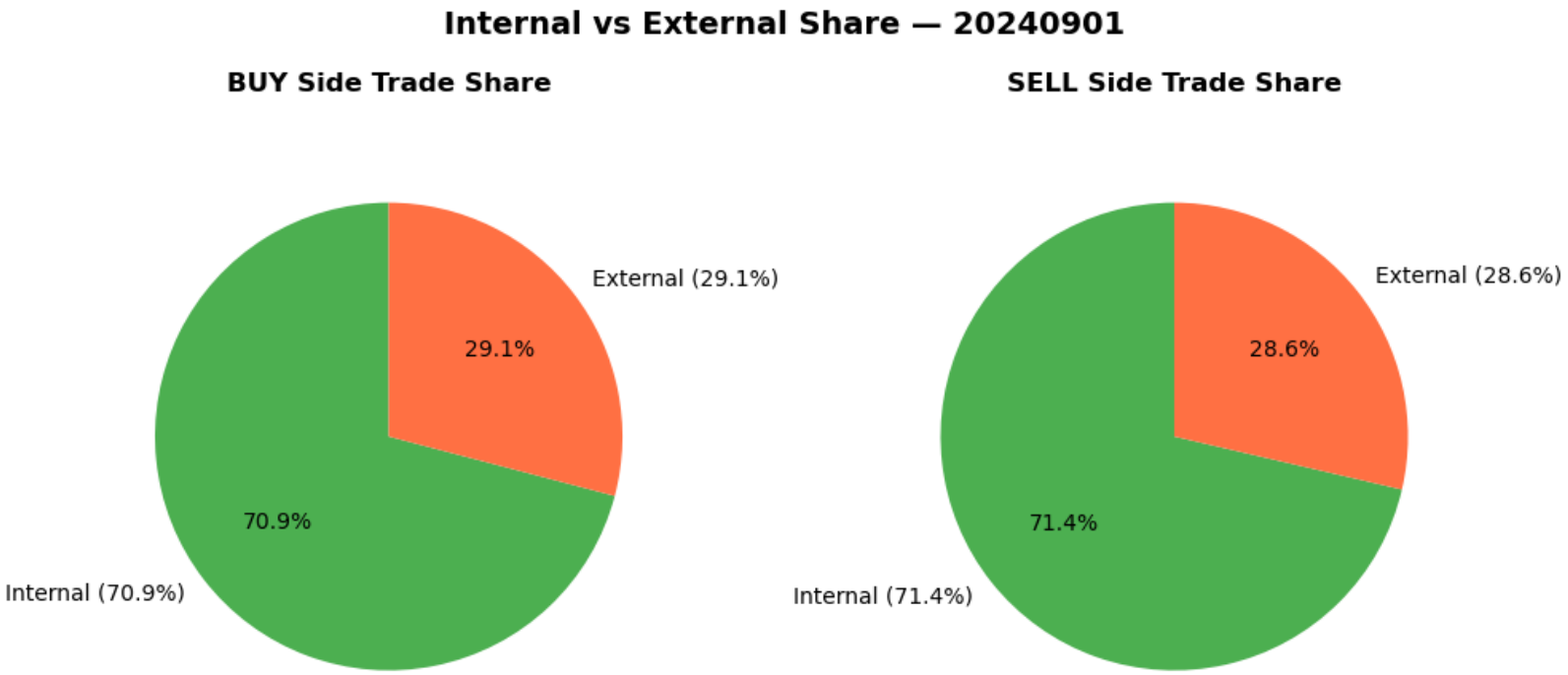




SAPB

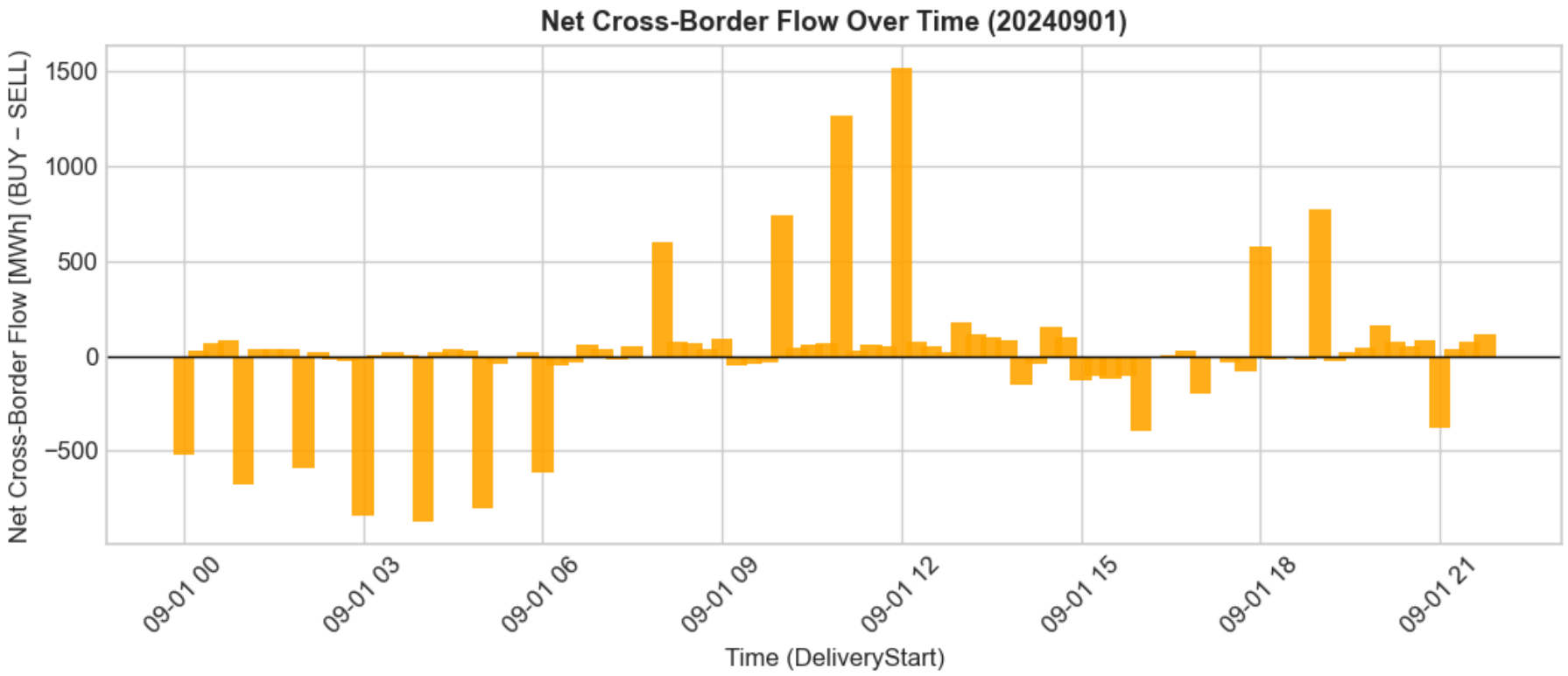
Price volatility (standard deviation) per time interval

Share of External Trade

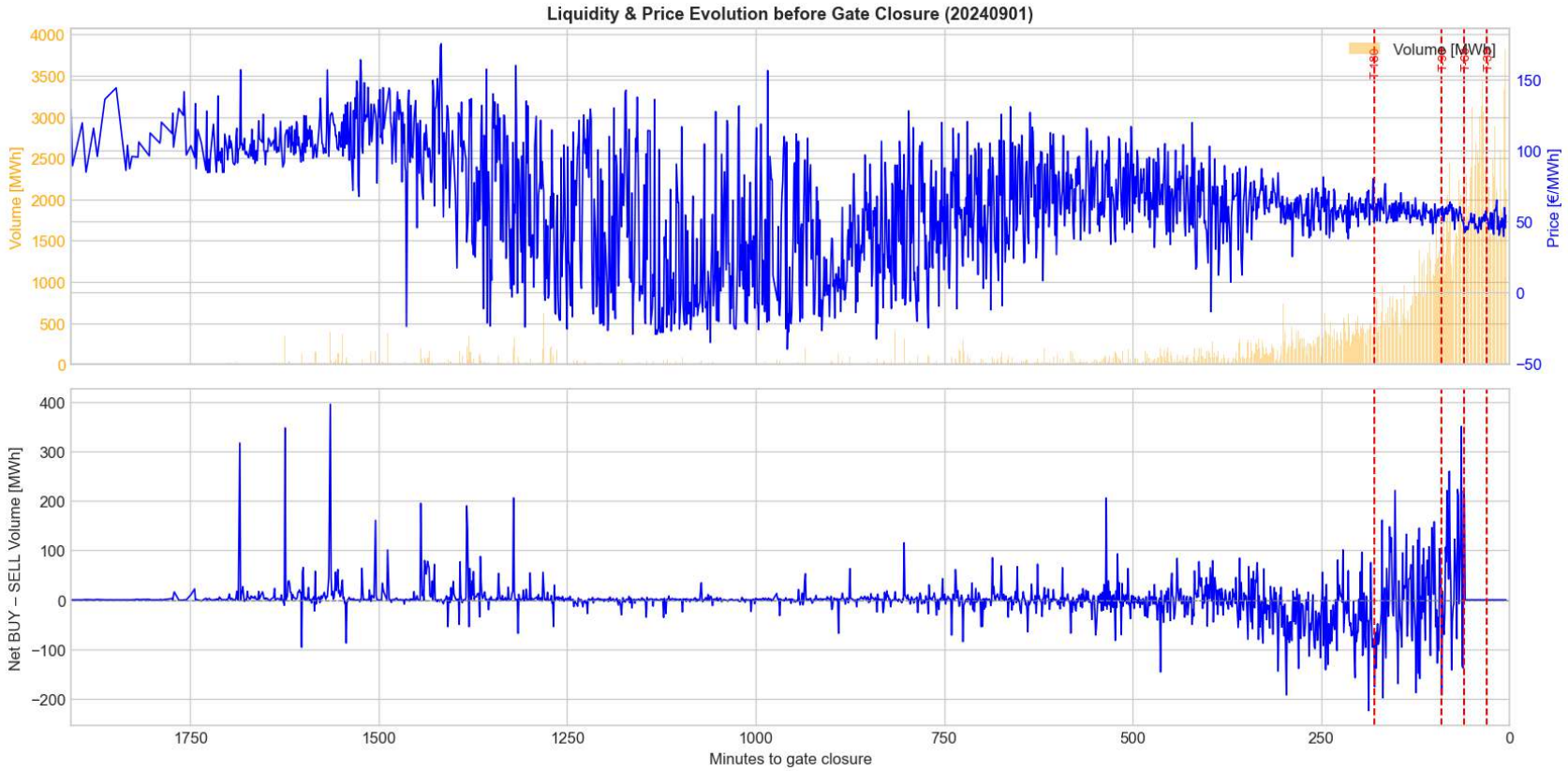


SAPB

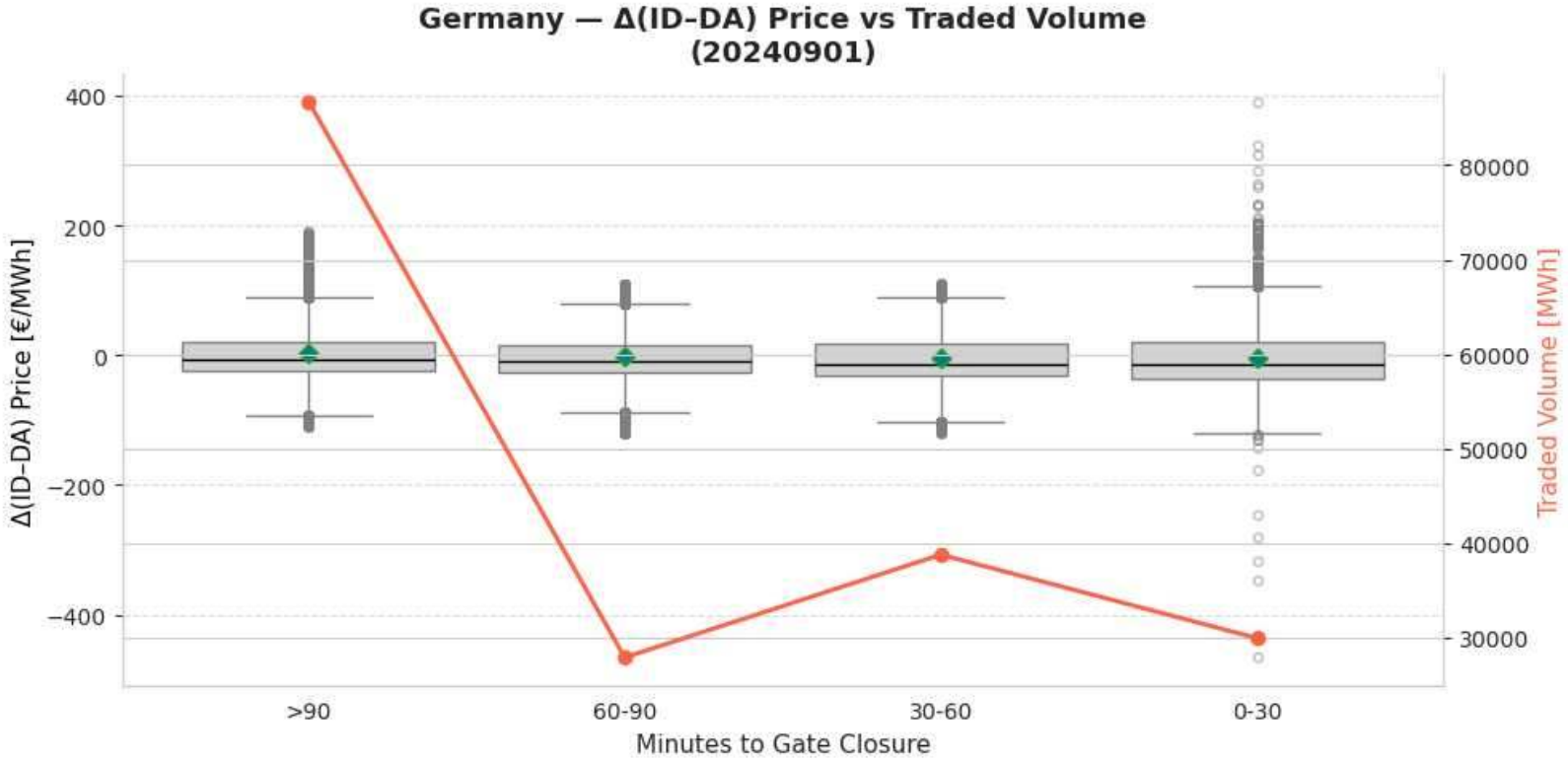
Cross-border Trade



Results: Cross-border vs. internal Trades



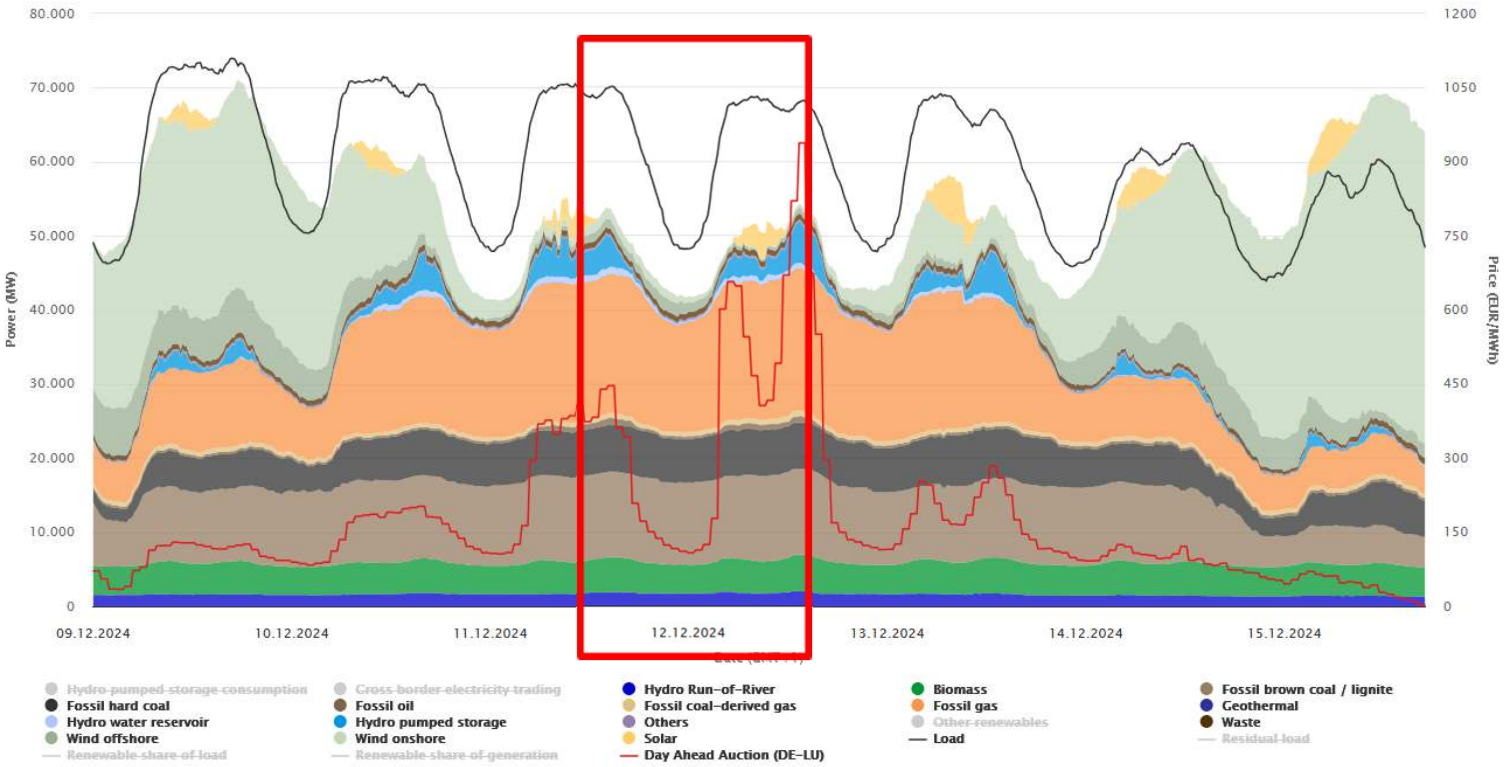
Analysis result: Deviation to Day Ahead prices



SAPB

Analysis 12th Dec (High Price)

12th Dec (High Price)

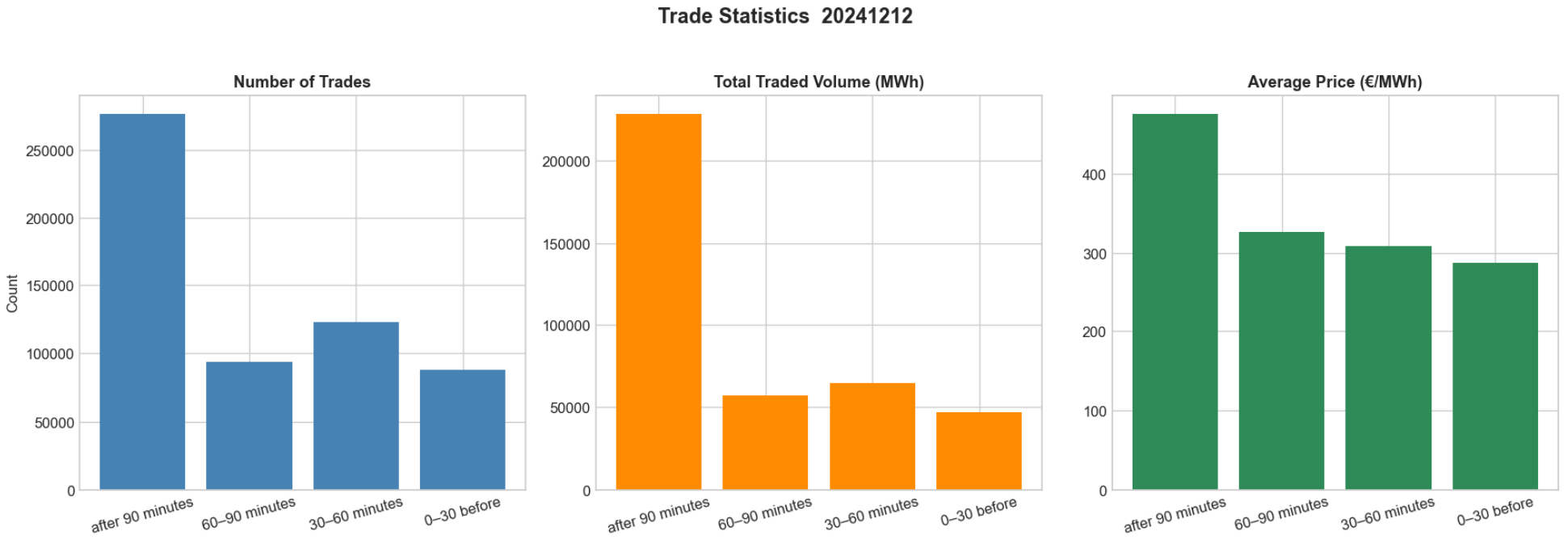


Brandenburg University of Technology Cottbus - Senftenberg

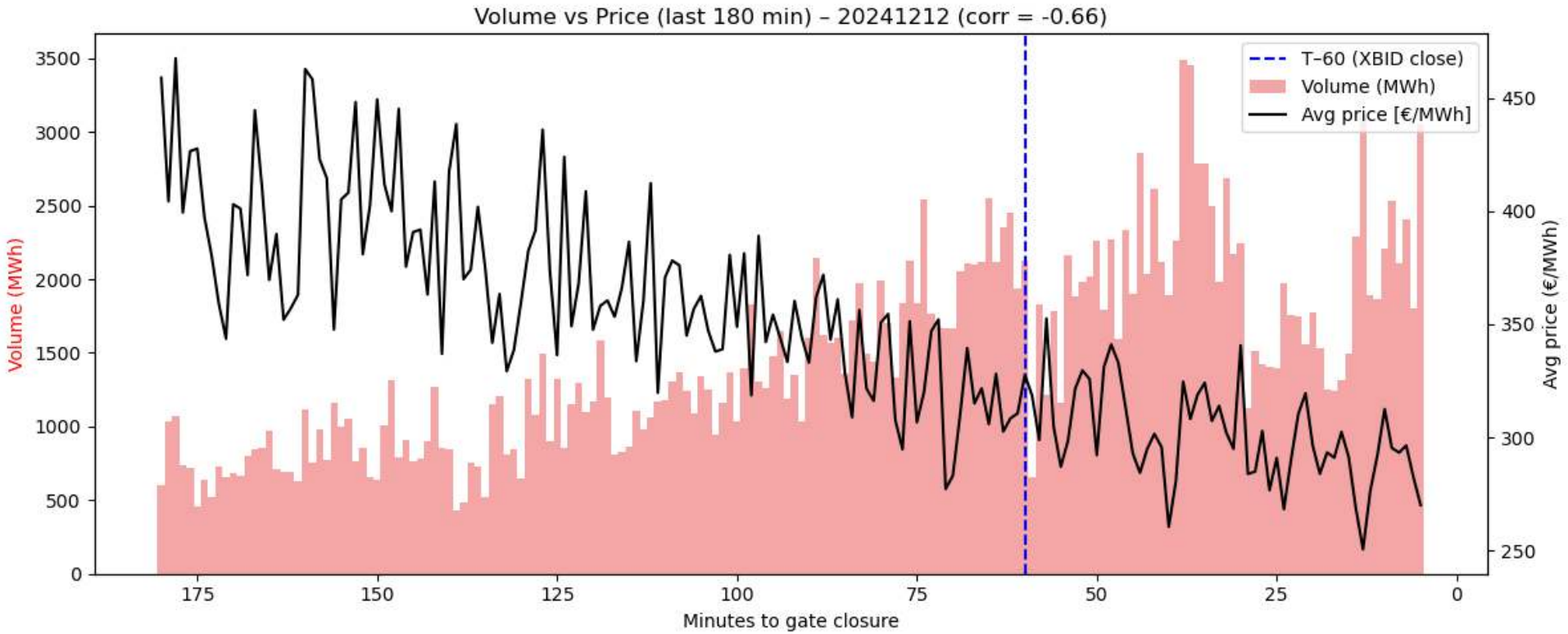
Steinbeis

https://www.energy-charts.info/

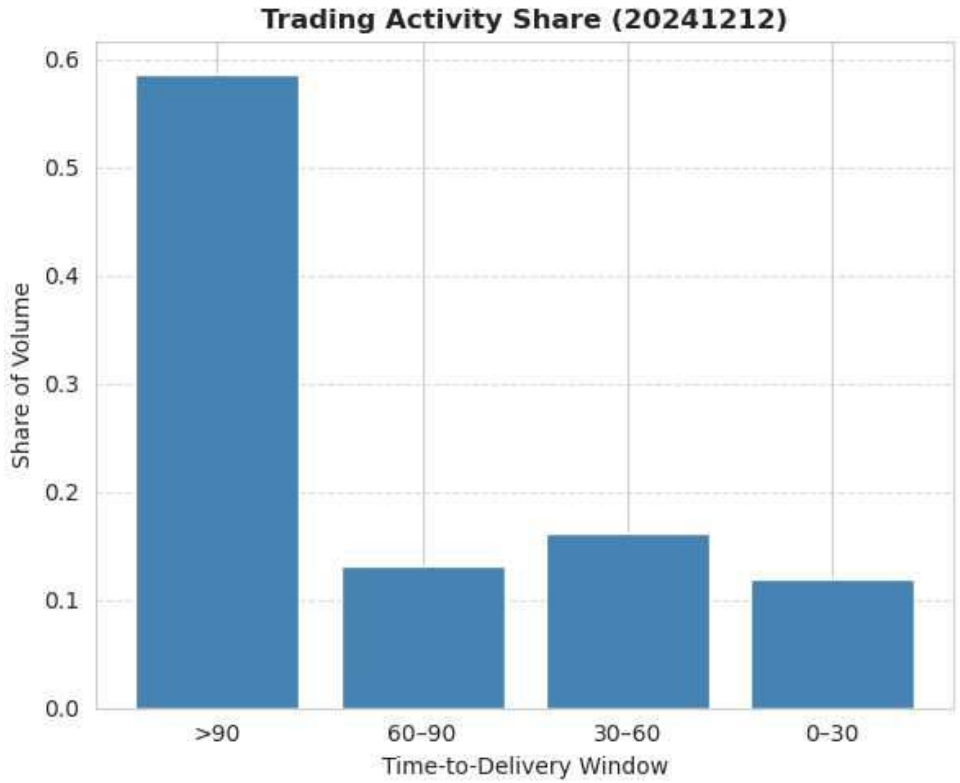
Trade Statistics



12th Dec (high Price)

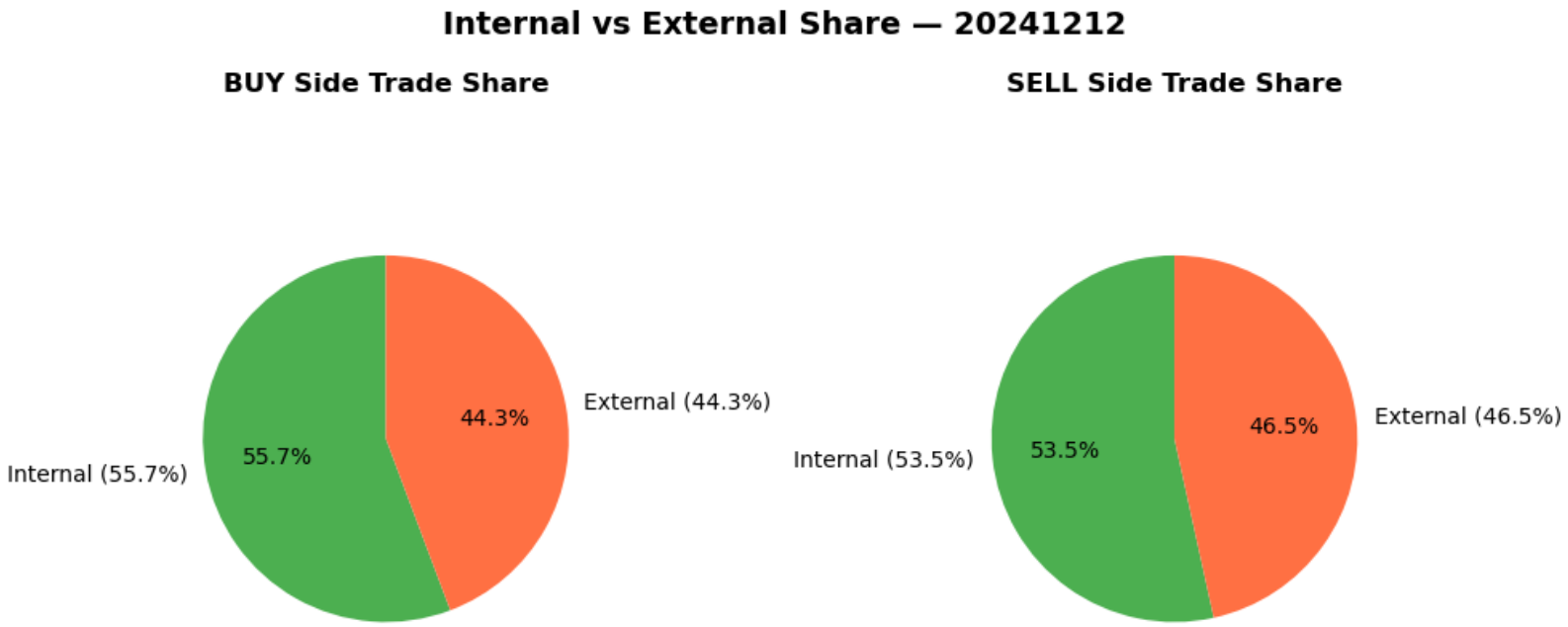


Analysis results: volumes and prices

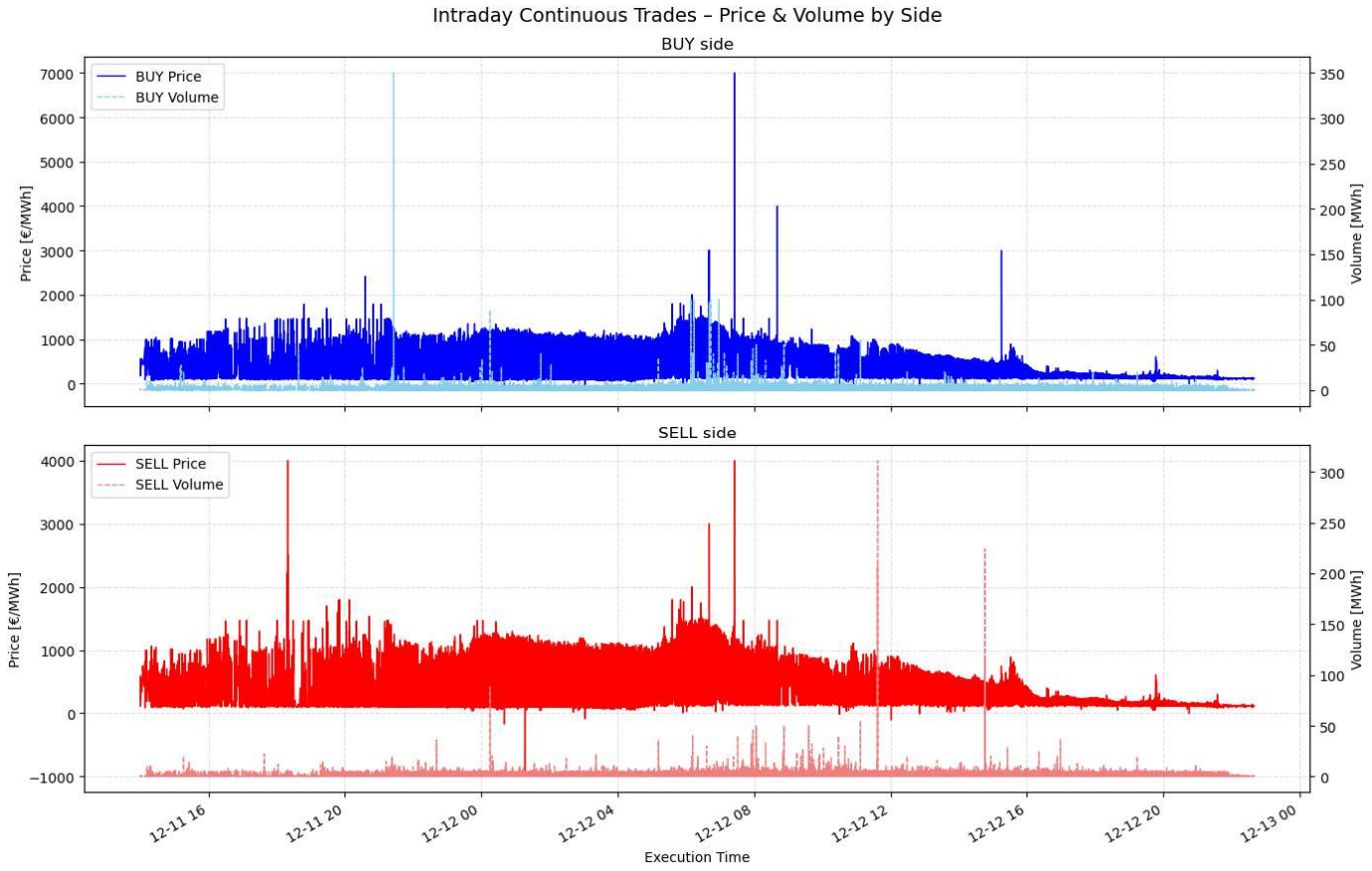


Price volatility (standard deviation) per time interval

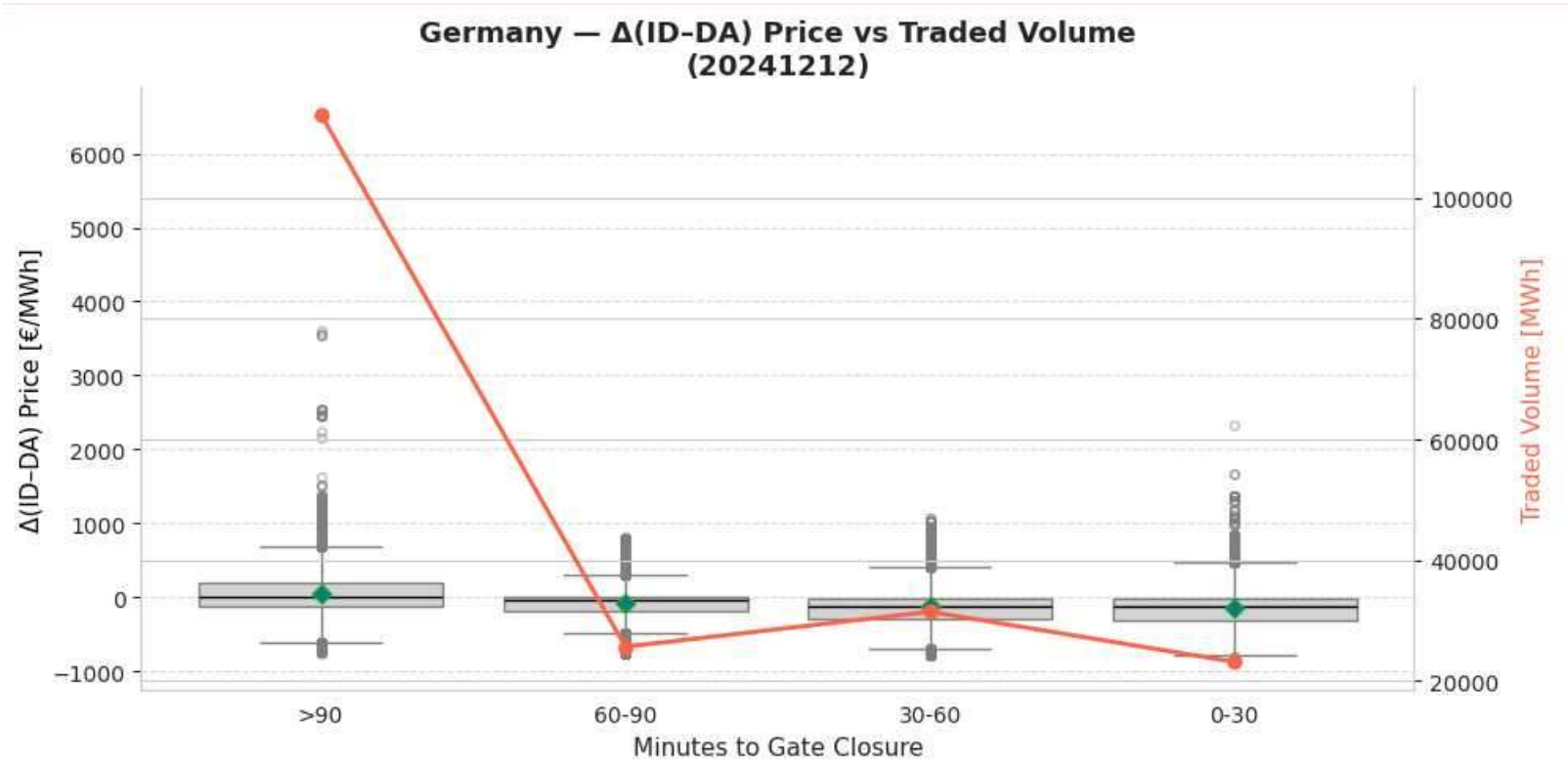
Share of External Trade



Analysis result: Deviation to Day Ahead prices

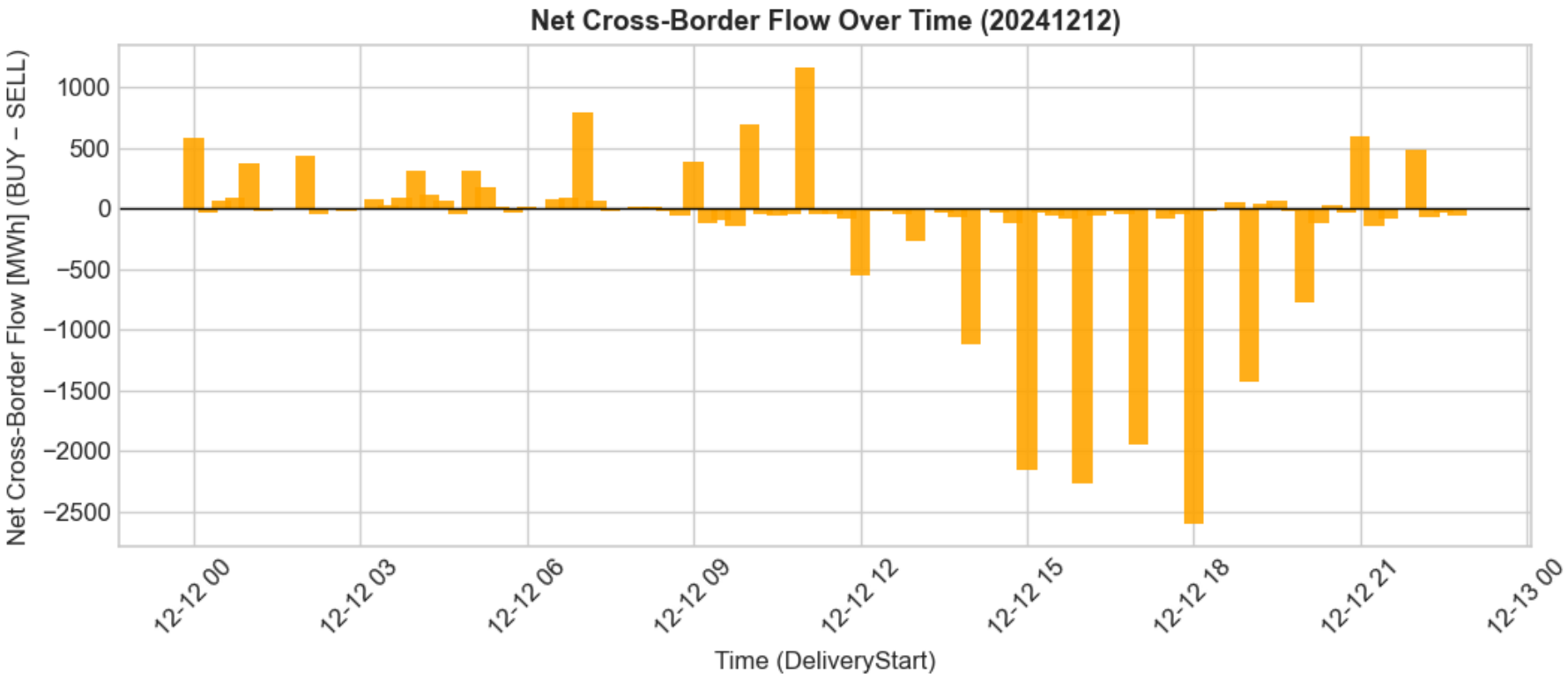


Analysis result: Deviation to Day Ahead prices

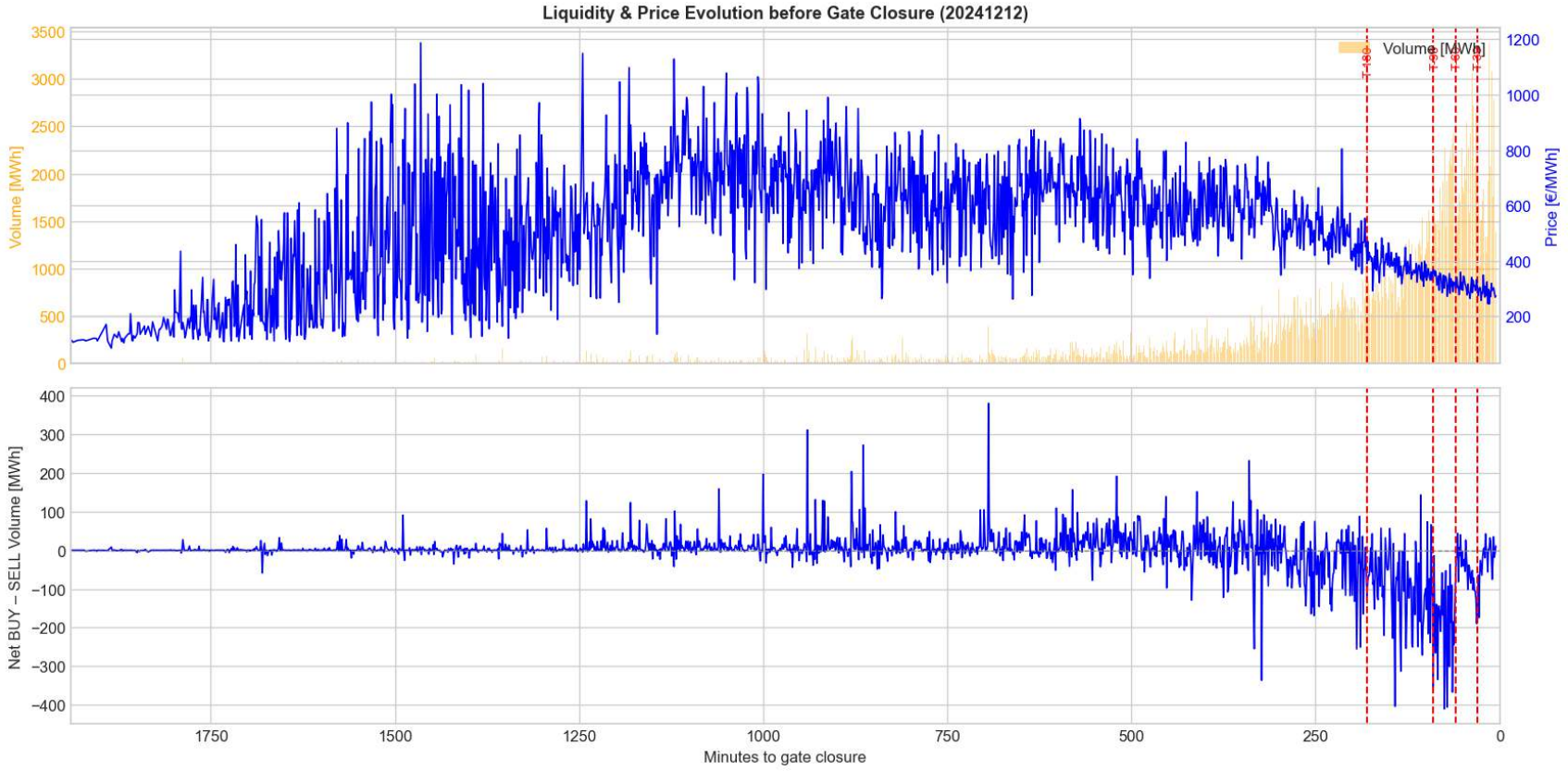


SAPB

Cross-Border Flow (BUY − SELL)



Results: Cross-border vs. internal Trades



Brandenburg University of Technology Cottbus - Senftenberg

Steinbeis

SAPB

Interpretation

- Extreme oversupply days → traders wait until the last moment, but concentrated volume pushes prices further down.
- Moderate oversupply (summer) → liquidity closer to gate closure stabilizes prices instead of worsening them.
- Scarcity (winter) → early hedging dominates, but late trades are still necessary and costly
- Balanced days → stable prices, spread trading, low sensitivity to volume