AP 5.5:
Evaluation and Efficiency of Flexibility Platforms

Contributors:

University of St.Gallen
Institute for Operations Research and Computational Finance

With the support from:

AUSTRIAN INSTITUTE OF TECHNOLOGY

APG

FICHTNER IT CONSULTING

KIT Karlsruher Institut für Technologie

THU Technische Hochschule Ulm

TRANSNET BW

Funding from:

Supported by: Federal Ministry for Economic Affairs and Climate Action on the basis of a decision by the German Bundestag

FFG Forschung wirkt.

Dieses Projekt wird aus Mitteln der FFG gefördert. www.ffg.at

powered by klima+ energie fonds

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Bundesamt für Energie BFE

Smart Energy Systems ERA-Net

This project has received funding in the framework of the joint programming initiative ERA-Net Smart Energy Systems' focus initiative Digital Transformation for the Energy Transition, with support from the European Union's Horizon 2020 research and innovation program under grant agreement No 883973.

Authors

Karl Frauendorfer, ior/cf-HSG

Gido Haarbrücker, ior/cf-HSG

Michael Schürle, ior/cf-HSG

Date: 11/07/2025

Acknowledgement: Claus Liebenberger's contributions to the software package for analyzing order books, the generation of HPFCs and the customized implementation for the valuation of energy contracts are recognized.

Abstract

The focus of this work is on the intraday market for the German market area and the balancing energy market for secondary reserve for estimating the value creation through trading with flexible capacities. A gas power plant, pre-qualified for providing positive and negative balancing energy, serves as a representative flexible capacity for an exemplary profitability calculation.

After the introduction, the *second section* characterizes the quality of intraday trading based on the indicators of liquidity and bid-ask spreads. The dynamics of intraday prices are modeled using a copula approach to cover the nonlinear dependencies between price and feed-in changes. In the *third section*, the impacts of the PICASSO platform for the international coordination and cross border activation of secondary reserve on intraday prices and the procurement of secondary and tertiary balancing energy are shown by comparing the year 2021 (before PICASSO) with the year 2023 (with PICASSO).

The *fourth section* documents the value development of flexible capacities depending on their performance. The revenue potential in the balancing energy market for the German market area is compared to the revenue potential of the four control zones within the SDAT phase of intraday trading. Based on an economic decision rule, the choice is made whether to offer the flexible capacity in the balancing energy market or to opt for intraday trading because a higher revenue is expected within the respective control zone. Additionally, the value of perfect information is determined under the idealized assumption that prices for balancing energy and intraday market in the respective control zones are already known *ex ante*. Potential system risks related to hedging strategies are also reflected. Finally, in the *fifth section* we summarize the insights gained.

Kurzfassung

Im Fokus dieser Arbeit stehen der Intraday-Markt für Marktgebiet Deutschland und der Regelarbeitsmarkt für Sekundärreserve zur Abschätzung der Wertschöpfung durch Handel mit flexiblen Kapazitäten. Für eine beispielhafte Wirtschaftlichkeitsrechnung dient ein Gaskraftwerk, das für die Erbringung von positiver und negativer Regelenergie präqualifiziert ist, als repräsentative flexible Kapazität.

Nach der Einleitung wird im *zweiten Abschnitt* die Qualität des Intraday-Handels anhand den Indikatoren Liquidität und Bid-Ask Spreads charakterisiert. Die Dynamik der Intraday Preise werden mittels eines Copula-Ansatzes modelliert, und um die nichtlinearen Abhängigkeiten zwischen Preis- und Einspeiseänderungen abzudecken. Im *dritten Abschnitt* werden die Auswirkungen der PICASSO-Plattform zum Austausch von Sekundärregelleistung auf die Intraday-Preise sowie dem Bedarf an sekundärer und tertiärer Regelenergie aufgezeigt, indem das Jahr 2021 (vor PICASSO) mit dem Jahr 2023 (mit PICASSO) verglichen wird. Der *vierte Abschnitt* dokumentiert die Wertentwicklung der flexiblen Kapazitäten in Abhängigkeit ihrer Leistung. Das Erlöspotenzial im Regelenergiemarkt für Marktgebiet Deutschland wird dem Erlöspotenzial der vier Regelzonen innerhalb der SDAT-Phase des Intraday-Handels gegenübergestellt. Auf Basis einer ökonomischen Entscheidungsregel wird die Wahl getroffen, ob die flexible Kapazität im Regelenergiemarkt angeboten wird, oder ob man sich für den Intraday-Handel entscheidet, weil im Intraday-Handel innerhalb der jeweiligen Regelzone ein höherer Erlös erwartet wird. Ergänzend wird der Wert der perfekten Information bestimmt unter der idealisierten Annahme, dass die Preise für den Regelenergie- und für den Intraday-Markt in den jeweiligen Regelzonen bereits *ex ante* bekannt sind. Weiter werden die potenziellen Systemrisiken reflektiert, die im Zusammenhang mit Absicherungsstrategien entstehen können. Abschliessend fassen wir die gewonnen Erkenntnisse im *fünften Abschnitt* zusammen.

Table of contents

List of abbreviations

aFRR	Automatic Frequency Restauration Reserve
AOF	Activation Optimization Function
BE	Balancing Energy
BEM	Balancing Energy Market
BoD	Board of Directors
BSP	Balancing Service Provider
CBMP	Cross-Border Marginal Price
CSA	Credit Support Annex
DigIPlat	Digital Solutions for Interoperability of Flexibility Platforms
ECC	European Commodity Clearing AG
EEX	European Energy Exchange
EU	European Union
FV	Fair Value
GC	Gate Closure
ID	Intraday
ID1	weighted average price of all continuous trades at the intraday market executed within the last trading hour of a contract
ID3	dto. for the trades executed within the last three trading hours of a contract
IDM	Intraday Market
ior/cf-HSG	Institute for Operations Research and Computational Finance, University of St. Gallen
LOB	Limit Order Book
mFRR	Manual Frequency Restauration Reserve
OTC	Over-the-Counter
PICASSO	Platform for the International Coordination of Automated Frequency Restoration and Stable System Operation
SDAT	Single Delivery Area Trading
SIDC	Single Intraday Coupling
TSO	Transmission System Operator

1 Introduction

1.1 Context and motivation

Decentralized, flexible capacities are increasingly becoming the backbone of supply security. Their digital networking requires data exchange and thus a redefinition of cooperation between transmission and distribution system operators. The establishment of electronic communication and trading platforms for cross-border spot trading, incorporating balancing services and capacity management, is a natural consequence of this and further increases the value-added potential in an integrated European electricity market.

To date, access to the markets for system services has been dominated by large electricity suppliers. With increasing decentralized feed-in and storage capacities at the distribution grid level, there is a growing need for stabilization mechanisms across all voltage levels and, as a result, for the integration of smaller suppliers and consumers. Decentralized, flexible generation and storage capacities, as well as conversion into other energy carriers such as hydrogen, synthetic gases, or thermal energy, require efficient and effective coordination. Accompanied by sector coupling, the energy system is becoming more decentralized and interconnected. Digitalization generates the necessary data and enables internal networking as well as external networking with the markets.

The allocation of decentralized flexibility is based on its opportunity costs and is carried out if these are lower than the marginal costs of market power plants. Cross-border trade in flexible capacities helps to cushion the volatility of stochastic feed-in in order to maintain stability, while also monetizing flexibility along a new value chain via price signals in the market.

Trade is supported by successful horizontal market integration in Europe over the last ten years, in particular through the phased implementation of market coupling, the integration of different market areas into continuous intraday trading, and international cooperation on the coordinated, cost-optimized dispatch of balancing reserves with the recent launch of the European balancing platform PICASSO. This promotes both technically effective and economically viable stabilization of the power grid to ensure security of supply.

Flexible capacities of different technologies represent options with complex execution structure. The complexity is characterized by technical restrictions concerning the operation of the flexible capacity as well as by physical restrictions in the power grid. In a perfect market without transaction costs and unlimited liquidity, the option value is defined by the price distribution and the execution structure. Due to the grid-bound nature of electricity as a commodity, electricity markets are imperfect and exhibit highly volatile transaction costs and varying liquidity, causing high-cost frictions in electricity trading. For the economic evaluation of a flexible capacity, the restrictions of the technologies, the physical restrictions in the power grid, frictions in the spot markets as well as the monitoring of profit and loss in corresponding trades must be considered. With respect to the latter, the performance of trading units must be adjusted for special influences (e.g., geopolitical tensions).

1.2 Overview of document

The remainder of this work consists of three core contributions. Chapter 2 characterizes the intraday market, the focus lies on the identification of key information (liquidity, frictions, price dynamics) which drive the economic value of flexible technologies. A methodology for analysing the price effects of PICASSO on the German intraday market is introduced in chapter 3. Chapter 4 deals with economic value of the flexible technologies through trading in the intraday market in combination with the auctioning of reserve energy markets. The main findings and an outlook for major challenges lying ahead are summarized in chapter 5.

2 The Quality of Intraday-Markets

The stochastic nature of electricity generation based on wind, photovoltaics, and water has a strong impact on the open volume and traded prices on the intraday market for electricity at a power exchange like EpexSpot. Transmission system operators (TSOs) take over the generation from renewable energies such as wind or photovoltaic that is not directly marketed. This requires that the TSO forecasts and trade this electricity on the day ahead as well as on the intraday market. The forecasted infeed is offered by the TSO on the day-ahead auction market. As the prognosis for day-ahead market closure is not perfect and subject to changes when new information becomes available, the prognoses for the final power production in each of the 96 quarter hours are frequently updated up to the actual time of delivery. Intraday trading covers all 15-minute contracts and hourly contracts up to the very next day plus block contracts comprising several hour contracts. The quality of forecasts typically improves with decreasing lead time and the transmission system operator, like any other market participant, can trade the ever-changing balance between the already marketed position and the expected production on the intraday market until the gate closure of the corresponding 15-minute delivery period. Remaining open positions have to be cleared at the balancing energy (BE) markets with normally considerable price surcharges or discounts for open short or long positions, respectively.

This leads to dynamic open positions that must be closed through efficient trades on the intraday market. Key risk factors (volumes, prices, forecasts, order book liquidity etc.) are to be identified, associated dynamics modelled with corresponding multivariate probability distributions reveal the volatile risk exposures for each product tradable on the respective intraday market. From the perspective of a trader, the goal is to minimize the residual energy for which the cost of BE will become effective under observation of the underlying risk management guidelines.

Within the framework of Single Intraday Coupling (SIDC), bids from 25 EU and Nordic countries are aggregated into a common limit order book (LOB). This cross-border trading ends for each product one hour before delivery (T – 60); thereafter, trading is only possible within the individual market areas. In Germany, this phase ends 30 minutes before delivery (T – 30); after that trades can only be executed within the individual control areas until GC in T – 5, formerly known as SDAT phase (Single Delivery Area Trading, see Frauendorfer et al., 2025).

In the next subsections, we introduce a metric for measuring liquidity and frictions based on an analysis of the intraday market for the German control areas. In addition, we explain an approach for modelling price and volume dynamics based on corresponding empirical data. The implemented analysis tools for measuring liquidity and frictions are also applicable to the common LOB in the SIDC phase.

2.1 Liquidity and Frictions

For ID trading, a cost-liquidity metric is derived that quantifies frictions in basis points (bps) for LOBs of an individual trading product. For selected trading periods in 2021 and 2022, empirical LOB analyses are applied for identifying frictions of trading products. The focus lies on the implementation of performance indicators, which help assess the quality of order books with dependence of the volatility in the market. This subsection intends to break down the information into two main components: measurement of liquidity and spread risks during continuous trading of 24 hour contracts and 96 quarter hour contracts for the day ahead.

2.1.1 Measurement of liquidity during continuous trading

With the increasing level of stochastic injections, the assessment of liquidity becomes more difficult. While *average relative spread (ARS)* and *best-bid-offer (BBO)* quantify the quoted prices, we have extended the analysis with more execution-relevant aspects. For the BBO, we added additional weighting schemes that would emphasize the minimum amount of volume available at the top of the book, which is of particular importance for the execution of large trades.

In the last years the ior/cf-HSG has designed and implemented analysis tools for the measurement of *persistency of liquidity and execution quality* based on the cooperation with the Swiss stock exchange (SIX) and with European power traders. We aim to determine how efficiently clients trade within the *exchange* with respect to timing and transaction costs as well as with respect to the provision of liquidity on the sell- and buy side.

Below we characterize the core information retrievable from our analysis tools. We base our characterization on analyses we have conducted for *full order books.*

The *multivariate cost-liquidity metric* is composed of *average relative spread* and relevant *liquidity measures* and allows for estimating trading costs across spot markets. The comparison of pairs of full order books reveals important information about competitiveness across different control areas or across exchanges (e.g., EpexSpot vs. Nordpool). In addition, it allows for the assessment of transaction timing within several exchanges and the ranking of trades, and their market participants conditioned on that timing quality. The latter requires at least an anonymous identification number.

The *average relative spread (ARS)* – measured in *basis points* (*bps)* – is defined on an event-driven basis by the difference of best bid and best ask on the top of the order book (i.e. quoted spread). Any event on the top of the order book for a specific instrument triggers a new evaluation of the *relative spread*, which is subsequently aggregated based on various averaging schemes. The persistence of the ARS is calculated based on the *duration (time-weighted averages)* throughout the trading day with paying attention to the volatility regime. This way, one may assess the quality of liquidity: supplying liquidity during time with slim demand is not as valuable as doing so during periods of volatile demand.

The value-based best-bid-offer (BBO) represents the minimum amount of liquidity supply in either direction (bid or ask). This aspect becomes particularly important when we have to check for one-sided pressure in markets or volatility in general. Due to its weighting, it is designed to emphasize the *BBO* with large available volumes on each side of the order book. For a power trader, the *value-based BBO-presence* is of importance as this accounts for market depth.

Value-based performance measuring helps to rank the performance of spot exchanges, intraday markets respectively, with respect to the *multivariate cost-liquidity metric*, and it will also reveal recommendations for improving the incentive structures for *liquidity providers*. The intraday variability of *average relative spread* is triggered by the volatility of the intraday prices and intraday liquidity, which primarily depend on the order placements of market participants with large flexible capacities. Those play the role of *liquidity providers.* Given the enhanced results, we see its application on an intraday-basis (rather than on a daily basis) for the assessment of *event-based trading patterns* of liquidity providers and their impacts to the intraday liquidity evolution within spot markets.

Summarizing, the above structure allows for more multi-faceted analysis of the competition in European power markets (e.g., EpexSpot vs. Nordpool) and provides better insights. This helps to identify the OTC trading platforms and liquidity providers which act as *price leader* for each product tradable

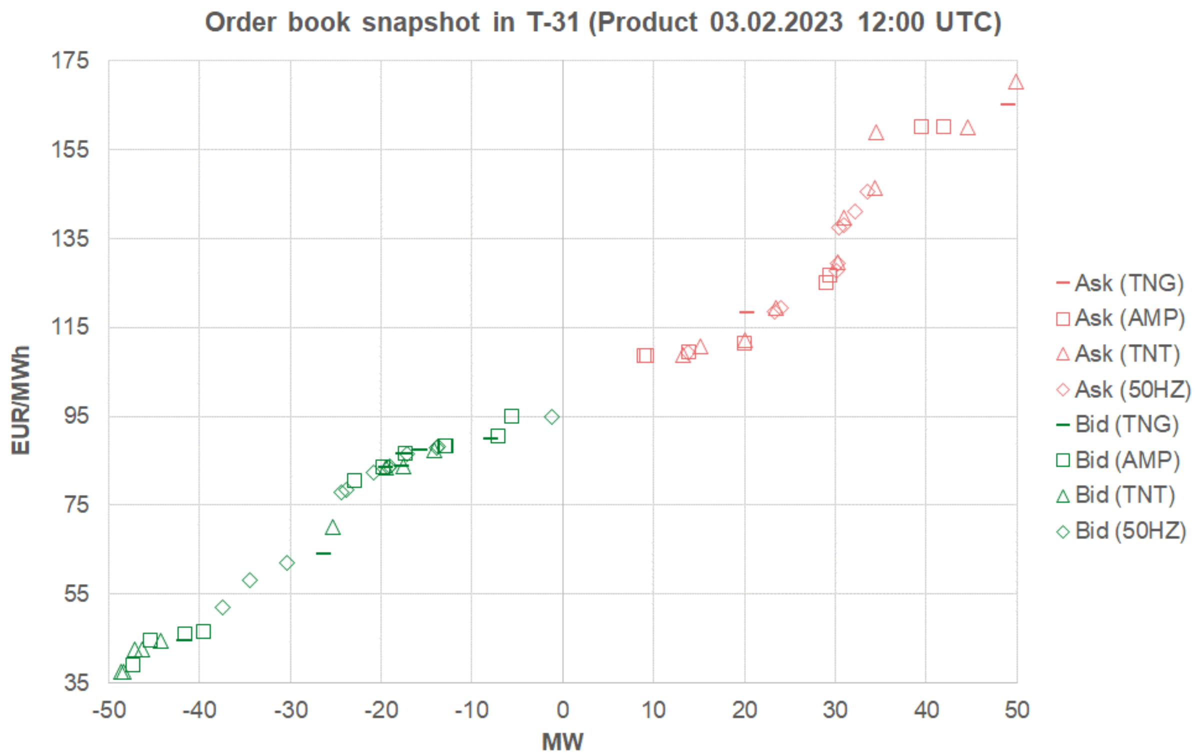


Figure 1: Extract from the orderbook for 15-min products with bids differentiated by control areas. Each green and red marker represents one bid, its type stands for the control area from which it originates. The values along the x-axis are the cumulative volumes. For clarity, the chart is limited to the range up to 50 MW.

in the intraday market. Finally, the *multivariate cost-liquidity metric* helps characterize the quality of intraday markets with respect to economically and statistically significant generation of added value.

2.1.2 Volume-structure of transaction premia in LOBs

As soon as the *buy market order volume* exceeds the *best ask volume* its transaction price will be *larger* than the *best ask price*. These *additional costs on the sell side* are evaluated volume dependent and define the *volume structure of transaction premia on the sell side* (see Figure 1). Analogously, as soon as the *sell market order volume* exceeds the *best bid volume*, its transaction price will be *lower* than the *best bid price*. These *additional costs on the buy side* are evaluated volume dependent and define the *volume structure of transaction premia on the buy side*.

The intraday dynamics of the two *volume structures of transaction premia* on the buy and sell side reveal the *imbalance in the full order book* for each individual intraday market. Given the methodology and the underlying software for evaluating *average relative spread* and the *volume structure of transaction premia*, one can characterize the market participants with respect to liquidity maker and taker.

2.1.3 Frictions and stressful trading days

In Table 4 to Table 8 (Appendix A), we have summarized the spread risks for the hour products as well as the quarter hour products across two of the four German control areas and the entire market area Germany over five minutes before the SDAT phase starts. We have determined the average spread and its standard deviation for the four six-hours blocks of a trading day and in dependence on the remaining time to gate closure. The tables reveal the friction sizes in the various control areas, which indicate the liquidity in their intraday markets.

Given that the standard deviation is a multiple of the average spread, we may think that the spread risks can be approximately modelled as Gamma distributions with shape and scale parameters. In this way, we can estimate the savings if the spread in the respective control area decreases by 1 EUR/MWh.

Furthermore, we may introduce "*stressful trades*" as trades, which make up a particularly large fraction of total daily volume, and "*stressful trading days*" as days with unusually high volatility. The corresponding analyses measure and rank the performance of liquidity providers for each instrument and trading day with respect to the following criteria:

- the level of activity without one-sided pressure in the order book,
- the liquidity provision without one-sided pressure in the order book,
- the dynamics of the spread size of each participant,
- the willingness of providing/demanding liquidity to permanent price changes,
- the willingness to absorb shocks,
- the tendency to create phantom liquidity,
- the behavioral difference between participants before/after large trades happen.

In addition to the analysis of *liquidity provision*, we may also bring in the associated dynamics of the LOBs of OTC-platforms.

2.2 Price dynamics

A common challenge for market participants involved in intraday electricity trading is to evaluate the efficiency of own intraday trades. An obvious step is for benchmarking the profit & loss of own intraday trades is a comparison with a preselected intraday price index. Volume-weighted average prices over a certain trade time window like, for example, the indices ID1[1] or ID3[2] published by the EpexSpot power exchange (EpexSpot, 2025) are suitable for application. For benchmarking, one has to take into account that the earnings potential in intraday trading depends on the share of flexible capacities within the generation portfolio to market in continuous intraday trading. The larger the share of flexible capacities, the lower the risk exposure and the larger the share of the risk-weighted earnings potential. We may conclude that an asset-backed trader with access to flexible capacities is in a much more comfortable position than, e.g., a TSO that is obliged to market renewable energy without access to flexible capacities. The latter has to manage the open positions depending on the risk exposure, which is exclusively defined by the stochastic, highly volatile injections. In contrast, an energy producer with flexible capacities has the opportunity to stack his offer and pick favorable intraday prices according to the inner value of the flexible capacity.

This results in a so-called flexibility premium which the community of the "inflexible" traders implicitly pays to the flexible, asset-backed traders who may benefit from volatile intraday price through application of delta hedging. Delta hedging is a very powerful approach for monetarizing volatility applicable to arbitrage-free markets with multivariate stochastic price dynamics (Björk, 2009). In case the market is frictionless and the stochastic price dynamics represent Black Scholes dynamics, delta hedging can be implemented based on analytical formulas (Hull, 2011). In case the market suffers from frictions and the stochastic price dynamics must be modelled in a more general setting than the Black Scholes dynamics, delta hedging is applicable through numerical approximations.

A meaningful benchmarking approach for an individual market participant without access to flexible capacities requires an adequate quantification of the flexibility premium. Unlike producers with a portfolio of flexible generation or pumping assets, a market participant without such physical flexibility cannot pursue a so-called asset-backed trading strategy. For example, a TSO who (i) has to market

[1] The ID1 index is the weighted average price of all continuous trades executed within the last trading hour of a contract. It catches the market's last minute imbalance needs, reflecting amongst other the increasing renewable breakthrough and system balancing flexibility.
[2] The ID3 index is the weighted average price of all continuous trades executed within the last 3 trading hours of a contract. This index focuses on the most liquid timeframe of a continuous contract trading session.

some renewable energies (with a stochastic energetic delivery) and (ii) is obliged to close its open positions until delivery lacks these additional actions: there is no option to adapt his physical production or consumption. The only way to act is to close the open position at the quoted intraday price shortly before delivery starts.

Flexible asset-backed traders have the advantage that they can "ride the intraday volatility" (Frauendorfer, 2023). Highly volatile phases are benevolent for an asset-backed trading strategy. The flip side of the coin is that these higher buy prices and lower sell prices have a direct impact on the risk exposure of inflexible market participants who close their open positions at unfavorable prices, implying a “flexibility premium” that they implicitly pay in favor of the flexible asset-backed dealers.

Therefore, a meaningful benchmark approach for an individual inflexible market participant has to take into account an adequate buy surcharge and sell discount towards the preselected price index (e.g., ID1 or ID3).

The ior/cf-HSG has developed a benchmark approach which meets various requirements: (a) measuring the efficiency of own trades over predefined trading periods; (b) in order to rely on "fair" benchmark prices that take into account the flexibility premium, the benchmarking procedure incorporates penalties that represent asymmetric buy surcharges and sell discounts; (c) the adjusted measures for efficiency allow for aggregation to assess the overall performance weekly or monthly basis across the trading products.

In our approach the penalties consist of three components, each contributing to a final buy and sell premium: (1) a spread-based component depicting the top-of-the-book liquidity; (2) a component relying on the volume structure of transaction costs and thus reflecting the bid/ask-side dependent order book depth and quality; (3) a volatility-based component representing the systematic variation of the mid prices or index prices. This way we approximate the flexibility premium for market participants without access to flexible capacities.

Risk assessment relies on distributional information for price and volume dynamics. Flexible consumers and producers of electricity may earn flexibility premiums on intraday markets with the equivalent of the delta hedge premium given the respective price dynamics.

It is therefore of invaluable importance to derive stochastic multivariate models that capture the inherent stochastic nature of regularly updated generation forecasts and volatile dynamics of intraday market prices. We have developed an approach for the modeling of short-term variations of electricity intraday prices and of renewable energy generation forecasts (see Figure 2) using copula and marginal distributions. It is implemented in the form of Python-based routines that perform a primary analysis, based on which marginal distributions and the connecting copula are estimated. The associated multivariate probability distributions characterize the joint price and forecast variations over corresponding time horizons.

The previously mentioned stochastic, multivariate dynamics characterize the continuous trading phase of the intraday market. These dynamics hold for market participants with access to flexible capacities as well as for market participants without access to flexible capacities. The market participants without access to flexible capacities implicitly pay a flexibility premium to those market participants with access to flexible capacities. The size of the flexibility premium determines the target performance across all market participants, based on which out- or underperformance of an individual market participant can be assessed.

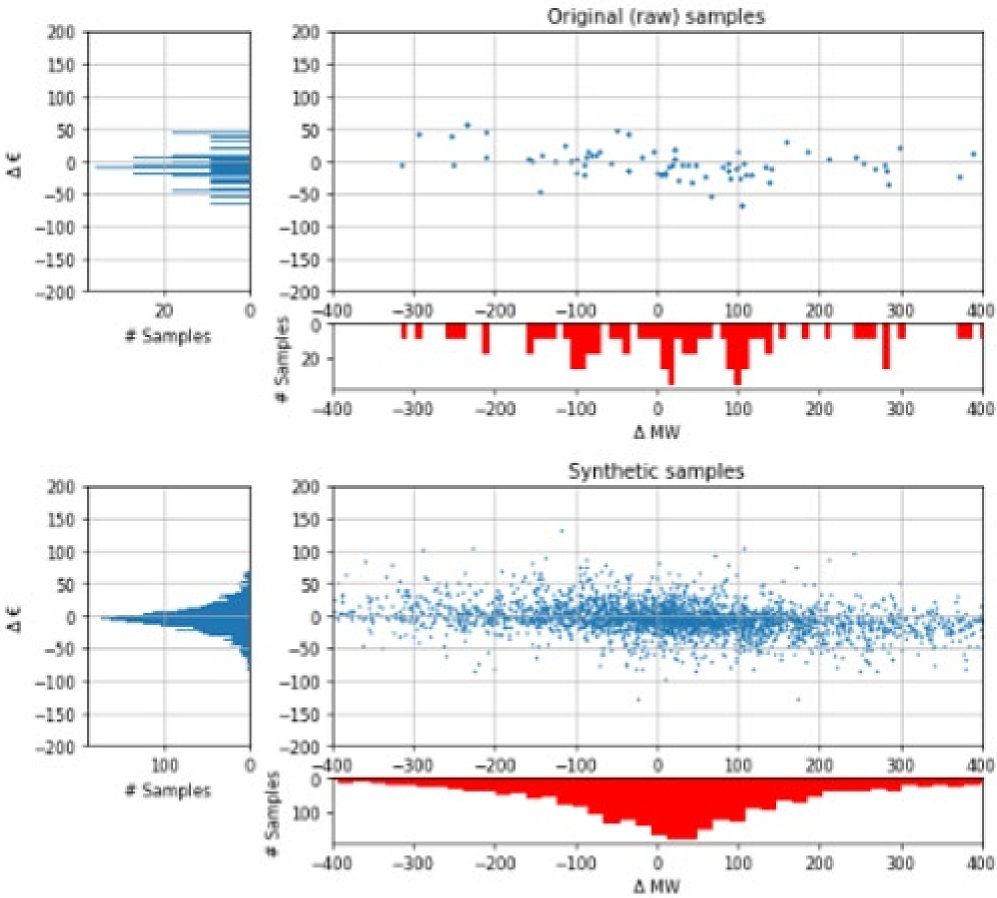


Figure 2: Marginal distributions & Copula – Observed sample and synthetic sample based on estimated distribution of joint price and forecast changes with respect to feed-in. Example for changes from 60 min to 30 min before delivery for hourly contracts on weekday afternoons.

3 Price effects of PICASSO on the German Intraday Market

3.1 Fundamental drivers of the intraday market price

According to a study by Hirth & Mühlenpfordt (2021), the activation of balancing capacity, i.e., automatic and manual frequency restauration reserve (aFRR and mFRR), is followed by significant price movements on the intraday market, especially for products with short remaining time to gate closure. The activation of positive (negative) reserve energy increases (decreases) prices, and this effect is larger for 15-min than for 60-min products and more pronounced when a large volume is activated since this implies a significant imbalance of the power system. In fact, the activation of aFRR turned out to be the variable with the highest impact among several other fundamental factors although the corresponding volumes are only published on the following day with one second time resolution. A few minutes after the end of each 15 min time slice the TSOs publish information only on the totally activated volume during that period on their jointly operated platform "netztransparenz.de". The price reaction following this delayed publication is much smaller. The observation that the price reacts most strongly in the moment of the activation suggests that certain participants in the intraday market have an information advantage.

In the sequel, we will discuss how certain market participants gain an information advantage and show that the influence of this proprietary information has decreased significantly following the introduction of the PICASSO platform. To this end, we have implemented our own estimation model similar to the one in the above-mentioned paper and calculated estimates separately for data from 2021 and 2023. While Hirth & Mühlenpfordt (2021) use as dependent variable the (absolute) intraday price, we explain the difference between the price observed in the continuous trading phase and the auction price of the same product. Our explanatory variables are chosen from the following list:

- aFRR activation: Second-based values from "netztransparenz.de", aggregated to 1-min steps by averaging.
- mFRR activation: We use here the sum of the reported values from all four control areas that are published immediately after the end of each 15-min time slice. However, we assume that the activation signal was already transmitted 12.5 minutes before the beginning of the respective delivery period, so that the information was at this time known to the recipient. Note that activated mFRR must be provided over the whole 15-min interval.
- Last published aFRR activation aggregated over the previous 15-min time slice (average value), summed up over all four control areas. This information becomes available 9 minutes after the end of the interval.
- Last published mFRR activation aggregated over the previous 15-min time slice (average value), summed up over all four control areas. This information becomes immediately available after the end of the period.
- Control area balance as (netted) sum of all four control areas: This information is published on netztransparenz.de 15 minutes after the end of each 15-min delivery period. The control area balance corresponds to the sum of all balancing group deviations within a control area. Typically, they arise from differences between forecast and actual generation and consumption. A positive (negative) value represents a deficit (surplus) of electricity that requires the use of reserve energy (50Hertz et al., 2023).
- Symmetric imbalance price: A preliminary value is available on the ENTSO-E Transparency Platform with 15 minutes delay.

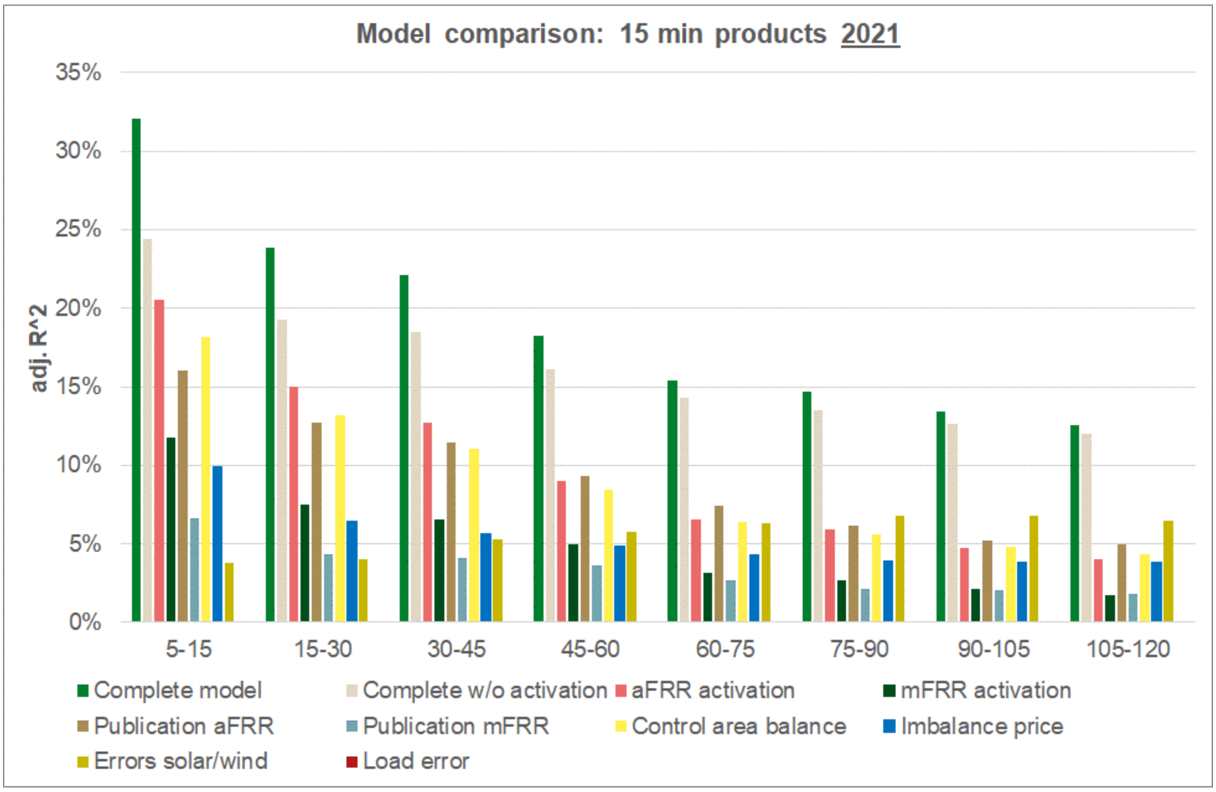


Figure 3: Comparison of different versions of the regression model for the deviation of prices for 15-minute products during the continuous intraday trading from the auction price using data for the year 2021 (before launch of PICASSO). Data were grouped into different classes according to time to delivery, (shown along the x-axis) for which individual models were estimated. The bars represent the corresponding adjusted coefficients of determination. The first model uses all variables described in the text, the second model omits the variables for the activation of aFRR and mFRR. The remaining models are simple linear regression models with only one explanatory variable.

- Forecast error of renewable generation: Difference between observed generation from PV, on- and offshore wind for Germany and the corresponding forecast at 18:00 on D – 1 (day-ahead). The effective generation values are published on the ENTSO-E Transparency Platform with 60 minutes delay. We distinguish between positive and negative deviations since the price reaction may be asymmetric.
- Load forecast error: Difference between the observed value for Germany and the corresponding forecast at 18:00 on D – 1 (day-ahead). The effective load is published on the ENTSO-E Transparency Platform with 45 minutes delay.

Note that all the aforementioned data are publicly available. The intraday market prices for the dependent variable were aggregated to 1-min time steps by calculating the volume-weighted average price using transaction data of 15-min products during the continuous trading phase from EpexSpot. The observations were then assigned to different bins depending on their remaining time to gate closure: 0 – 15 minutes, 15 – 30 minutes etc., and the model is estimated with one minute time resolution for each group individually, leading to different coefficients for each estimation. In this way, it is taken into account that the price impact of changes in the explanatory variables is stronger for products with imminent delivery. To assess the relevance of the various drivers for the intraday price, several model versions were estimated for different sets of explanatory variables from the list above.

We focus first on the results for 2021, the year before the launch of the PICASSO platform. The columns in Figure 3 show the adjusted coefficients of determination, each group represents data with a different time to delivery, which is shown along the x-axis. In each group, the left-most column represents the adjusted coefficient of determination for the full model, including all listed variables. The second column from the left refers to the full model without the aFRR and mFRR activations, i.e., those data that are not publicly known at the time of the signal. Without this proprietary information, the explanatory power of the model deteriorates significantly. The other columns represent the goodness of fit of simple regression models, using only a single explanatory variable from the list (exception: forecast errors for the renewable generation from solar and wind were combined in one estimation).

It is noticeable the activation of aFRR alone explained over 20% of the price variability (third column), almost as much as the model with all other variables. Also, the last published control area balance has a significant explanatory power, higher than the publication of aggregated aFRR activations after the end of the corresponding time slice. Looking at the estimated coefficients in Figure 22 (upper panel) in Appendix C on page 46, large activations of positive aFRR energy (POS > 1'500 MW) have the highest coefficient. A value of 0.27 implies an increase of the intraday price of approximately 400 EUR/MWh following an activation of 1.5 GW positive aFRR for the product with less than 15 minutes time to delivery. The coefficient for the activation of positive mFRR energy is similarly high (POS mFRR). Note that mFRR is only activated when the available aFRR is already largely used. Together with large aFRR activations, this is an indicator of a larger system imbalance. Minor activations of positive aFRR have a comparably smaller price impact. Positive frequency restauration reserve is required when there is an energy deficit in the power system, which requires an increase in the generation, possibly by ramping up additional plants. On the other hand, negative frequency restauration reserve is activated when there is a surplus, which can be handled much easier, e.g., by curtailing renewable generation. Therefore, it is not surprising that the coefficients for the activation of negative aFRR of any size and mFRR are of much smaller magnitude. In general, both the explanatory power and the coefficients for the individual explanatory variables are the highest for the front product and decrease with longer lead times to beginning of the delivery period. As Figure 23 in Appendix C (page 47, upper panel) shows, the price reaction following the publication of aggregated activations is insignificant except for positive mFRR, which is available immediately after the end of each 15-min interval. Apparently, the information about a system imbalance requiring the use of aFRR had already been processed by relevant market participants. Only the indication of a greater shortage resulting from the use of positive mFRR has still an impact on the price after it became generally known (the coefficients for negative mFRR are statistically not significant).

For a comparison of the magnitude of the price reaction following frequency restauration activations, Figure 24 (Appendix C, page 48) shows in the upper panel the coefficients for other variables that relate to deviations between forecasted and actual generation and consumption. As the control area balance has the highest coefficients for the front products, it was also the variable with the highest explanatory power after aFRR activations in the simple regression estimations. The increase of the coefficient for the imbalance price with longer lead times to delivery in 2021 appears not plausible. It could be caused by several modifications in the underlying calculation and publication times[3]. The coefficients for PV and wind generation forecast errors are relatively small and of similar magnitude for all remaining trading times, which could result from the relatively long delay between end of the respective 15-min interval and their publication, i.e., the information is already "outdated" when published. The slightly larger coefficients (in absolute values) for negative deviations (lower actual generation when forecasted) are consistent with findings in the literature. The impact of the load forecast error was insignificant in 2021.

3.2 Impact of non-publicly available information

These results are largely consistent with the observations in Hirth & Mühlenpfordt (2021), which we extend now by a discussion of the cause-effect relationship for the high explanatory power of frequency restauration reserve activations and the large sensitivity of the intraday price on these factors.

[3] See https://www.netztransparenz.de/de-de/Regelenergie/Ausgleichsenergiepreis.

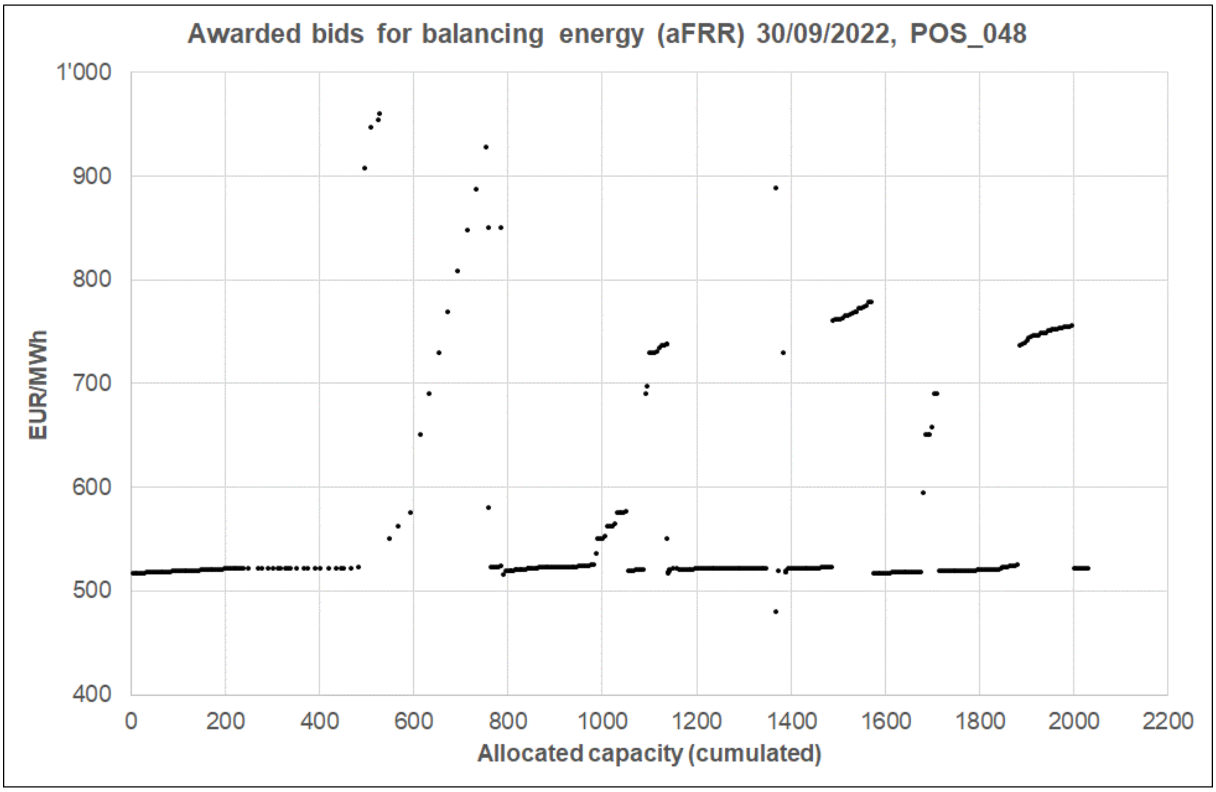


Figure 4: Visualization of the awarded bids for an arbitrary product as published on "regelleistung.net".

As already emphasized, the information on an activation is not publicly available when it occurs, and in this moment only known to the TSO sending the signal and to the activated provider. However, although the prequalified capacity for the provision of frequency restauration reserve is quite large in Germany[4], the volume of submitted bids for aFRR balancing capacity is typically just 2 – 2.5 times of the tendered volumes of ca. 2’000 MW, depending on the product (direction and delivery period). For mFRR, amounts of 2’000 – 3’000 MW are offered, but the tendered volume is only 300 – 600 MW. Bidders who have been awarded the capacity auction are also obliged to submit bids for BE. In addition, voluntary (“free”) bids can be submitted by any prequalified market participant. The volume of these bids amounts to approx. 10% (17%) of the awarded positive (negative) balancing capacity for aFRR.

In fact, despite the large available capacity the markets for balancing capacity and energy are rather concentrated. According to the Federal Cartel Authority, over 80% of the reserved positive aFRR balancing capacity is allocated to only five providers (EnBW, Illwerke, RWE, Vattenfall, Uniper). In contrast, for negative balancing capacity the concentration is significantly lower since this can relatively easily also be provided by smaller power generators including wind by curtailing. On average, 60-65% are offered by the five largest providers (EnBW, Illwerke, RWE, Energy2Market, Vattenfall), which includes one aggregator of small capacities (Bundeskartellamt, 2024). Looking only at the free bids, over 60% (40%) come just from one provider (Illwerke).

It can be assumed that large electricity producers are active in both the intraday and the balancing energy market (BEM). This implies that most signals of frequency restauration reserve activation go only to a few players. In this context, the visualization of the published list of accepted bids for BE from regelleistung.net for an arbitrary delivery period in Figure 4 shows an interesting structure. Bids are not sorted in ascending order by offered price but exhibit a "block structure" with lines of low gradient

[4] In February 2024: 22.54 GW pos. aFRR, 23.69 GW neg. aFRR, 26.01 GW pos. mFRR, 26.24 neg. mFRR (see https://www.regelleistung.net/xspproxy/api/staticfiles/regelleistung/startseite/pq-leistung-in%20deutschland.pdf)

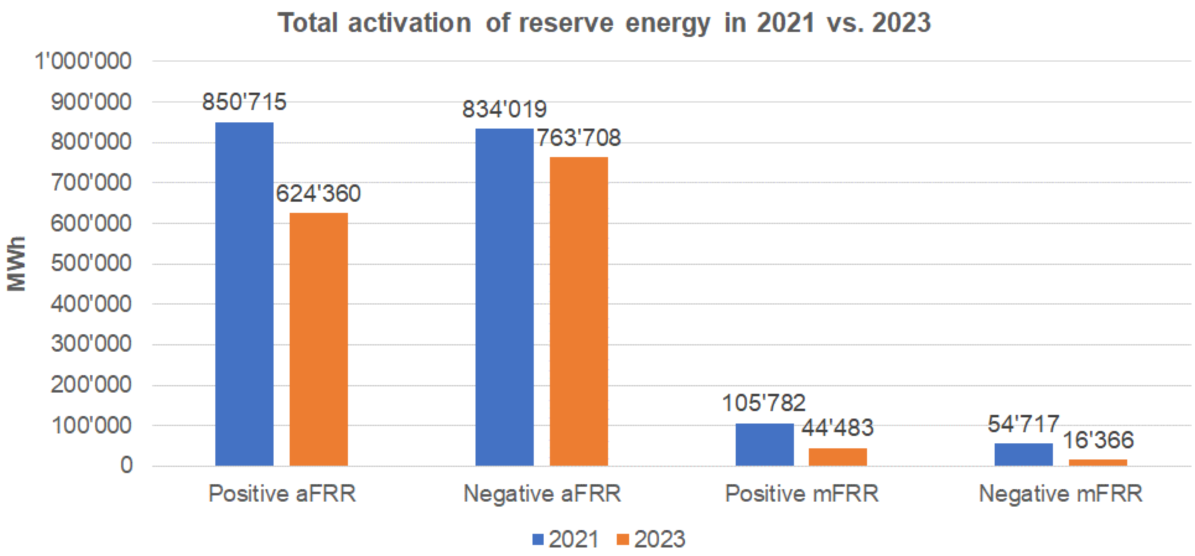


Figure 5: Sum of activated positive and negative aFRR and mFRR in 2021 (before introduction of PICASSO platform) and 2023 (after go-live of PICASSO).

followed by a sharp rise and single expensive bids. This suggests that the prices are sorted by (anonymous) bidders, of which there are in fact only a few. In this case, a supplier who has submitted bids at different price levels and subsequently receives an activation signal can draw conclusions about an imbalance in the electricity grid, especially if an expensive bid is activated, and use this information for its bidding strategy in the intraday market. *It should be emphasized that we expressly do not imply that any of the above-mentioned companies from the market concentration report have used this strategy for frontrunning (buying and selling using proprietary knowledge), and the applied methodology would also not reveal this.*

The introduction of the PICASSO platform in June 2022 has led to important changes in the activation of balancing capacity. First, the amount of activated aFRR and mFRR was reduced significantly from 2021 to 2023 (full years before and after going live of the platform) as Figure 5 shows.

As it can be seen in Figure 6, both the average positive and negative control area balances as proxy for the demand of reserve energy were of similar magnitude in both years or even slightly higher in 2023[5], but the PICASSO platform for the coordinated aFRR activation allows for a more efficient netting of imbalances than the earlier introduced International Grid Control Cooperation (IGCC), which increased the compensation of positive and negative activations in different areas. In particular, the use of mFRR was reduced by a higher factor. This implies that the magnitude of activations got smaller overall since mFRR is only activated when the secondary reserve is not sufficient. Secondly, with PICASSO frequency restauration reserve is procured and activated cross-border. This means that the merit order list now also contains offers from providers abroad and activation signals do no longer go only to participants active in the German market area. Therefore, players in the German intraday market receive less activation signals that they could use for trading decisions since the launch of PICASSO.

As shown in Figure 7, the explanatory power of the different model versions has decreased significantly with the data from 2023 compared to the situation before PICASSO (in comparison with Figure 3). In particular, the adjusted coefficient of determination of the model including all variables and the simple regression estimation using only aFRR activations dropped by almost 10%, which confirms that

[5] However, going along with the go-live of PICASSO the calculation method has slightly changed, see https://netztransparenz.tennet.eu/electricity-market/transparency-pages/transparency-germany/network-figures/control-area-balance/.

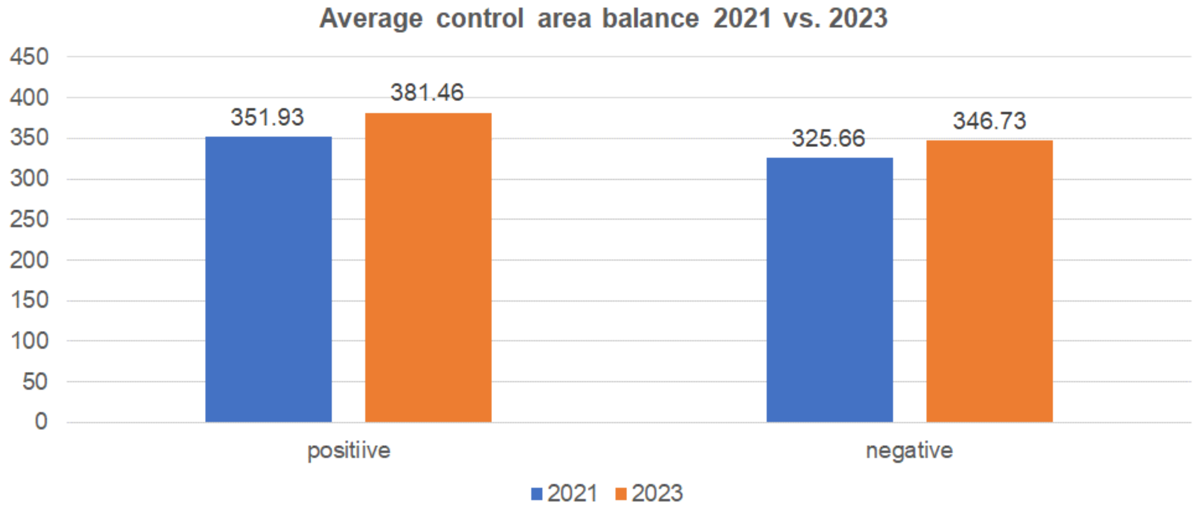


Figure 6: Average values of positive and negative control area balance in 2021 and 2023 as proxy for the demand of reserve energy.

intraday market participants can benefit less from proprietary knowledge gained through balancing activation signals. Also, the explanatory power of the last published control area balance decreased since deviations lead less frequently to frequency restauration reserve activations because of netting, while the last observed imbalance price kept its relevance for the front products. On the other hand, as Figure 22 in the Appendix C (page 46, lower panel) shows, the estimated coefficients for aFRR and mFRR activations increased significantly for 2023. While these can now be exploited less systematically for conclusions on the system imbalance, they are still the most relevant individual price driver. As this information is used, the reduction in the activated energy volumes is compensated by higher absolute coefficient values. This is especially true for mFRR in both directions, which is activated less frequently, indicating a greater imbalance. The publication of aggregated frequency restauration reserve activations in a previous 15-minute interval has still little impact except for mFRR, where the sensitivity rose significantly because a larger imbalance in the immediately preceding time slice becomes known to all market participants (see Figure 23, lower panel). However, due to the small number of occurrences the estimated coefficients for publications of negative mFRR usage have a large standard error for the two front products and are not significant.

Regarding the other data published by the TSOs for previous time periods, there is a noticeable increase in the coefficient for the imbalance price while the sensitivity with respect to the control area balance dropped. Note that also the mean absolute value of the imbalance price itself increased from 2021 to 2023 from 112.92 EUR/MWh to 128.33 EUR/MWh. While the coefficients for wind forecast errors have not changed much compared to 2021, the coefficients for a negative solar forecast error are smaller and have an implausible negative sign for the two front products, although these values are statistically not significant. On the other hand, the estimated coefficients for the load forecast error are small but significant in contrast to 2021.

To sum up, the findings from Hirth & Mühlenpfordt (2021), according to which the activation of aFRR and mFRR is followed by price movements on the intraday market, particularly for products with imminent delivery, could be confirmed. Since in Germany data on activations or the system balance are not published in real-time, it must be assumed that providers who receive the activation signal use this for conclusions regarding imbalances in the grid. This gives them an information advantage for trading

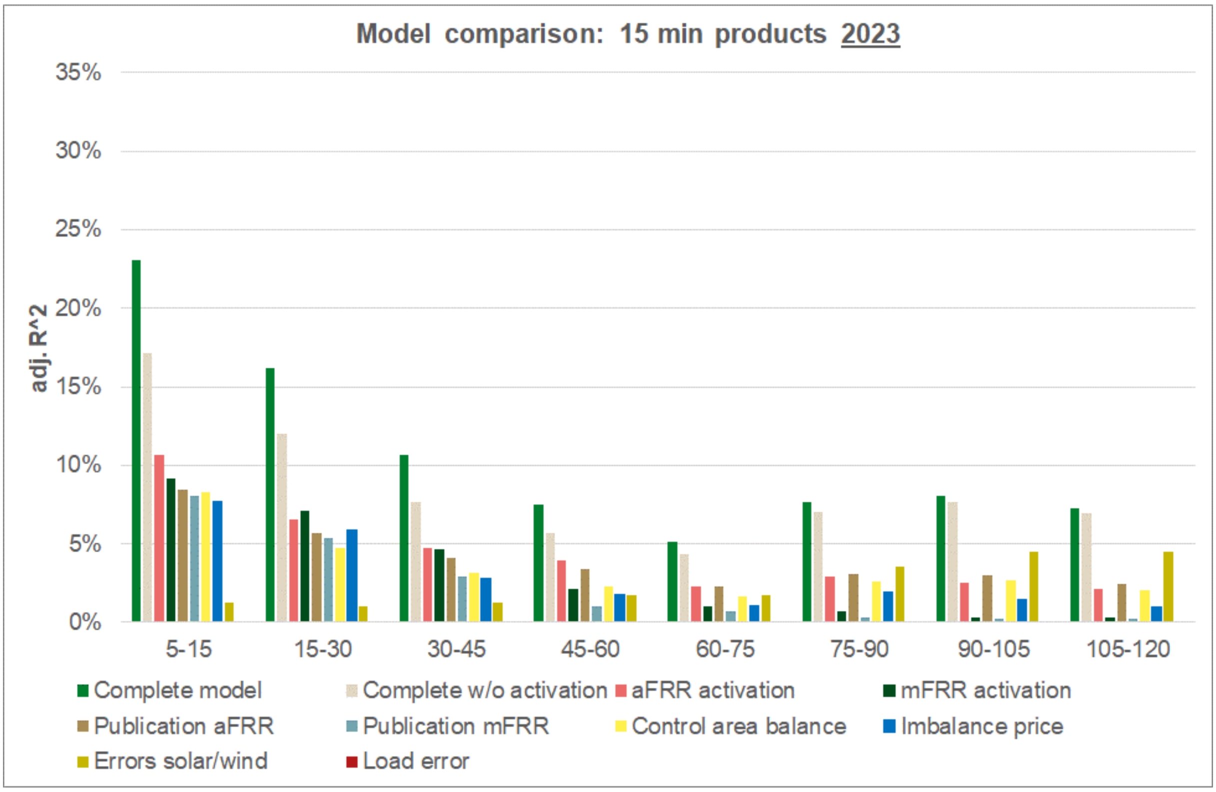


Figure 7: Comparison of different versions of the regression model for the deviation of prices for 15-minute products during the continuous intraday trading from the auction price for data from 2023 (after launch of PICASSO). Compare with Figure 3.

decisions in the intraday market. However, with the going live of the PICASSO platform this effect became weaker. Since activations signals can go now also to providers from foreign control areas, conclusions on the system balance became more difficult. In this respect, the PICASSO platform has reduced the information advantage of large market participants who are simultaneously active in the ID and BE markets. *Since the exploitation of this proprietary information for trading decisions is to the detriment of other market participants, it would ultimately be desirable that TSOs publish data on reserve energy activations or the system balance in real time to ensure full transparency.*

4 Trading flexibilities

Asset-backed trading on the electricity intraday market means the acting on the market itself (i.e., buying and selling the tradable products) having simultaneously the possibility of steering a flexible asset – or a whole portfolio of flexible assets (turbines and or pumps, power storages, etc.). Referring to modern option price theory (Björk, 2009), such flexible assets may be priced on generalized valuation concepts for options. Instead of "selling" the flexibility of an asset and receiving the monetary option premium, one may use a so-called replication strategy to generate the option premium by efficient intraday trading (Björk, 2009).

Exploiting the flexibility in the assets' schedule, one is physically "backed" and does not have to close entered open positions at (potentially extremely) unfavorable prices – a severe risk which "prop traders" without physical assets are faced with and which is typically encountered by an appropriate margin to be deposited at the market clearing entity (Frauendorfer, 2023)

The economic success strongly relies on adequately determined trigger prices and effective modeling of price and volume dynamics. In the context of managing flexible capacities, we address issues of economic efficiency, performance measurement and risk management in energy trading, as well as the monetarization of volatilities. Furthermore, we deal with the modeling of price processes in short-term electricity trading as well as the influence of renewable energies on price formation.

Below, in the first subsection, we analyze the impact of frictions in the intraday market to the option value of the flexible capacity in dependence of its volume. In the second subsection we reflect the added value of combining the intraday market with the BEM and compare this to the value of perfect information as derived in Frauendorfer et al. (2025). In the third subsection we focus on the various components in energy trading and assess their contributions to the welfare.

4.1 Impact of frictions

The bid-ask spread is defined as difference between the best bid price and the best ask price offered. The offered volumes along the order curve represent the liquidity. Both characterize the frictions in continuous trading, which influence the option value of flexible capacities.

The price volume structure is a monotonous price function and illustrates the friction size in the order book: The steeper the price-volume structure, the larger the friction (see Figure 8).

The frictions are triggered through the size of the bid-ask spread and low liquidity on the bid side as well as on the ask side of the offer curve, which in turn leads to increasing costs with increasing volume of the flexible capacity. The slope reveals the costs per additional MW. The frictions represent additional costs in trading that must be considered in the valuation approach. The larger the bid-ask spread and the less the offered volume along the order curve, the smaller gets the option value with increasing volume of the flexible capacity.

Using reconstructed order book data from the entire year 2023, we focus on the valuation of a flexible capacity for producing and consuming, respectively, additional energy in dependence of its power in MW and across all 15-minute delivery periods in the ID-market. This amounts to the valuation of 35'040 (= 365 x 24 x 4) 15-minute delivery periods at a preselected time point before GC. We have chosen two valuation time points: the beginning of SDAT phase and the last 5 minutes before GC. This way, we may compare the evolvement of the option value over trading time.

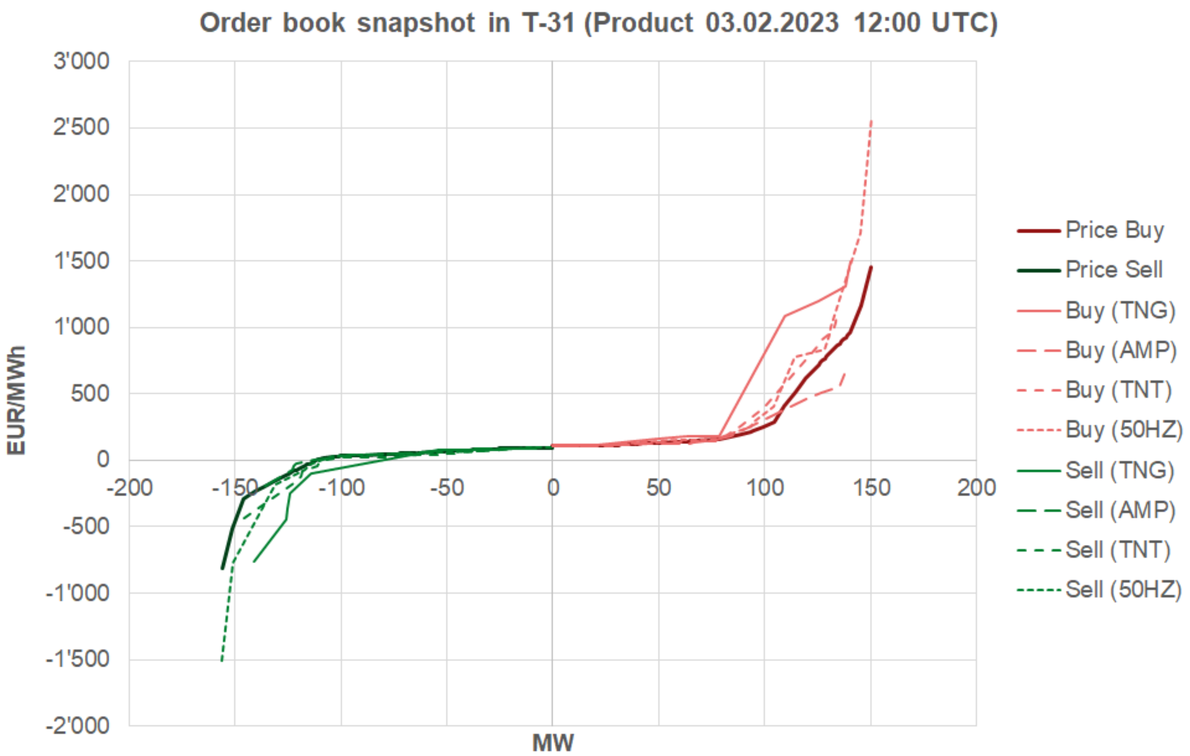


Figure 8: Price-volume structure, i.e., transaction prices at which a certain volume could hypothetically be bought (red) or sold (green). They are calculated as a volume-weighted average of the prices of the bids required to achieve the corresponding transaction size from the order book example in Figure 1. The thick solid lines refer to the situation before the end of the Germany-wide trading phase, before trade is split into the individual control areas. The remaining lines show the hypothetical transaction prices if the same bids were still in the order books of the individual control areas after the start of the SDAT phase.

We focus on the median of the 35’040 option values instead of taking the mean, as the latter is sensitive to the volatility over the year, in contrast to the median, which shows robustness to outliers and volatility, respectively.

In Figure 9 (top), we illustrate the median curve resulting from 35'040 option values for a call option embedded in a flexible gas power plant in dependence of its power in MW within the control areas Amprion and TransnetBW, valued at two different time points, as mentioned above. A call option refers to the flexibility of producing additional energy in a 15-minute delivery period. The corresponding Table 10 is listed in Appendix B (page 44). The median of the flexibility to produce additional energy in the Amprion zone over a 15-minute period with a capacity of 1 MW at the beginning of the SDAT phase is 28.60 EUR/MWh. This value decreases to 25.64 EUR/MWh with increasing capacity up to 10 MW. We assess that the option value decreases by approx. 3 EUR/MWh (≈10%) with increasing capacity from 1 MW to 10 MW.

Considering the last 5 minutes before GC of the SDAT phase, we receive 22.62 EUR/MWh for a capacity of 1 MW and 19.59 EUR/MWh for a capacity of 10 MW. We assess that the value decreases by approx. 6 EUR/MWh (≈20%) when comparing the median for the option value at the beginning of SDAT phase with the median for option value at the last 5 minutes of the SDAT phase.

In Figure 9 (bottom), we illustrate the corresponding median curve resulting from 35'040 option values for a put option embedded in a flexible gas power plant in dependence of its capacity in MW analogously to the representation of the calls. A put option refers to the flexibility of consuming additional energy in a delivery period of 15 min.

The corresponding values for the Amprion area are also listed in Table 10 (Appendix B, page 44). The median of the flexibility to consume additional energy over a period of 15 min with a capacity of 1 MW

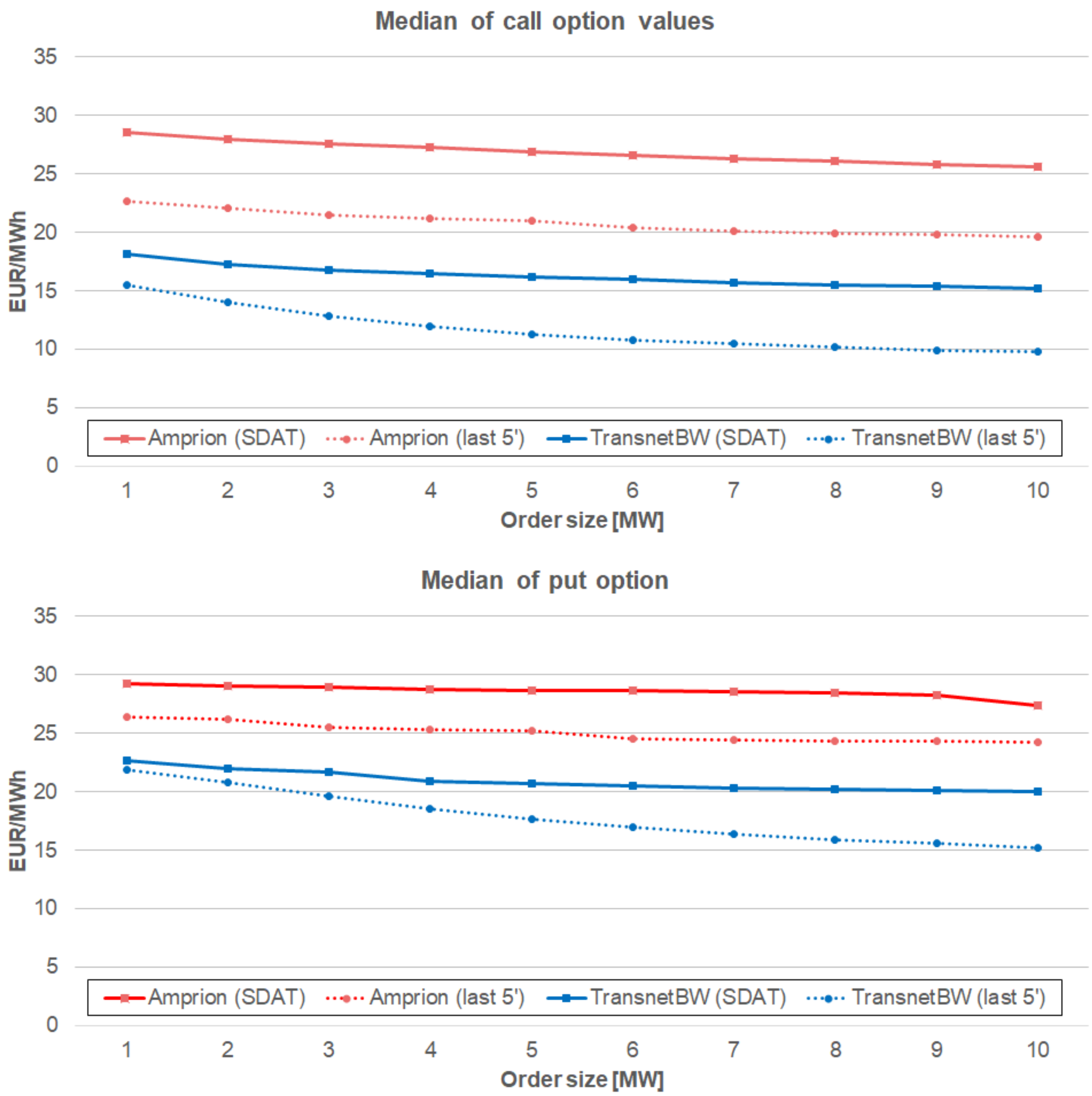


Figure 9: The medians for the call (top) and put (bottom) option referring to the flexibility of gas power plant (calculated using data from 2023).

at the beginning of the SDAT phase is 29.27 EUR/MWh. This value decreases to 27.35 EUR/MWh with increasing capacity up to 10 MW. We assess that the option value decreases by approx. 2 EUR/MWh (≈7-8%) with increasing capacity from 1 MW to 10 MWh.

Considering the last 5 minutes before GC of the SDAT phase, we receive 26.39 EUR/MWh for a capacity of 1 MW and 24.21 EUR/MWh for a capacity of 10 MW. We assess that the value decreases by approx. 2 EUR/MWh (i.e. ca. 7-8%) when comparing the median for the option value at the beginning of SDAT phase with the median for option value at the last 5 minutes of the SDAT phase.

Option theory tells us that the put-call parity holds independent of the price dynamics (Hull, 2011), i.e., independent of the stochastic price process within the ID-Market. As we consider very short holding periods of 30 minutes and 5 minutes, we may neglect the factor interest rate. With the interest rate set to 0, the put-call parity tells us that for put and call options with identical strike price$X$ and identical time to GC, the value P of the put option determines the value C of the call option $S + P = X + C$ with S denoting the spot price and X denoting the strike price (Hull, 2011). This implies in frictionless markets that $P - C$ is independent of the power of the flexible gas power plant and independent of the price process in the ID-market.

Referring to the values listed for the control area Amprion in Table 10 on page 44 in Appendix B, we observe that for a power of 1 MW the value for the put option (29.27 EUR/MWh) and the value for the call option (28.60 EUR/MWh) add up to 57.87 EUR/MWh. Analogously, for a power of 10 MW we obtain for the put option (25.64 EUR/MWh) and for the value for the call option (27.35 EUR/MWh) adding up to 52.99 EUR/MWh. The difference (i.e. 57.87 – 52.99 EUR/MWh) of ca. 5 EUR/MWh can be explained by the increased friction (passing from 1 MW to 10 MW) in the ID-Market of the control area Amprion at the beginning of the SDAT phase.

Referring to the values listed for the control area TransnetBW in the Table 13 on page 45 in Appendix B, we observe that for a power of 1 MW the value for the put option (22.69 EUR/MWh) and the value for the call option (18.09 EUR/MWh) add up to 40.78 EUR/MWh at the beginning of the SDAT phase. Analogously, for a power of 10 MW we obtain for the put option (20.03 EUR/MWh) and for the value for the call option (15.19 EUR/MWh) adding up to 36.22 EUR at the beginning of the SDAT phase. The difference of ca. 4.5 EUR/MWh can be explained by the increased friction (passing from 1 MW to 10 MW) in the ID-Market of the control area TransnetBW at the beginning of the SDAT phase.

We obtain similar results when analyzing the impact of the frictions 5 minutes before GC of the ID-market in the respective control areas. In Appendix B, we have also listed the corresponding option values for a hard coal-fired power plant.

In addition, we have summarized the average and the standard deviation of the 35'040 values for the flexibility to produce or to consumer additional energy over a 15 min delivery period. Median and arithmetic average would coincide in case the 35'040 values were symmetrically distributed around the mean. As option values are nonnegative, we have per se asymmetrically distributed values around the median. The asymmetry of the corresponding empirical distribution allows to identify the tertiles, which help assess those trading products, whose delivery periods reveal low, medium and high volatile regimes. Mean and standard deviation of the empirical distribution would allow for an approximation of the empirical distribution by a Gamma distribution with assessing the associated shape and scale parameters over time. In this way, seasonal effects may be analyzed for incorporating the time dependency in the stochastic price processes.

4.2 Value of perfect information

In Frauendorfer et al. (2025), we have assessed the earnings opportunities in the SDAT phase for the German IDM and the BEM. Therein, the potential revenues from marketing flexible capacity in one of the two markets have been derived through an ex-post analysis using the realized price and activation data from the 2nd half of 2023 for a case study. Since the chosen time window of our ex-post analysis falls into the SDAT phase, we do consider the four control areas in the German IDM separately. In this way, we pay attention to the different liquidity within the each of the associated four IDM. We remember that the resulting market frictions are measured through bid-ask spreads (see Figure 1) and the price-volume structure (see Figure 8).

It is assumed that a provider on the BEM bids at its marginal costs or accepts a bid on the IDM that is above (in the case of a sale) or below (in the case of a purchase) these marginal costs. We have chosen the marginal costs of a flexible gas-fired power plant. Table 1 shows the share across the 17'668 delivery periods of 15 minutes[6] for which in the SDAT phase a transaction in the respective control area would take place, or a bid would have been activated on the BEM.

[6] (181 days x 24 hours + 1 extra hour last Sunday of October) x 4

Market	Selling	Buying
TransnetBW	37.73%	51.31%
Amprion	52.18%	64.46%
Tennet	53.80%	65.24%
50Hertz	52.87%	64.28%
BEM	31.98%	37.59%

Table 1: The share of sell and buy transactions of size 1 MW in the control areas and the share of bid acceptance in the BEM for providing positive and negative energy of 1 MW (data of 2nd half of 2023). Note that a seller must accept the lower bid price (offered by a potential buyer), the buyer must accept the higher ask price (demanded by a potential seller).

The listed numbers reveal the share of sell and buy transaction in the four control areas, and the share of bids activated for providing positive and negative BE. The smallest number of ID transactions were executed in the TransnetBW zone, where due to higher bid-ask spreads the prices are less favorable. In general, bids were activated less frequently on the BEM than on the IDM. We recall that realized prices in the IDM of the four control areas as well as the activation data in the BEM represent primary input data for the year 2023. The revenues that would have been achieved by selling or buying 1 MW in the IDM of the control areas and for providing 1 MW of positive and negative BE are illustrated in Figure 10 and Figure 11.

It is assumed that the option to sell or to buy is given, i.e., the capacity is available across all 17'668 delivery periods of 15 min. For ID trading in all areas, the revenues from purchases (avoiding production costs) are higher than those from sales (generation). In the TransnetBW zone, the lowest revenues were achieved due to the higher bid-ask spreads. If the revenues in the respective control area refer to marketing a flexible capacity of 1 MW, it is the bid-ask which is of relevance. In the case the flexible capacity exceeds 1 MW, we would also have to consider the price-volume-structure in the IDM of the respective control area. The revenues achieved from negative BE are higher than those achievable on the IDM through purchases. For positive BE, significantly higher revenues are achieved compared to ID trading in the TransnetBW zone. According to the observed transaction price in the IDM of the control areas Amprion, Tennet and 50Hertz, the achieved revenues exceed the one achieved for delivering positive BE by around 10%.

Next, we adopt the approach in Frauendorfer et al. (2025), where the provider bids in the market with the higher option value. Again, we focus on marketing 1 MW of a flexible gas-fired power plant on the IDM in the four control areas as well as on the BEM. However, we have to consider the different characteristics of ID and BE products: For the "intraday option", energy is delivered over 15 minutes if exercised, with the expected value being the ID auction price for the respective period, adjusted by spreads.

In the case of the "balancing energy option", the delivery quantity is unknown in advance because, in general, the capacity is not fully activated over the entire 15-minute interval. It is also not obvious which value should be used as the expected value in the option pricing model. Our analyses have shown that there is only a weak relationship between the price levels on the IDM and the BEM or the realized cross-border marginal prices (CBMP). Moreover, since the CBMPs result from bids from different countries, no clear price signals for BE can be derived from the (German) IDM. It is also to mention that other "fundamental data", e.g., published activations of aFRR and mFRR, control area imbalances etc., which can be empirically shown to influence price formation in continuous intraday trading (Hirth & Mühlenpfordt, 2021), are only available with a delay. However, the "balancing energy option" must be evaluated before the GC of the BEM, i.e., (currently) at least 25 minutes before delivery begins.

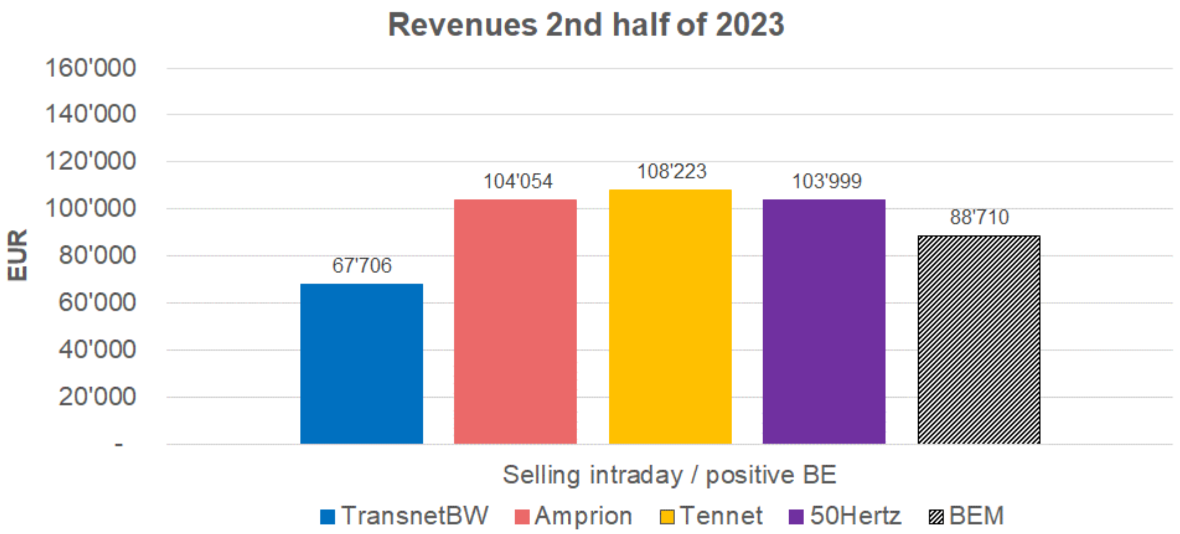


Figure 10: The revenues for sales transactions of size 1 MW in the control areas and for activated bids in the BEM for providing positive BE of 1 MW.

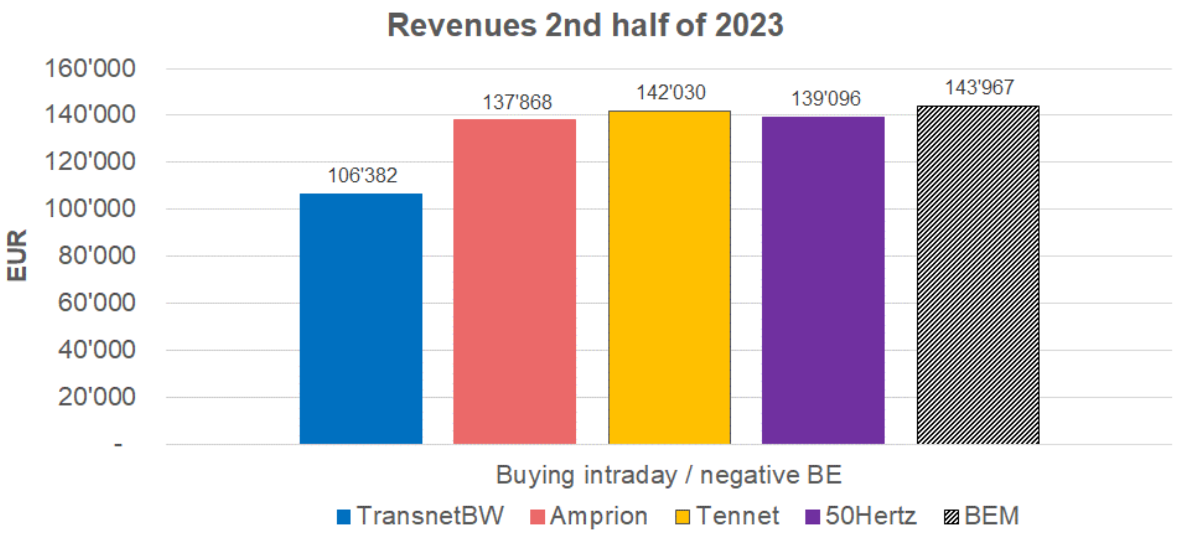


Figure 11: The revenues for purchase transactions of size 1 MW in the control areas and for activated bids in the BEM for providing negative BE of 1 MW

In the underlying case study this was resolved as follows: As the expected value, the last known CBMP average for the product (separately for positive or negative BE) for activations during a preceding 15-minute interval is used. The CBMPs are published with a 15-minute delay; that is, at T – 30 the values from the period [T – 60, T – 45) are known. The option value determined from this is then weighted with a forecasted activation duration. Under the assumption that a flexible capacity follows the activation signals of the activation optimization function (AOF) immediately and that activations can occur every four seconds, the forecast model for the activation durations is applied, see Frauendorfer et al. (2025, p. 18) for details.

The estimation reveals a coefficient of determination of about 12%. With an analysis of alternative variables, e.g., the values of activated BE, which are published by the TSOs with a delay, no higher explanatory power could be achieved. In contrast, if the GC on the BEM were set to T – 15 and if the CBMP were available immediately after the preceding the 15-minute interval, the coefficient of determination would increase to 40%.

Market	Selling: BEM preferred over IDM	Buying: BEM preferred over IDM
TransnetBW	48.26%	57.30%
Amprion	34.48%	45.49%
Tennet	33.43%	44.50%
50Hertz	34.01%	44.80%

Table 2: BEM in competition with the IDM of the four control areas.

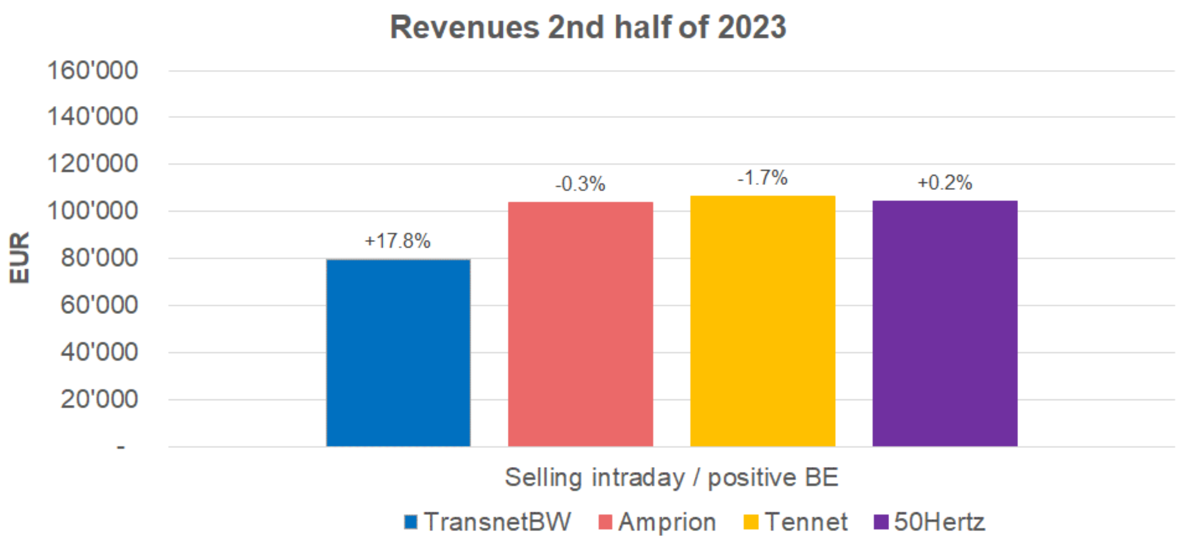


Figure 12: Revenues achieved by application of the decision rule for a sales bid of 1 MW in the IDM of the respective control area or for offering 1 MW positive BE. The percentages represent improvements over the strategy of bidding only in the IDM.

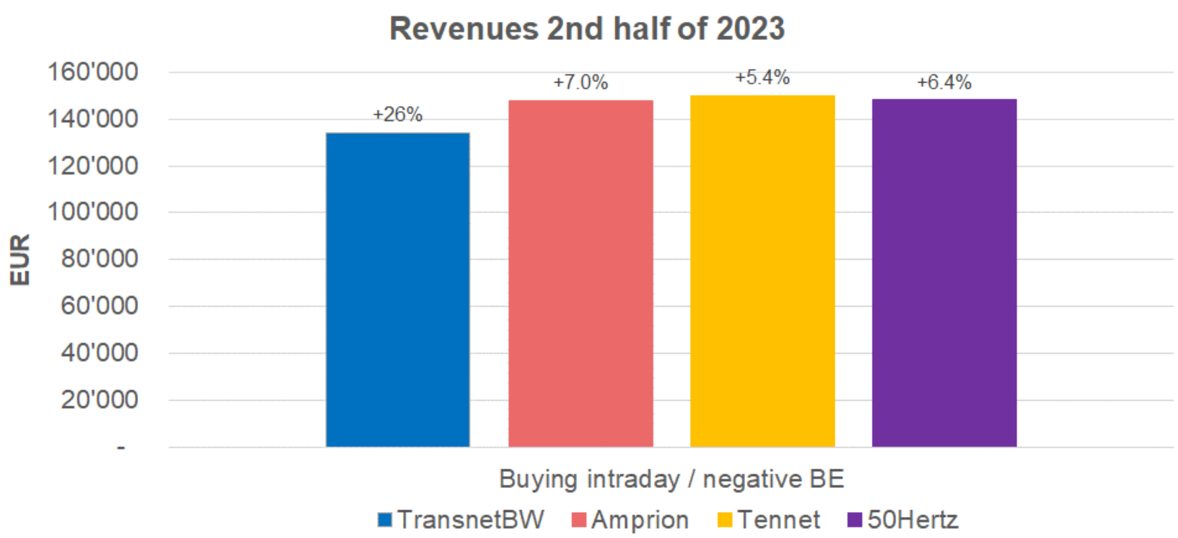


Figure 13: Revenues achieved by application of the decision rule for a purchase bid of 1 MW in the IDM of the respective control area or for offering 1 MW negative BE. The percentages represent improvements over the strategy of bidding only in the IDM.

For testing the decision rule "choose at T – 30 the market with the higher option value", the parameters of the model equations were estimated using data from the first half of 2023.

The evaluation of the rule was then carried out with data from the second half of the year; the results are summarized in Table 2, Figure 12 and Figure 13. The table indicates how often a bid on the BEM would have been preferred over the IDM because – according to the model – BE provides a higher

Market	Selling: BEM preferred over IDM	Buying: BEM preferred over IDM
TransnetBW	54.23%	56.90%
Amprion	45.23%	48.61%
Tennet	44.16%	47.71%
50Hertz	44.87%	48.53%

Table 3: BEM and IDM perfectly exploiting competition.

option value. Note that, in contrast, Figure 10 and Figure 11 show the revenues, as calculated from the realized price and activation data, that would have resulted from participation in only one market.

The decision rule provides mixed results compared to bidding in just one market for selling or providing positive BE, respectively. Only for the control area TransnetBW a more significant improvement of 18% is observed compared to bidding in the IDM only, which can be explained by the market frictions (higher bid-ask spreads) that make the BEM more competitive in this area. On the other hand, for purchases or providing negative BE, respectively, the rule provides better results compared to bidding in just one market.

In the final step we derive the value of perfect information. It is assumed that a provider has perfect foresight and offers the capacity in each 15-minute delivery period in the market (IDM vs. BEM) that yields the higher revenue. We may assess empirically the share of the 17'668 15-minute delivery periods, in which providing BE of 1 MW is more attractive than marketing 1 MW in the IDM of the respective control area. Table 3 shows the numbers for delivering positive and negative BE, respectively, and identifies the delivery periods of 15 minutes, where the BEM is preferred in the individual control areas. Figure 14 and Figure 15 reveal the revenues that could be achieved under perfect information. These numbers are compared with those revenues that are achievable under the decision rule outlined above.

We observe that the value of perfect information is in relative terms larger for selling transactions in the IDM or delivering positive BE to the BEM, respectively, than for buying transaction or delivering negative BE, respectively. This may be explained by the different supply structure of flexible technologies qualified for providing negative BE.

Overall, the proportions in which bids are submitted on the IDM or the BEM are balanced, i.e., there is not one market that is "significantly worse" per se, so that, for example, participants in the IDM would need to be offered an additional incentive to allow their bid to be transferred to the BEM.

4.3 Welfare effects

Enabling distributed flexible capacities to participate in the energy system through aggregation is a backbone in the energy transition. We put liquidity and equity capital in the focus of a sanity check for energy trading.

Above, we presented a methodology for analyzing the earnings potential through trading in the short-term markets, i.e., in the IDM and the BEM. These trading activities impact liquidity and income in the annual financial results, as they run into realization within the business year.

Focusing on hedging the production in front years, the context becomes more complex. As a starting point, we draw attention to the liquidity risk of an energy trader who hedges electricity production evenly over 3 years in advance using futures. This hedging strategy will serve as a benchmark for us.

The initial margin is the security deposit that the energy exchange demands from energy traders to cover losses that may arise if the futures are closed out within two trading days. If the energy trader does not comply with the margin requirements of the exchange within the specified period, the futures

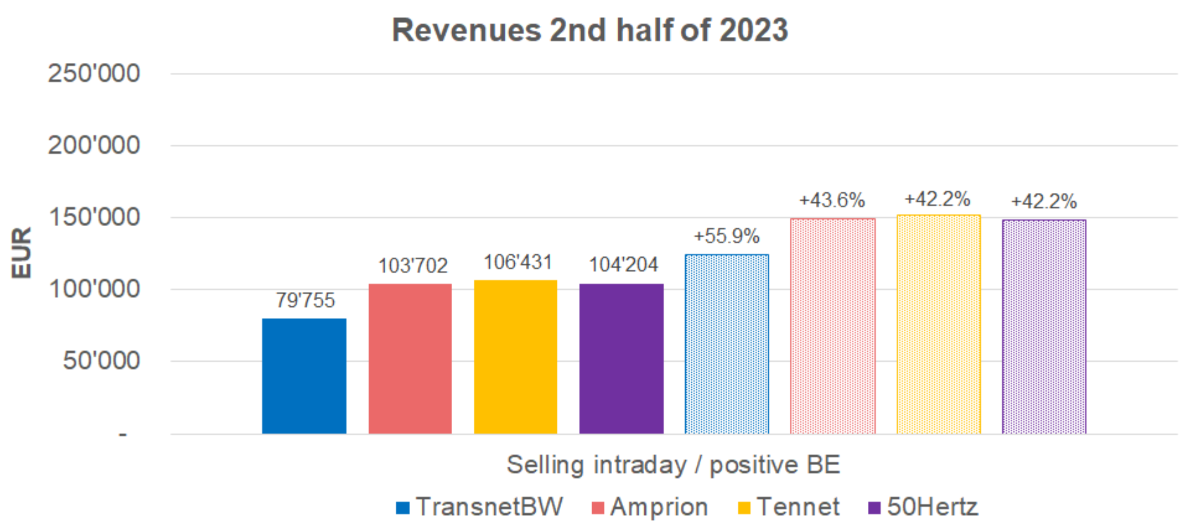


Figure 14: Revenues achieved with the decision rule (see Figure 12) vs. revenues achieved with perfect information (shaded) on providing positive BE.

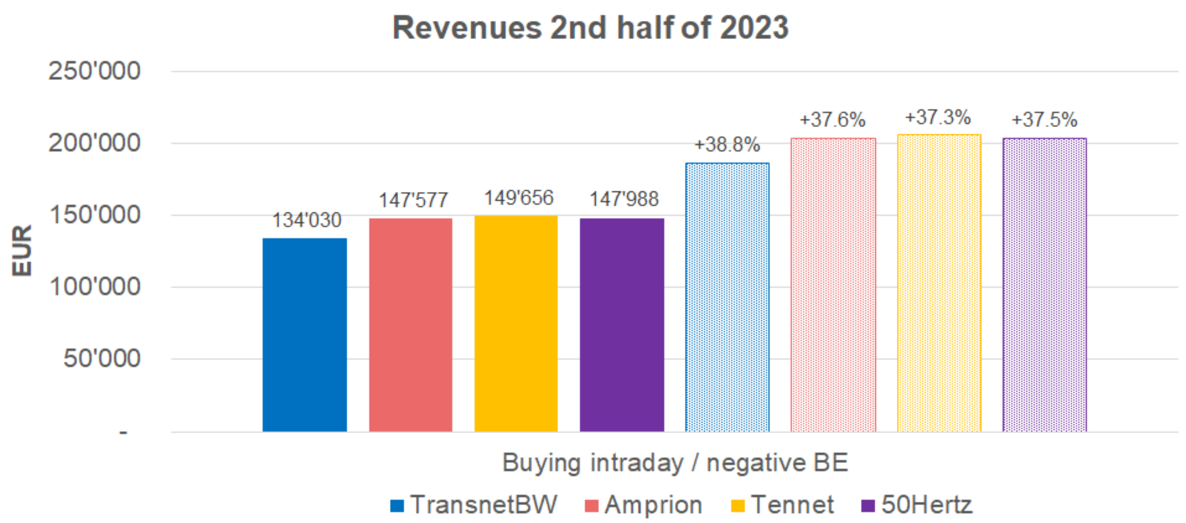


Figure 15: Revenues achieved with the decision rule (see Figure 13) vs. revenues achieved with perfect information (shaded) on providing negative BE.

are closed out by the exchange. The initial margin therefore covers the losses incurred by the exchange if market prices move against the position during these two trading days.

We use the German market area as the basis for hedging. Figure 16 shows the liquidity risk for the initial margin on the futures portfolio over the individual trading days per MWh produced. In the derivation of the liquidity risk for the hedge portfolio, we rely on the relevant data provided to us by the European Commodity Clearing AG (ECC).

We have presented the liquidity outflow for the initial margin on the futures portfolio over the individual trading days per MWh produced. In deriving the liquidity outflow for the hedge portfolio, we rely on the initial margin actually required by the European Energy Exchange (EEX).

The initial margin covers, as one component of the collateral provided to the exchange, any losses that may arise in the event of a close-out over two trading days. It is essentially determined by the price level of the futures and their volatility (European Commodity Clearing AG, 2022).

The so-called variation margin represents the second component. The liquidity required for the variation margin depends on the daily price changes in the futures. If prices change in a way that is contrary

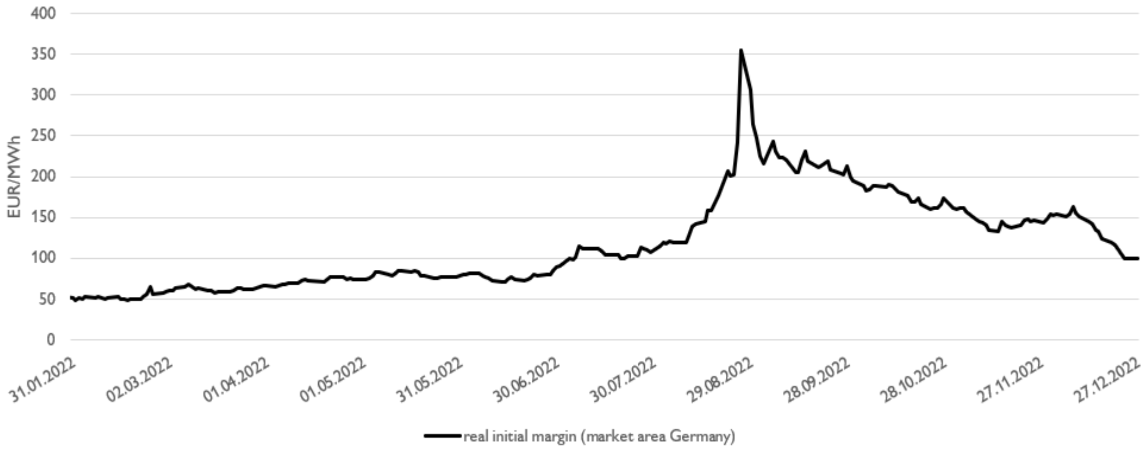


Figure 16: Call for the initial margin associated with the portfolio of open futures positions, which represent the underlying hedge portfolio for production capacities in market area Germany.

to the position, this leads to an outflow of liquidity to the exchange. If prices change in line with the open position, the exchange credits the variation margin accordingly (Hull, 2011).

The profits or losses resulting from the price changes are settled daily. The variation margin thus characterizes the current status of the daily accumulated profits and losses (Burger et al., 2014; Hull, 2011). All electricity companies that hedge their production in advance with futures are exposed to these two liquidity risks.

It is important to understand that the liquidity outflow for the initial margin can be used to determine the liquidity that must be maintained to meet the collateral required by the exchange, the variation margin, for a period of, say, one month. Without going into the derivation: four times the initial margin must be maintained to meet the variation margin with the required collateral for 32 days (McNeil et al., 2015).

If the credit line granted by the syndicate banks is insufficient, a corresponding extension would have to be agreed within one month. The extent of an electricity trader's liquidity risk depends on how "aggressively" the electricity trader hedges. Our benchmark provides for a hedging volume of two years' production. The hedging strategy can also be more aggressive by hedging three years' production or even four years' production. In these cases, the extent of the liquidity risk would be even more accentuated. If the electricity company were to hedge only one year's production, the liquidity risk would be less pronounced.

Hedging strategies do not contribute directly to added value. The benefit of hedging lies primarily in reducing the volatility in the revenues generated from the sale of the energy produced. As a direct consequence, this contributes to reduced volatility in the annual results, which leads to a higher credit rating by analysts and thus to reduced interest expenses in the procurement of capital and liquidity.

In the following, we use a hedging volume of two annual productions as a benchmark for the liquidity risk, which is hedged evenly over three years in advance. The resulting liquidity risk serves as benchmark. Focusing on hedging the production or purchase contracts referring for the front years, we must distinguish between hedging with futures and hedging with forwards. As forwards are priced based on the corresponding futures, the fair value change of the forward may be seen as equivalent to the variation margin.

Hedging flexible capacities with futures impact liquidity through margin calls by the exchange or its clearing institution, respectively. The liquidity is triggered by the initial margin and the variation margin. A liquidity outflow is accounted as receivable, as this outflow is assigned to the hedge of own-use

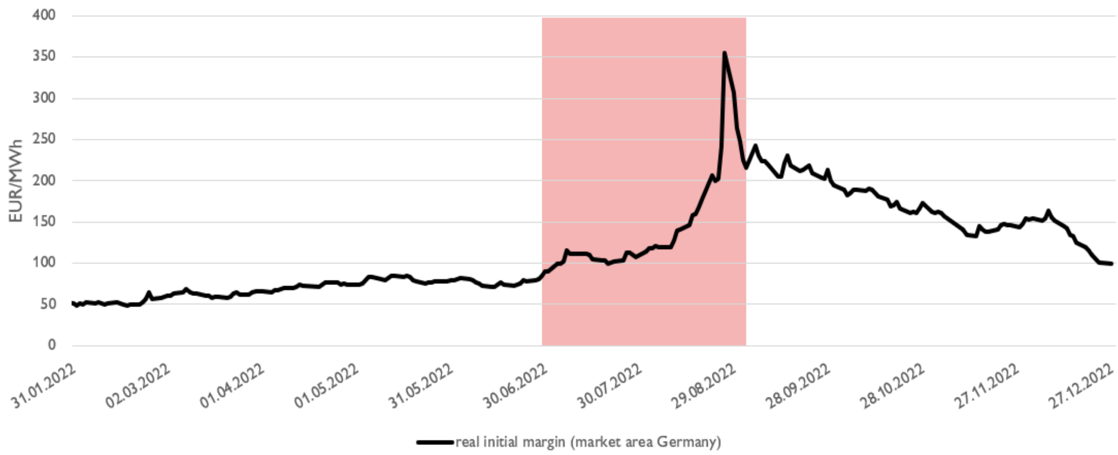


Figure 17: Call for the initial margin associated with the portfolio of open futures positions, which represent the underlying hedge portfolio for production capacities in market area Germany.

contracts with reference to the flexible capacities. This way, the liquidity outflow has no impact on the income in the current business year. The liquidity outflow gets compensated in the forthcoming business years, when the underlying contracts run into realization, and only then with the corresponding impact on the income.

Hedging flexible capacities with forwards, which refer to forthcoming business years, impact liquidity to the extent defined bilaterally with the OTC counterparty in the Credit Support Annexes (CSAs) of the corresponding OTC contract (Burger et al., 2014).This liquidity is again accounted as receivables in case it represents a security given to the counterparty, therefore this liquidity outflow has no impact on the income of the current business year. The fair value change of the forwards, which refer to own-use contracts running into realization in the forthcoming business years, does impact income in the current year. As a direct consequence, the fair value change impact the equity.

We may summarize: A liquidity outflow based on futures impact liquidity but have no impact on income of the current business years, and therefore no impact on equity. The same holds for liquidity given as guarantee to the OTC-counterparty. The fair value change of forwards referring to forthcoming business years have no im pact on liquidity but do have an impact on income in the current business years, and therefore do have an impact on equity.

The above is valid only under the going-concern premise. In case the going-concern premise can no longer be confirmed, the trading unit must build provisions in the amount of the liquidity outflow. Building provisions impact the EBITDA and therefore impact equity (IFRS, 2022).

In Figure 17, we focus on the period 30th June 2022 until 31st August 2022. It illustrates the calls for the initial margin triggered through open futures positions, which are designated to the underlying benchmark hedge for production capacities. Based on data from the ECC, we derived that for holding an open futures position associated with the hedge portfolio the call for the initial margin is 89.26 EUR/MWh on 30th June 2022. The call reaches its maximum 351.82 EUR/MWh on 26th August 2022. This means that within two months the margin call has increased by a factor 3.92. According to ECC, the price of the futures and the daily volatility over 250 trading days are the key factors which determine the value of the call for the initial margin.

In Figure 18 we illustrate the evolvement of the volatility of the underlying hedge portfolio of open futures, which represent the uniform hedge of production capacities three years ahead. This way we visualize the contribution of the daily volatility to the call for the initial margin.

Figure 18: Daily volatility of the portfolio of open futures positions, which represent the underlying hedge portfolio for production capacities in market area Germany.

Looking at the first half of 2022, we note that the initial margin has almost doubled relative to the benchmark, from 48 to 90 EUR/MWh. The daily volatility of the hedge portfolio remained constant at approximately 5% throughout the first half of the year, which is why the doubling of the initial margin primarily resulted from the doubling of futures prices.

It is also important to note that the equity capital reported on the last balance sheet date of 31st December 2021 forms the basis for the sanity check of energy trading in the current fiscal year.

Our aim is to assess the welfare risk by quantifying the system risk based on the fair value change in the hedge portfolio and calls for initial margins. Therefore, we focus on power companies which are considered systemically relevant and suppose that the short hedge portfolio for the production in front years consists of equal shares of futures or forwards, respectively.

We assess the initial margin, the variation margin, the delivered guarantees for the OTC-counterparties and the fair value change of the short hedge portfolio as primary risk factors for the systemic risk (see Figure 19). The initial margin and the variation margin refer to the future-portfolio, the delivered guarantees and the fair value change refer to the forward-portfolio. For a sanity check of energy trading, we use the above selected balance sheet items as a basis, which we define as primary risk factors for liquidity and equity within energy trading. These have the following characteristics:

- The first indicator quantifies the outflow of liquidity for the initial margin, which is dependent on price level and volatility of the futures (European Commodity Clearing AG, 2022).
- The second indicator quantifies the outflow of liquidity for the variation margin, which represents a loss or profit dependent on the price change of the futures and forwards against the position.
- The third indicator quantifies the net delivered guarantees in OTC trading, which depend on the bilateral agreements in the Credit Support Annexes (CSAs).
- The fourth indicator quantifies the passive overhang in energy derivatives. This documents the extent to which the negative fair value change exceeds the positive fair value change in the balance sheet item "energy derivatives" as at the reporting date[7].

The first three balance sheet items are colored blue, the fourth is colored yellow in Figure 19. We use blue coloring to document that initial margin, variation margin and CSAs provided are recognized "affecting liquidity" but "not affecting income". This means that liquidity outflows on exchanges or to

[7] Passive overhang = $\max(0, \text{negative FV changes} - \text{positive FV changes})$;
active overhang = $\max(0, \text{positive FV changes} - \text{negative FV changes})$.

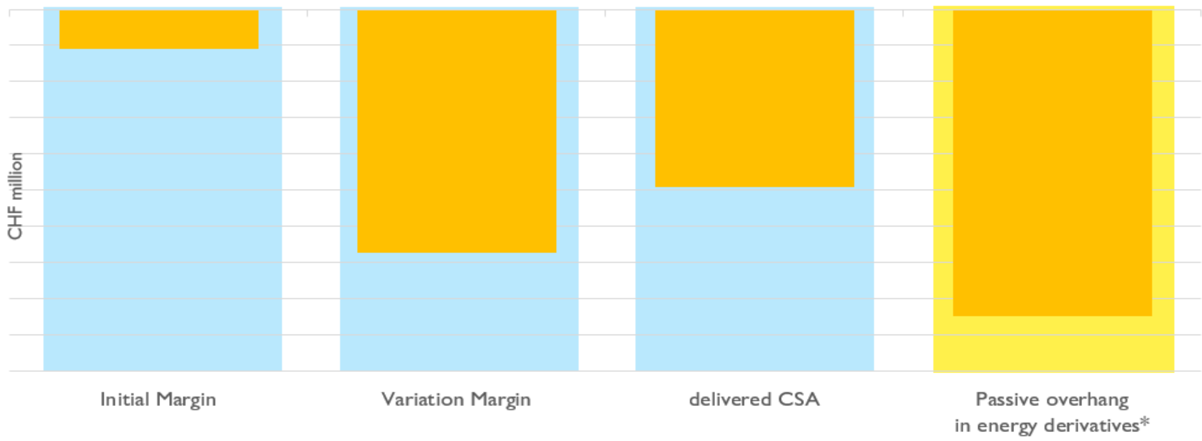


Figure 19: Primary risk factors for liquidity and equity capital in energy trading.

counterparties in bilateral trading do not burden the equity. These loss items are recognized as a receivable on the assets side of the balance sheet and therefore have no effect on profit or loss.

The permissible argumentation in accordance with accounting principles is as follows: if the liquidity outflows relate to hedging transactions, then these are neutralized by the realization of the underlying transactions in subsequent years. However, this assumes that the company will be able to continue its business activities in subsequent years. The "going concern principle" is not called into question as at the balance sheet date. Under the "going concern premise", the realization of the underlying transaction in subsequent years is considered certain. The liability surplus shown in yellow is recognized as "non-liquidity-effective" but is charged to equity. This means that the passive overhang is already included in the reported equity as at the balance sheet date.

In order to assess whether these risk factors are material or not, equity must be taken into account. We quantify the liquidity outflows and passive overhang relative to equity as at the last balance sheet date 31st December 2021. It is of importance to keep that equity constant over the following fiscal year. The sanity check reveals the preselected four balance sheet items of energy trading set in relation to that equity.

With the intention to define critical thresholds, we suppose that regarding the future positions per 30th June 2022, the balance sheet of a systemically relevant power company reveals initial margins paid to the power exchange that amount to 10% of the equity capital and a variation margin that amounts to 60% of the equity capital. Regarding the forward hedge positions, we suppose that liquidity that amounts to 40% of the equity capital has been assigned to OTC-counterparties as guarantees. The fair value change of the forward hedge portfolio is supposed to be 60% of the equity capital. Notice that there is an agreed risk limit of 20% above which guarantees must be provided. For didactic purposes, we visualize the risk exposure on 30th June 2022 in Figure 20.

We focus first on the liquidity outflow for the initial margin: The liquidity outflow for the initial margin relative to the most recently reported equity allows for a ranking among the electricity companies as of the trading day: The greater the value swings above 10% as of 30th June 2022, the more aggressive the hedging strategy. A value above 10% indicates that the hedging volume relative to equity exceeds twice the annual production. If an electricity company reports a value below 10% as of 30th June 2022, this indicates that the hedging volume relative to equity is less than twice the annual production.

What should one be aware of regarding an increase in the liability surplus? Knowing that futures prices are highly volatile, a sensitivity analysis must be conducted: If the liability surplus were to increase again by 50% of equity, the total increase would be 110% [= 60% + 50%]. This means that this increase

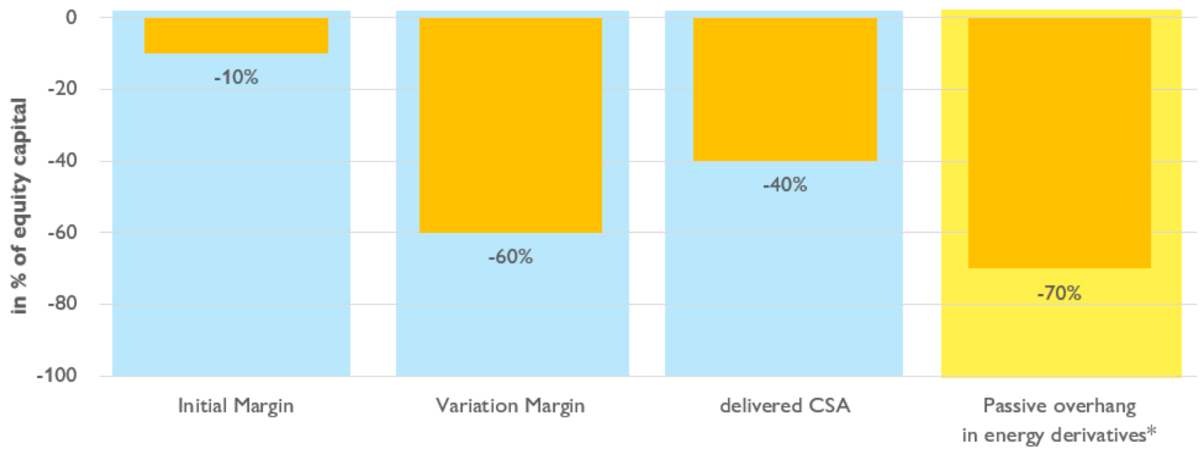


Figure 20: Benchmark for the risk exposure of the distinguished short hedge portfolio on 30th June 2022.

would wipe out the equity reported as of the last balance sheet date and result in over-indebtedness amounting to 10% of the last reported equity.

We deliberately do not include other business activities here, such as the regulated grid business. Including the regulated grid business, for example, one could argue that over-indebtedness would not necessarily occur. Rather, it is important to be prepared for the following "worst case": a surprisingly significant negative interim result in energy trading could call into question the company's ability to continue as a going concern. Knowing that the initial margin increased almost fourfold between 30th June and 26th August, the question immediately arises: What will the key figures look like at the end of the trading day on 26th August 2022?Based on market data and the call for initial margins derived by the ECC in period 30th June to 26th August 2022, we have estimated the corresponding calls for the initial margin of the hedge portfolio. In the same way, we have considered the evolvement of the relevant futures prices in that period.

These critical thresholds can be used to derive the contribution of systemically important energy suppliers to systemic risk. The closer the risk factors are to the critical thresholds, the greater the risk of insolvency. The smaller the risk factors, the healthier the energy trading. The Board of Directors (BoD) can now request an internal audit to investigate these four risk factors for the last 90 trading days. This will give the BoD a clear picture of energy trading. As audits become increasingly risk-oriented (Schwintowkski et al., 2018) the collaboration and information exchange between internal audit and risk control become critical. This cooperation forms the foundation for the BoD to fulfill the supervisory responsibilities.

We now know from futures market data that between 30th June and 26th August 2022, liquidity risk rose fourfold, and futures prices tripled. For a short hedge on future production, without further intervention in the hedging portfolio, the risk factors would change until 26th August 2022, in line with the development of liquidity risk. The impact on cash outflows and the passive overhang as of 26th August 2022, can be estimated relative to equity as follows (compare with Figure 21):

- The liquidity outflow to the energy exchanges for the initial margin will amount to approximately 40% of equity, as the liquidity risk has almost quadrupled between 30th June and 31st August 2025 (see Figure 17 and the further explanations on page 30).
- The liquidity outflow to the energy exchange for the variation margin will be rounded to 180% of equity, as futures prices have tripled, and a short hedge loses value accordingly.

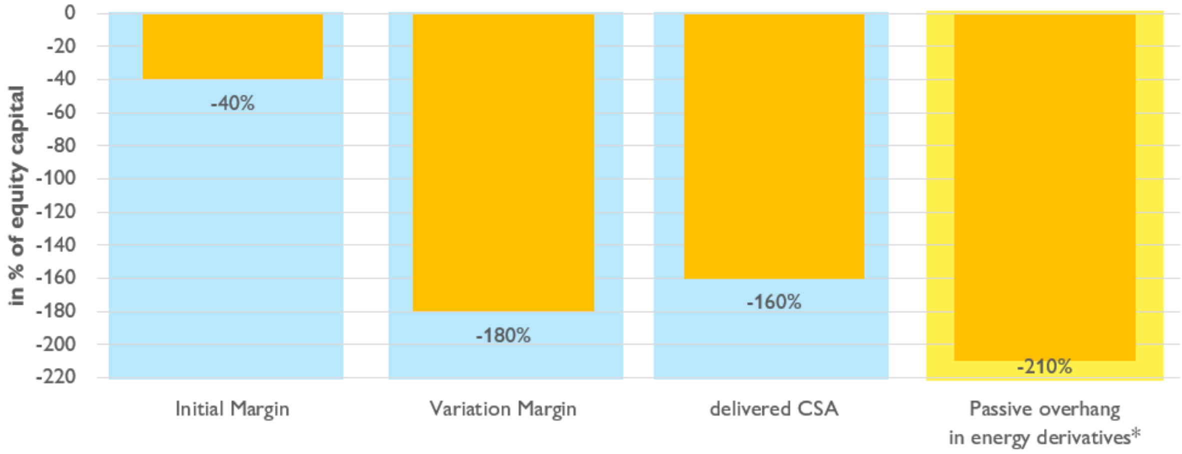


Figure 21: Risk exposure (estimated by the ior/cf-HSG, based on benchmark per 30th June 2022) of the selected short hedge portfolio on 26th August 2022.

- The CSAs provided to counterparties will now amount to 160% of equity, also due to the tripling of futures prices, provided that the contractual agreements remain unchanged.[8]
- The passive overhang in energy derivatives will now amount to 210% of equity, as fair value (FV) changes in hedging transactions related to production have tripled.

This new situation indicates that the balance sheet is likely to be out of balance. The reason for this can be summarized as follows: The increase in negative fair value changes in energy derivatives to 210% has resulted in the destruction of equity and the emergence of debt amounting to *minus* 110% of the previously reported equity.

This means that there is a risk of insolvency, the going concern premise no longer applies, but instead

- valuation at liquidation values,
- write-offs of all assets for which no economic benefit is expected (e.g., collateral, margin requirements),
- immediate recognition of expected losses and risks, particularly in the form of provisions (IAS 37.14 ff).

In this case, the cash outflows recognized in other comprehensive income would result in losses of the same amount, which would further increase negative equity. This would raise debt to minus 330% of the equity reported as of the last balance sheet date[9]. If the most recently reported equity amounted to 10 billion, this would result in over-indebtedness of 33 billion.

We recognize that the critical thresholds defined earlier were set almost four times too high based on the price distortions between 30th June and 31st August 2022.

This leads to the following insights:

- Production capacity and supply contracts must be in a healthy relationship with liquidity and equity capital.
- Aggressive hedging strategies are only justifiable if sufficient liquidity is available.

---

[8] 160% = 3 * 60% – (60% – 40%), where the first term is the FV change. Recall from page 32 that guarantees are due if the risk limit of 20% is exceeded, which explains the second term in parenthesis.

[9] 40% from change in initial margin, 180% from change in variation margin, 210% from change in passive overhang, see Figure 21. Note that the delivered CSAs represent a collateral for already stated losses from the passive overhang and have no additional negative impact on the debt. It is assumed that forward prices are based on futures prices

If the relevant balance sheet items reach critical thresholds, this is an indication that equity is too low in relation to production capacities and supply contracts, or that the hedging strategy with the underlying hedging volume is too aggressive, or both. In any case, caution and action on the part of operational and strategic management are required.

We recognize that the values used above for the four primary risk factors as of 30th June 2022 represent critical thresholds for systemically important energy suppliers. The closer an electricity company's actual balance sheet items relative to equity are to the critical thresholds, the greater the risk of insolvency. The smaller the actual balance sheet items relative to equity, the healthier the electricity company's energy trading.

The contribution of a systemically important electricity company to systemic risk can be derived from the development of the four selected balance sheet items in energy trading. If the selected balance sheet items in relation to equity as of the most recent balance sheet date are presented to the BoD on a rolling basis over the last 100 trading days, it receives an X-ray picture of energy trading for the current fiscal year.

5 Conclusions

Chapter 2 introduced a cost-liquidity metric for intraday trading that quantifies frictions in basis points (bps) for LOBs of an individual trading product. For selected trading periods in 2021 and 2022, empirical LOB analyses are applied for identifying frictions of trading products. The focus lies on the implementation of performance indicators, which help assess the quality of order books with dependence of the volatility in the market. The approach breaks down the information into two main components: measurement of liquidity and spread risks during continuous trading of 24 sixty-minute contracts and 96 fifteen-minute contracts for the day ahead.

The *multivariate cost-liquidity metric* is composed of the *average relative spread* and the relevant *liquidity measures*. As soon as the *buy market order volume* exceeds the *best ask volume*, its transaction price will be *larger* than the *best ask price*. These *additional costs on the sell side* are evaluated volume dependent and define the *volume structure of transaction premia on the sell side*. Analogously, as soon as the *sell market order volume* exceeds the *best bid volume*, its transaction price will be *lower* than the *best bid price*. These *additional costs on the buy side* are evaluated volume dependent and define the *volume structure of transaction premia on the buy side*. The intraday dynamics of the two *volume structures of transaction premia* on the buy and sell side reveal the *imbalance in the full order book* for each individual intraday market.

The *multivariate cost-liquidity metric* allows for estimating trading costs across spot markets and helps characterize the quality of intraday markets with respect to economically and statistically significant generation of added value.

Flexible asset-backed traders have the advantage that they can "ride the intraday volatility" (Frauendorfer, 2023). Highly volatile phases are benevolent for an asset-backed trading strategy. The flip side of the coin is that those higher buy prices and lower sell prices do have direct implications on the risk exposure of inflexible market participants which trigger to close their open positions at unfavorable prices, entailing a "flexibility premium" which is implicitly paid by them in favor of the flexible asset-backed traders.

Therefore, a meaningful benchmark approach for an individual inflexible market participant must take into account an adequate buy surcharge and sell discount onto an index price (e.g., ID1 or ID3 published by the EpexSpot exchange).

The crucial price surcharges and reductions consist of several components, each contributing to a final buy and sell premium which is superimposed to the chosen index price. We have identified three separable main constituents of this premium: first, a spread-based component depicting the top-of-the-book liquidity; second, a component relying on the volume structure of transaction costs and thus reflecting the bid/ask-side dependent order book depth and quality; third, a volatility-based component representing the systematic variation of the mid prices or index prices.

Risk assessment relies on distributional information for price and volume dynamics. Flexible consumers and producers of electricity may earn flexibility premiums on intraday markets with the equivalent of the delta hedge premium as the target, given the respective price dynamics.

Spot markets move towards continuous exchanges for both day-ahead and intraday electric power. Price levels and fluctuations determine the operational optimum for the market participants and feed back into the availability and liquidity of those markets. Quarter hour resolution and quantiles for the spot price forecasts might improve the valuation and the risk management of electricity portfolios.

To support an efficient intraday trading strategy, it is of importance to derive stochastic models which capture the inherent stochastic nature of regularly updated generation forecasts and volatile intraday market prices. We have developed an approach using copula and marginal distributions for the modeling of short-term variations of electricity intraday prices and of renewable energy generation forecasts. The approach includes estimation procedures for the marginal distributions and the linking copula. This way, multivariate probability distributions are derived which serve for modelling jointly price and forecast variations over preselected short time horizons, which cover nonlinear dependencies.

The effects of the PICASSO platform on the German intraday market were discussed in chapter 3. PICASSO, a European balancing platform introduced in 2022, provides a cross-border procurement and activation of aFRR. Prior to its launch, certain market participants that were involved in both intraday and balancing energy markets exhibited an information advantage since the activation of BE bids (aFRR and mFRR) that were submitted at a certain price level allowed them to draw conclusions on current imbalances in the power system, which they then used for their trading decisions in the intraday market. This effect is more pronounced for products with short remaining time to delivery as it is more likely that the observed imbalance will still exist.

This effect became weaker after the launch of PICASSO, i.e., the quantitatively verifiable price effect of activation signals has decreased. This can be explained on the one hand by the smaller amount of activated energy due to a more efficient netting of imbalances. On the other hand, BE is also activated cross-border, i.e., activation signals go to providers in other areas that are not active in the German market and are therefore not used for trading strategies in the intraday market. This has reduced the opportunities for exploiting proprietary information, which will continue with the inclusion of additional control areas in the platform. Independent of the PICASSO platform, one way to increase market transparency would be if regulators were to require providers who have received a call signal to publish it on a transparency platform immediately after its reception, so that the same information is available to all market participants simultaneously.

In chapter 4, we explained that liquidity outflows on exchanges and counterparties, as well as gross trading volumes and liability overhangs in energy derivatives, are relevant for assessing systemic risks. These metrics must be monitored not only on balance sheet dates, but daily. Based on the daily trends of these metrics, management's "operational performance" can be differentiated from geopolitical or external economic influences. The sanity check generates an X-ray image of energy trading and can support the BoD in its supervisory duties.

Extreme surpluses for electricity producers caused by exogenous factors mean extreme burdens for electricity-intensive industries in national economies. Legislators have the opportunity to create the necessary balance to protect the welfare of an economy.

The complexity of the accounting presentation of trading and hedging transactions must not lead to opacity. Especially in areas with high earnings volatility and inherent risk – such as energy trading – it is the responsibility of companies to create transparency where possible and necessary.

This applies not only to investors and the public, but especially to the relationship between management and the BoD. The latter is responsible for monitoring material risks. It must not rely solely on aggregated key performance indicators, but must also critically examine the origin, sustainability, and risk structure of earnings. Where value creation and risk diverge, where earnings contributions arise from valuation assumptions, internal allocations, or delayed effects on earnings, more than just formal (IFRS) compliance is needed: it requires understanding, openness – and the courage to be clear.

Literature

50Hertz et al. (2022). *PICASSO MARI Stakeholder Workshop.* Von https://eepublicdownloads.azureedge.net/webinars/2021/MARI_PICASSO_Stakeholder_Workshop_20211202-final.pdf. abgerufen

50Hertz et al. (2023). *Erläuterungen zu Daten Regelenergie.*

Björk, T. (2009). *Arbitrage Theory in Continuous Time.* Oxford University Press.

Bundeskartellamt. (2024). *Wettbewerbsverhältnisse im Bereich der Erzeugung elektrischer Energie 2023/24.* Bonn.

Burger, M., Graeber, B., & Schindlmayr, G. (2014). *Managing Energy Risk: A Practical Guide for Risk Management in Power, Gas and Other Energy Markets* (2nd Ausg.). Wiley.

EpexSpot. (2025). *Description of Epex Spot Market Indices.* Von https://www.epexspot.com/sites/default/files/download_center_files/EPEX%20SPOT%20Indices%202019-05_final.pdf abgerufen

European Commodity Clearing AG. (2022). Derivative Market Margining; Version 1.6.1 (5. April 2022), Version 1.10.1 (undated).

Frauendorfer, K. (2023). *On the Difference between Asset-backed Trading vs. Proprietary Trading.* Tutorial Paper, University of St. Gallen, Ior/cf-HSG. Von https://www.alexandria.unisg.ch/handle/20.500.14171/118113 abgerufen

Frauendorfer, K., Haarbrücker, G., & Schürle, M. (2025). *Relevance of Intraday Markets for Flexibility Valuation.* Report, University of St. Gallen, ior/cf-HSG.

Hirth, L., & Mühlenpfordt, J. (2021). *Handel auf Basis des Regelleistungs-Abrufs.* Berlin: neon neue energieökonomik.

Hull, J. C. (2011). *Options, Futures and Other Derivatives* (8th Ausg.). Boston, Mass.: Prentice Hall.

IFRS. (2022). *International Financial Reporting Standards (IFRS) 2022.* Wiley.

McNeil, A. J., Frey, R., & Embrechts, P. (2015). *Quantitative Risk Management: Concepts, Techniques and Tools* (revised ed. Ausg.). Princeton: Princeton University Press.

Schwintowkski, H.-P., Scholz, F., & Schuler, A. (2018). *Handbuch Energiehandel* (4. Aufl. Ausg.). Erich Schmidt Verlag.

Appendix A

DE (60 min)	[0,6)		[6,12)		[12,18)		[18,24)	
	Mean	*Std.dev.*	Mean	*Std.dev.*	Mean	*Std.dev.*	Mean	*Std.dev.*
35	12.57	*125.49*	13.08	*106.37*	18.68	*159.03*	16.85	*175.67*
34	13.91	*135.80*	15.16	*132.48*	18.10	*137.78*	18.07	*148.14*
33	12.53	*120.81*	14.39	*117.30*	16.30	*126.00*	13.55	*107.91*
32	110.99	*424.06*	102.70	*403.70*	124.17	*454.90*	114.72	*444.78*
31	142.30	*495.97*	135.94	*487.10*	158.00	*534.08*	148.77	*519.37*

DE (15 min)	[0,6)		[6,12)		[12,18)		[18,24)	
	Mean	*Std.dev.*	Mean	*Std.dev.*	Mean	*Std.dev.*	Mean	*Std.dev.*
35	22.78	*161.76*	24.21	*172.08*	28.23	*197.88*	25.39	*188.18*
34	44.36	*316.13*	36.03	*248.64*	43.22	*286.25*	49.97	*327.68*
33	44.59	*314.18*	38.86	*268.40*	43.43	*271.68*	51.35	*325.26*
32	21.57	*119.25*	24.61	*148.70*	27.19	*167.56*	26.87	*195.84*
31	23.24	*117.10*	26.90	*153.46*	29.46	*161.24*	29.92	*199.80*

Table 4: Spread risks for hourly (top) and 15-min (bottom) products in the entire German market area in the five minutes before trading is split into the four control areas. For each day in 2023, the average bid-ask spreads and its standard deviation are calculated. It is noticeable that the spreads of the hourly products increase shortly before the end of the German-wide trading phase. This is due to bids being removed from the order book by market participants, while the bids for 15-min products are kept. The subsequent tables show the corresponding values for the four control areas and are organized analogously. The comparison reveals the different friction sizes, which indicate the liquidity in the different control areas.

TNG (60 min)	[0,6)		[6,12)		[12,18)		[18,24)	
	Mean	Std.dev.	Mean	Std.dev.	Mean	Std.dev.	Mean	Std.dev.
25	77.27	282.07	69.38	169.99	67.48	245.12	73.76	259.80
24	69.13	249.86	75.32	395.96	54.90	126.55	63.43	199.37
23	62.56	201.00	73.10	386.05	53.03	123.65	59.88	215.06
22	57.70	190.34	71.26	293.04	55.16	185.51	59.86	272.26
21	68.30	292.53	72.15	291.51	54.95	116.16	56.67	253.26
20	76.36	413.22	62.14	187.69	53.24	197.56	67.90	376.60
19	224.20	453.24	174.88	348.30	173.29	387.89	205.99	520.88
18	234.10	507.93	173.23	285.29	176.68	414.03	190.90	351.87
17	393.53	752.47	297.92	531.85	269.75	561.69	303.80	632.65
16	344.21	310.09	262.21	273.01	249.14	225.64	290.33	328.91
15	346.12	338.51	257.22	271.35	249.83	263.04	294.41	360.59
14	397.52	350.27	273.24	228.68	297.96	318.78	352.49	367.82
13	402.32	386.25	273.45	228.00	304.24	442.73	357.86	408.69
12	433.71	407.45	298.29	223.67	332.28	413.08	400.34	519.31
11	417.55	294.54	296.48	219.28	336.89	459.71	392.59	469.49
10	430.28	316.20	309.28	297.35	345.09	471.61	406.11	500.14
9	447.51	283.08	302.13	243.63	343.16	389.73	396.71	281.38
8	466.08	324.60	307.38	301.41	345.50	408.68	416.20	306.27
7	469.37	326.41	315.15	349.64	344.35	353.35	418.25	307.81
6	489.22	327.77	315.39	348.28	359.14	352.49	455.51	324.69

TNG (15 min)	[0,6)		[6,12)		[12,18)		[18,24)	
	Mean	Std.dev.	Mean	Std.dev.	Mean	Std.dev.	Mean	Std.dev.
25	81.28	208.73	61.36	118.62	67.86	192.05	96.09	300.18
24	87.86	214.12	70.47	205.41	75.82	246.42	104.92	350.18
23	87.84	241.00	66.31	132.21	70.09	196.31	105.40	397.53
22	77.79	209.96	57.81	117.07	63.46	217.51	86.27	304.89
21	70.56	186.07	53.87	100.50	60.12	209.03	83.16	308.91
20	67.62	154.79	53.34	94.31	57.39	175.04	82.07	299.62
19	186.19	296.71	141.02	291.29	155.05	339.90	213.73	473.33
18	187.52	321.36	136.54	278.09	154.89	367.08	213.84	461.78
17	162.89	230.31	117.09	169.30	126.39	223.09	182.67	362.79
16	160.02	216.44	114.01	141.94	124.56	218.83	173.37	301.78
15	157.66	214.87	111.70	153.21	123.02	236.35	167.90	282.75
14	285.40	275.84	210.46	274.11	218.22	237.79	296.05	396.02
13	264.99	265.60	191.05	210.00	198.67	207.46	269.10	309.68
12	198.56	192.19	142.91	142.89	151.70	181.61	195.63	267.00
11	183.37	194.78	134.69	157.68	139.86	145.49	178.65	267.91
10	183.84	167.12	135.27	130.55	141.09	148.92	179.06	262.37
9	247.01	201.21	172.44	175.23	185.05	187.25	244.73	280.24
8	188.15	173.50	131.80	140.09	143.15	155.28	186.91	241.79
7	171.36	144.63	114.58	156.09	126.59	168.77	164.93	214.03
6	170.55	142.58	116.73	159.29	129.18	183.39	166.24	231.87

Table 5: Average spreads and their standard deviations for the hourly (top) and 15-min products (bottom) products in the last 25 minutes before delivery in the TransnetBW area.

AMP (60 min)	[0,6)		[6,12)		[12,18)		[18,24)	
	Mean	*Std.dev.*	Mean	*Std.dev.*	Mean	*Std.dev.*	Mean	*Std.dev.*
25	16.85	*171.90*	13.03	*28.24*	12.45	*27.50*	19.56	*176.34*
24	15.16	*171.96*	11.89	*47.86*	10.98	*26.06*	16.98	*175.70*
23	15.15	*171.75*	11.77	*26.35*	11.89	*26.13*	20.58	*245.51*
22	14.75	*171.73*	11.96	*28.13*	12.90	*74.26*	17.51	*190.22*
21	13.72	*171.97*	10.89	*29.92*	11.02	*54.29*	14.42	*180.07*
20	14.86	*171.80*	13.01	*35.49*	11.83	*37.66*	19.05	*212.00*
19	16.37	*171.99*	13.67	*30.61*	13.65	*31.33*	22.87	*244.75*
18	16.46	*171.86*	13.56	*30.90*	12.99	*28.53*	19.67	*194.72*
17	19.72	*172.64*	16.59	*50.48*	15.68	*31.76*	22.32	*196.58*
16	22.20	*174.71*	17.43	*34.38*	17.25	*36.83*	30.02	*290.74*
15	22.07	*173.99*	20.13	*163.41*	17.85	*49.16*	24.62	*228.18*
14	27.79	*229.05*	19.34	*47.03*	20.33	*40.02*	25.63	*170.63*
13	28.92	*217.13*	19.90	*47.00*	21.59	*60.04*	33.76	*274.27*
12	26.43	*176.15*	20.25	*34.94*	22.01	*47.92*	22.80	*93.34*
11	27.05	*174.20*	21.19	*40.13*	22.82	*39.07*	24.99	*98.06*
10	27.64	*174.04*	22.28	*41.95*	23.00	*41.11*	30.39	*235.20*
9	24.08	*36.30*	22.38	*39.12*	24.29	*48.29*	29.70	*187.92*
8	24.85	*35.93*	23.33	*40.03*	27.72	*108.84*	27.62	*112.94*
7	25.56	*35.60*	24.86	*42.81*	27.60	*64.65*	30.43	*121.93*
6	32.70	*153.08*	30.16	*157.34*	36.75	*173.90*	40.23	*217.40*

AMP (15 min)	[0,6)		[6,12)		[12,18)		[18,24)	
	Mean	*Std.dev.*	Mean	*Std.dev.*	Mean	*Std.dev.*	Mean	*Std.dev.*
25	13.21	*23.49*	16.28	*50.52*	17.98	*57.05*	22.78	*225.74*
24	16.67	*27.74*	19.25	*60.29*	21.56	*124.25*	28.94	*258.80*
23	17.84	*28.35*	21.07	*41.08*	23.74	*94.62*	30.02	*247.29*
22	16.76	*36.36*	20.95	*85.85*	22.95	*95.41*	28.33	*244.07*
21	16.61	*39.36*	21.12	*47.63*	23.23	*88.93*	27.91	*246.20*
20	16.14	*23.51*	22.13	*36.62*	23.79	*87.37*	25.56	*236.44*
19	19.72	*25.91*	24.07	*37.46*	27.50	*104.44*	28.88	*223.03*
18	19.84	*29.56*	23.47	*45.61*	25.88	*75.65*	28.56	*212.04*
17	18.80	*48.49*	21.93	*47.91*	23.57	*51.03*	26.24	*222.98*
16	18.86	*30.78*	21.94	*45.48*	23.88	*53.45*	27.00	*217.93*
15	17.77	*26.21*	21.13	*48.28*	23.71	*83.49*	25.45	*214.56*
14	16.05	*30.47*	17.88	*37.16*	19.56	*59.86*	20.38	*143.31*
13	15.94	*29.76*	18.01	*37.77*	18.99	*39.03*	18.29	*107.00*
12	13.67	*21.63*	15.72	*32.09*	17.45	*50.87*	17.00	*120.41*
11	13.30	*23.27*	16.50	*53.60*	17.49	*54.53*	14.26	*127.19*
10	13.55	*21.02*	17.40	*38.92*	17.84	*42.61*	15.18	*135.12*
9	17.88	*29.46*	22.38	*84.02*	21.99	*45.01*	22.09	*132.47*
8	18.95	*29.43*	22.30	*49.92*	22.83	*46.77*	23.85	*138.71*
7	18.10	*27.80*	25.10	*89.22*	23.87	*46.14*	23.29	*139.18*
6	22.14	*79.39*	32.38	*125.46*	34.05	*168.31*	30.26	*180.00*

Table 6: Average spreads and their standard deviations for the hourly (top) and 15-min products (bottom) products in the last 25 minutes before delivery in the Amprion area.

TNT (60 min)	[0,6) Mean	[0,6) Std.dev.	[6,12) Mean	[6,12) Std.dev.	[12,18) Mean	[12,18) Std.dev.	[18,24) Mean	[18,24) Std.dev.
25	7.67	49.38	6.79	8.25	8.36	55.11	7.82	15.51
24	7.46	49.64	7.26	30.67	7.89	49.68	7.38	19.86
23	7.31	49.83	7.06	10.57	8.04	44.61	7.30	16.40
22	7.49	49.86	7.47	10.17	8.34	48.49	8.17	43.85
21	7.22	49.76	7.09	8.63	8.12	48.41	9.85	108.88
20	7.46	49.93	7.29	8.29	8.13	43.55	9.80	75.68
19	9.25	50.09	8.65	9.50	9.78	31.97	10.31	39.10
18	10.21	55.65	9.25	9.59	10.57	46.39	11.54	82.15
17	12.30	52.04	11.81	18.80	12.08	37.91	14.16	80.24
16	13.45	52.05	12.01	13.72	13.13	35.30	14.85	59.44
15	14.52	51.66	13.82	35.73	14.31	35.20	15.86	56.40
14	27.92	63.37	20.17	30.97	23.80	115.65	26.99	70.66
13	18.70	52.26	15.92	23.70	18.64	76.01	20.30	61.09
12	18.01	51.65	14.86	12.87	16.79	36.07	18.91	49.35
11	17.87	51.69	15.08	17.20	16.41	30.35	18.94	53.30
10	17.56	50.52	15.09	14.90	16.60	27.31	21.37	113.04
9	17.25	15.19	16.19	17.01	18.11	28.61	20.66	83.77
8	17.92	20.19	16.29	15.76	19.78	71.77	19.40	32.95
7	17.87	14.53	17.16	17.19	19.67	46.90	20.68	68.90
6	19.59	21.73	17.90	21.60	20.17	36.72	23.11	82.39

TNT (15 min)	[0,6) Mean	[0,6) Std.dev.	[6,12) Mean	[6,12) Std.dev.	[12,18) Mean	[12,18) Std.dev.	[18,24) Mean	[18,24) Std.dev.
25	16.32	118.63	15.45	216.16	16.42	84.60	21.79	196.16
24	16.40	108.46	17.00	215.70	17.76	87.83	22.82	242.21
23	16.50	112.33	18.09	216.54	18.29	86.23	22.26	227.98
22	14.66	108.38	17.91	228.25	16.98	80.67	21.07	240.84
21	14.62	108.42	17.82	216.25	16.80	39.73	20.43	215.45
20	15.22	108.33	19.39	216.51	17.60	34.97	21.94	222.89
19	21.14	109.23	24.88	217.75	23.72	40.90	28.38	216.19
18	21.27	110.20	24.05	217.60	24.65	109.11	27.90	217.45
17	19.66	108.75	20.49	44.74	22.20	86.22	26.25	222.52
16	20.22	108.83	21.07	46.82	22.85	77.28	27.20	225.07
15	20.93	131.48	20.92	45.64	22.09	38.91	26.32	214.54
14	14.92	107.85	14.38	22.02	15.55	29.84	17.82	163.38
13	13.79	107.71	13.54	37.40	14.30	26.08	15.35	147.01
12	11.70	107.43	11.58	24.40	11.85	18.01	11.97	132.04
11	11.80	108.47	11.56	21.46	12.29	23.96	13.37	89.61
10	11.67	15.16	13.37	20.47	14.03	22.75	14.65	98.67
9	16.17	20.15	17.83	31.45	19.33	67.26	18.68	114.81
8	15.78	18.99	18.24	67.51	17.68	23.78	19.06	98.14
7	14.20	13.52	18.00	28.69	18.04	26.04	16.78	93.63
6	21.32	24.30	26.44	88.37	27.52	78.28	27.54	182.53

Table 7: Average spreads and their standard deviations for the hourly (top) and 15-min products (bottom) products in the last 25 minutes before delivery in the Tennet area.

50HZ (60 min)	[0,6)		[6,12)		[12,18)		[18,24)	
	Mean	Std.dev.	Mean	Std.dev.	Mean	Std.dev.	Mean	Std.dev.
25	12.21	171.49	8.28	19.26	9.45	38.20	14.54	175.10
24	11.48	171.42	8.59	23.57	9.19	31.68	13.36	174.74
23	11.86	171.62	9.23	22.77	10.05	35.09	17.18	231.30
22	11.34	171.49	9.44	24.72	10.49	55.27	14.46	183.37
21	10.70	171.51	8.25	13.39	9.99	37.36	11.09	181.09
20	11.74	171.53	9.49	18.80	11.14	50.10	17.11	210.29
19	19.21	172.78	15.91	27.98	18.73	58.45	24.91	216.46
18	20.29	174.51	15.59	24.29	18.35	55.32	22.32	187.65
17	31.89	176.59	24.64	37.98	26.67	62.13	38.35	267.40
16	34.69	175.52	25.31	33.86	27.97	59.10	34.71	188.65
15	38.20	176.25	27.81	38.26	30.17	61.07	38.46	211.53
14	41.62	176.98	29.79	43.06	33.72	71.51	47.70	368.89
13	43.04	197.20	29.94	51.89	34.46	78.81	39.14	108.20
12	40.23	176.24	29.02	38.05	32.58	50.55	37.10	108.48
11	44.54	229.73	28.89	39.33	32.62	45.04	45.69	234.51
10	43.62	229.54	29.30	42.14	31.86	43.55	43.57	161.02
9	44.90	176.33	32.18	43.70	36.30	54.66	42.75	106.15
8	49.18	65.54	35.85	45.68	41.83	71.43	53.84	99.50
7	52.69	165.08	37.30	49.09	42.62	70.97	53.42	115.44
6	52.84	68.59	38.65	59.34	47.44	67.59	64.17	145.71

50HZ (15 min)	[0,6)		[6,12)		[12,18)		[18,24)	
	Mean	Std.dev.	Mean	Std.dev.	Mean	Std.dev.	Mean	Std.dev.
25	15.18	87.74	14.60	28.92	17.00	65.26	25.08	239.07
24	15.73	21.37	16.60	33.32	18.52	48.28	27.39	248.77
23	16.42	25.64	18.09	31.60	20.05	51.32	27.73	237.58
22	15.08	21.46	17.63	43.19	19.22	58.74	23.83	225.07
21	14.00	23.64	17.30	39.18	18.39	50.45	23.00	229.10
20	15.89	21.90	19.23	34.60	20.59	52.14	24.99	229.07
19	24.67	28.46	27.36	48.71	29.35	76.03	34.89	229.04
18	24.67	26.46	26.61	49.43	28.54	72.74	34.65	210.91
17	23.53	23.98	25.39	49.04	27.47	102.74	32.37	208.35
16	24.18	25.89	25.54	47.43	27.60	96.56	32.42	213.19
15	26.43	25.12	27.22	46.79	29.37	71.30	36.76	239.00
14	19.18	20.86	18.57	23.46	20.67	44.33	24.24	165.33
13	18.57	19.44	18.23	31.40	19.95	41.86	22.43	120.80
12	15.53	20.07	15.77	27.15	17.09	40.55	17.42	106.94
11	15.01	17.50	15.72	29.17	16.65	26.15	18.27	113.61
10	14.68	15.79	15.97	21.09	17.35	37.40	18.00	114.95
9	20.79	22.76	23.01	83.94	23.21	39.59	26.20	114.28
8	20.61	20.21	23.73	70.87	23.57	68.12	26.50	115.34
7	18.58	21.20	22.12	40.57	21.22	26.16	22.70	135.75
6	27.16	26.75	30.88	53.23	31.67	79.05	35.17	162.44

Table 8: Average spreads and their standard deviations for the hourly (top) and 15-min products (bottom) products in the last 25 minutes before delivery in the 50Hertz area.

Appendix B

Amprion		Order Size [MW]									
Type	Phase	1	2	3	4	5	6	7	8	9	10
Call (HardCoal)	[T-30,T-5)	33.22	32.33	31.70	31.21	30.78	30.29	29.88	29.55	29.24	28.98
	[T-10,T-5)	26.17	25.55	24.77	24.46	24.20	23.68	23.39	23.14	22.92	22.72
Put (HardCoal)	[T-30,T-5)	57.47	57.37	57.20	57.11	56.98	56.94	56.92	56.91	56.44	54.43
	[T-10,T-5)	52.24	52.84	51.65	50.87	50.77	48.95	48.86	48.80	48.79	48.63
Call (Gas)	[T-30,T-5)	43.11	42.05	41.29	40.69	40.17	39.57	39.07	38.67	38.29	37.98
	[T-10,T-5)	34.78	34.00	33.04	32.65	32.32	31.66	31.29	30.97	30.69	30.43
Put (Gas)	[T-30,T-5)	41.93	41.84	41.69	41.61	41.49	41.43	41.39	41.36	41.05	39.16
	[T-10,T-5)	38.38	38.81	37.86	37.17	37.07	35.36	35.27	35.21	35.18	35.03

Table 9: Average call (sales) and put (purchase) option values as function of the order sizes for typical gas and hard coal fired power plants. The values are calculated for the whole SDAT phase and the last five minutes before GC with data for the whole year 2023 for the Amprion control area.

Amprion		Order Size [MW]									
Type	Phase	1	2	3	4	5	6	7	8	9	10
Call (HardCoal)	[T-30,T-5)	16.02	15.58	15.32	15.11	14.93	14.71	14.50	14.35	14.21	14.07
	[T-10,T-5)	12.15	11.78	11.45	11.29	11.14	10.77	10.63	10.50	10.38	10.27
Put (HardCoal)	[T-30,T-5)	46.08	45.88	45.68	45.57	45.49	45.51	45.43	45.39	44.88	44.03
	[T-10,T-5)	41.27	41.21	40.40	39.75	39.61	38.90	38.81	38.73	38.65	38.55
Call (Gas)	[T-30,T-5)	28.60	27.96	27.54	27.23	26.91	26.58	26.30	26.06	25.85	25.64
	[T-10,T-5)	22.62	22.07	21.45	21.19	20.94	20.39	20.15	19.94	19.77	19.59
Put (Gas)	[T-30,T-5)	29.27	29.09	28.91	28.78	28.69	28.64	28.53	28.45	28.21	27.35
	[T-10,T-5)	26.39	26.23	25.54	25.34	25.21	24.55	24.45	24.37	24.29	24.21

Table 10: Medians of option values as function of order sizes with data for the whole year 2023 for the Amprion control area.

Amprion		Order Size [MW]									
Type	Phase	1	2	3	4	5	6	7	8	9	10
Call (HardCoal)	[T-30,T-5)	44.84	42.93	41.94	41.24	40.68	39.93	39.31	38.82	38.36	37.98
	[T-10,T-5)	37.51	36.65	35.85	35.45	35.14	34.51	34.06	33.70	33.41	33.14
Put (HardCoal)	[T-30,T-5)	42.11	42.26	42.28	42.29	42.24	42.27	42.40	42.58	42.38	39.88
	[T-10,T-5)	39.05	40.38	39.17	38.87	38.94	36.34	36.33	36.36	36.43	36.35
Call (Gas)	[T-30,T-5)	47.42	45.46	44.44	43.70	43.12	42.33	41.68	41.18	40.69	40.30
	[T-10,T-5)	40.30	39.37	38.54	38.11	37.77	37.13	36.66	36.28	35.98	35.70
Put (Gas)	[T-30,T-5)	39.66	39.79	39.80	39.81	39.78	39.84	39.97	40.13	39.94	36.99
	[T-10,T-5)	36.44	37.42	36.51	36.10	36.16	33.14	33.14	33.16	33.23	33.12

Table 11: Standard deviations of option values as function of order sizes with data for the whole year 2023 for the Amprion control area.

TransnetBW		Order Size [MW]									
Type	Phase	1	2	3	4	5	6	7	8	9	10
Call (HardCoal)	[T-30,T-5)	23.48	22.57	21.83	21.28	20.84	20.48	20.10	19.77	19.48	19.23
	[T-10,T-5)	18.88	17.38	16.19	15.27	14.59	13.98	13.53	13.15	12.85	12.63
Put (HardCoal)	[T-30,T-5)	48.28	46.41	46.27	44.65	44.61	44.55	44.47	44.45	44.43	44.39
	[T-10,T-5)	41.72	40.57	37.83	36.35	35.43	34.50	33.95	33.50	33.37	32.74
Call (Gas)	[T-30,T-5)	31.31	30.15	29.24	28.55	28.01	27.56	27.10	26.69	26.33	26.01
	[T-10,T-5)	24.69	22.83	21.37	20.22	19.36	18.59	18.05	17.59	17.23	16.98
Put (Gas)	[T-30,T-5)	35.09	33.34	33.19	31.68	31.62	31.55	31.45	31.41	31.36	31.31
	[T-10,T-5)	32.19	31.09	28.55	27.24	26.44	25.64	25.16	24.77	24.62	24.02

Table 12: Mean option values as function of order sizes with data for the whole year 2023 for the TransnetBW control area.

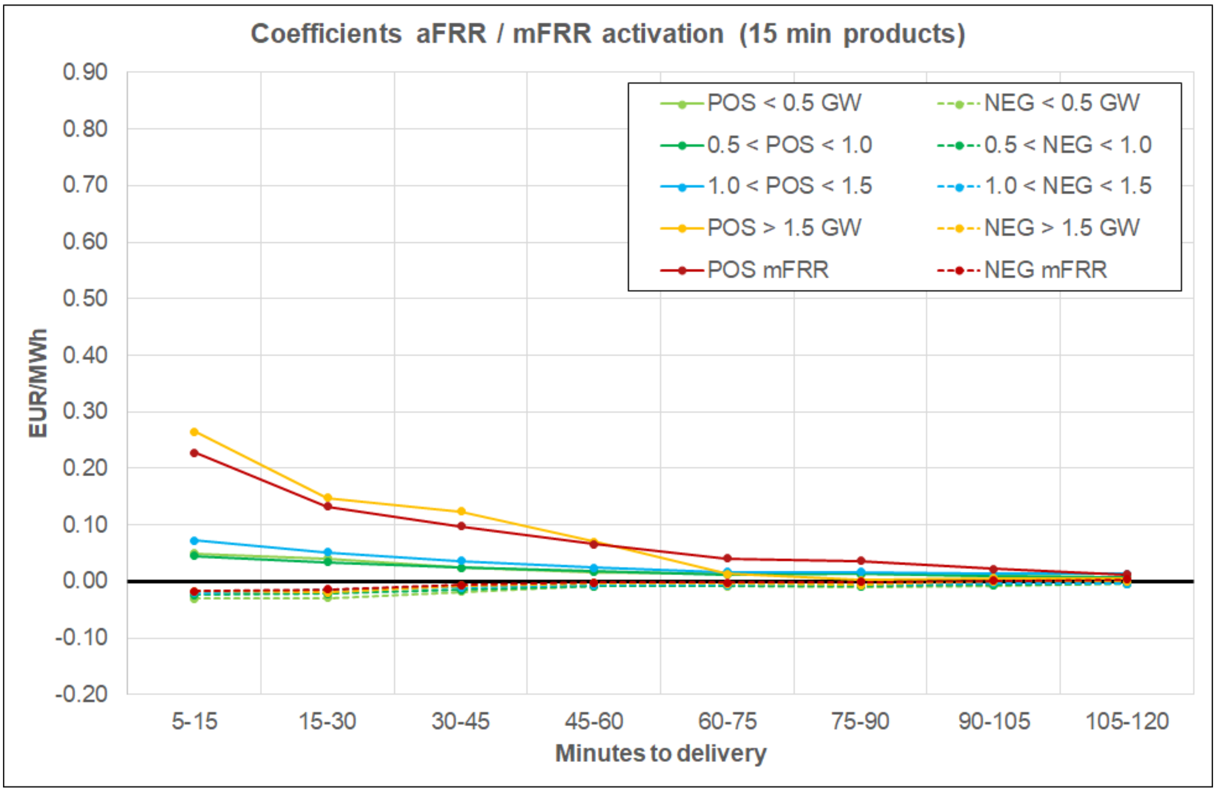
TransnetBW		Order Size [MW]									
Type	Phase	1	2	3	4	5	6	7	8	9	10
Call (HardCoal)	[T-30,T-5)	8.94	8.43	8.09	7.85	7.67	7.52	7.37	7.24	7.13	7.03
	[T-10,T-5)	9.34	8.23	7.43	6.82	6.39	6.09	5.85	5.65	5.49	5.38
Put (HardCoal)	[T-30,T-5)	36.52	35.10	34.75	33.90	33.68	33.46	33.29	33.23	33.15	33.05
	[T-10,T-5)	31.23	30.00	28.65	27.38	26.37	25.59	24.92	24.36	23.98	23.52
Call (Gas)	[T-30,T-5)	18.09	17.30	16.79	16.43	16.17	15.95	15.73	15.54	15.36	15.19
	[T-10,T-5)	15.52	13.99	12.82	11.92	11.25	10.80	10.45	10.15	9.93	9.78
Put (Gas)	[T-30,T-5)	22.69	22.00	21.66	20.85	20.65	20.45	20.28	20.21	20.13	20.03
	[T-10,T-5)	21.91	20.76	19.62	18.55	17.66	16.99	16.41	15.93	15.60	15.24

Table 13: Medians of option values as function of order sizes with data for the whole year 2023 for the TransnetBW control area.

TransnetBW		Order Size [MW]									
Type	Phase	1	2	3	4	5	6	7	8	9	10
Call (HardCoal)	[T-30,T-5)	35.61	34.49	33.55	32.84	32.27	31.78	31.27	30.79	30.39	30.03
	[T-10,T-5)	27.82	26.23	25.00	24.05	23.37	22.75	22.22	21.77	21.38	21.06
Put (HardCoal)	[T-30,T-5)	39.90	38.27	38.78	36.88	37.07	37.21	37.32	37.43	37.54	37.64
	[T-10,T-5)	34.31	34.81	32.25	32.36	32.73	32.76	33.10	33.39	34.05	33.86
Call (Gas)	[T-30,T-5)	38.57	37.40	36.38	35.61	34.98	34.45	33.89	33.37	32.93	32.55
	[T-10,T-5)	30.30	28.66	27.37	26.38	25.67	25.00	24.44	23.95	23.52	23.17
Put (Gas)	[T-30,T-5)	36.82	34.71	35.18	33.05	33.21	33.34	33.43	33.53	33.63	33.72
	[T-10,T-5)	31.56	31.78	28.64	28.48	28.68	28.65	28.88	29.07	29.60	29.12

Table 14: Standard deviations of option values as function of order sizes with data for the whole year 2023 for the TransnetBW con-trol area.

Appendix C



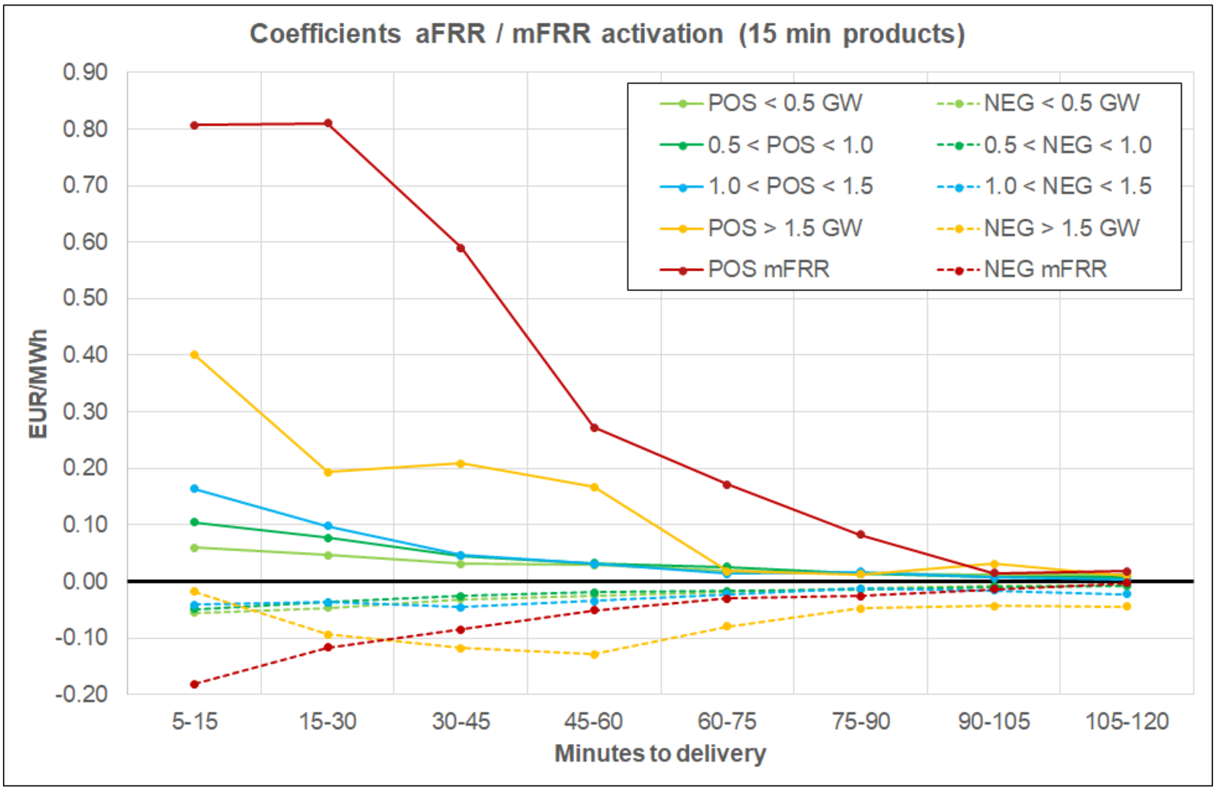
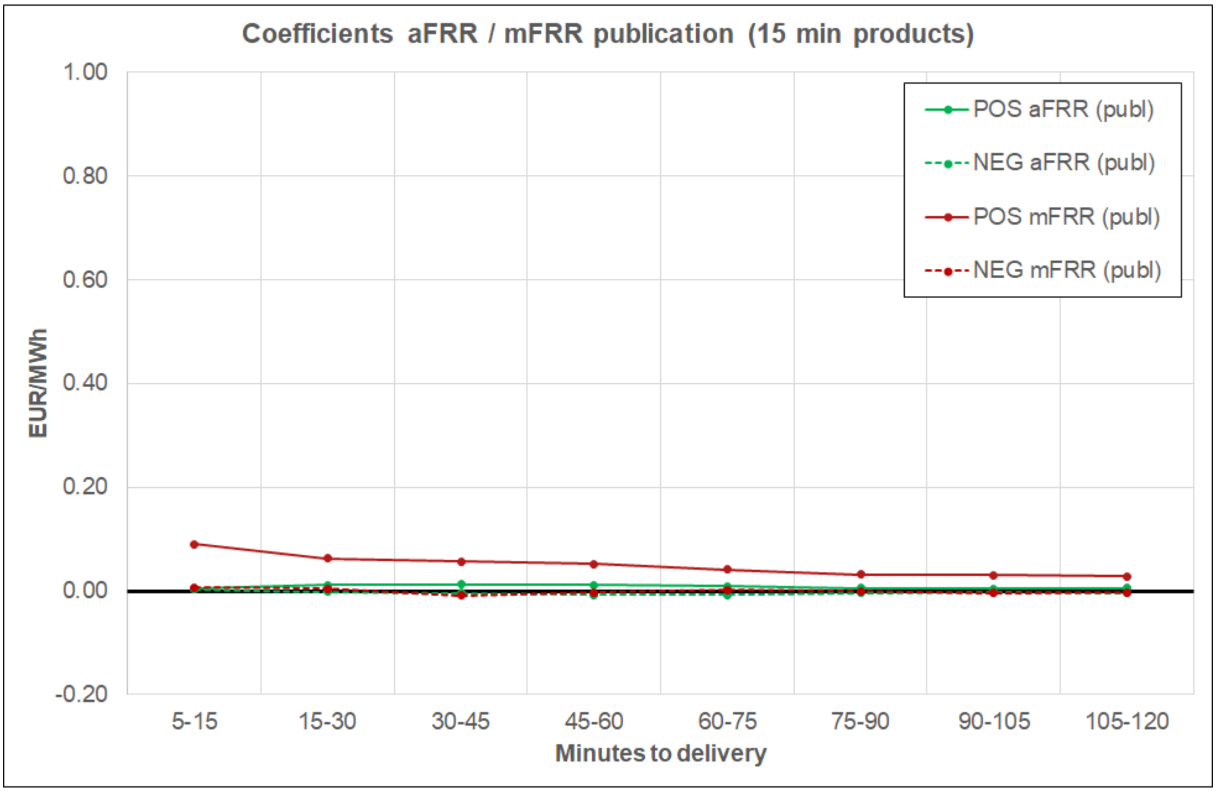


Figure 22: Coefficients of the variables for aFRR and mFRR activation from the estimation of the full model for the sample periods 2021 (upper panel) and 2023 (lower panel). Different magnitudes of aFRR activation were modeled as individual variables to take into account a nonlinear relationship between price and activated energy. A similar differentiation was not possible for mFRR due to the much smaller number of occurrences.



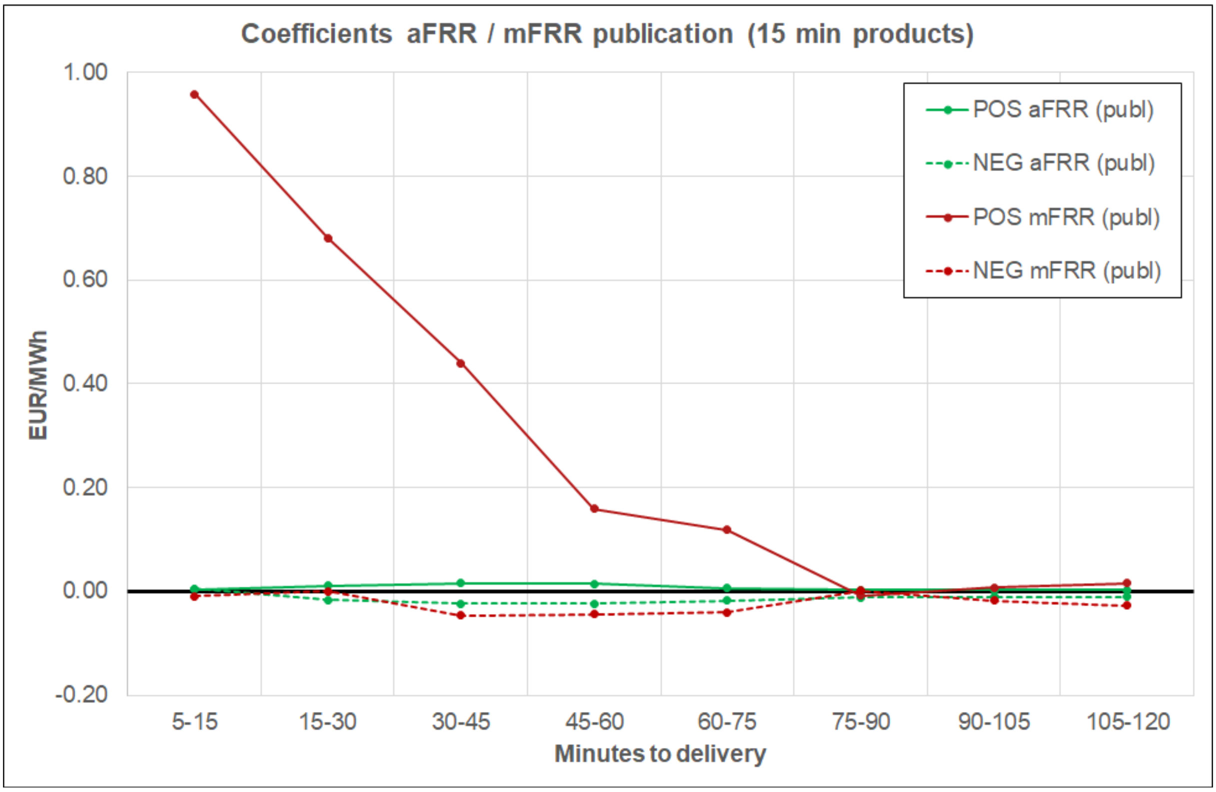


Figure 23: Coefficients of the variables for publications of aFRR and mFRR aggregated activations after the end of a previous 15-min time slice from estimation of the full model for the sample periods 2021 (upper panel) and 2023 (lower panel).

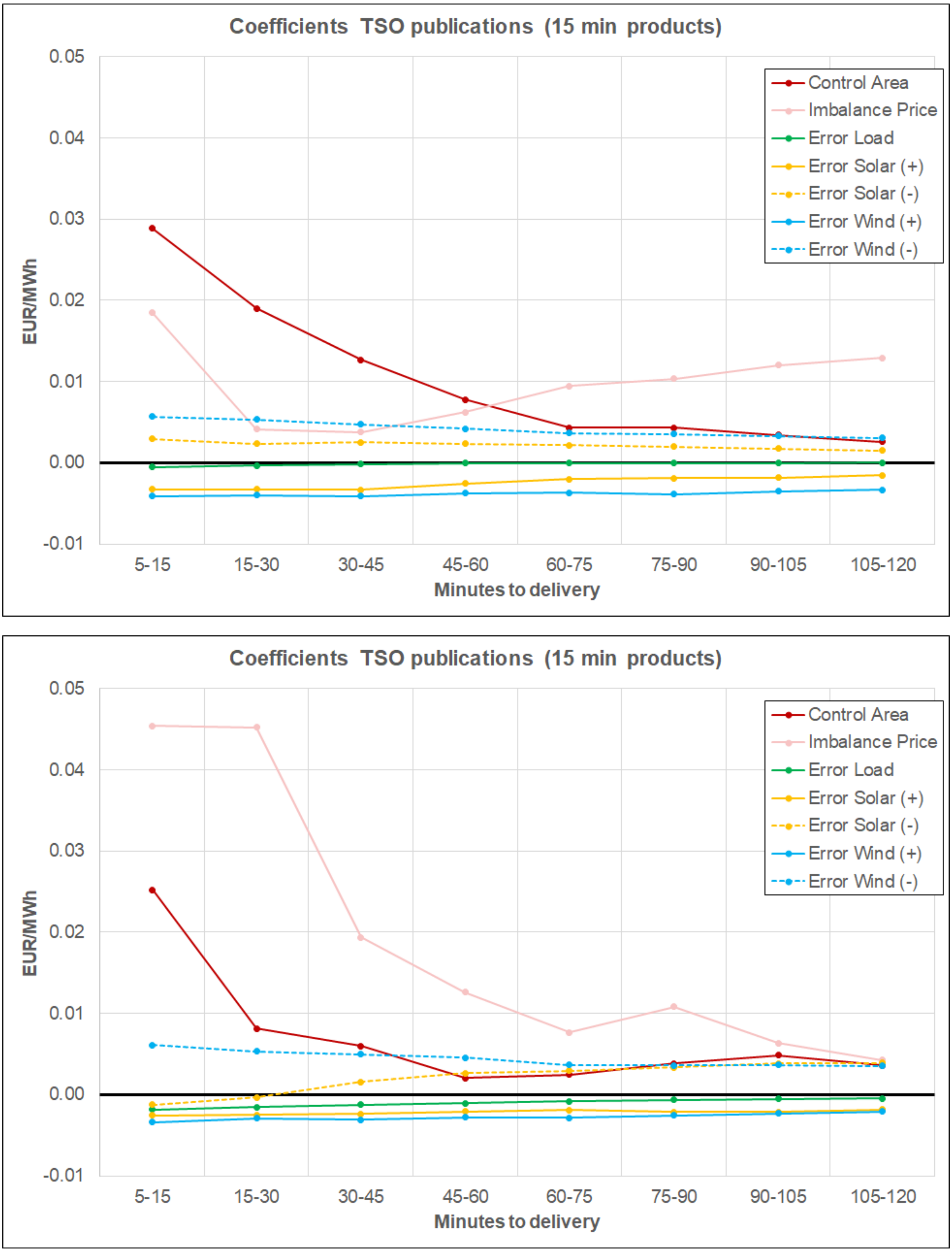


Figure 24: Coefficients of the variables for other TSO publications after the end of a previous 15-min time slice from the estimation of the full model for the sample periods 2021 (upper panel) and 2023 (lower panel). "Error" refers to the difference between the realized value and its day-ahead forecast. For wind and solar, it is distinguished between positive and negative deviations, both entering the regression equation with positive sign. A negative deviation means that the actual generation is lower than forecasted. Note that the coefficients of "Error Solar (-)" for the two products closest to delivery are not significant for the sample period 2023 (p-value 11%). The control area balance is the difference between feed-in and withdrawal in the electricity grid. A positive value represents a deficit of energy, which must be compensated by reserve energy.