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# DigIPlat – Digital Solutions for Interoperability of Flexibility Platforms

## Economic Evaluation

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# Summary

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 DigIPlat project deals with the interoperability of flexibility platforms through which the allocation of flexible capacities can be better coordinated, thereby increasing their economic efficiency as well as the security of supply. To this end, solutions for the cross-platform utilization of flexibility for redispatch, balancing energy, and intraday markets are being conceptually developed from an information and procedural engineering perspective and analyzed from an economic viewpoint. The latter involves a thorough analysis of those short-term markets where a flexible capacity could be offered: The balancing energy market (BEM) and the intraday market (IDM). We estimate the value added by a flexible capacity that is offered in the BEM and IDM. To assess the earnings potential of intraday and balancing energy products from a supplier's perspective, intraday and balancing energy products are modeled as financial options.

Empirical analyses with 2023 data indicate that, despite different product characteristics, in general both markets are similarly attractive. Offering balancing energy would only be more profitable than trading in the intraday market in the last 30 minutes before delivery for providers in a control area with low liquidity (reflected by a low depth of the intraday order book, high bid-ask spreads and a small number of transactions). The evaluation methodology also allows forecasts of returns in upcoming delivery periods and, thereby, the development of rules as to whether a supplier should bid on the intraday or balancing energy market, since the capacity can only be marketed once. As a use case, we investigate a potential transfer of bids from the intraday to the BEM. This increases the liquidity of the latter and, due to a shift in the merit order curve by the additional bids, can lead to lower costs for balancing energy. Since the earnings opportunities in the intraday and the balancing energy market are similar, no additional incentives would be needed for participants in the intraday market to allow their bids to be transferred.

To assess the quality of the intraday market, we introduce a matric that quantifies frictions for limit order books of an individual trading product. We also describe a general model for the of joint dynamics of prices and the volume of an open position based on copulas.

Next, we show the impact of PICASSO on the demand for automatic and manual frequency restauration reserve, and we analyze the impact on the bidding behavior of market participants in the intraday market by comparing the years 2021 and 2023 (before and after go-live of PICASSO). A last section reflects on the potential system risks that may arise in connection with hedging strategies.

# Zusammenfassung

Dezentrale, flexible Kapazitäten werden zunehmend zum Rückgrat der Versorgungssicherheit. Ihre digitale Vernetzung erfordert Datenaustausch und damit eine Neufassung der Zusammenarbeit zwischen Übertragungs- und Verteilnetzbetreibern. Die Einrichtung elektronischer Kommunikations- und Handelsplattformen für den grenzüberschreitenden Spotmarkt, die Einbeziehung von Ausgleichsdiensten und Kapazitätsmanagement, ist eine natürliche Folge davon und steigert das Wertschöpfungspotenzial im integrierten europäischen Strommarkt weiter.

Bisher dominierten Grossstromversorger den Zugang zu den Märkten für Systemdienstleistungen. Mit zunehmenden dezentralen Einspeisungen und Speicherkapazitäten auf Verteilnetzebene besteht ein wachsender Bedarf an Stabilisierungsmechanismen auf allen Spannungsebenen und somit an der Integration kleinerer Anbieter und Verbraucher. Dezentrale, flexible Erzeugungs- und Speicherkapazitäten sowie die Umwandlung in andere Energieträger wie Wasserstoff, synthetische Gase oder thermische Energie erfordern eine effiziente und effektive Koordination. Begleitet vom Sektorkopplung wird das Energiesystem immer dezentraler und vernetzter. Die Digitalisierung erzeugt die erforderlichen Daten und ermöglicht eine interne Vernetzung sowie eine externe Vernetzung mit den Märkten.

Das DigIPlat-Projekt beschäftigt sich mit der Interoperabilität von Flexibilitätsplattformen, über die die Zuteilung flexibler Kapazitäten besser koordiniert werden kann, was sowohl deren Wirtschaftlichkeit als auch die Versorgungssicherheit erhöht. Zu diesem Zweck werden Lösungen für die plattformübergreifende Nutzung von Flexibilität für Redispatch, Regelenergie und Intraday-Märkte konzeptionell aus einer Informations- und Verfahrenstechnikperspektive entwickelt und ökonomisch analysiert. Letztere umfasst eine gründliche Analyse der kurzfristigen Märkte, auf denen flexible Kapazitäten angeboten werden könnten: Regelarbeitsmarkt (RAM) und Intraday-Markt (IDM). Wir schätzen den Mehrwert einer flexiblen Kapazität ab, die im RAM und IDM angeboten wird. Um das Ertragspotenzial von Intraday- und Regelenergieprodukten aus der Sicht eines Anbieters zu bewerten, werden Intraday- und Regelenergieprodukte als Finanzoptionen modelliert.

Empirische Analysen mit Daten aus dem Jahr 2023 deuten darauf hin, dass trotz unterschiedlicher Produktmerkmale im Allgemeinen beide Märkte gleichermassen attraktiv sind. Das Angebot von Regelenergie wäre nur profitabler als der Handel im Intraday-Markt in den letzten 30 Minuten vor der Lieferung für Anbieter in einer Regelzone mit geringer Liquidität (dargestellt durch eine geringe Tiefe des Intraday-Orderbuchs, hohe Geld-Brief-Spannen und eine geringe Anzahl von Transaktionen). Die Bewertungsmethodik ermöglicht auch Prognosen über Erträge in kommenden Lieferperioden und damit die Entwicklung einer Entscheidungsregel dafür, ob ein Lieferant auf dem Intraday- oder Regelenergiemarkt bieten sollte, da die Kapazität nur einmal vermarktet werden kann. Als Anwendungsfall untersuchen wir die potenzielle Übertragung von Geboten vom Intraday-Markt auf den RAM. Dadurch erhöht sich die Liquidität des Letzteren und kann aufgrund einer Verschiebung der Merit-Order-Kurve durch die zusätzlichen Gebote zu niedrigeren Kosten für Regelenergie führen. Da die Verdienstmöglichkeiten im Intraday- und im Regelenergiemarkt ähnlich sind, wären keine zusätzlichen Anreize erforderlich, damit Teilnehmer am Intraday-Markt ihre Gebote übertragen lassen.

Zur Bewertung der Qualität des Intraday-Marktes führen wir eine Metrik ein, die Friktionen für Limit-Orderbücher eines einzelnen Handelsprodukts quantifiziert. Zudem beschreiben wir ein allgemeines Modell für die gemeinsame Dynamik von Preisen und dem Volumen einer offenen Position auf Basis von Kopulas.

Anschliessend zeigen wir die Auswirkungen von PICASSO auf die Nachfrage nach sekundärer und tertiärer Regelreserve und analysieren die Auswirkungen auf das Gebotsverhalten der Marktteilnehmer im Intraday-Markt durch den Vergleich der Jahre 2021 und 2023 (vor und nach dem Go-Live von PICASSO). Ein letzter Abschnitt reflektiert über potenzielle Systemrisiken, die im Zusammenhang mit Absicherungsstrategien auftreten können.

# Résumé

Les capacités décentralisées et flexibles deviennent de plus en plus le pilier de la sécurité d'approvisionnement. Leur mise en réseau numérique nécessite un échange de données et ainsi une redéfinition de la coopération entre les opérateurs de systèmes de transmission et de distribution. L'établissement de plates-formes électroniques de communication et de trading pour les échanges transfrontaliers au comptant, intégrant des services d'équilibrage et de gestion des capacités, est une conséquence naturelle de cela et accroît encore le potentiel de création de valeur sur un marché européen de l'électricité intégré.

Jusqu'à présent, l'accès aux marchés des services systémiques a été dominé par de grands fournisseurs d'électricité. Avec l'augmentation des capacités décentralisées d'injection et de stockage au niveau du réseau de distribution, il y a un besoin croissant de mécanismes de stabilisation à tous les niveaux de tension et, par conséquent, d'intégration de plus petits fournisseurs et consommateurs. Les capacités de génération et de stockage décentralisées et flexibles, ainsi que la conversion en d'autres vecteurs énergétiques tels que l'hydrogène, les gaz synthétiques ou l'énergie thermique, nécessitent une coordination efficace et efficiente. Accompagné par le couplage des secteurs, le système énergétique devient de plus en plus décentralisé et interconnecté. La digitalisation génère les données nécessaires et permet la mise en réseau interne ainsi que des interactions externes avec les marchés.

Le projet DigIPlat traite de l'interopérabilité des plates-formes de flexibilité grâce auxquelles l'allocation des capacités flexibles peut être mieux coordonnée, ce qui accroît leur efficacité économique ainsi que la sécurité d'approvisionnement. À cette fin, des solutions pour l'utilisation interplateformes de la flexibilité pour le redispatch, l'énergie de réglage et les marchés intraday sont développées conceptuellement d'un point de vue de l'ingénierie de l'information et des procédures, et analysées d'un point de vue économique. Cette dernière implique une analyse approfondie des marchés à court terme où une capacité flexible pourrait être offerte : le marché de l'énergie de réglage (BEM) et le marché intraday (IDM). Nous estimons la valeur ajoutée par une capacité flexible offerte dans le BEM et l'IDM. Pour évaluer le potentiel de revenu des produits intraday et d'énergie de réglage du point de vue d'un fournisseur, les produits intraday et d'énergie de réglage sont modélisés comme des options financières.

Les analyses empiriques avec les données de 2023 indiquent que, malgré des caractéristiques de produit différentes, en général les deux marchés sont également attrayants. L'offre d'énergie de réglage ne serait plus rentable que le trading sur le marché intraday dans les 30 dernières minutes avant la livraison pour les fournisseurs dans une zone de contrôle avec une faible liquidité (reflétée par une faible profondeur du carnet de commandes intraday, des écarts de prix acheteur-vendeur élevés et un petit nombre de transactions). La méthodologie d'évaluation permet également des prévisions de rendements pour les prochaines périodes de livraison et, par conséquent, le développement de règles pour déterminer si un fournisseur devrait proposer des offres sur le marché intraday ou d'énergie de réglage, puisque la capacité ne peut être commercialisée qu'une seule fois. À titre de cas d'utilisation, nous étudions un transfert potentiel des offres du marché intraday vers le marché BEM. Cela augmente la liquidité de ce dernier et, en raison d'un déplacement de la courbe de mérite par les offres supplémentaires, peut entraîner des coûts plus bas pour l'énergie de réglage. Comme les opportunités de revenus sur les marchés intraday et de l'énergie de réglage sont similaires, aucun incitatif supplémentaire ne serait nécessaire pour que les participants au marché intraday permettent le transfert de leurs offres.

Pour évaluer la qualité du marché intraday, nous introduisons une métrique quantifiant les frictions pour les carnets d'ordres limites d'un produit de trading individuel. Nous décrivons également un modèle général pour la dynamique conjointe des prix et du volume d'une position ouverte basé sur des copules.

Ensuite, nous montrons l'impact de PICASSO sur la demande de réserve de restauration de fréquence automatique et manuelle, et nous analysons l'impact sur le comportement d'offre des participants du marché intraday en comparant les années 2021 et 2023 (avant et après la mise en service de PICASSO). Une dernière section reflète sur les risques systémiques potentiels pouvant survenir en lien avec les stratégies de couverture.

# Main findings («Take-Home Messages»)

- We investigate as a use case the transfer of bids from the intraday to the balancing energy market. This can increase the liquidity of the latter due to a shift in the merit order curve and potentially reduces the costs of balancing energy.
- The intraday and balancing energy markets offer similar earnings potential. This implies that no additional incentives must be offered to participants in the intraday market to allow their bids to be transferred.
- The introduction of the PICASSO platform for the international exchange of automatic frequency restauration reserve has led to less balancing energy activations and has impacted the price finding process on the intraday market. Bidders that act in the intraday and balancing energy market simultaneously have less possibilities to use the information provided by activation signals for trading decisions in the intraday market.
- The abolition of the release of non-awarded bids on the German balancing energy market by the regulator has increased the bid prices. This leads to higher costs for balancing energy.

# Contents

**List of abbreviations**

| | |
|---|---|
| ABM | Arithmetic Brownian Motion |
| aFRR | Automatic Frequency Restauration Reserve |
| AOF | Activation Optimization Function |
| ARA | Amsterdam, Rotterdam, Antwerp (harbors) |
| BE | Balancing Energy |
| BEM | Balancing Energy Market |
| BNetzA | Bundesnetzagentur (Federal Network Agency, Germany) |
| 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 |
| ElCom | Federal Electricity Commission (Switzerland) |
| EEX | European Energy Exchange |
| EU | European Union |
| FV | Fair Value |
| GC | Gate Closure |
| ID | Intraday |
| ID1 | volume-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 |
| IGCC | International Grid Control Cooperation |
| ior/cf-HSG | Institute for Operations Research and Computational Finance, University of St. Gallen |
| LOB | Limit Order Book |
| mFRR | Manual Frequency Restauration Reserve |
| MO | Merit Order |
| OTC | Over-the-Counter |
| PICASSO | Platform for the International Coordination of Automated Frequency Restoration and Stable System Operation |
| SDAT | Single Delivery Area Trading |
| SFOE | Swiss Federal Office of Energy |
| SIDC | Single Intraday Coupling |
| THE | Trading Hub Europe |
| TSO | Transmission System Operator |
| XBID | Cross-border Intraday Market |

# Extended management summary

## Overview

The focus of the project work is on the intraday market for the market area Germany and the balancing energy market to estimate the value creation through trading with flexible capacities. A gas power plant, is prequalified for the provision of positive and negative balancing energy, serves as a representative flexible capacity. We concentrate in our analyses on the German market area due to its higher liquidity and, mainly, because of data availability.

We analyze:

i) The revenue potential of a flexible capacity on the balancing energy market vs. intraday trading, considering the liquidity in the intraday market and its impact on volume-dependent transaction prices,

ii) the economic value of a flexible capacity, supplemented by a use case that deals with the integration of bids from the order book of the intraday market into the bid list of the regular energy market,

iii) the value of perfect information,

iv) the impact of the new PICASSO platform for the exchange of frequency restauration reserve with automatic activation on the activated volumes of secondary and tertiary balancing energy,

v) the impact of PICASSO on the bidding behavior of market participants,

vi) system risks related to hedging strategies, and finally

vii) insights for the Swiss market area.

We define as T the time at which a 15-minute electricity delivery begins. T thus represents the start of delivery. Intraday trading for this electricity delivery begins at 3:00 p.m. the day before. We consider the so-called SDAT phase (Same Delivery Area Trading) of the intraday market for Germany, which covers a period from 30 minutes up to 5 minutes before the start of the delivery and in which trading takes place separately in the four control areas TransnetBW, Amprion, Tennet and 50Hertz. For simplicity, we characterize this trading phase as the interval [T – 30, T – 5]. The time T – 5 is also referred to as the gate closure for the intraday trading of the corresponding trading product. A day consists of 96 quarter hours, so in the intraday market, 96 trading products for the respective 15-minute electricity delivery are tradable (we concentrate on 15-minute products since their delivery period is identical to the products in the balancing energy market; 60-minute products are not discussed here).

For completeness, it should be mentioned that in the time interval [T – 60, T – 30] intraday trading is possible in the entire German market area, i.e., also between different control areas. The period from the start of trading (3:00 p.m. the day before) to T – 60 includes the Single Intraday Coupling (SDIC), which allows intraday trading between different European market areas (excluding the Swiss market area).

In the first section of this report, we formulate the research questions, followed in section two by a characterization of the short-term electricity markets (intraday and balancing energy markets) on which flexible capacities can be traded.

In the third section, we determine the revenue potential of a flexible capacity in the balancing energy market for the German market area and compare this to the revenue potential of intraday trading in the four control areas within the SDAT phase. The different liquidity in the individual market areas is explicitly considered. Based on an economic decision rule at time T – 30, a decision is made as to whether the flexible capacity will be offered in the balancing energy market or whether a higher revenue can be expected from intraday trading within the respective control area over the period [T – 30, T – 5]. We analyze the value of perfect information under the idealized assumption of knowing the prices for the balancing energy market and for the intraday market in the respective control areas already at time T – 30. Finally, we describe a use case of transferring bids from the order book of the intraday market to the balancing energy market and assess its benefits.

In section four, we provide a general characterization of the quality of intraday markets and measures for liquidity in the different trading phases. We also describe a general model for the of joint dynamics of prices and the volume of an open position based on copulas. In a fifth section, we show the impact of PICASSO on the demand for automatic and manual frequency restauration reserve, and we analyze its impact on the bidding behavior of participants in the intraday market by comparing the years 2021 and 2023 (before and after go-live of PICASSO). Section six reflects on the potential system risks that may arise in connection with hedging strategies. Finally, we summarize in the seventh section the findings that can be derived for the Swiss market area.

In the sequel, we summarize some main findings.

## #1: Revenue potential for a flexible capacity: balancing energy vs. intraday trading

We assess the revenue potential for balancing energy in the amount of 1 MW separately for positive and negative balancing energy. In the case of positive balancing energy, we calculate the revenue for the additional production of 1 MW and for negative balancing energy the revenue for an additional consumption of 1 MW. Assuming that we can determine a trigger price for a flexible capacity at which additional production is beneficial, or below which additional consumption is beneficial, respectively, it can be derived for each quarter-hour of a day whether additional production or consumption of 1 MW generates added value in the electricity market.

For a case study, we are looking at the second half of 2023. The cross-border marginal prices (CBMP) for positive and negative balancing energy from the PICASSO platform, as well as the market prices of 15-minute products for electricity delivery in the intraday market are available for all 17'668 quarter-hours of the sample period. This allows us to identify those quarter-hours separately based on the balancing energy market and on the intraday trading in different balancing zones where an increase in production or consumption of 1 MW generates added value. The revenue achievable in this quarter-hour in the balancing energy market is determined by the corresponding CBMP marginal price. The revenue achievable in the intraday market is determined by the corresponding market price.

Figure 1 shows the revenues achievable for positive and balancing energy in the second half of 2023. It is noticeable that the revenue potential for providing positive balancing energy at EUR 88'710 is significantly lower than the revenue potential for providing negative balancing energy at EUR 143'967. Since the number of quarter-hours in which a surcharge and thus a call is made in the balancing energy market is approximately comparable, we can conclude that the marginal prices for negative balancing energy are significantly higher than those for positive balancing energy.

Alternatively, instead of submitting a bid for positive balancing energy, a sales transaction can be triggered in the intraday market if the order book on the sales curve shows a positive intrinsic value of the flexible capacity for additional production. Likewise, instead of submitting a bid for negative balancing energy, a purchase transaction can be triggered if the order book on the purchase curve shows a positive intrinsic value of the flexible capacity for additional consumption of 1 MW. Thus, the revenues achievable in the balancing zones are determined by the transaction prices derived from the order books.

Figure 1 shows also the revenues achievable in the second half of 2023 for the sale of additional production or for the purchase of additional consumption each at 1 MW. It is evident that the revenue potential for both selling and buying an additional MW in the control area TransnetBW is significantly lower than the revenue potential in the other three control areas (Amprion, Tennet, 50Hertz). This is because the order book in the TransnetBW area shows significantly lower liquidity than the order books in the other three balancing zones. An order book with lower liquidity leads to higher bid-ask spreads and thus to lower intrinsic values of a flexible capacity. This means that in the TransnetBW control area,

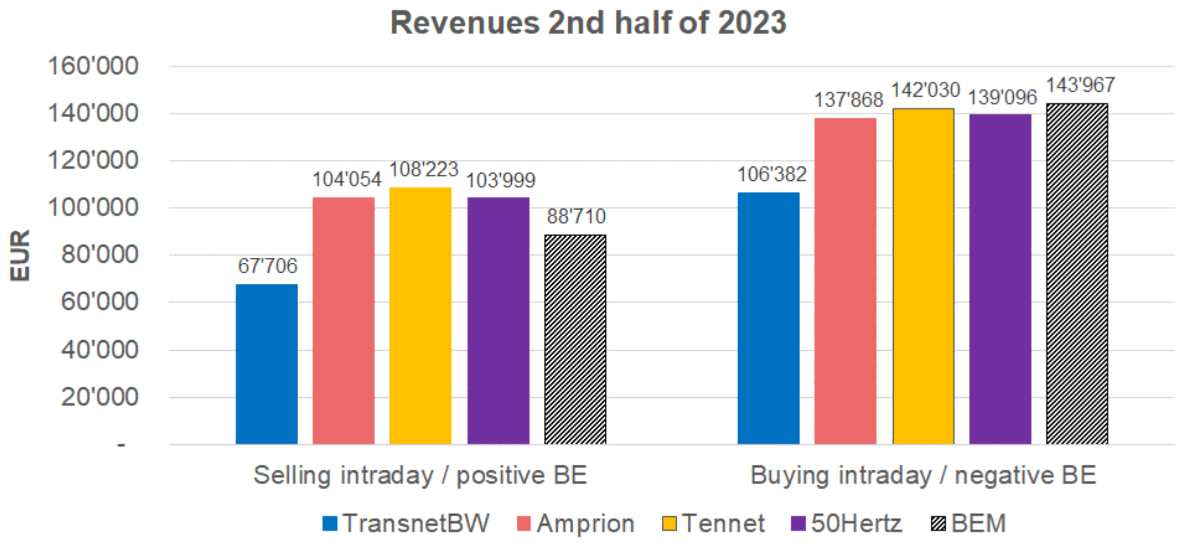



Figure 1: Revenues achievable on the intraday market in the individual control areas and for balancing energy (BE) in the second half of 2023

higher transaction costs burden the success potential of a flexible capacity both for the sale and the purchase of an additional MW.

Figure 2 shows a snapshot of an order book at time T – 31, in which the intraday trading of a selected quarter-hour for the German market area occurs just before the segmentation into the four balancing zones. The green bids (submitted by potential buyers) represent the prices of the offer curve at which, if accepted, production with the corresponding volume can be sold. The red bids (submitted by potential sellers) represent the prices of the offer curve at which consumption with the corresponding volume can be bought. The larger the volume sold, the lower the realized selling price; the larger the volume bought, the higher the realized purchase price. The steeper the offer curve in the order book, the lower the liquidity of the order book. In the continuous trading of the intraday market, the bid curves change constantly and accordingly the liquidity in the order book.

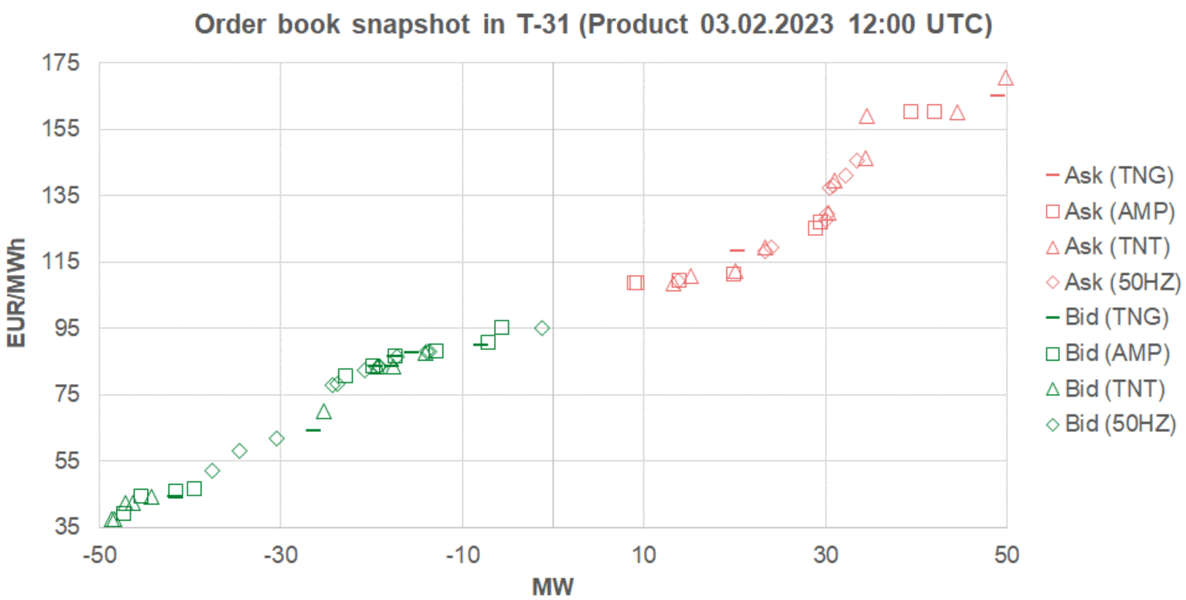



Figure 2: Snapshot of the intraday market order book at T – 31.

Figure 2 also reveals the segmentation of the offer curve into the four control areas. Empirically, for 2023, we have shown that the liquidity in the TransnetBW balancing zone is significantly lower than in the Amprion, Tennet, and 50Hertz control areas. The revenue potentials in the latter three are comparable, which leads us to conclude that the order books have comparable liquidity.

## #2: Economic value of a flexible capacity

A flexible capacity cannot be offered in the balancing energy market and the intraday market at the same time. Based on option values for a bid in the balancing energy market or for marketing the flexible capacity in the intraday market, an economic decision rule can be derived: At time T – 30, one chooses the market that shows the higher option value, equivalent to the expected revenue, for the flexible capacity.

From the results in Figure 1, we observe that the revenue potential of EUR 67'706 for the sale of an additional MW in the intraday market within the TransnetBW control area is significantly lower than the revenue potential of EUR 88'710 for providing positive balancing energy. Likewise, we note that the revenue potential of EUR 106'382 for the purchase of an additional MW in the intraday market within the TransnetBW control area is significantly lower than the revenue potential of EUR 143'967 for providing negative balancing energy. These relations suggest that offering the option in the balancing energy market for flexible capacities within the TransnetBW control area offers significantly higher added value compared to flexible capacities in the other control areas Amprion, Tennet, 50 Hertz.

Figure 3 shows the economic value of being able to decide at time T – 30 whether the flexible capacity is offered in the intraday market of a control area or in the balancing energy market. From this, we receive confirmation that the revenue potential of an additional, flexible production in the TransnetBW control area can be increased by 17.8% to EUR 79'775. Similarly, we find that the revenue potential of an additional, flexible consumption in the TransnetBW control area can be increased by 26% to EUR 134'030. The potential for added value of an additional, flexible production in the control areas Amprion, Tennet, and 50 Hertz is not significantly different from zero. This was to be expected, as the revenue potential for positive balancing energy is significantly lower than the potential for an additional, flexible production in the respective intraday market of the three control areas.

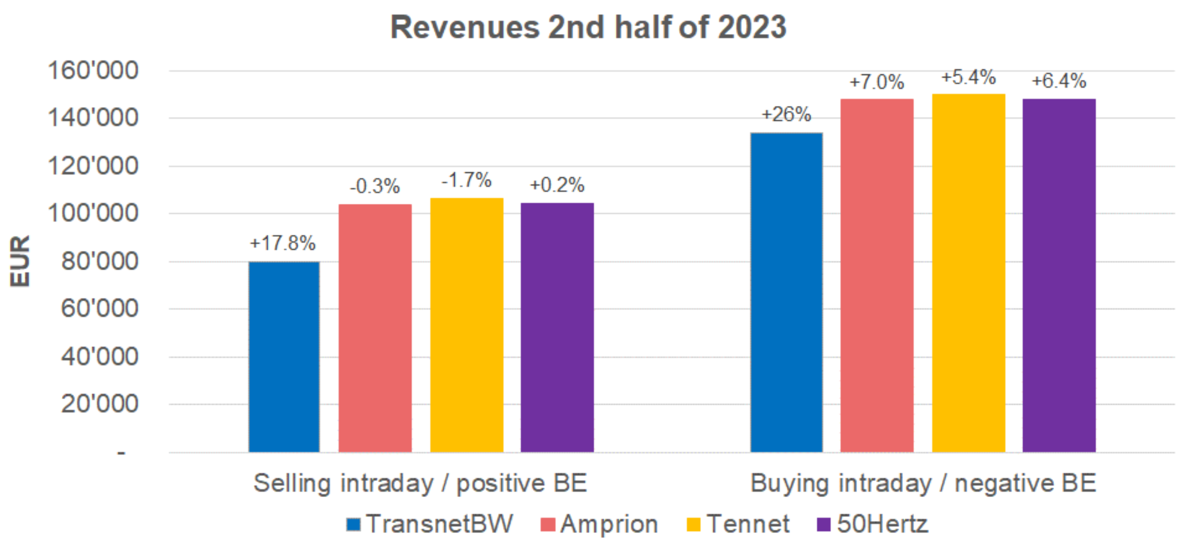



Figure 3: Added value (in %) of the economic decision rule as to which market to bid in.

The potential for added value of an additional, flexible consumption in the control areas Amprion, Tennet, and 50 Hertz shows a significant positive impact of +7.0%, +5.4% and +6.4%. We recall that the revenue potential of an additional flexible consumption in the intraday market of the respective control areas is comparable to the revenue potential for providing negative balancing energy. Thus, intraday trading in the three control areas is in direct competition with the balancing energy market, which explains the reported added value (+7.0%, +5.4%, +6.4%) using the applied economic decision rule.

Table 1 lists the frequencies with which the balancing energy market is preferred over intraday trading in the respective control areas when the economic decision rule is applied, separated by positive and negative balancing energy.

| 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 1: Frequency with which the balancing energy market (BEM) is preferred over the intraday market using the decision rule.

## #3: Value of perfect information

While the economic decision rule is based on a stochastic modeling approach and choses the market in which to bid without foresight of the realized prices, we document next the value of perfect information under the idealized assumption that prices for the balancing energy and intraday markets in the respective control areas are already known at time T – 30.

Figure 4 and Figure 5 document the achievable revenues under perfect information and are contrasted with the revenue potential achievable under the economic decision rule. The assumption of perfect information represents a situation in which the intraday prices and CBMPs would be perfectly predictable, which is equivalent to the volatility of these prices being perfectly, or 100%, explainable.

When we compare the revenue potential under the economic decision rule to the achievable revenues under perfect information, we find that for an additional flexible production, the economic decision rule for the TransnetBW control area captures approximately 64% of the achievable revenues under perfect information. For the Amprion, Tennet, and 50Hertz control areas, rounded percentages of 70% are captured each (see Figure 4).

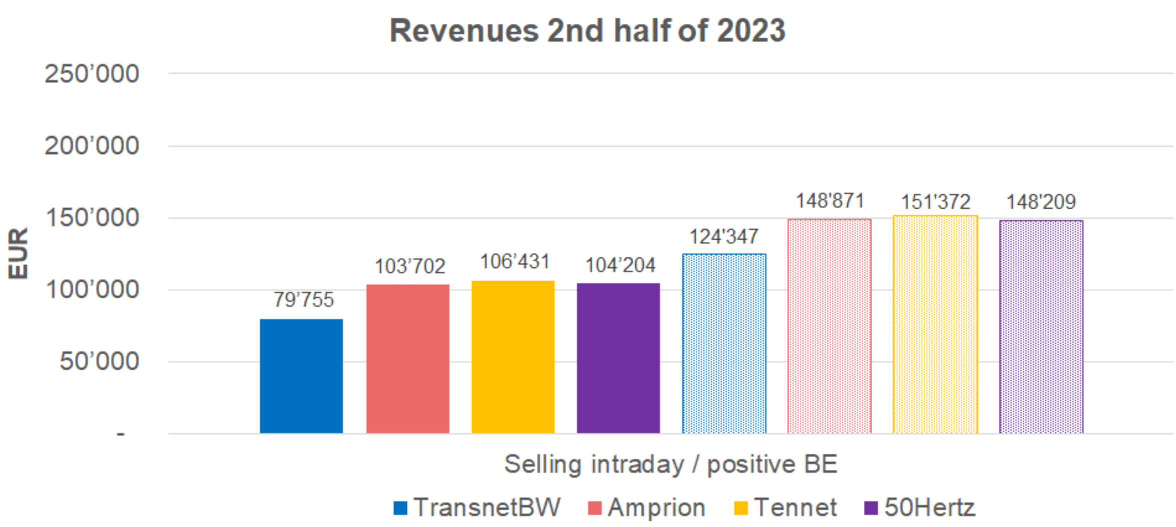



Figure 4: Value of perfect information (coloured shaded) compared with the revenues achieved with the economic decision rule (coloured solid) for selling in the intraday market or providing positive balancing energy (BE).

For an additional flexible consumption (see Figure 5), approximately 72% of the revenues achievable under perfect information are captured across all four control areas. The value of perfect information highlights the limits that an investment in purchasing information or in developing forecasting models should not exceed compared to the status quo.

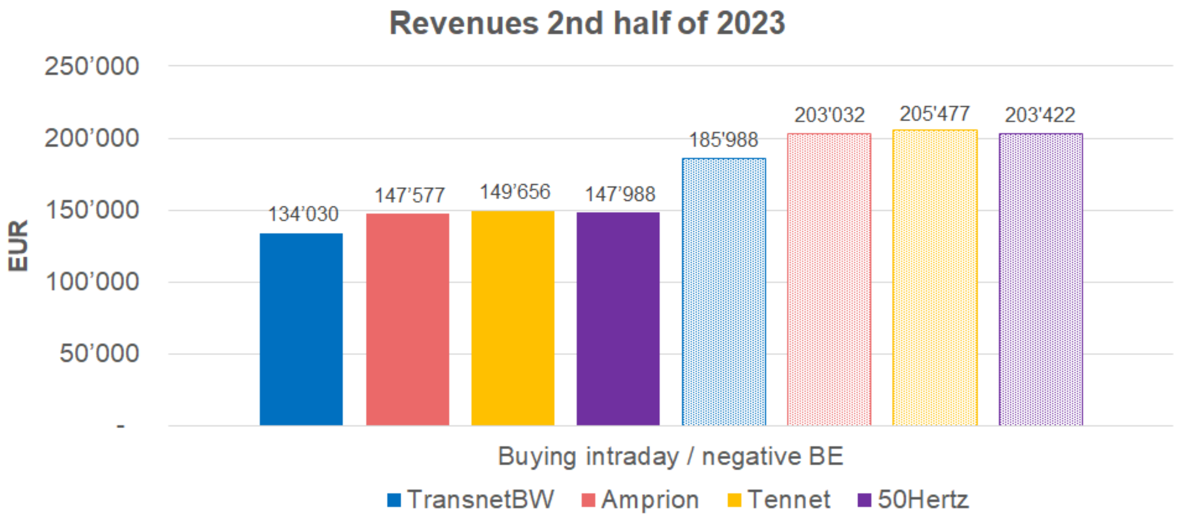



Figure 5: Value of perfect information (coloured shaded) compared with the revenues achieved with the economic decision rule (coloured solid) for buying in the intraday market or providing negative balancing energy (BE).

## #4: PICASSO's impact on the demand for frequency restauration reserve

The PICASSO platform for the international exchange of automatic frequency restauration reserve (aFRR) was launched on 22nd June 2022. For a comparison of the demand for balancing energy, we refer to the years 2021 (without PICASSO) and 2023 (with PICASSO). Figure 6 illustrates the decrease in activated volumes of automatic and manual frequency restauration reserve for positive and negative balancing energy, separately.

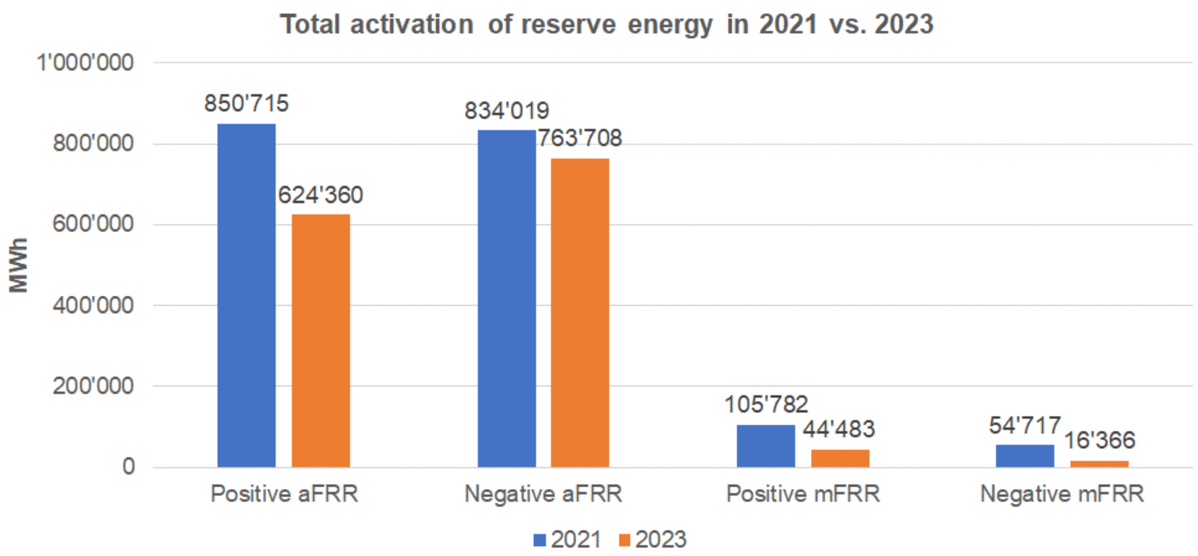



Figure 6: Activated volumes of automatic and manual frequency restauration reserve in 2021 (without PICASSO) and 2023 (with PICASSO).

Figure 7 illustrates the average control area balance, calculated separately for positive and negative values over all 15min products. Deviations from zero correspond to imbalances in the power grid that must be compensated by frequency regulation reserve. The reported numbers may be interpreted as demand for balancing energy. The numbers reveal a more efficient netting between different (foreign) control areas caused by the introduction of PICASSO.

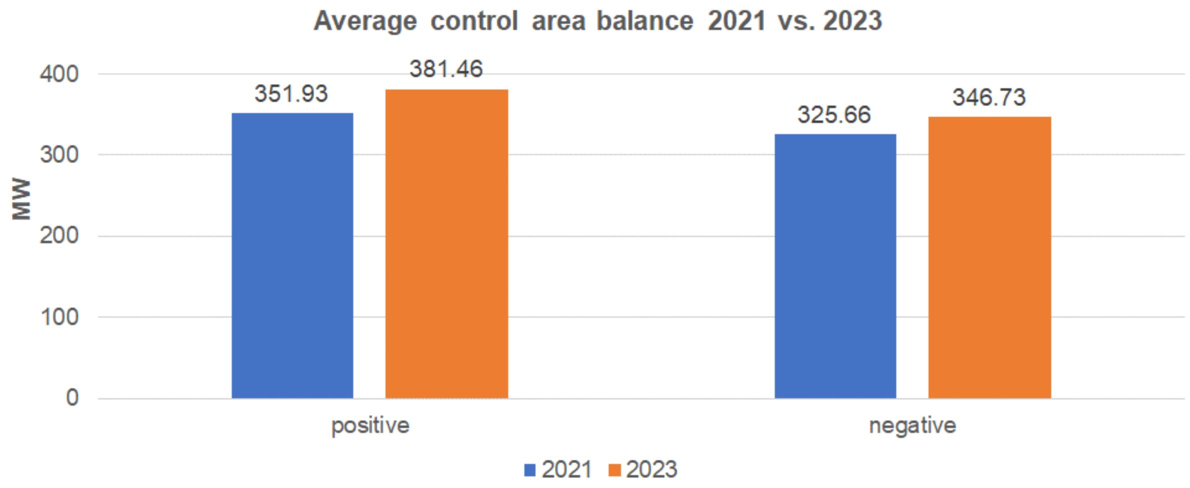



Figure 7: Average control area balance that must be compensated by balancing energy in 2021 and 2023.

## #5: Impact of regulation in the ancillary services on intraday trading

For analyzing the dynamics of the intraday prices in the German market area within the national intraday trading phase in period [T – 60, T – 30] before the start of delivery T, various fundamental factors were tested that help explain the variability of intraday prices. Figure 8 summarizes the findings for the years 2021 (without PICASSO) and 2023 (with PICASSO). For both years, the explanatory power of the model and of selected factors is quantified in dependence of the remaining time until the start of delivery T.

The upper panel of Figure 8 reveals an explanatory power for the year 2021 (without PICASSO) of about 32% for the *complete model* shortly before the start of delivery [T – 15, T – 5], considering all fundamental factors selected for the analysis. The explanatory power of the *complete model* decreases to about 12% with increasing remaining trading time up to trading period [T – 120, T – 105] (i.e., up to two hours before delivery). The *complete model* also covers information on the activation of automatic and manual frequency restauration reserve, which are published after the end of the corresponding delivery period. As those market participants of the intraday market who submit bids in the balancing energy market which are later activated obtain the information at the time of the call. From the price of the activated bid, these privileged market participants can draw conclusions about imbalances of the power system. This fact enables those privileged market participants to adapt their bids in the order book of the IDM, accordingly. The single factor *aFRR activation* carries an explanatory power of 20%, the single factor *mFRR activation* carries an explanatory power of 12%. We may conclude that privileged market participants take advantage of the asymmetric information. With excluding these two factors in the *complete model* the explanatory power of the resulting *reduced model* decreases to 24% for the trading period [T – 15, T – 5] (i.e. shortly before the start of delivery at T), and to about 12% for the trading period [T – 120, T – 105] (i.e. two hours before the start of delivery at T).

The lower panel of Figure 8 reveals a reduced explanatory power for the year 2023 (with PICASSO), of about 22% for the *complete model* shortly before the start of delivery [T – 15, T – 5], which decreases to about 7% up to the trading period [T – 120, T – 105]. The *reduced model* (excluding the factors *aFRR*

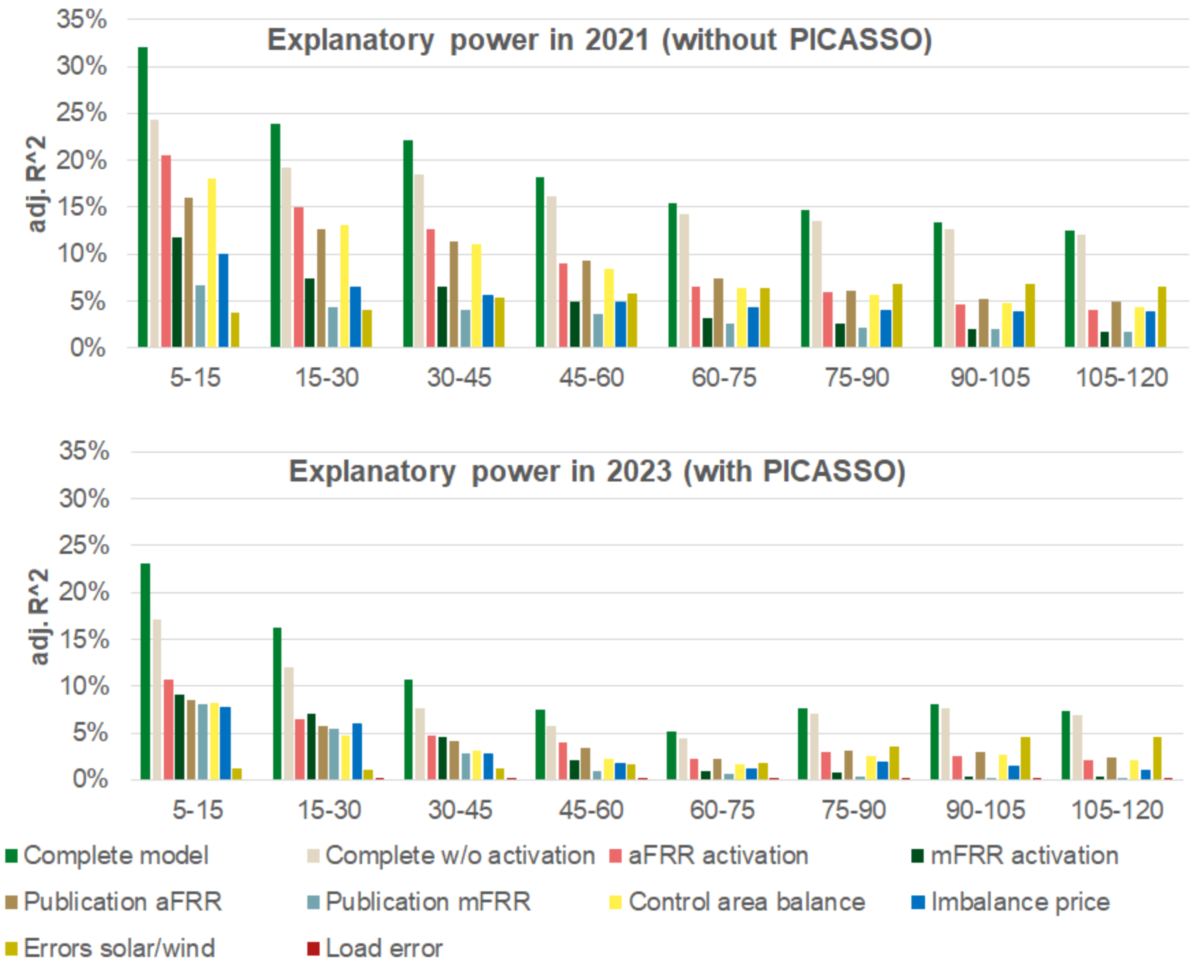



Figure 8: Comparison of the explanatory power for the deviation of prices for 15-minute products during the continuous intraday trading from their prices achieved in the opening auction using data of the years 2021 (before go-live of PICASSO, upper panel) and 2023 (after go-live of PICASSO, lower panel). Data are grouped into different classes according to time to delivery (shown along the x-axis) for which various models are applied. The bars represent the corresponding adjusted coefficients of determination of the different model versions. The first model uses a complete set of fundamental data described in the legend. The second model is a reduced version without activation signals for frequency restauration reserve. The other models are simple regression models with single factors as specified in the legend.

*activation* and *mFRR activation*) reveals a reduced explanatory power of about 18% for the trading period [T – 15, T – 5] (i.e. shortly before the start of the delivery at T). The explanatory power of the *reduced model* decreases to about 7% with increasing remaining time up to trading period [T – 120, T – 105] (i.e. two hours before the start of delivery at T). The single activation calls provide an explanatory power of 10% (for the factor *aFRR activation*) and 6% (for the factor *mFRR activation*) for the trading period [T – 15, T – 5]. Compared to the year 2021 (without PICASSO), the advantage of the asymmetric information has halved for the privileged market participants.

The decrease in the explanatory power of both the *complete model* and the *reduced model* without activation calls, as well as the decrease in explanatory powers across all factors indicate that netting between neighboring areas has become more efficient implying reduced volumes in the activations. Further, as activations are exercised across borders, bids from providers outside Germany are integrated in the merit order of the balancing energy market. Therefore, market participants active in both the balancing energy and the (German) intraday market receive fewer activation signals and thus less information that can be exploited in intraday trading. We do conclude that the introduction of PICASSO on 22nd June 2022 has led to a more efficient and fairer intraday market.

With the introduction of PICASSO, the time intervals for the products of balancing energy were reduced from four hours to 15 minutes, going along with a shift from a "pay-as-bid" to a "pay-as-cleared" auction. The bids submitted are ranked in the procurement auction of the national transmission system operators in ascending order of the prices offered. In Germany, the most expensive bids, which were not allocated to cover the tendered balancing energy volume, were returned to the providers. Due to a directive effective 8th December 2022, these non-allocated bids are now forwarded to the PICASSO platform and remain available for cross-border activation. This measure was expected to result in lower balancing energy prices.

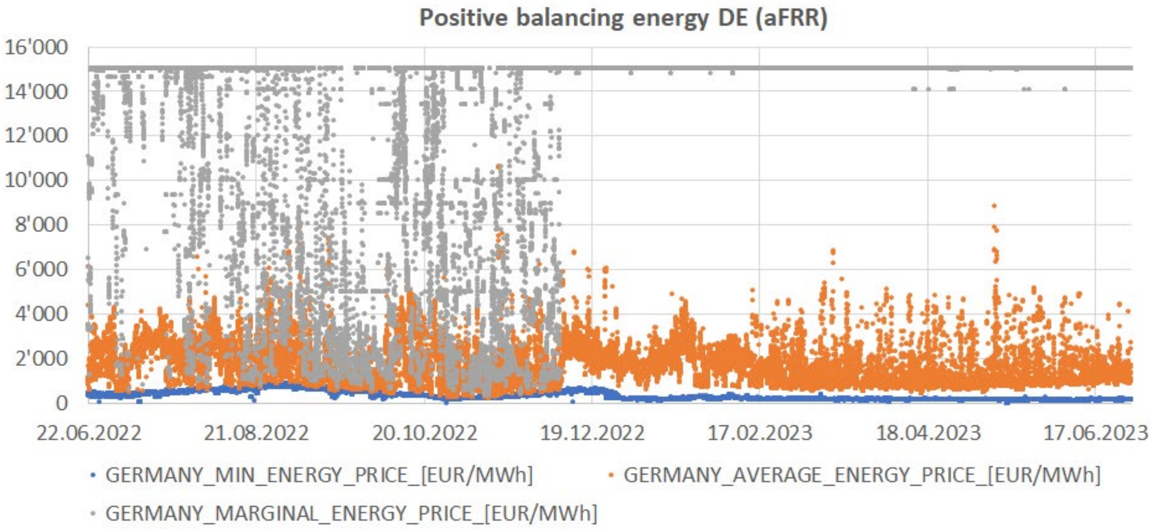



Figure 9: Minimum, average and maximum prices of submitted bids for positive balancing energy (aFRR).

In fact, the opposite has occurred: Figure 9 reveals that since 8th December 2022, maximum bids for positive balancing energy (aFRR) are consistently submitted at the highest feasible bid price (+15'000 EUR/MWh). Also, the level of average prices of the submitted bids has increased. Likewise, as illustrated in Figure 10, for negative balancing energy (aFRR) the submitted bids are consistently submitted at the

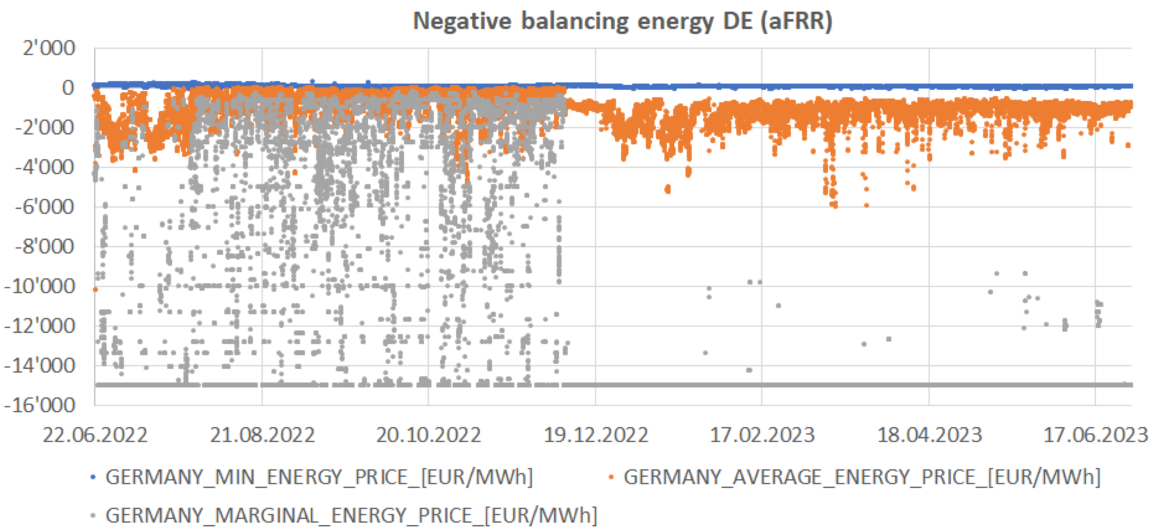



Figure 10: Minimum, average and maximum prices of submitted bids for negative balancing energy (aFRR).

price limit of −15'000 EUR/MWh since the regulator's directive became effective. Note that a negative price for negative balancing energy means a payment from the TSO to the provider, i.e., these negative bids submitted at the price limit are the most expensive ones from the TSO's perspective.

Analyses[1] show that bids submitted at the price limit are activated only in approximately 0.01% of cases. We explain this extreme bidding behavior of individual large market participants by the fact that the common flexible capacity is marketed as effectively as possible in the remaining time. In the event of an unusually high aFRR activation, these large market participants can exploit the opportunity to source the balancing energy in the very last minute from other sources at an attractive compensation and deliver it to the TSO in compliance.

## #6: Systemic Risk Related to Hedging Strategies

The increasing demand for flexible technologies expands the generation portfolio of systemically relevant electricity companies, thereby increasing the need for hedging volumes. Price distortions in the years 2021 − 2022 have shown that, *in extremis*, liquidity risks and debt risks can jeopardize the continuity of a company.

We introduce a sanity check of energy trading, for which we use a benchmark hedge and apply it to determine the liquidity and debt risks for the period from 30th June to 26th August 2022. The benchmark hedge characterizes the uniform hedging of production and procurement volumes for commodity electricity three years in advance. This results in a hedge portfolio with a hedging volume twice that of the production and procurement volume. In the investigated period, the futures prices of the hedge portfolio tripled, and the initial margin quadrupled. This scenario has empirically occurred and should be integrated into the risk management of energy supply companies.

For the sanity check, we select specific relevant balance sheet items and present them in relation to the equity as of 31st December 2021: We base a P&L-neutral liquidity outflow of 10% of the equity as of 30th June 2022 for variation margin, a P&L-neutral liquidity outflow of 60% of the equity, and a P&L-relevant increase in the passive surplus of energy derivatives in the first half of the year amounting to 70% of the equity reported as of 31st December 2021. If the uniform hedging strategy remains unchanged, a P&L-neutral balance sheet liquidity outflow of 40% of the equity resulted as of 26th August as the initial margin for the hedge portfolio quadrupled. For the P&L-neutral booked variation margin, a liquidity outflow of 180% of the equity resulted as the futures prices tripled. The P&L-effective passive surplus of energy derivatives increases with the tripling of futures prices to 210% of the equity as of 31st December 2021. Thus, energy trading turns the equity into negative territory, leading to a debt amounting to 110% of the equity reported as of 31st December 2021.

Note: We intentionally do not include other business activities, such as regulated network operations. With the inclusion of other business activities, one could argue that over-indebtedness is not present or at least in a mitigated form. Instead, we consider it essential to be prepared for the following "worst-case scenario”: a surprisingly significant negative interim result in energy trading could raise doubts about the company's continuity.

Under the above assumptions, insolvency risk exists at the latest on 26th August 2022. The going concern premise is no longer valid. Instead, the following applies:

- Valuation based on liquidation values.
- Write-offs of all assets for which no economic benefit is expected (e.g., collateral, margin claims).
- Immediate recording of expected losses and risks, particularly in the form of provisions.

In this case, the P&L-neutral recorded liquidity outflows lead to losses in a corresponding amount due to the provisions to be formed, which further burden the already negative equity. The result of the energy

[1] See Deliverable 5.4 of the DigIPlat project: Frauendorfer et al. (2025)

trading leads to indebtedness of approximately minus 300%, triple the equity reported as of the last balance sheet date.

If the last reported equity amount was 5 billion, over-indebtedness amounted to 15 billion. For a last reported equity amount of 10 billion, over-indebtedness amounted to 30 billion.

The lessons we take from this are:

- Production capacities and the volumes of contracted procurement agreements must be in a healthy relation with existing liquidity and reported equity.
- Aggressive hedging strategies are only justifiable if there is sufficient liquidity and equity.

We recognize that the values we used for the four primary risk factors as of 30th June 2022, represent critical thresholds for systemically relevant energy providers. The closer the real balance sheet positions of an electricity company are to the critical thresholds relative to the equity, the greater the risk of insolvency. The smaller the real balance sheet positions relative to the equity, the healthier the energy trading of the electricity company.

Based on the development of the four selected balance sheet positions of energy trading, the contribution of a systemically relevant electricity provider to the system risk can be derived. If the selected balance sheet positions are presented to the Board of Directors in relation to the equity of the last balance sheet date over the past 100 trading days, then the board receives an X-ray image of the energy trading for the current fiscal year.

## #7: Insights for the market area Switzerland

Due to the missing eletcricity aggrement between Switzerland and the EU, Switzerland has been excluded from participation in the Single Intraday Coupling (SIDC, formerly XBID) launched on 12th June 2018. This introduced a platform for continuous cross-border intraday electricity trading based on continuous allocations of border capacities. Being excluded from SIDC has the consequence that intraday trading for the Swiss market area takes place exclusively within the Swiss control area from the start of intraday trading at 3:00 p.m. of the previous day until gate closure, currently up to 5 minutes before the start of delivery of the respective trading product. Thus, similar conditions apply for Switzerland over the entire trading period as for the four control areas in Germany during the last 25 minutes of trading.

After the conclusion of negotiations with the EU on institutional issues at the end of 2024, this will require adoption by the Swiss legislature and possibly a vote. As long as the agreement between the EU and Switzerland is not ratified, Switzerland's access to the liberalized European electricity market is still strongly limited.

The trading volume in the Swiss intraday market has dropped after the introduction of SIDC on 12th June 2018. In return, the trading volumes of Swiss market participants on the intraday markets in Germany and France have increased. For example, the trading volumes of Swiss market participants on the German intraday market increased to approximately twice the volume that they contributed before the introduction of SIDC on this market.

With the collapse of trading volume in the Swiss intraday market by 90 – 95%, it can also be assumed that the quality of the order book for the Swiss market area has deteriorated. Due to the lack of data, we limit ourselves to qualitative statements: The frictions in the order books of the individual trading products are likely to have significantly increased with decreased liquidity and sharply rising spreads. This not only reduces the potential value-added for flexible capacities in the Swiss intraday market, but the decline in order book quality also contributes to an increase in the demand for automatic and manual frequency restauration reserve in the Swiss control area, leading to higher balancing energy prices.

The collapse in trading volume and thus liquidity in intraday trading for the Swiss market area is likely to impact more than just welfare effects. We understand that, from the perspective of the Swiss regulator and the Swiss supervisory authorities, compliance with antitrust requirements for electricity trading in the Swiss market area is in the focus. We base our concerns on the findings for the four control areas in the German market area in 2023.

The lower liquidity in intraday trading in the TransnetBW control area leads to a 15% lower revenue potential for flexible generation compared to positive control energy and to a 40% lower revenue potential for flexible consumption compared to negative control energy. Greater revenue potential for providers of flexible capacity in the control energy market means higher costs for the end consumer. If the revenue potential for flexible capacity in the intraday market exceeds that of the balancing energy market, as in the case of flexible generation capacities within the control areas of Amprion, Tennet, and 50Hertz in 2023, we consider this to be uncritical, as the revenue potential in ID trading is generated and financed by market participants.

Since Switzerland is excluded from SIDC trading, it would be expected that the revenue potential for flexible generation capacity within Switzerland's intraday trading would be significantly lower than 15% of the revenue potential for positive balancing energy, or that the revenue potential for flexible consumption would be significantly lower than 40% of the revenue potential for negative balancing energy. This eliminates the incentives for systemically important Swiss electricity companies to participate as liquidity providers in intraday trading in the Swiss market area. End customers finance the high revenues in the balancing power and balancing energy market. This places an additional burden on the quality of the Swiss intraday market.

One should keep in mind that the market design of liquid intraday trading in the liberalized electricity market is aimed at reducing the demand for control energy and thus the costs for end customers. If there is no fair competition in intraday trading in Switzerland, fair pricing in intraday trading within the Swiss market area, which can serve as the basis for bids in the control energy market, is not guaranteed. Therefore, from our perspective, it can currently be assumed that the interplay between the intraday market (IDM) and the balancing energy market (BEM) within Switzerland, which would generate welfare gains under fair competition, is lacking. Being aware of the upcoming *Heimfall* events it is our perception that the Swiss power market faces even the risk that the market power of a few large power producers could be strengthened. Whether the market power gets more balanced with the *Heimfall* events depends on the priorities of the concessionary municipalities. It is our intention to sensitize the decision makers to support a framework for sound and fair competition.

Based on the achieved results for the four control areas of Germany we recommend for market area Switzerland the assessment of the

- economic value of flexible capacities (+/-) in the intraday market CH
- earnings potential (+/-) in the BEM CH
- effectiveness (+/-) of the economic decision rule
- relevance (+/-) of perfect information
- explanatory power of the factors driving ID-prices
- evolvement of activation and control area balance
- impact of PICASSO on market area CH
- effectiveness of ElCom's cap (+/-) for bids on aFRR
- market power in market area CH
- welfare effects for Switzerland
- compliance with antitrust law
- impact of distinguished *Heimfall* events on market power

The value creation potential in the IDM as well as in the BEM of the Swiss control area could be quantified analogously to those value creation potentials for the IDM in the four control areas in Germany and for the German BEM. The prerequisite for this lies solely in the availability of data. As a direct consequence, the welfare effect for the Swiss market area could be verified as well as the impact on market power and the compliance with antitrust law.

Finally, extreme surpluses for electricity producers caused by market power and/or exogenous factors mean extreme burdens for electricity-intensive industries in Switzerland. The Swiss legislator could 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.

# 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 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 pow-er 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, changes in regulation).

## 1.2 Project objectives

The DigIPlat project deals with the interoperability of flexibility platforms through which the allocation of flexible capacities can be better coordinated, thereby increasing their economic efficiency as well as the security of supply. To this end, solutions for the cross-platform utilization of flexibility for redispatch, balancing energy, and intraday markets are being conceptually developed from an information and procedural engineering perspective and analyzed from an economic viewpoint. The latter involves a thorough analysis of those short-term markets where a flexible capacity could be offered: The balancing energy market (BEM) and the intraday market (IDM). We concentrate in our analyses on the German market area due to its higher liquidity and, mainly, because of data availability.

For a direct comparison of the revenue potential in both markets, we focus on the last 30 minutes before delivery because bids can be submitted at the BEM up to its gate closure (GC) at T – 25. Thus, a bidder at the BEM must then reserve the capacity and sees the potentially lost revenues from intraday trading in the remaining time up to delivery as opportunity costs. However, in this period the trading in the German intraday market is already split into the individual control areas. These have different liquidity and, thus, offer different potential for executing trading decisions, which must be considered in the economic assessment.

Currently, the procurement of balancing capacity (BC) by transmission system operators (TSOs) is carried out via tenders on the previous day (D – 1); bids for balancing energy (BE) can be submitted independently on the BEM up to its gate closure (GC), which is currently 25 min before delivery (T – 25). The proximity in time of the BC tender and the planning of redispatch on D – 1 suggests that both could be procured in a coordinated manner, also because these services can conflict each other, e.g., a balancing service cannot be provided by a generator that is redispatched to resolve congestion, or the activation of BC may aggravate congestion (Poplavskaya et al., 2020). The BEM, in turn, potentially competes with the IDM since, under the current design, capacity can be offered on only one of the two markets at the same time. The capacity offered on the BEM could be increased if, at an appropriate time before its gate closure (GC), bids from pre-qualified balancing service providers (BSPs) from the intraday market's order book were transferred into the BEM's bid list, which should tend to lower the prices for balancing energy.

By linking offers between markets, flexible capacities can be used more efficiently, which can reduce the costs of grid usage for end consumers. For an economic assessment, several use cases were defined within the project. One of these cases deals with the procurement of balancing capacity and redispatch via an integrated market mechanism by investigating the bidding strategies of market participants as well as potential gaming behavior using agent-based modeling (Zobernig, Hemm, Strömer, Fanta, & Esterl, 2025). In our study, we analyze in the central section 3 as another use case the integration of the IDM and BEM, specifically for automatic frequency restauration reserve (aFRR).

Other questions that are also addressed concern the quantification of liquidity on the intraday market (section 4) and the influence of the PICASSO platform on balancing energy demand, as well as on bidding behavior on the intraday market (section 5). Finally, we address issues of systemic risk through hedging transactions (section 6) and a qualitative assessment for market area Switzerland (section 7).

# 2 Description of short-term markets

## 2.1 Intraday market

Continuous trading on the IDM offers the opportunity to trade electricity up until shortly before the delivery in the respective product. This enables market participants to correct unfavorable trades or bids made earlier, e.g., due to forecasting errors in the marketing of renewable energies (Garnier & Madlener, 2015), or to react to new information on short notice, such as the publication of the control area balance or an activation of balancing energy as a timely sign of an imbalance between generation and consumption (Hirth & Mühlenpfordt, 2021). At the same time, the IDM opens earning potential for flexible capacities that can react quickly to price fluctuations (Goutte & Vassilopoulos, 2019). Along with the increase in electricity production from renewable energies from 117.6 TWh in 2012 to 237.6 TWh in 2022, the volume in continuous trading on EpexSpot for the German market has risen from 16 TWh to 62.3 TWh during the same period. In addition, there are trading volumes from the auction of the 15-minute products (8.1 TWh) as well as from the Nord Pool exchange (8.7 TWh) in 2022 (Bundesnetzagentur, 2017 & 2023).

Trading on the IDM begins on the previous day (D – 1) at 15:00 with an opening auction for 15-minute products. For Germany, 24-hour and 96 quarter-hour products are traded for each delivery day until 5 minutes before delivery (Gate Closure T – 5). Market participants may submit, modify, or cancel limited buy and sell bids at any time; these bids are anonymously collected in a limit order book (LOB) for each product. A transaction is triggered when a participant accepts a bid (or several bids for larger volumes) from the LOB. Consequently, each transaction results in its own price; there is no single uniform price in continuous trading on the IDM as there is, for example, in the day-ahead auction. If a buy or sell order exceeds the offered volume of the most favorable bid on the opposite side of the order book, the additional required quantities are traded at correspondingly higher prices (provided that the available volumes are sufficient and that any specified price limit is not exceeded); otherwise, the order is only partially executed.

A snapshot of the order book for an arbitrarily selected product (delivery period 13:00–13:15 on 3rd February 2023) at time T – 31 is shown in Figure 11. Along the x-axis, the cumulative volumes of the currently available bids are plotted. Positive values represent the ask side (sell bids), negative values the bid side (buy bids). The lowest buy bid was set at −9’999 EUR/MWh and the highest sell bid at 9’999 EUR/MWh, corresponding to the smallest and largest feasible bid prices, respectively. The difference between the highest bid and the lowest ask price is called the bid-ask spread; a small (large) spread is interpreted as a sign of high (low) market liquidity. Another measure of liquidity is the so-called order book depth, which is understood as the cumulative volume of buy or sell orders. This is relevant for the purchase or sale of a given quantity Y. For example, the best bid price at which a sale could be executed might be 95.01 EUR/MWh; however, only 1.2 MW are offered at that price. A sale of 10 MW could only be realized at 92.50 EUR/MWh, which corresponds to the volume-weighted average of those five buy bids whose cumulative volume reaches 10 MW[2]. In an illiquid market, the effective transaction price for a purchase (or sale) rises (falls) with increasing quantity in line with the slopes on both sides of the LOB.

Within the framework of Single Intraday Coupling (SIDC), bids from 25 EU and Nordic countries are aggregated into a common LOB. The 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 (Single Delivery Area Trading, SDAT). Typically, two-thirds of all transactions take place during the last two hours of the trading period. Figure 12 illustrates the trading volumes per minute for a quarter-hour product with delivery during the period [00h00-00h15] in the night and during the period [12h00-12h15] at noon. Due to the marketing of photovoltaic generation, volumes

[2] 1.2 MW at 95.01 EUR/MWh (50Hertz area), 4.4. MW at 95 EUR/MWh and 1.5 MW at 90.50 EUR/MWh (Amprion Area), 0.8 MW at 90 EUR/MWh (TransnetBW area), 4.9 MW at 88.23 EUR/MWh (Amprion Area).

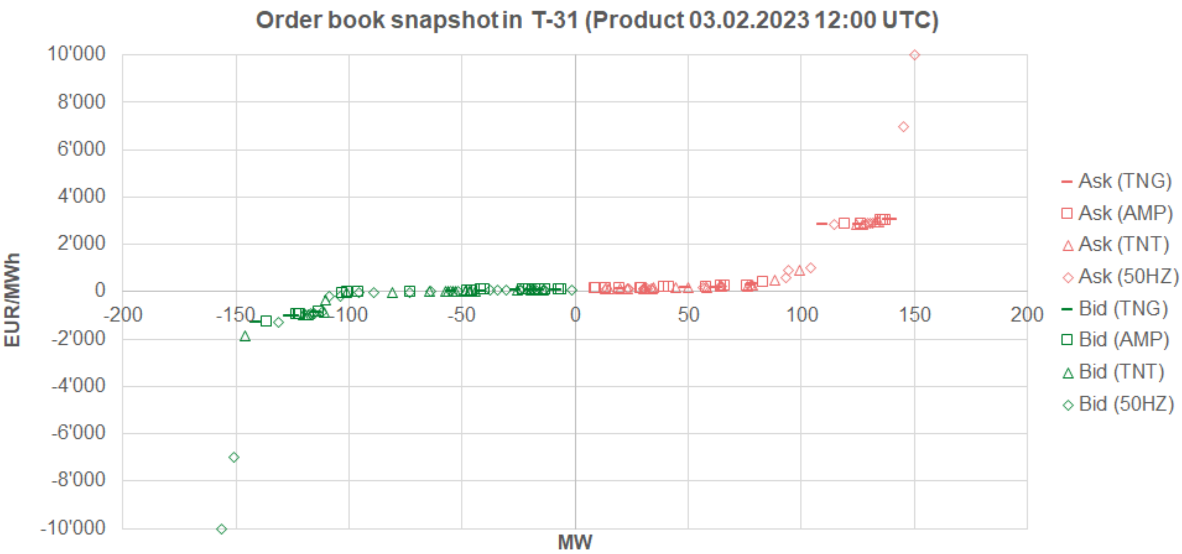



Figure 11: Snapshot of the order book for a 15-minute product at T-31 (before the start of the SDAT phase). The cumulative quantities are plotted along the x-axis (negative values for buy bids = bid side, positive values for sell bids = ask side). The markers specify the control area to which the bid refers.

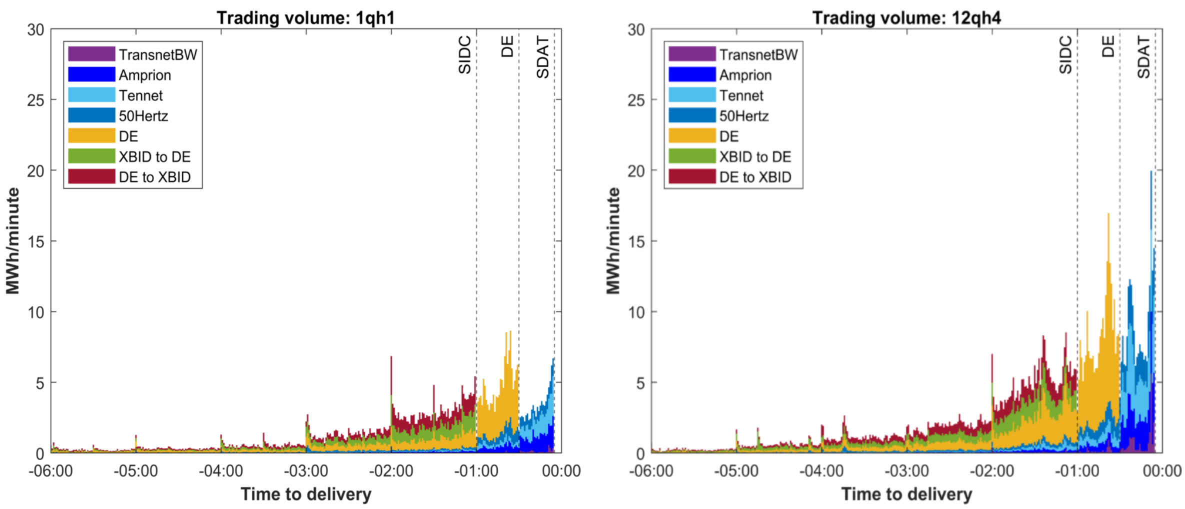
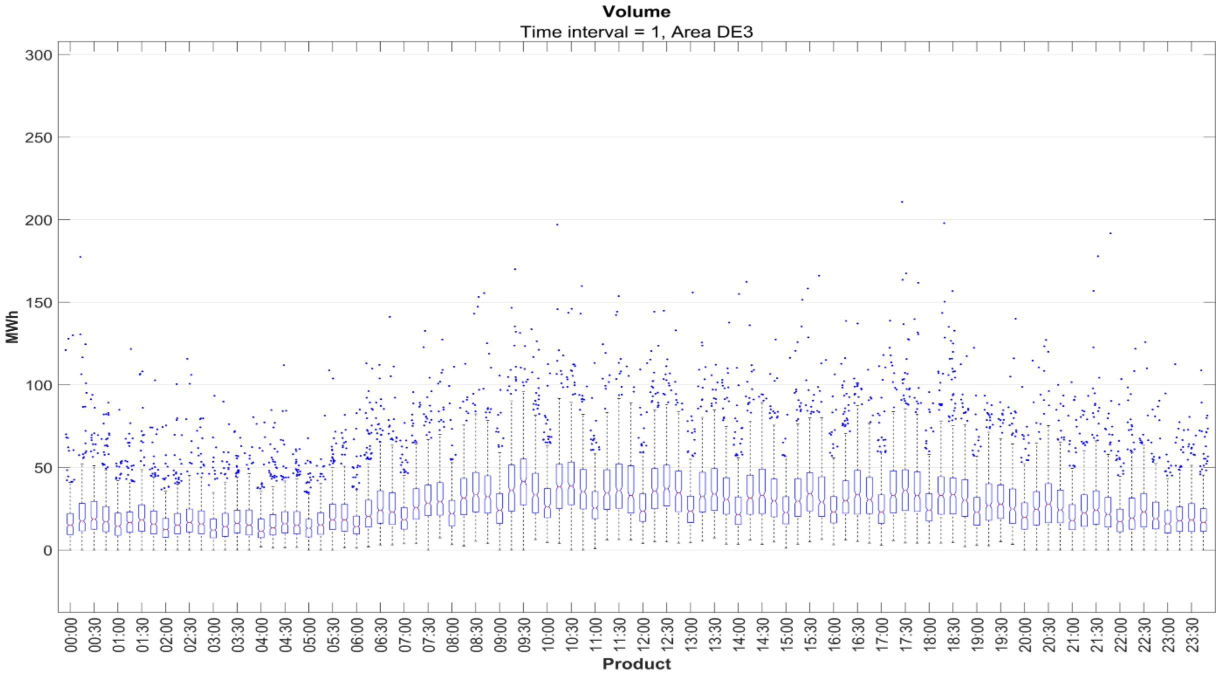



Figure 12: Development of the transaction volume per minute for two 15-minute products with delivery at night (00:00 – 00:15, left) and during the day (11:45 – 12:00, right) in the last six hours of trading. The colours indicate the areas involved: red and green are exports/imports to/from other market areas during cross-border intraday trading (SIDC). Yellow stands for an exchange between different German control areas. The remaining four colours represent trading <u>within</u> the four control areas.

during the day are significantly higher. It is also evident that the transaction volume at the end of a trading phase initially drops, then increases significantly as the remaining time to GC diminishes.

The four German control areas differ significantly in terms of liquidity during the SDAT phase: the trading volume in the TransnetBW zone is the lowest, in particular at night, because in this zone photovoltaic generation is considerably higher compared to wind generation. Figure 13 compares the trading volumes of all 96 quarter-hour products in a "liquid" control area (Tennet) with those in the "illiquid" TransnetBW area in the form of box plots for the last 10 minutes before GC. It is apparent that in the latter zone, the transaction volumes during the nighttime are statistically insignificant.



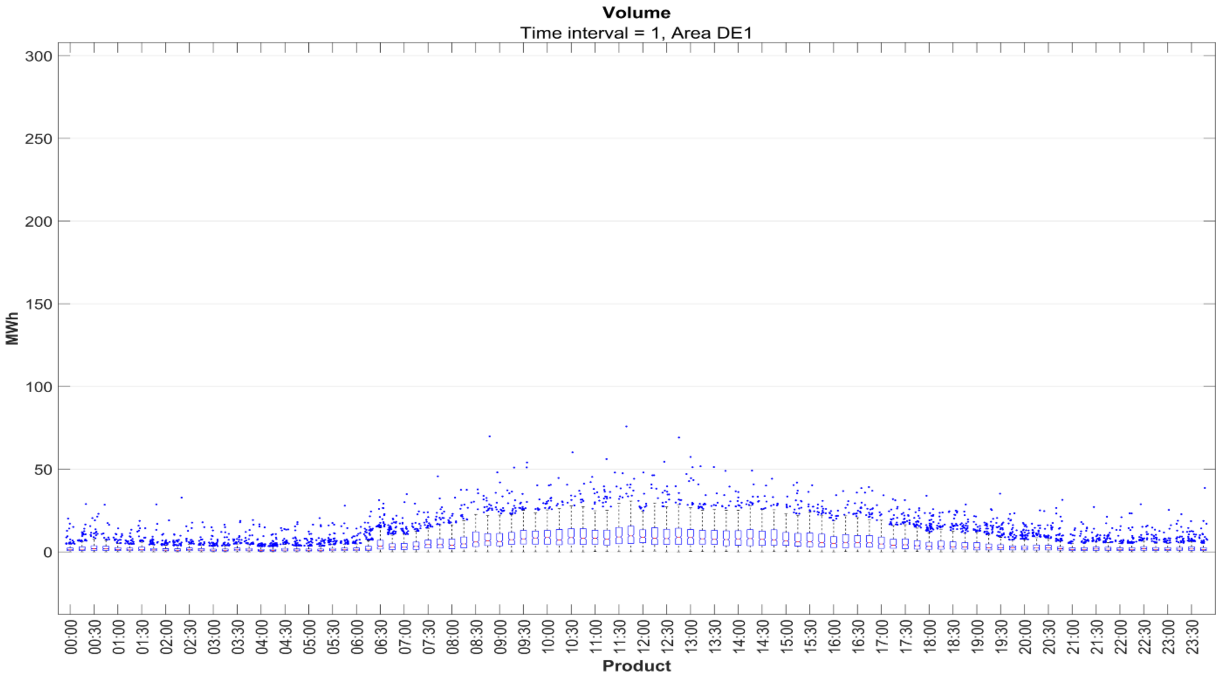




Figure 13: Box plots of the transaction volumes of the 15-minute products in the last quarter of an hour before the start of delivery for two German control areas (Tennet above, TransnetBW below) in 2023. The antenna lines ("whiskers") mark the smallest and largest values that are within 1.5 interquartile intervals from the first and third quartiles, respectively; dots represent outliers.

Figure 14 shows the average cumulative volumes of all 15-minute products in the order book at T – 25 for 2023, broken down by control area. Accordingly, comparable quantities were available on both the buy and sell sides in all four areas. Appendix A documents on page 73 the bid-ask spreads in the German intraday market for deliveries at different times (hours) of the day in the last minutes before the beginning of the SDAT phase. The spreads after trading have been allocated to the different control areas, the corresponding averages and standard deviations are listed on the pages 74 to 77 in Appendix A. As Table 7 (Appendix A) illustrates, the bid-ask spreads in the less liquid TransnetBW zone were

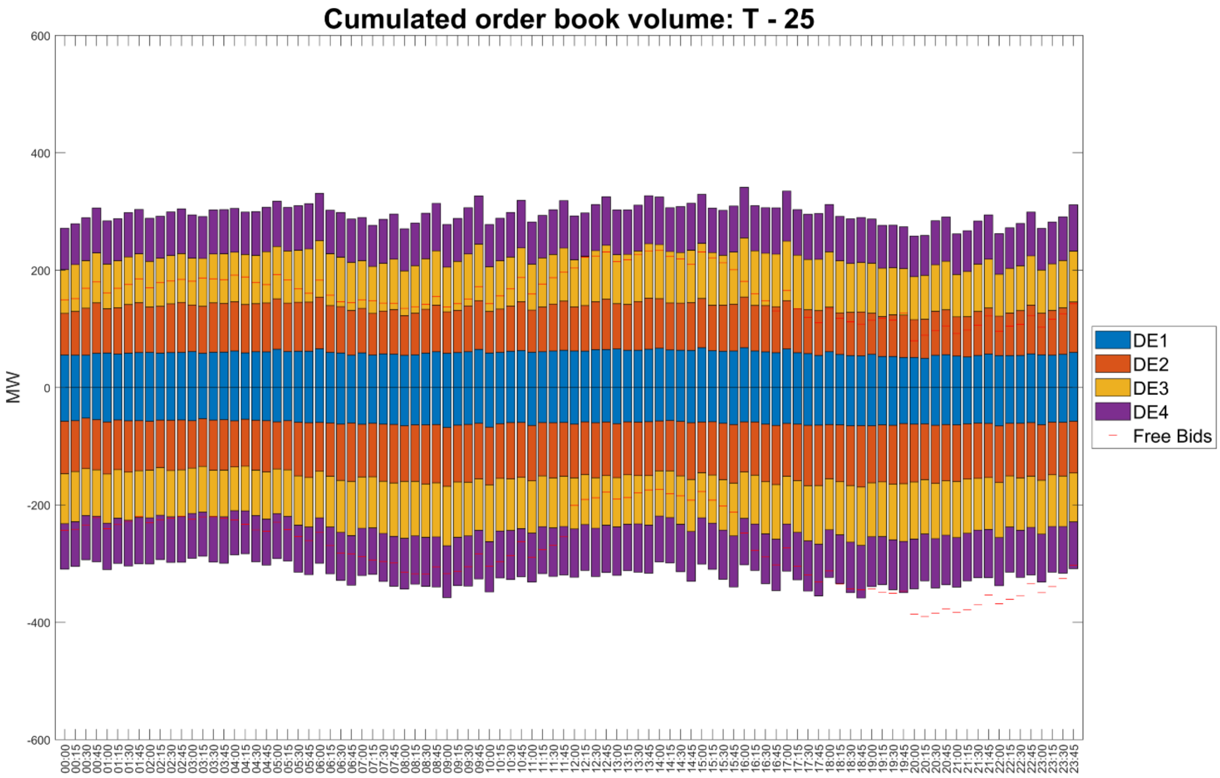



Figure 14: Average order book volume in T – 25 for the 96 quarter-hour products in 2023 by control zone: DE1 = TransnetBW, DE2 = Amprion, DE3 = Tennet, DE4 = 50Hertz. In comparison, the red lines represent the average volume of free bids on the BEM. Sell bids are in the upper half (ask side of the order book or positive balancing energy), buy bids in the lower half (bid side or negative balancing energy).

significantly larger than in the other more liquid zones Amprion (Table 8), Tennet (Table 9) and 50Hertz (Table 10). The prices for buyers and sellers were correspondingly less attractive, which explains the lower number of completed transactions illustrated in Figure 13 (lower panel).

By splitting up trading into individual control areas, transaction prices for the market participants are more unfavorable than in a joint market area. The order book from the example given reveals that the best bid stems from the 50Hertz zone. Assuming that all bids in the order book at T – 31 were transferred unchanged to the SDAT phase (i.e. no bid was withdrawn or accepted by another market participant, and no further bids were added) the achievable price for a transaction of 10 MW in the 50Hertz zone would deteriorate from 92.50 EUR/MWh at the end of joint trading to 87.94 EUR/MWh after the split from the perspective of a seller, as the "more favorable" bids from the other areas would no longer be accessible.

Historical order book "snapshots" of the bids on the bid and ask sides at a predefined time stamp are not directly available. From the EpexSpot exchange, bid data are available in chronological order (i.e., bids with price, quantity, control area; cancellations of bids). For 2023, this corresponds to a data volume of 42 GB. An algorithm has been developed, which derives the order book for preselected time stamps from the order flows. For the figures shown above (and the tables in Appendix A) as well as for the further analyses of the use case, the order book data from the SDAT phase were stored at one-minute intervals, resulting in approximately 43 million data records.

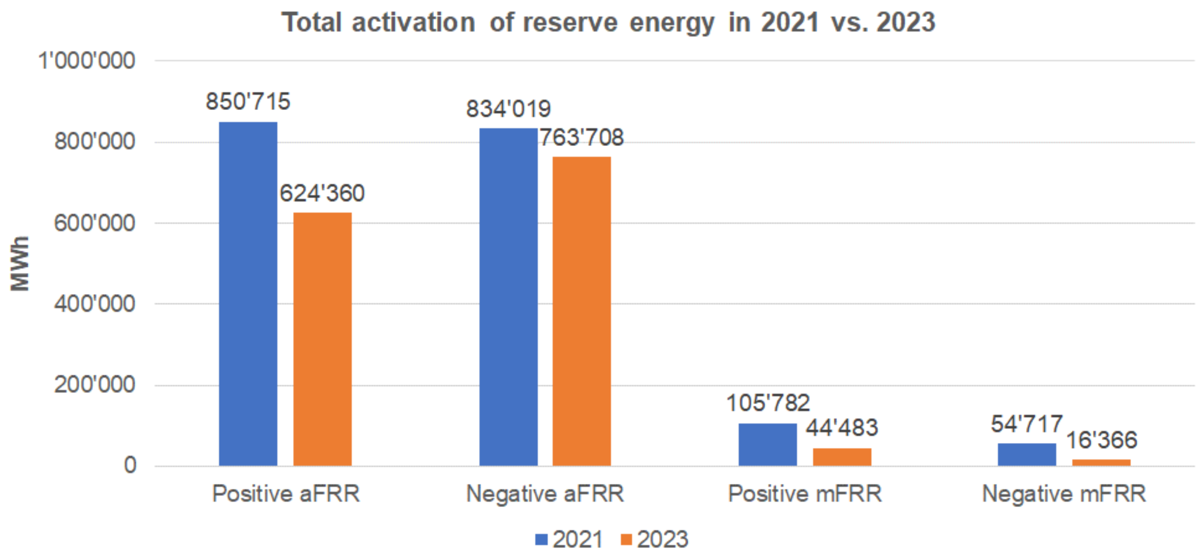



Figure 15: Annual volumes of activated secondary (aFRR) and tertiary control energy (mFRR) according to the reports of the German TSOs in 2021 (before introduction of the PICASSO platform) and 2023 (after PICASSO go-live).

## 2.2 Balancing energy market

The procurement of BC and BE is carried out by (national) tenders organized by the respective TSOs. The auction for BC takes place on the previous day (D – 1). With the introduction of the BEM on 3rd November 2020, balancing energy is procured separately from the capacity auction. Providers who have been awarded in the capacity auction are obliged to submit a bid in the BEM. Other qualified providers, particularly those who did not participate in the capacity auction, can submit additional bids for balancing energy until the GC of the BEM (currently T – 25). Bids submitted independently of the capacity auction are referred to as *free bids*. Providers, who submit *free bids*, receive no compensation for the reservation of capacity. At T-10 it is announced, which bids have been awarded.

With the go-live of the European PICASSO platform on 22nd June 2022 for the cross-border exchange of secondary reserve, the time slices of the BE products were reduced from four hours to 15 minutes in the interest of international harmonization. Consequently, the remuneration for activated energy is no longer determined by the bid-price method ("pay-as-bid") but rather by uniform pricing ("pay-as-cleared"). The aim of the PICASSO cooperation is, in addition to the existing International Grid Control Cooperation (IGCC), to improve the netting of imbalances and furthermore to activate balancing capacity across borders. Accordingly, the balancing energy bids collected by the national TSOs are forwarded to the central PICASSO platform, which constructs a common *merit order* from the bids of all participating TSOs. If there is a need for BC in one area, the system (after any netting) derives a cost-minimal activation from this *merit order*, considering the available transmission capacities.

Figure 15 shows the activated quantities of BE for the years 2021 and 2023, i.e., before and after the go-live of the PICASSO platform, from the reports of the German TSOs. It is evident that the activated quantities for secondary (aFRR) and tertiary reserve (mFRR) have dropped significantly. On the other hand, according to Figure 16 the average positive and negative control area balances are comparable in both years. These numbers measure the imbalance in the transmission grid that must be compensated by BE. The demand for frequency restauration reserve was roughly the same in both years. It should be noted that mFRR is typically activated when the allocated aFRR activations have already been exhausted. This indicates that the PICASSO platform indeed enables more efficient netting.

When the German BEM was introduced, there were concerns that the BEM might withdraw significant liquidity from the IDM. For this reason, the German Federal Network Agency (BNetzA), invoking an

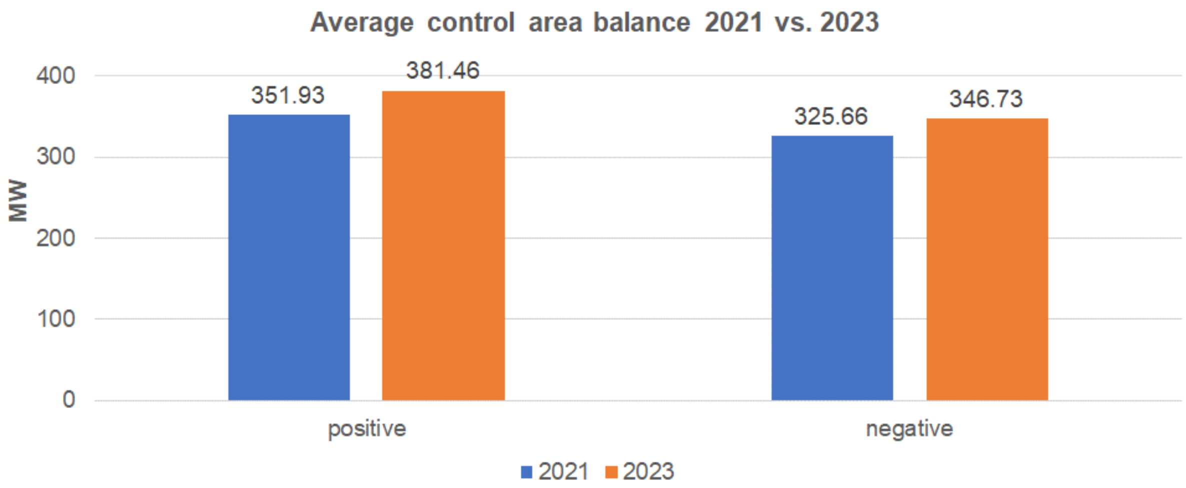



Figure 16: Average values of positive and negative control area balance in 2021 and 2023 as proxy for the demand of reserve energy.

exemption under Article 29 (10) of the European "Guideline on Electricity Balancing" (European Commission, 2017), mandated the release of bids that were not awarded on the BEM. According to that, those bids could be marketed elsewhere – particularly on the IDM – in the remaining trading time after the tender results were published. In Figure 14 the average volumes of the free bids on the BEM for all 96 products in 2023 are compared with the order book volumes of corresponding products on the IDM. For positive secondary reserve the volume of free bids generally accounts for less than 10% of the average aFRR demand of about 2000 MW. The hypothesis that non-awarded bids released on the BEM might increase liquidity on the IDM could also not be confirmed in practice (Bundesnetzagentur, 2022).

For this reason, the release of non-awarded bids was revoked by the BNetzA with effect from 8th December 2022, implying that these bids are now forwarded to the European PICASSO platform. In weighing the possible advantages and disadvantages of this measure, it is argued that the non-released bids would nevertheless be available for balancing energy activations in the event of demand from abroad or an incorrect forecast of requirements, thereby increasing security of supply. Conversely, a possibly lower submission of free bids is considered unproblematic, as their volume is already low compared to those bids that must be submitted obligatorily following an award in the capacity auction. Furthermore, the BNetzA adopts the argument of the appealing TSOs that the previous release of balancing energy bids has the potential to drive up prices, as providers would consider the opportunity costs of lost marketing at the IDM in the offered balancing energy price. By repealing the release, such a surcharge would no longer be factored into the balancing energy bid, which let expect a price-reducing effect (Bundesnetzagentur, 2022).

In fact, with the revocation of the release, the opposite has occurred. Since 8th December 2022, the level of bid prices on the BEM has risen significantly. As Figure 17 illustrates, for both positive and negative balancing energy not only have the average bid prices (in absolute terms) clearly increased. Even the most expensive bid is now practically submitted for any product at the highest (or lowest) permissible price, i.e., 15,000 EUR/MWh for positive and −15,000 EUR/MWh for negative balancing energy (with the negative sign for the latter indicating a payment from the TSO to the provider).

A possible explanation for the higher bid price level is that providers now additionally price in the opportunity costs of the lost marketing opportunity for bids not awarded on the BEM in the remaining minutes of IDM trading. However, this does not explain why, in contrast to before, bids are systematically submitted at the maximum/minimum price. According to publications (TransnetBW, 2023) from the PICASSO platform, in 2023 bids submitted at the extreme prices (15,000 or −15,000 EUR/MWh) were activated only 1343 (351) times, i.e. in 0.05% (0.01%) of all cases for positive (negative) balancing energy in a German control area. Since activations are calculated every four seconds, these prices

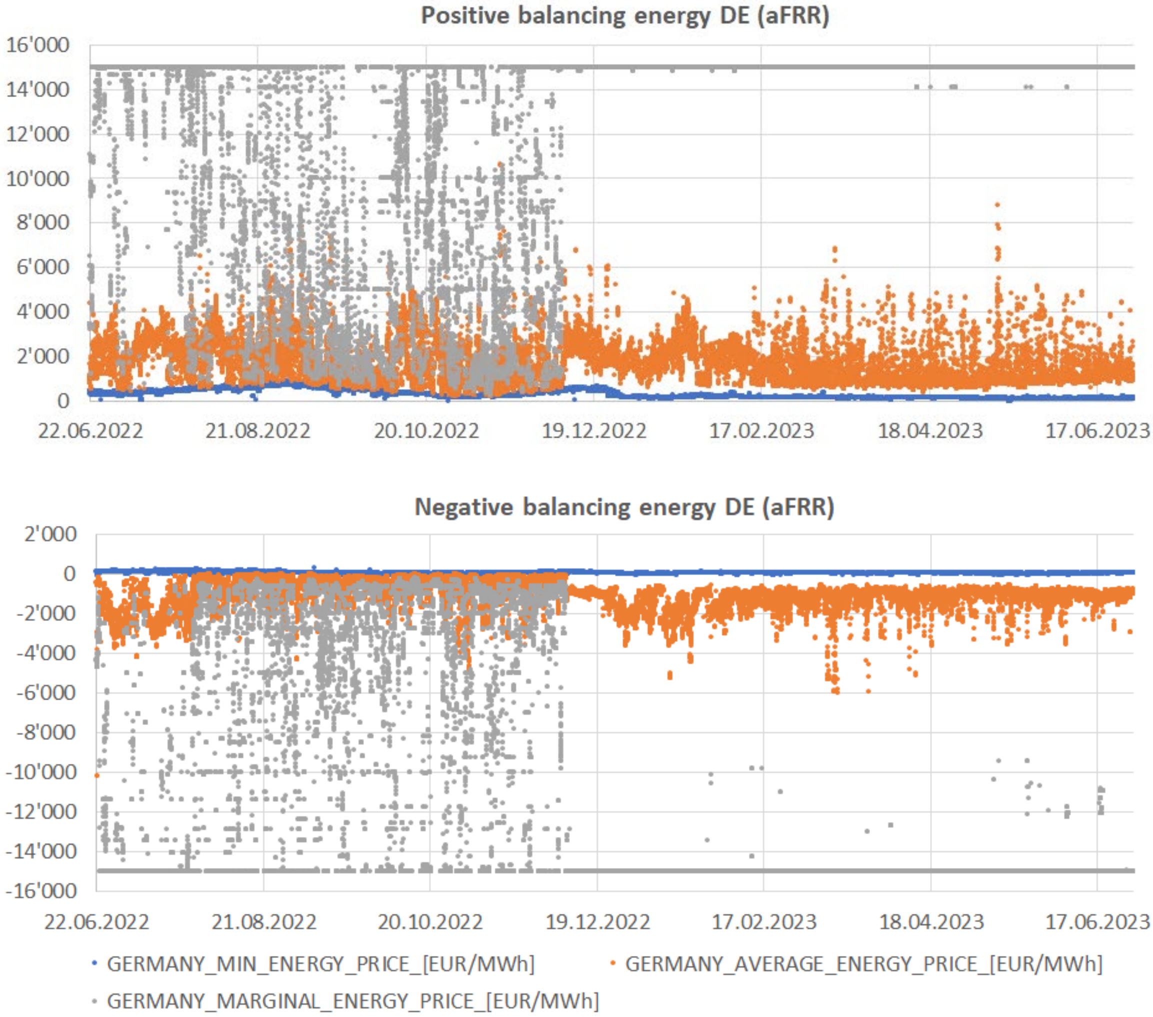



Figure 17: Development of bid prices for positive (upper panel) and negative (lower panel) BE before and after the lifting of the release of non-awarded bids at the BEM: Blue the cheapest bids, orange the average bid price, grey the most expensive bids (from the TSO perspective) that were still accepted to meet the tendered quantity.

would have yielded revenues of only 22'383 EUR per MW for positive and 5'850 EUR per MW for negative balancing energy over the entire year. Even considering that, at times of available transmission capacity at the borders, bids from foreign control areas can also be activated, activations at the extreme prices are equally rare abroad. Since providers of a free bid do not receive compensation for the reserved capacity, it is presumed that these extreme bids stem from participants who were awarded in the capacity auction. Those had already priced in their opportunity costs in their auction bid. Now, these providers have less interest in an energy activation, e.g., as they avoid changes in their scheduled production.

# 3 Trading flexibilities

Asset-backed trading on the electricity intraday market allows for steering the flexible capacity or a whole portfolio of flexible capacities (turbines and or pumps, power storages, etc.) through buying and selling the associated tradable products. Referring to modern option price theory (Björk, 2009), the economic value of such flexible assets may be determined based on generalized valuation concepts for options. Since the flexibility of the asset is not tradable as an option, one may apply a so-called replication strategy to generate the option premium by efficient intraday trading (Björk, 2009).

## 3.1 Valuation of flexible capacities as financial options

In the sequel, we are using the approach of (Weber, 2015) to determine the value of a flexible unit. This approach is also the basis for the guideline for the remuneration of redispatch in Germany (Bundesverband der Energie- und Wasserwirtschaft, 2018), whereby the opportunity costs derived from the ID1 price (the volume-weighted average price of all continuous trades at the intraday market executed within the last trading hour of a contract) serve as a measure for potentially lost revenues in the IDM. This concept may also be applied to the BEM. Here the potential earnings result from the cross-border marginal prices (CBMPs) calculated by the "Activation Optimization Function" (AOF) of the PICASSO platform (50Hertz et al., 2022). For a comparison of the potential earnings of IDM and BEM, we focus on the last 30 minutes of ID trading, i.e., the SDAT phase when the trading has already been split into the different control areas.

Specifically, any capacity unit can be represented as a call option if its net trading position from previous marketing (Day-Ahead, intraday auction, and continuous trading on the IDM) is less than the available generation capacity and, thus, additional energy can be sold, provided that the market price is above the marginal costs (variable production costs), which in this case correspond to the strike price. A put option exists if, after prior marketing of the unit, the price falls below the marginal costs (strike), so that the sold energy can be repurchased at a lower market price and the capacity reduced. It is assumed that the option to sell or buy is always given, i.e., the capacity is still available after any previous transactions in the day-ahead or ID market (auction, continuous trading).

Under the assumption that the stochastic prices follow an arithmetic Brownian motion (ABM), the following formulas (Weber, 2015) result for the values of the call and put:

$$V_C = \int_{-\infty}^{+\infty} max(p - X, 0) f_p(p) dp = \cdots = \sigma\big(d\Phi(d) + \phi(d)\big) \tag{1}$$

$$V_P = \int_{-\infty}^{+\infty} max(X - p, 0) f_p(p) dp = \cdots = \sigma\big(\phi(d) - d\Phi(-d)\big) \tag{2}$$

with $d = \frac{\mu - X}{\sigma}$. Furthermore, $\Phi$ and $\phi$ are the cumulative distribution and the density function, respectively, of the standard normal distribution. The parameters $\mu$ and $\sigma$ represent drift and volatility (expectation and standard deviation) of the underlying price process. No fixed value is assumed for the strike price $X$, the latter depends on the corresponding technology (e.g., type of power plant) and its marginal costs, which in case of fossil generation results from the prices of fuel and the required emission certificates:

$$marginal\ costs\ \left[\frac{\text{EUR}}{\text{MWh}_{el}}\right] = \frac{fuel\ price\ \left[\frac{\text{EUR}}{\text{MWh}_{th}}\right]}{efficiency\ \left[\frac{\text{MWh}_{el}}{\text{MWh}_{th}}\right]} + \frac{emission\ factor\ \left[\frac{\text{mt}_{CO2}}{\text{MWh}_{th}}\right] * EUA \left[\frac{\text{EUR}}{\text{mt}_{CO2}}\right]}{efficiency\ \left[\frac{\text{MWh}_{el}}{\text{MWh}_{th}}\right]} + VOM \tag{3}$$

In the following, the option values are calculated exemplarily for a hard coal-fired power plant and a gas-fired power plant with the following operational parameters:

- Gas: Efficiency = 0.59, Emission factor = 0.201
- Hard coal: Efficiency = 0.33, Emission factor = 0.336
- Variable operating costs (VOM) = 0
- Fuel costs based on daily (spot) market prices: THE Weekday/Weekend price (gas) or 6000 kcal ARA Forward 1 Month as substitute for the spot market price (coal).

The strike prices used in the option formulas as well as the resulting option values are time-dependent (the time index is dropped in the notation for simplicity). For the following analyses, the observed market prices for coal, gas, and emission certificates from 2023 will be used.

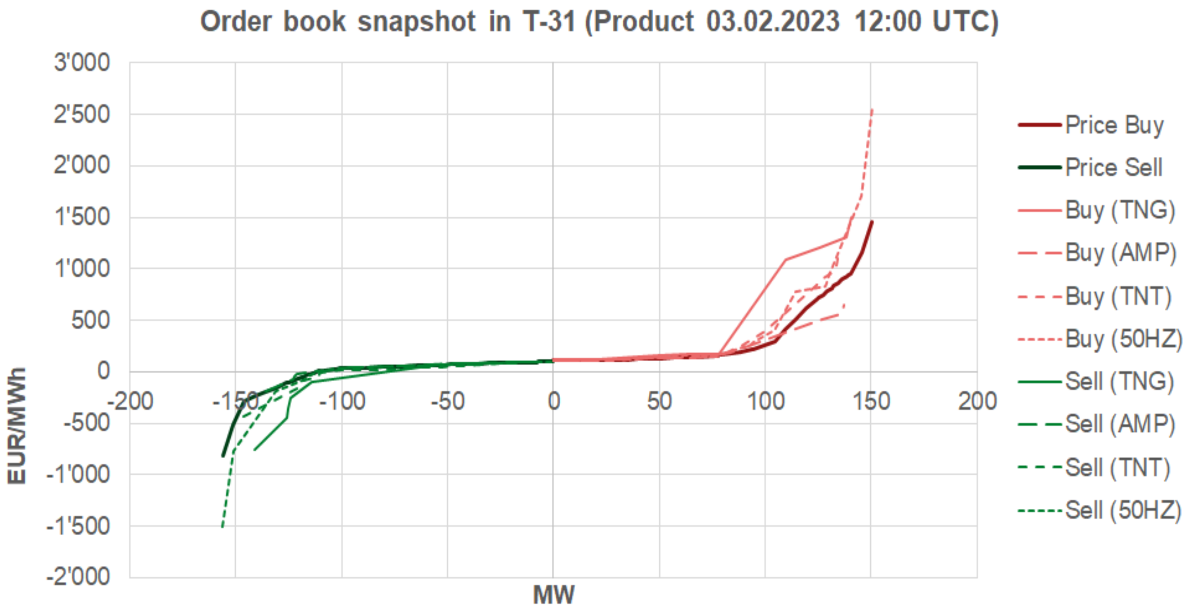



Figure 18: Price-volume structure, i.e., transaction prices at which a certain volume could hypothetically be bought (red) or sold (green). Those are calculated as a volume-weighted average of the prices of the bids required to achieve the corresponding transaction size derived from the order book example in Figure 10. 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.

## 3.2 Application to the intraday market and impact of frictions

For a direct comparison of the earning potentials in IDM and BEM, the value of the flexible capacity is evaluated at T – 30, when ID trading is split up into the individual control areas, each of which with a different level of liquidity. This implies that trading opportunities are, depending on the area, suffer from different friction sizes. We recall that the volume of realized trades in the less liquid TransnetBW area can be close to zero in night hours as Figure 13 shows, although the order book is not empty (see Figure 14). Thus, trading at these times is in principle possible under less favorable prices: the flexible generation capacity is exercised if the currently offered best bid price is above the trigger price (i.e. the strike price of the corresponding call option); the flexible consumption capacity is exercised if the offered best ask price is below the trigger price (i.e. below the strike price of the corresponding put option).

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 characterizes the friction size in the order book: The steeper the price-volume structure, the larger the friction (see Figure 18). The frictions are characterized by the size of the bid-ask spread and by 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 cause 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.

Consequently, with considering the price volume structure the value of a flexible capacity depends on the traded volume when the option pricing model is applied. Contrary to the usual procedure in literature (e.g., Kiesel & Paraschiv, 2017; Kremer, Kiesel, & Paraschiv, 2021), the parameters of the price process for the intraday products are therefore not derived from realized transaction prices, but derived from the volume-dependent prices at which a certain amount of energy could be bought or sold as illustrated in Figure 18: A seller receives the (lower) bid price depending on the offered volumes at the time of the transaction, while a buyer pays the (higher) ask price depending on the offered volumes at the time of the transaction.

Using reconstructed order book data from the entire year 2023, we determine these prices from the sell or buy bids at which 1 MW, 2 MW, etc., could be traded. For the time-dependent expected values (parameter $\mu$) in the formulas above, for each product the prices from the 15-minute auction for the respective delivery day – adjusted by the average historical spreads (deviations from the mean of the bid and ask prices) – are used to account for the different liquidity in the individual zones. The volatility for each of the 96 quarter-hour products is determined by the variation of the difference between the volume-dependent indices and the expected value for the respective delivery day. 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 for each of the four German control areas the evolvement of the option value over trading time. Furthermore, we focus on the median of the 35’040 option values per area 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 19 (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 12 is listed in Appendix B (page 78). 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 19 (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 12 (Appendix B, page 78). The median of the flexibility to consume additional energy over a period of 15 min with a capacity of 1 MW 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.

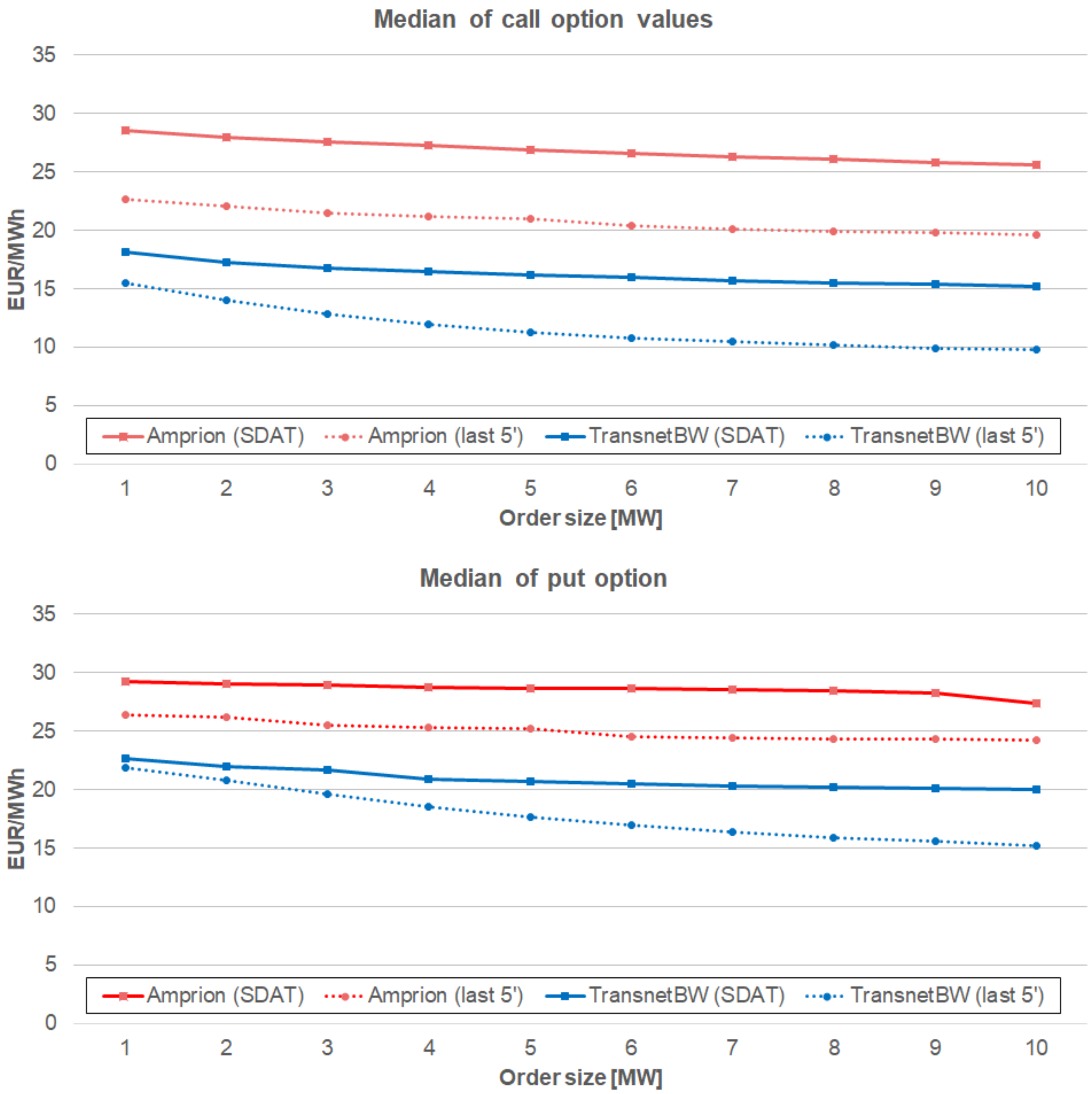



Figure 19: The medians for the call (top) and put (bottom) option referring to the flexibility of gas power plant (calculated using data from 2023).

According to option theory 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 12 (Appendix B, page 78), 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 Table 15 (Appendix B, page 79) 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 five minutes before GC of the ID-market in the respective control areas. In Appendix B, we have listed the corresponding option values for a hard coal-fired power plant, also.

To summarize, for the less liquid TransnetBW zone with higher bid-ask spreads, the value of a flexible capacity obtained from the option pricing models is lower than for the more liquid Amprion zone, as transactions in the former can only be executed by accepting worse prices. In both zones, the option values decrease for larger trading volumes because the effective prices of the total transactions deteriorate. Furthermore, Figure 19 and the tables in Appendix B compare the option values of the price indices that were formed from the bids of the entire SDAT phase (T – 30 to T – 5) with those that consider only bids from the final five trading minutes (T – 10 to T – 5). The latter correspond to the expected returns that could have been achieved on the IDM through the marketing of a released bid not awarded on the BEM. The limited trading opportunities in the last five minutes before GC lead to lower option values compared to trading during the entire SDAT phase. These values represent the previously existing opportunities for bidders on the BEM that were lost due to the abolition of the release of free bids, which would explain the now higher price level of the balancing energy bids.

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-minute 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 of the option values 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.

## 3.3 Application to the balancing energy market

The AOF (Activation Optimization Function) of the PICASSO platform calculates a new activation volume every four seconds and determines the activated providers based on the merit order of BE bids (including those from other control areas, provided that cross-border transmission capacity is available). However, if BE is activated by the TSO, then a provider cannot immediately adjust its output to the full requested amount but must comply with predefined acceptance channels (50Hertz et al., 2021). Compensation is provided only for the delivered energy, as long as the amount requested by the TSO is not exceeded. For positive (negative) aFRR energy, this compensation is based on the maximum (minimum) of the CBMP and the bid price. This principle is illustrated in Figure 20: If a provider is activated according to the AOF of the PICASSO platform, the provided balancing energy is compensated at the CBMP. While the provider still reduces the output according to TSO requirements after the AOF determines a lower activation volume, he receives the bid price for these so-called "Non-AOF Volumes."

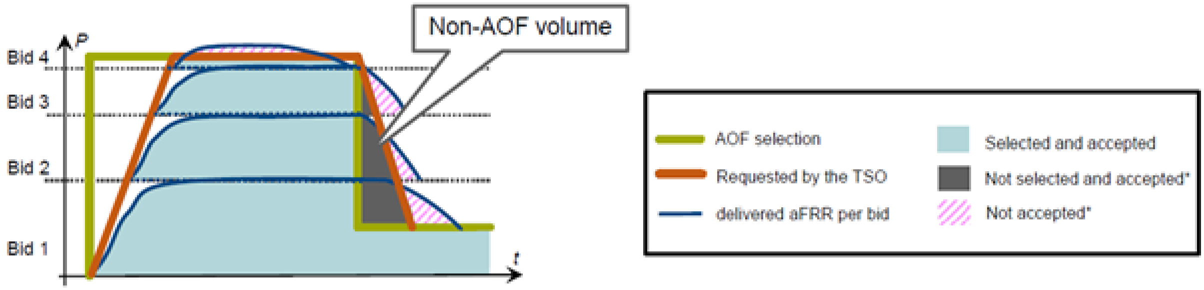



Figure 20: Selection of activated bids by the AOF and energy deliveries from the providers (50Hertz et al., 2021). The blue areas correspond to energy deliveries from the cheapest BSPs that – according to the AOF – are needed to provide the required power (green line). The call is made by the respective TSOs in accordance with the technical requirements for the adjustment period (red line)

The valuation approach presented above is applied analogously to the assessment of revenues from BE activations. Since PICASSO calculates a new activation signal every four seconds and potentially also a different CBMP, providers essentially issue 225 [=15*60/4] options over four-second delivery periods within the 15-minute product period, which may be exercised in full, in part, or not at all: Call options for positive BE (generation and sale to the TSO), or put options for negative BE (consumption/reduced generation and purchase from the TSO). These options are activated by the grid operator and their payoffs can be valued using the previously described formulas (1) and (2).

For the application of this concept, the following assumptions and simplifications are made: Since actual energy deliveries within the acceptance channels are difficult to model, it is assumed that providers can immediately adjust their output according to the AOF. A provider is activated if there is an activation in a German control area and the associated bid price for positive BE is below the current CBMP, for negative BE above the current CBMP[3], respectively. It is not considered that activations could also stem from other control areas, as potentially limiting transmission constraints are unknown. Finally, for valuation purposes, it is assumed that 1 MW of capacity is offered and fully delivered upon activation, implying the bid was not the price-setting one, as its capacity might otherwise only be partially activated. The volatility is determined for each product based on fluctuations in the CBMP at activation, relative to the average of the respective 15-minute delivery period. Intervals without activation are not considered. This results in 96 estimated values each for positive and negative BE over the sample period.

## 3.4 Comparison of earnings from bidding in IDM and BEM

For a first assessment of the earnings opportunities on the IDM and the BEM, the potential revenues from marketing a flexible capacity in one of the two markets are compared, independent of any modeling assumptions, in an ex-post analysis using the realized price and activation data from 2023. Since the relevant time window falls into the SDAT phase, in the case of the IDM the four control areas are considered separately due to their different market frictions measured by bid-ask spreads (see Figure 11) and price-volume structure (see Figure 18). 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 costs. As an example, the marginal costs for the assumed gas-fired power plant are calculated as described above. This implies that the bids on the BEM are always considered, as even bids submitted at ±15,000 EUR/MWh were awarded in the period under consideration (see Figure 17). Table 2 shows the share across the 17'668 delivery periods of 15 minutes[4] for which in the SDAT phase a transaction in the respective control area would take place, or a bid submitted to the BEM would have been activated. The revenues that would have been achieved by marketing 1 MW are shown in Figure 21.

[3] A positive sign for the price of negative control energy indicates a payment from the provider to the TSO, a negative value indicates a payment from the TSO to the provider, i.e. higher (positive) bids are cheaper from the TSO's point of view.
[4] (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 2: 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).

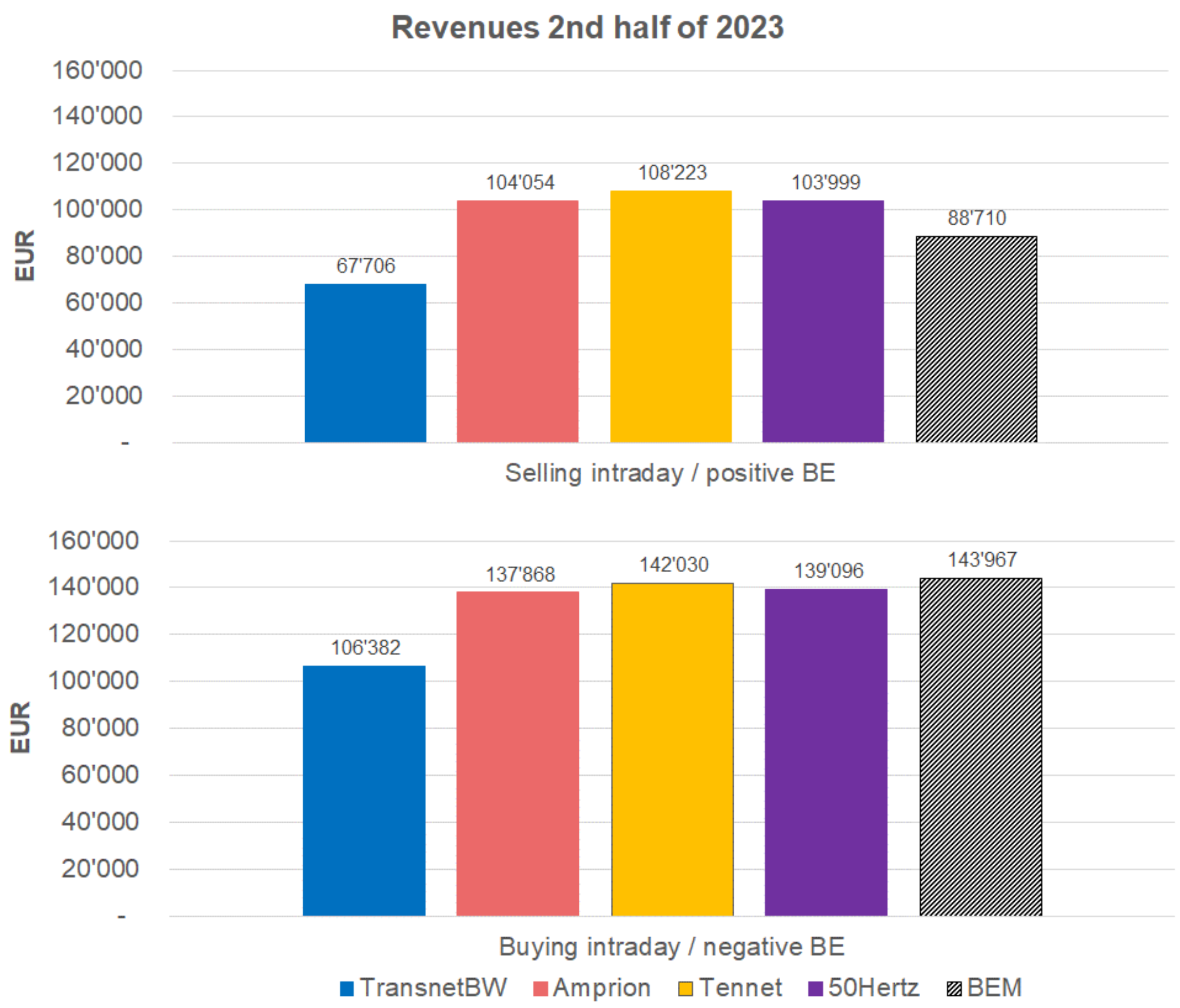



Figure 21: The revenues for transactions of size 1 MW on the IDM in the individual control areas during the SDAT-phase and for activated bids in the BEM. The upper panel shows the revenues for sales in the IDM when the currently offered bid prices are accepted, as well as for activated bids for providing positive BE of 1 MW. The lower panel shows the revenues for purchases in the IDM when the currently offered ask prices are accepted, as well as for activated bids for providing negative BE of 1 MW.

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 this zone, also the lowest revenues were achieved due to the higher bid-ask spreads. In the case the flexible capacity exceeds 1 MW, one must apply the price-volume-structure in the IDM of the respective control area. In general, bids have been activated less frequently on the BEM than on the IDM. For ID trading in all areas, the revenues from purchase transaction (consumption) are higher than those from sale transactions (generation). The revenues achieved from negative BE are higher than those achievable on the IDM through purchase transactions. For positive BE, significantly higher revenues are achieved compared to ID trading in the TransnetBW zone. In the control areas Amprion, Tennet and 50Hertz, the achieved revenues for trading 1 MW in the IDM exceed the one achieved for delivering positive BE by less than 10%.

Overall, the revenues achievable for trading in the IDM or bidding in the BEM are quite similar on average, except for the less liquid TransnetBW area. This already gives a first indication as to whether an additional premium should be offered to market participants in the IDM to allow that their bids are transferred to the BEM. We next examine whether flexibility providers – instead of consistently bidding in the same market – could achieve higher revenues by selecting the market that offers the higher profit prospects. 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. Taking into account that a providers have no foresight of the profit outcome at the time of deciding to bid either in the IDM or the BEM, we assume that providers apply the option pricing model (1) – (2) to estimate the expected profits in both markets.

We are aware of the different characteristics of ID and BE products: For the "*intraday option*", energy is delivered over 15 minutes if exercised. The ID auction price adjusted by spreads represents the expected value for the respective period. For the “*balancing energy option*”, the delivery quantity is unknown in advance because, in general, the capacity is not (in full) activated over the entire 15-minute interval. Our analyses have shown that there is only a weak relationship between the price levels on the IDM and the BEM (or the realized CBMPs). 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. It remains a challenge to model the expected value for the “*balancing energy option*”.

For the further analyses, this has been resolved as follows: As the expected value $\mu$, the last known CBMP average for activations during a preceding 15-minute interval is used. We apply the CBMP average for positive and negative BE separately. The CBMPs are published with a 15-minute delay; that is, at T – 30 the 225 values from the 15-minute interval [T – 60, T – 45) are known. The option value determined from this is then weighted with an adequate forecasted activation duration. Under the assumption that a flexible capacity follows the activation signals of the AOF immediately and that activations do occur every four seconds, the following forecast model for the activation durations is estimated for each time slot:

$$P_T^{act,+} = c^+ + a^+ \cdot P_{T-60}^{act,-} + b_1^+ \cdot P_{T-60}^{act,+} + b_2^+ \cdot P_{T-120}^{act,+} \tag{4}$$

$$P_T^{act,-} = c^- + a^- \cdot P_{T-60}^{act,+} + b_1^- \cdot P_{T-60}^{act,-} + b_2^- \cdot P_{T-120}^{act,-} \tag{5}$$

Here, $P_T^{act,+}$ (or $P_T^{act,-}$ ) stands for the proportion of 4-second intervals during the 15-minute interval starting at time T in which positive (negative) BE is activated and, thus, an option is exercised. This proportion is explained by the delayed values one (T – 60) and two (T – 120) hours before beginning of delivery. It is apparently difficult to predict future activations from previous time intervals; the coefficient of determination from the estimations of (4) and (5) amounts to about 12%. However, also with 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. On the other hand, the coefficient of determination would rise to

40% if the GC on the BEM were at T – 15 and the CBMPs were available immediately after the preceding 15-minute interval.

We rely on taking the average of the CBMPs separately for positive and negative BE in the 15-minute interval [T-45, T-30] and apply the decision rule "*choose the market with the highest option value evaluated at T-30* ". This time stamp lies before the GCT of the BEM (currently at T – 25). Also, at T-30 the ID trading is split into the individual control areas. The parameters of the equations (1) – (5) are estimated with data from the first half of 2023 and the rule is tested for the second half of this year (out-of-sample). Because all bids more favorable than ±15,000 EUR/MWh are considered in that period, a release of a BEM bid, that was previously transferred from the order book of the IDM to the BEM does not occur. Thus, the "short-term option" mentioned in Figure 17 of marketing the flexibility in the last five minutes of the remaining trading time is not existent during the year 2023.

The results are summarized on page 41: Table 3 indicates how often a bid on the BEM would have been preferred over the IDM because – according to the model – BE provides a higher option value. Figure 22 reveal the revenues and their relative changes, as calculated from the realized price and activation data, that would have resulted from participation in the market with the highest expected prospects at time stamp T-30. 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 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 improved results compared to bidding in just one market.

One must be aware of that the informative value of economic indicators decreases with increasing transaction costs in continuous-time intraday trading. This fact explains why the revenues generated within the TransnetBW control area for both markets are lower than the revenues generated in the balancing energy market alone. The higher liquidity in the Amprion, Tennet, and 50Hertz control areas, however, demonstrates the competitiveness of their continuous-time intraday trading with the balancing energy market.

In the final step we derive the value of perfect information. It is assumed that a flexibility 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 4 on page 42 shows the numbers for delivering positive and negative BE, respectively, and identifies the delivery periods of 15 minutes, where the BEM is preferred over the individual control areas. Figure 23 reveals 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. If we compare the revenue potential under the decision rule to the achievable revenues under perfect information, we obtain that for additional flexible production, the decision rule for the TransnetBW control area captures about 64% of the achievable revenues under perfect information. For the Amprion, Tennet, and 50Hertz control areas, about 70% is captured each. For additional, flexible consumption, roughly 72% of the achievable revenues under perfect information are captured across all four control areas. The value of perfect information indicates the limits for investments in the purchase of information or in the development of forecast models. Overall, the proportions in which bids are submitted on the IDM, or the BEM and the generated revenues are balanced.

| 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 3: BEM in competition with the IDM of the four control areas with applying the economic decision rule.

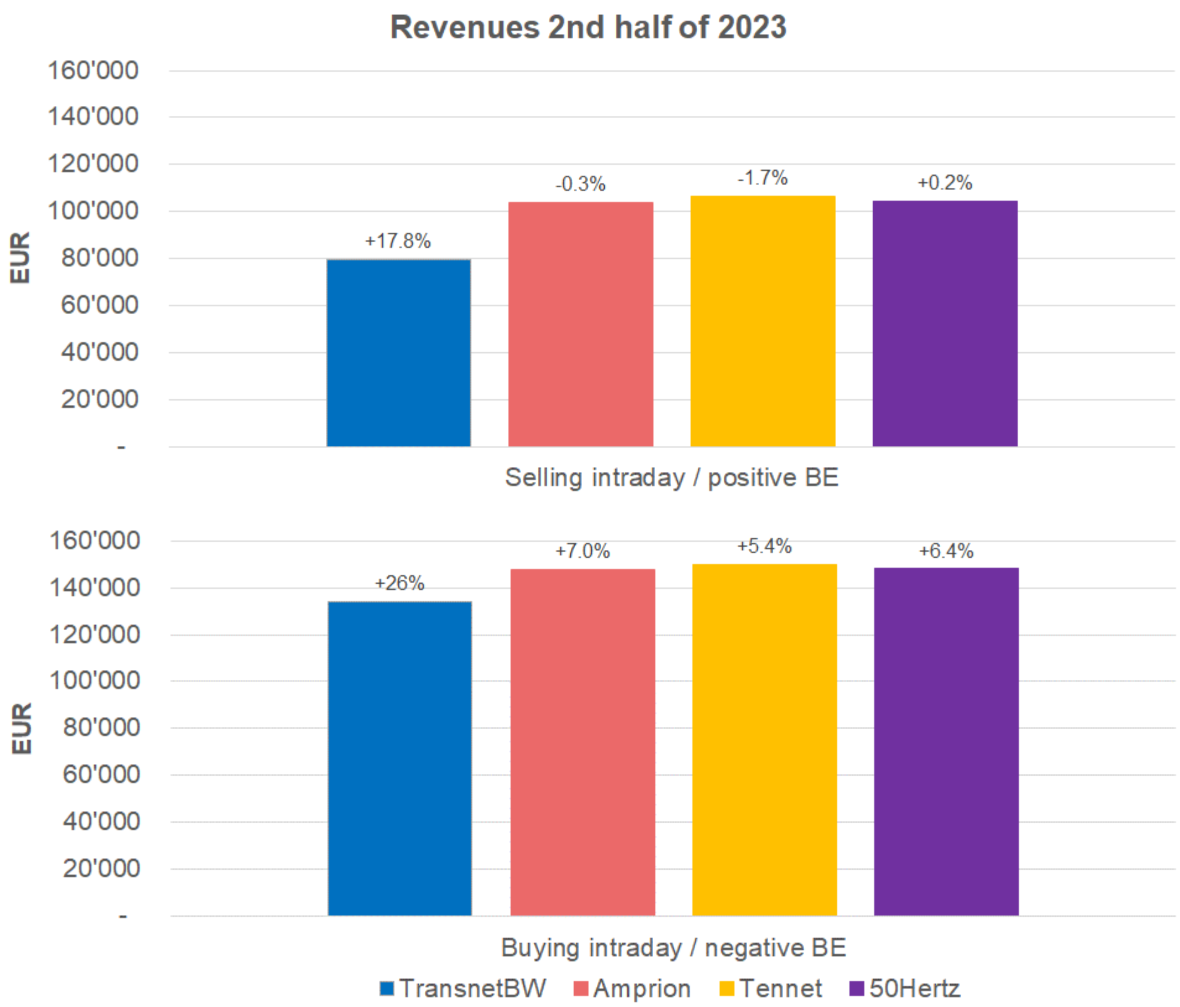



Figure 22: Additional revenues (in %) achieved by application of the decision rule for bidding 1 MW in the IDM of the respective control area or in the BEM. The upper panel shows the revenues for sales in the IDM or providing positive BE, respectively. The lower panel shows the revenues for purchases in the IDM or providing negative BE. The values are calculated based on realized prices.

| 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 4: BEM and IDM perfectly exploiting competition.

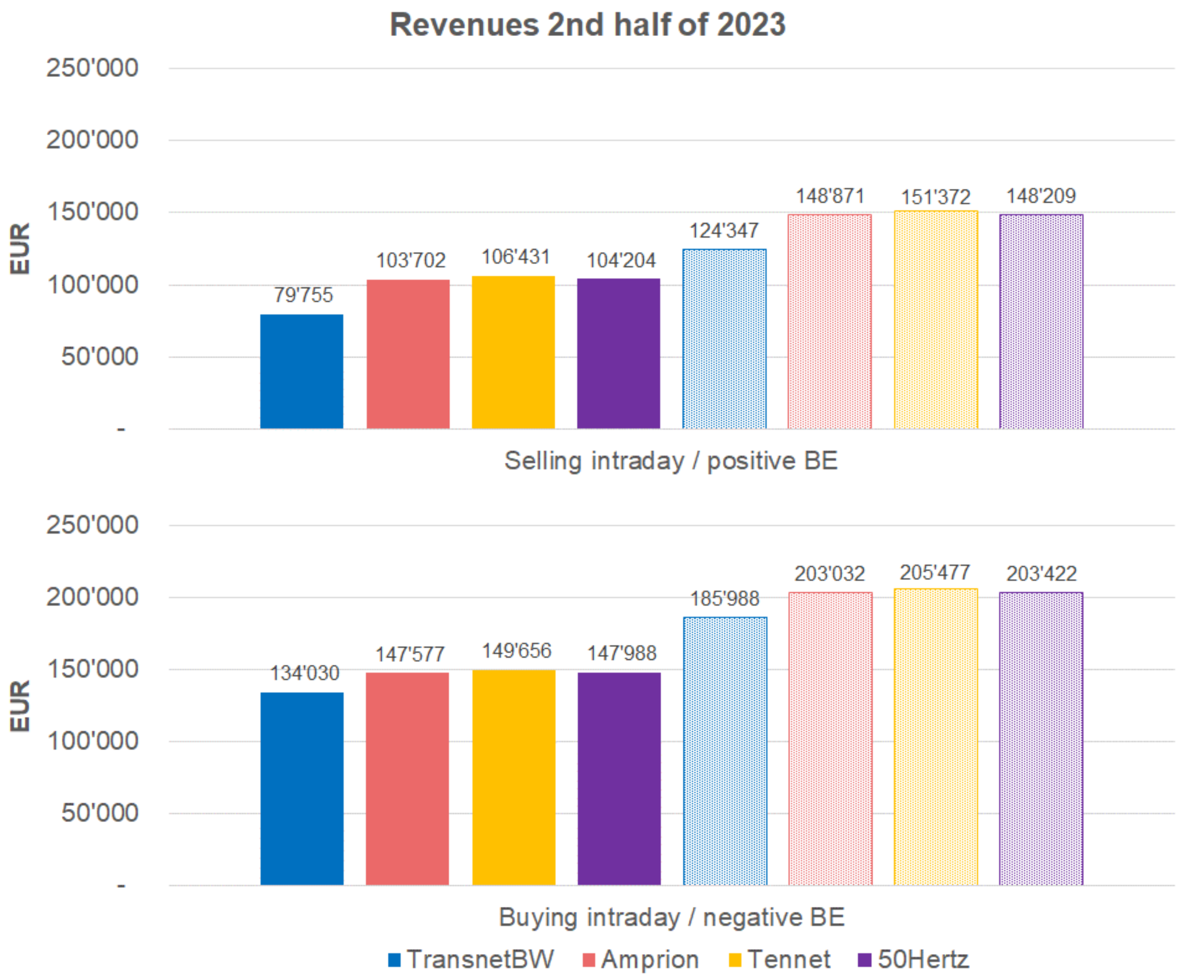



Figure 23: Revenues achieved with the decision rule (coloured solid) vs. revenues achieved with perfect information (coloured shaded). The upper panel shows the results for selling on the IDM or providing positive BE. The lower panel shows the results from buying in the IDM or providing negative BE.

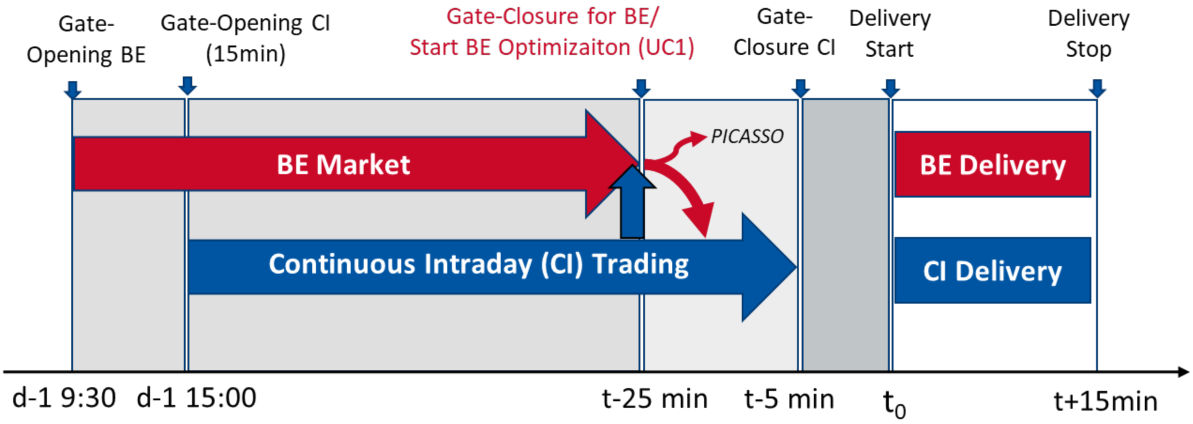



Figure 24: Illustration of the use case under consideration. Before GC of the BEM, bids from the ID order book are transferred into the bid list for balancing energy. If these bids are not awarded, they are released, and the capacity can still be marketed on the IDM during the remaining trading time. Bids originally submitted on the BEM and not awarded are passed on to the European PICASSO platform.

## 3.5 Use case: Transfer of intraday bids into the balancing energy market

In the remainder of this section, we analyze as a use case the integration of the IDM and BEM, specifically for secondary reserve (automatic frequency restauration reserve, aFRR). This case was specified in an earlier phase of the DigIPlat project. Its motivation lies in a possible increase in liquidity on the BEM. It is assumed that both markets, IDM and BEM, start as usual at their respective gate opening on the previous day (D – 1). Prior to the GC of the BEM, which currently takes place 25 minutes before delivery (T – 25), qualified bids for balancing energy from the IDM's order book are transferred into the BEM's bid list and inserted accordingly. Bids that are not awarded during the BEM's market clearing (currently at T – 10) may be returned to the IDM's order book, leaving an additional opportunity to market them during the last 5 minutes of trading until GC (T – 5). In this way, bids transferred from the IDM to the BEM differ from those originally submitted there; the latter are forwarded to the European aFRR-platform PICASSO for the exchange and cross-border activation of BC (see Figure 24). We assume here that the transfer of bids takes place at the end of nationwide trading at T – 31, because during the subsequent SDAT phase the order books in the individual control areas are newly formed.

Recall that the remuneration of BE is essentially based on the Cross-Border Marginal Price (CBMP), which the PICASSO platform calculates according to the merit order (MO) while taking into account the available transmission capacities, i.e., "pay-as-cleared" (see section 2.2). Only the delivered energy is compensated; the duration and amount of activation, as well as the remunerated price, remain uncertain. In contrast, on the IDM, settlement occurs at the price at which a bid was accepted, with delivery being constant over the product’s full delivery period. The previously described modeling of BE and ID products as financial options, whose value is determined at T – 30, allows for a direct comparison of the earning potentials in both markets, considering that the activation of balancing energy and the potential earnings on the IDM in the remaining trading time are uncertain.

When the use case was formulated, it was still an open question whether sufficient incentives exist for IDM participants to allow the transfer of their bids into the BEM or whether additional premiums would need to be offered. From the results of the previous section, according to which the earnings potentials in the IDM and BEM are largely balanced, it follows that such additional incentives are not necessary. The regulatory change to revoke the release of unawarded capacity allocation bids also came after the use case was formulated. This means that the last considered bids required to reach the tendered volume are now submitted at the maximum price of ±15,000 EUR/MWh, thus automatically awarding all bids transmitted by the IDM. Thus, also the value of the option of marketing the flexible capacity in the IDM in the last five minutes of trading does not have to be considered in the current market design.

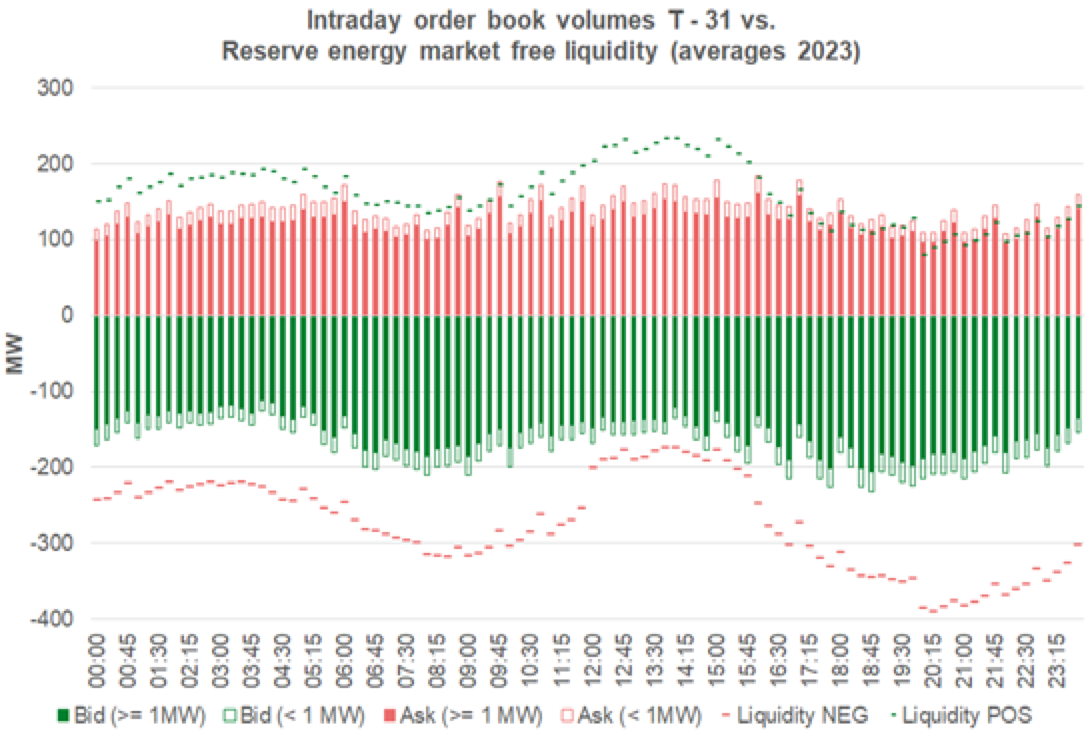



Figure 25: Average order book volume of all bids for the 96 quarter-hour products on the IDM and those ≥ 1 MW power. In comparison, the free bids on the BEM (referred to in the legend as "liquidity").

It remains to clarify to what extent bids from the IDM can be transferred to the BEM. In principle, only pre-qualified providers can bid on the BEM; however, the anonymous bids on the IDM do not reveal if a market participant meets the requirements for providing BE. For a rough estimation, we make the optimistic assumption that all bids from the IDM order book with a size of at least 1 MW (minimum bid size on the BEM) are qualified to provide aFRR. Since only whole-number bids are permitted on the BEM, non-integer bids from the IDM order book are rounded down. Under these assumptions, as shown in Figure 25, most bids would be transferred to the BEM. The additional volume thus realized is smaller than that of the existing free bids.

Through the insertion of additional bids, the merit order on the BEM is shifted, i.e., the procurement of a certain amount $Y$ of BE would thereby become less expensive for the TSOs. This is illustrated in Figure 26 on page 46 for an arbitrarily chosen delivery period from the past. Although the volume available for a possible transfer from the IDM's order book at T – 31 appears at first glance small compared to the free bids on the BDM, there is a significant shift in the merit order curve for BE if all bids above 1 MW are indeed transferred.

Table 5 shows the corresponding changes for specific capacity levels as averages for 2023. For both positive and negative BE, the procurement of a given quantity becomes less expensive. Since for negative BE mostly negative prices are demanded (equivalent to payments from the TSO to the provider), positive changes represent lower costs for the system operator.

The average change in the prices of those bids required to procure 100% of the contracted capacity by approximately −9'700 EUR/MWh (positive BE) and +8'000 EUR/MWh (negative BE) indicates that the most expensive bid considered is no longer systematically submitted at the extreme prices of ±15,000 EUR/MWh. Thus, bids originally transferred from the IDM to the BEM could potentially be passed back to the IDM as assumed in the use case. However, their price levels would still be too high and unless they are modified, it is unlikely that they will be matched by another trader's bid in the remaining trading time on the IDM.

| | 0.1 | 0.15 | 0.2 | 0.25 | 0.3 | 0.35 | 0.4 | 0.45 | 0.5 | 0.55 |
|---|---|---|---|---|---|---|---|---|---|---|
| POS | -22.04 | -7.69 | -5.99 | -7.79 | -8.48 | -9.74 | -10.94 | -14.35 | -20.07 | -27.00 |
| NEG | 19.10 | 7.62 | 6.08 | 6.82 | 8.73 | 11.90 | 16.62 | 22.88 | 33.13 | 68.25 |

| | 0.6 | 0.65 | 0.7 | 0.75 | 0.8 | 0.85 | 0.9 | 0.95 | 1 |
|---|---|---|---|---|---|---|---|---|---|
| POS | -44.24 | -71.25 | -136.98 | -287.91 | -499.24 | -878.10 | -1'471 | -4'325 | -9'744 |
| NEG | 97.95 | 110.48 | 131.99 | 218.00 | 415.95 | 809.65 | 1'406 | 4'491 | 8'029 |

Table 5: Average change in the prices of those bids required to cover 10%, 15%, 20%, ... of the required secondary reserve capacity by transferring them from the ID order book to the BEM bid list with data from 2023.

Apart from the previous optimistic assumption that all bids from the IDM's order book above 1 MW are available, it remains open how many bids could be transferred into the BEM. Balancing energy can in principle be provided only by pre-qualified providers, and the facility, to which a bid in the IDM's order book refers to, is not transparent. Moreover, many bids on the IDM come from operators of renewable generation plants that hedge against forecast errors from previous marketing to avoid paying the imbalance price. Even if such facilities were (in the future) qualified to offer reserve power, these providers would not be indifferent between marketing on the IDM and providing BE, since in the latter case the activated quantity is unknown and costs for imbalance energy could arise. It is in the end difficult to derive the shift in the merit order curve resulting from the integration of the IDM and BEM and to estimate the potential cost reduction for network services for end users precisely.

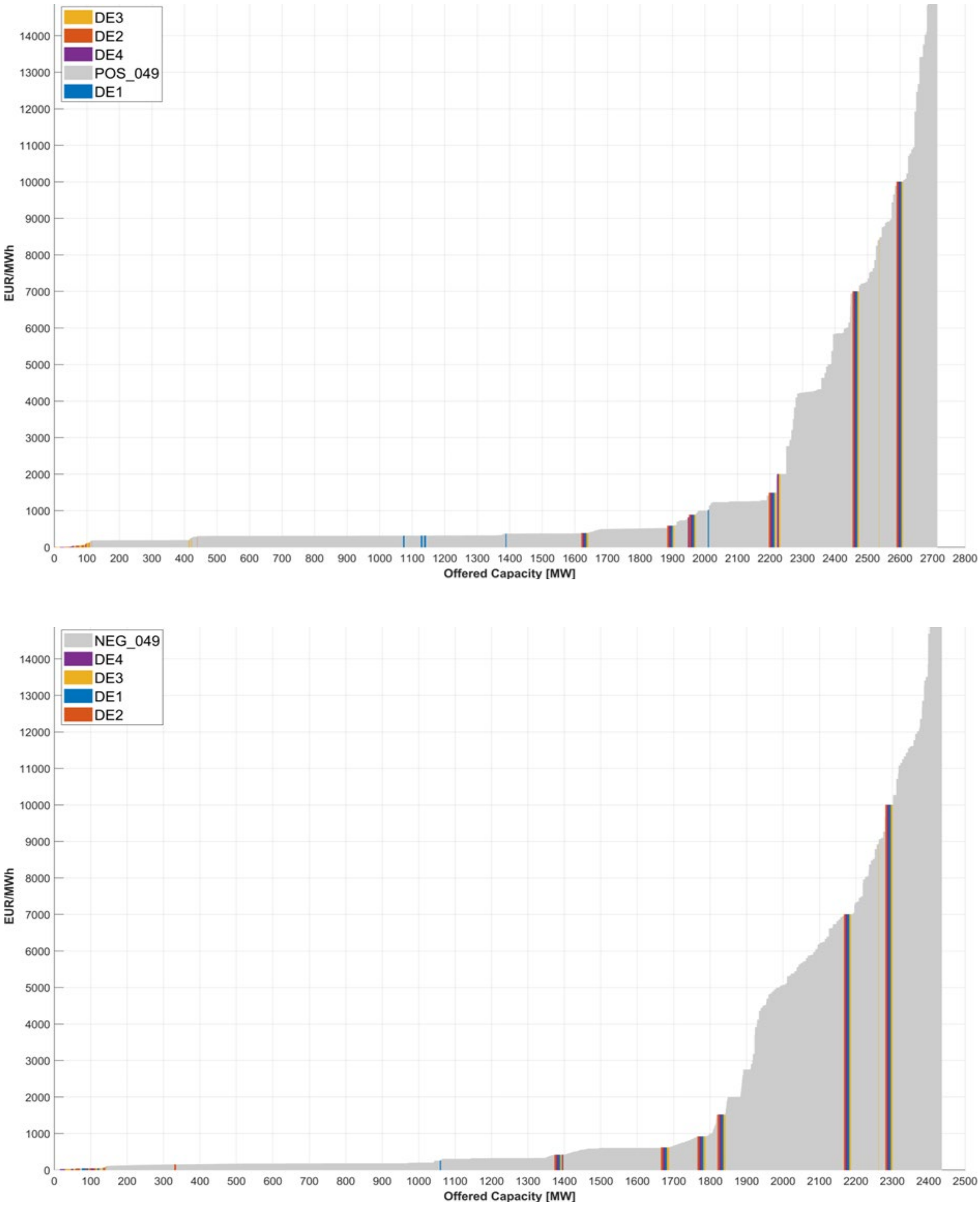



Figure 26: Sorting the bids from the intraday order book for the delivery period 12:00 – 12:15 on 1st January 2023 into the merit order at the RAM for positive (top) and negative (bottom) control energy. The x-axis represents the cumulative capacity offered. Prices for negative control energy were multiplied by –1, i.e., in both graphs, positive values correspond to payments from the TSOs to the providers. The gray areas correspond to the original bid lists at the RAM, the colored columns to the bids taken over from the IDM, which shift the merit order to the right. The abbreviations of the control areas stand for TransnetBW (DE1), Amprion (DE2), Tennet (DE3) and 50Hertz (DE4).

# 4 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 must 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.

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 modeling price and volume dynamics based on corresponding empirical data. The implemented analysis tools for measuring liquidity and frictions are also applicable to the common *limit order book* (LOB) in the SIDC phase.

## 4.1 Liquidity and frictions

For ID trading, a cost-liquidity metric is derived that quantifies frictions in *basis points* 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.

### 4.1.1. Liquidity and frictions

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 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* 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 *best-bid-offer* with large available volumes on each side of the order book. For a power trader, the *value-based bid-offer-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 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.

#### 4.1.2. 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 27). 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.

#### 4.1.3. Frictions and stressful trading days

In Table 6 to Table 10 (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.

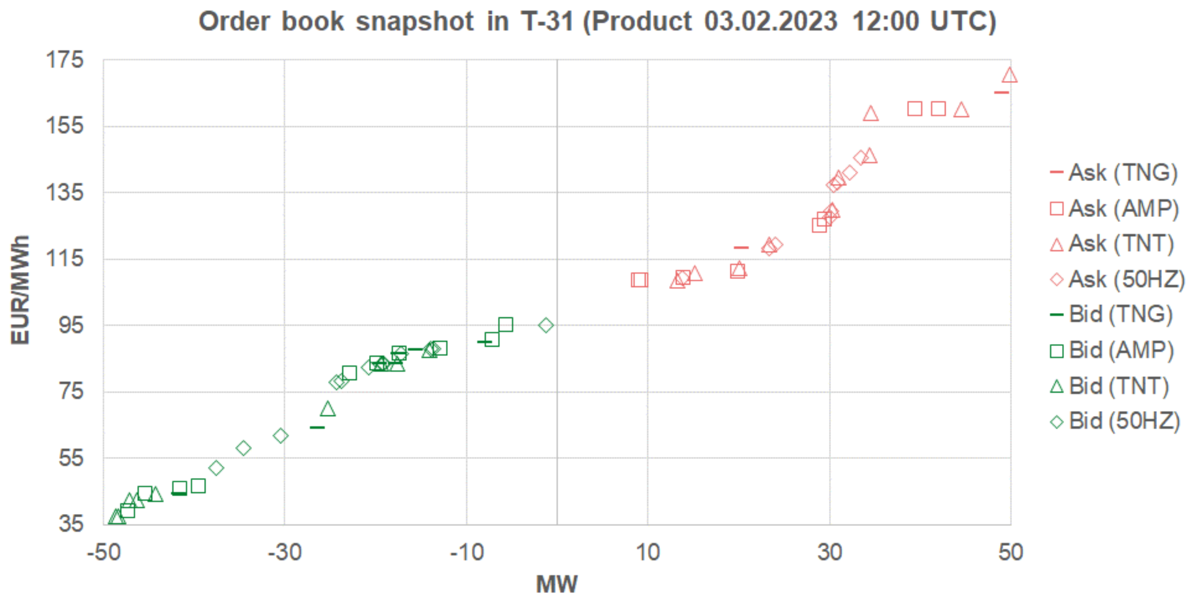



Figure 27: Extract from the orderbook for 15-min products in Figure 10 with bids differentiated by control areas. Each green and red marker represents one bid, its type stands for the control area from which it originates. The values along the x-axis are the cumulative volumes. For clarity, the chart is limited to the range up to 50 MW.

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.

## 4.2 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[5] or ID3[6] 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 could 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 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, On the Difference between Asset-backed Trading vs. Proprietary Trading, 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

[5] 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.

[6] 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.

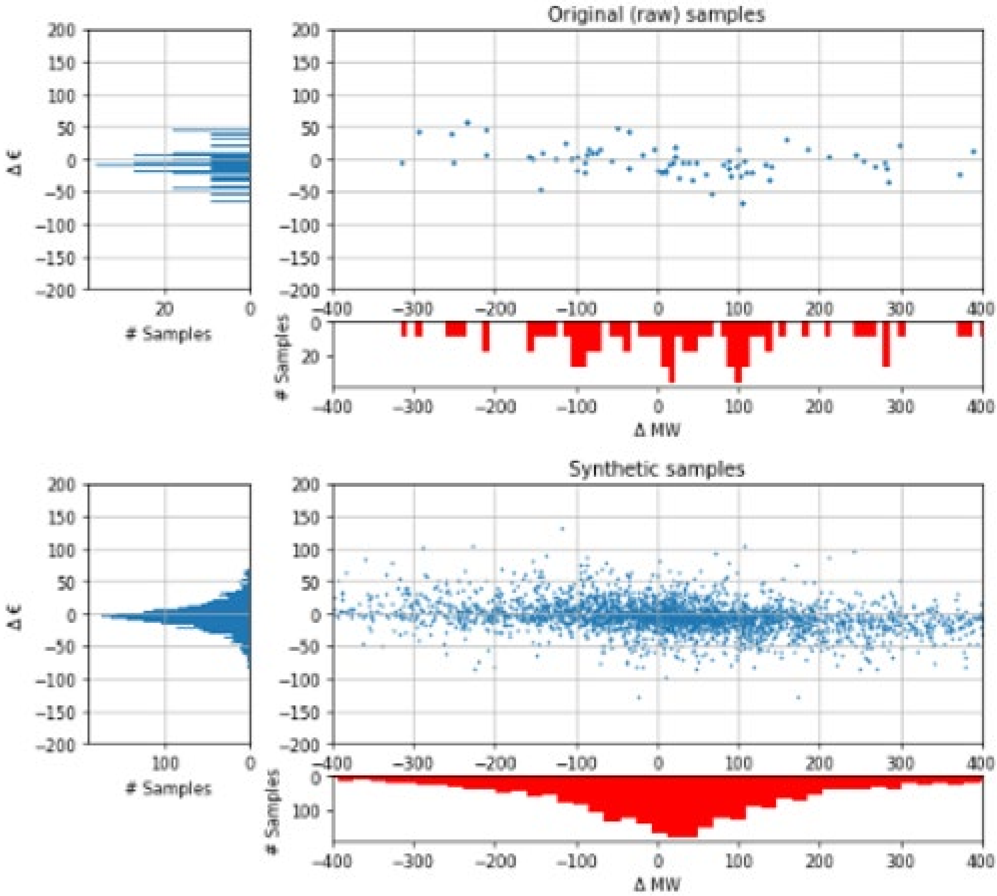



Figure 28: Marginal distributions & Copula – Observed sample and synthetic sample based on estimated distribution of joint price and forecast changes with respect to feed-in. Example for changes from 60 min to 30 min before delivery for hourly contracts on weekday afternoons.

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 28) 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.

# 5 Price effects of PICASSO on the German Intraday Market

## 5.1 Transfer of intraday bids into the balancing energy market

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 IDM, 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 IDM 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 delivery period.
- 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.

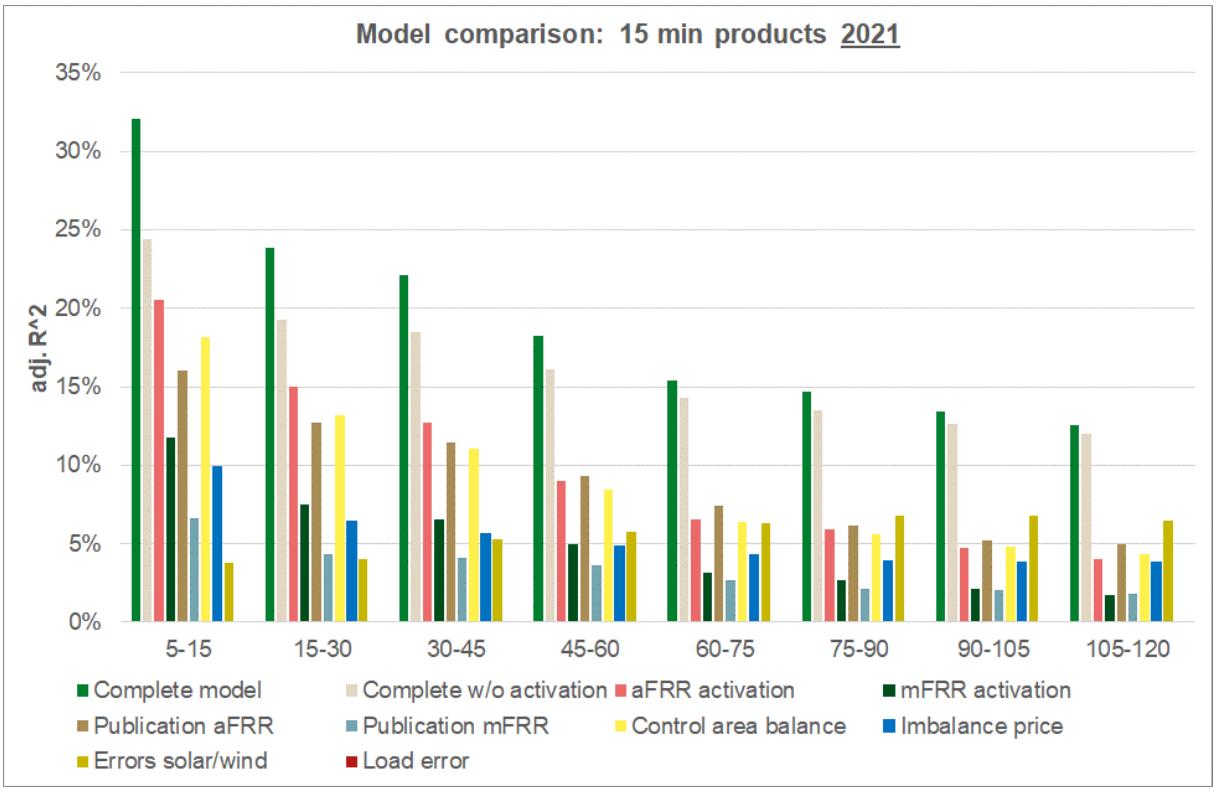



Figure 29: Comparison of the explanatory power for the deviation of prices for 15-minute products during the continuous intraday trading from their prices achieved in the opening auction using data of the years 2021 (before go-live of PICASSO, upper panel) and 2023 (after go-live of PICASSO, lower panel). Data are grouped into different classes according to time to delivery (shown along the x-axis) for which various models are applied. The bars represent the corresponding adjusted coefficients of determination of the different model versions. The first model uses a complete set of fundamental data described in the legend. The second model is a reduced version without activation signals for frequency restauration reserve. The other models are simple regression models with single factors as specified in the legend.

- 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 IDM 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 considered that the price impact triggered by 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 29 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 factors aFRR activations 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 decreases significantly. The remaining columns represent the goodness of fit of simple (i.e. one-dimensional) regression models, using a single factor from the list. Note, that in Figure 29 forecast errors for the renewable generation from solar and wind are combined in one factor.

It is noticeable the single factor *activation of aFRR* explained over 20% of the price variability (third column), almost as much as the model with all other variables. Also, the factor last published *control area balance* has a significant explanatory power, higher than the publication of the factor aggregated *aFRR activations* after the end of the corresponding time slice.

Looking at the estimated coefficients in Figure 40 (upper panel) in Appendix C on page 82, 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 factor *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 activated 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, the coefficients for the factor *activation of negative aFRR* (independent of size) and *activation of mFRR* are of much smaller magnitude. In general, both the explanatory power and the coefficients for the single factors are the highest for the prices of the front product and decrease with increasing time to delivery period. As Figure 41 (Appendix C, page 81) shows, the price reaction following the publication of aggregated activations is insignificant except for the factor *positive mFRR*, which is available immediately after the end of each 15-min interval. Apparently, the information about a system imbalance requiring the activation of aFRR had already been processed by relevant market participants. Only the indication of a greater shortage resulting from the activation of positive mFRR has still an impact on the price after being published. The coefficients for the factor *negative mFRR* are statistically not significant.

For a comparison of the magnitude of the price reaction following frequency restauration activations, Figure 42 (Appendix C, page 82) shows in the upper panel the coefficients for the listed factors that relate to deviations between forecasted and actual generation and consumption. As the factor *control area balance* reveals the highest coefficients for the front products, it is also the factor with the highest explanatory power after aFRR activations in the simple regression estimations. The increase of the coefficient for the factor *imbalance price* with increasing time to the delivery period for year 2021 appears not plausible[7]. The coefficients for the factors *PV generation forecast errors (+/-)* and *wind generation forecast errors (+/-)* are relatively small and of similar magnitude for all remaining trading times. This observation could be explained by the relatively long delay between end of the respective 15-min interval and their publication, which indicates that 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 factor *load forecast error* is statistically insignificant in year 2021.

[7] It could be caused by several modifications in the underlying calculation and publication times, see https://www.netztransparenz.de/de-de/Regelenergie/Ausgleichsenergiepreis.

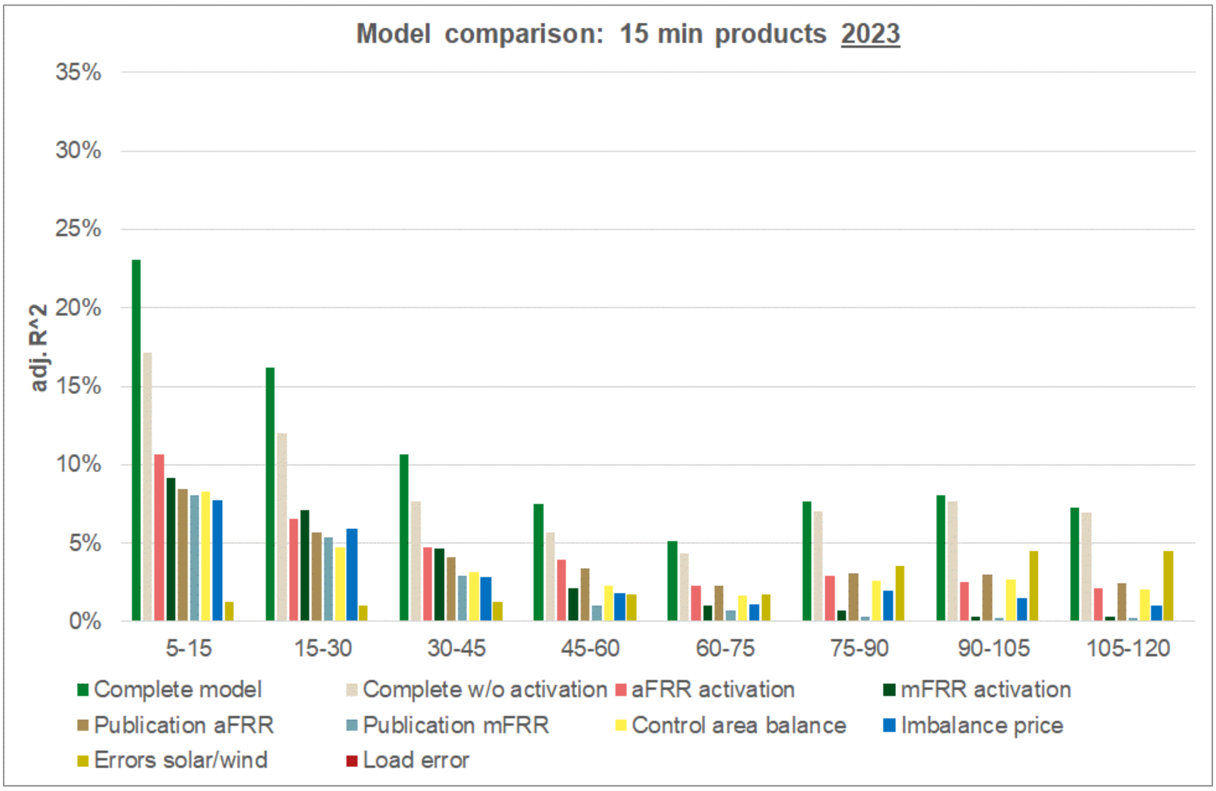



Figure 30: Comparison of the explanatory power for the deviation of prices for 15-minute products during the continuous intraday trading from their prices achieved in the opening auction using data of the year 2023 (after launch of PICASSO).

The introduction of the PICASSO platform in June 2022 has led to important changes in the activation of balancing capacity:

Firstly, the amount of activated aFRR and mFRR decreased significantly from year 2021 to year 2023 (years before and after going live of the platform) as Figure 15 shows. As it can be seen in Figure 16, both the average positive and negative control area balances serve as proxy for the demand of reserve energy and were of similar magnitude in both years or even slightly higher in 2023[8]. 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 lead to an increase in the compensation of positive and negative activations in different areas. In particular, the activation of mFRR was reduced by a noticeable multiplier. 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 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 IDN receive less activation signals that they could exploit for trading decisions since the launch of PICASSO.

As shown in Figure 30, the explanatory power of the different model versions has decreased significantly with the data from year 2023 compared to the situation before PICASSO (Figure 29). In particular, the adjusted coefficient of determination (i.e. the explanatory power) of the model including all variables and of the simple (i.e. one-dimensional) regression using only aFRR activations dropped by almost 10%, which confirms that IDM participants can benefit less from proprietary knowledge gained through

[8] 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/.

balancing activation signals. Also, the explanatory power of the factor last published *control area balance* decreased since deviations lead less frequently to frequency restauration reserve activations because of netting, while the factor last observed *imbalance price* kept its relevance for the front products. On the other hand, as Figure 40 (Appendix C, page 80) in the lower panel shows, the estimated coefficients for the factors *aFRR activation* and *mFRR activations* increased significantly for year 2023. While these activations 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 larger 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 41, lower panel). However, due to the small number of occurrences the estimated coefficients for publications of negative mFRR activation have a large standard error for the two front products and are not significant.

Regarding the remaining factors published by the TSOs for previous time periods, there is a noticeable increase in the coefficient for the factor *imbalance price* while the sensitivity with respect to the factor *control area balance* dropped (see Figure 42, lower panel). Note that also the mean absolute value of the factor *imbalance price* itself increased from year 2021 to year 2023 from 112.92 EUR/MWh to 128.33 EUR/MWh. While the coefficients for the factor *wind forecast errors* have not changed much compared to year 2021, the coefficients for the factor *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 factor *load forecast error* are small but statistically significant in contrast to year 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 IDM, particularly for products with imminent delivery, could be confirmed. We have extended those results 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.

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 decisions in the IDM. 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.

## 5.2 Impact of non-publicly available information

As already emphasized, the information of an activation is not publicly available when it occurs. In the moment of activation this is known to the provider getting activated by the TSO through sending the signal. Although the prequalified capacity for the provision of frequency restauration reserve is quite large in Germany[9], the volume of submitted bids for aFRR balancing capacity is typically 2 – 2.5 times of the tendered volumes of ca. 2’000 MW, depending on the product (direction and delivery period). For mFRR, with submitted bids amounting to 2’000 – 3’000 MW, the tendered volume covers a range 300

[9] 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).

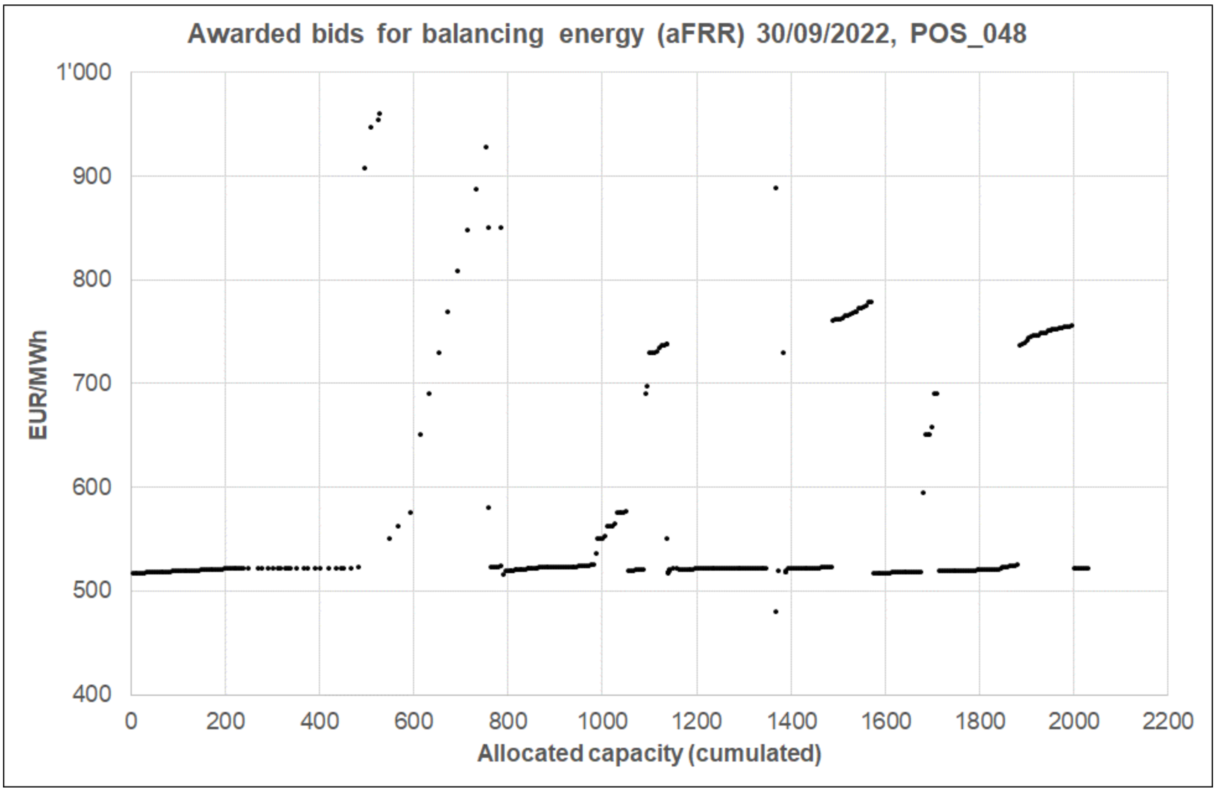



Figure 31: Visualization of the awarded bids for an arbitrary product as published on "regelleistung.net".

– 600 MW. Bidders who have been awarded the capacity auction are also obliged to submit bids for BE. In addition, *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 31 shows an appealing structure: bids are not sorted in ascending order by offered price but exhibit a "block structure" with lines of low gradient 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. Therefore, this information can be exploited for the bidding strategy in the IDM. We do not conclude that any of the above-mentioned companies from the market concentration report have used this strategy for frontrunning (buying and selling using proprietary knowledge). The applied methodology does not reveal this information.

# 6 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 three 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 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 32 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 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 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 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.

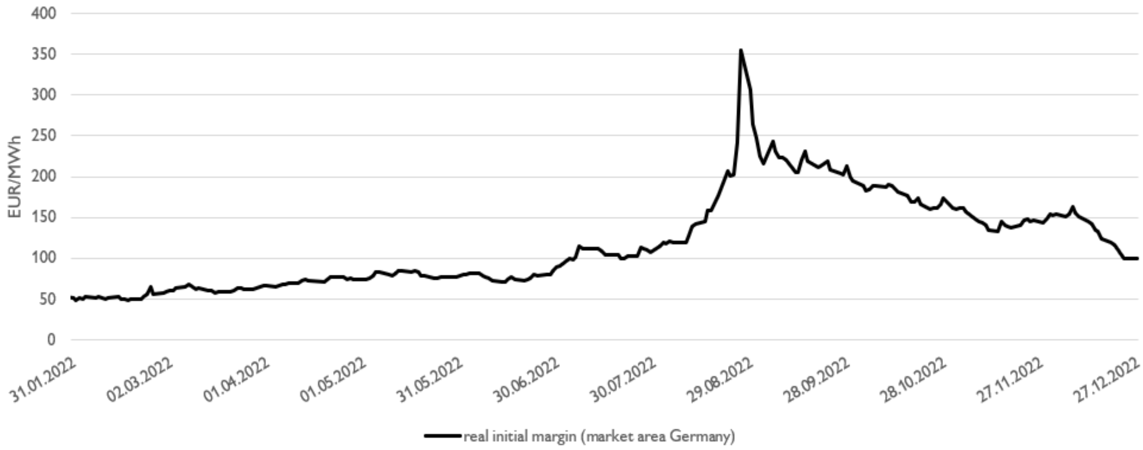



Figure 32: Call for the initial margin associated with the portfolio of open futures positions, which represent the underlying hedge portfolio for production capacities in market area Germany.

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 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.

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 33, we focus on the period 30$^{th}$ June 2022 until 31$^{st}$ 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 30$^{th}$ June 2022. The call reaches its maximum 351.82 EUR/MWh on 26th August 2022. Within two months the call for the initial margin almost quadrupled as it 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 34 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.

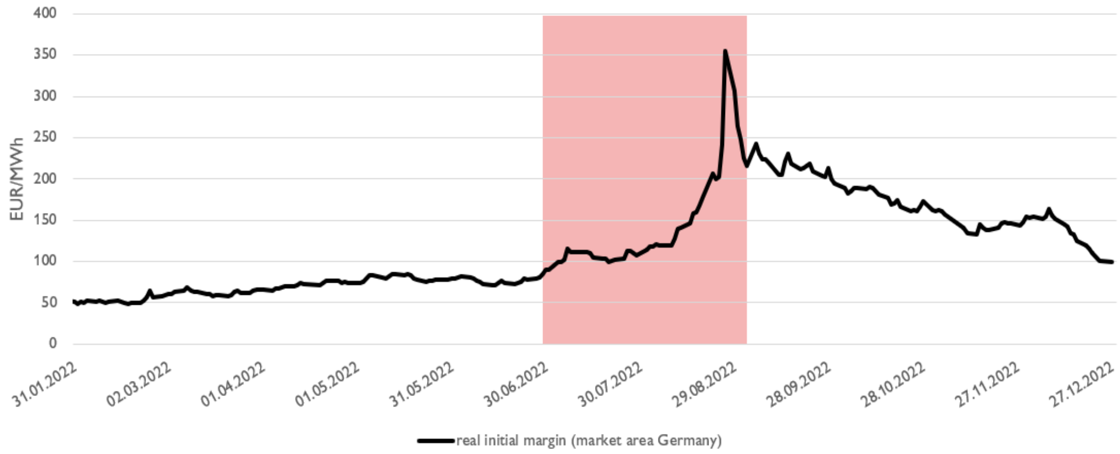



Figure 33: In year 2022 call for the initial margin associated with the portfolio of open futures positions, which represent the underlying hedge portfolio for production capacities in market area Germany. In focus the period 30th June 2022 to 31st August 2022 [calculated by the ior/cf-HSG based on data from the ECC].

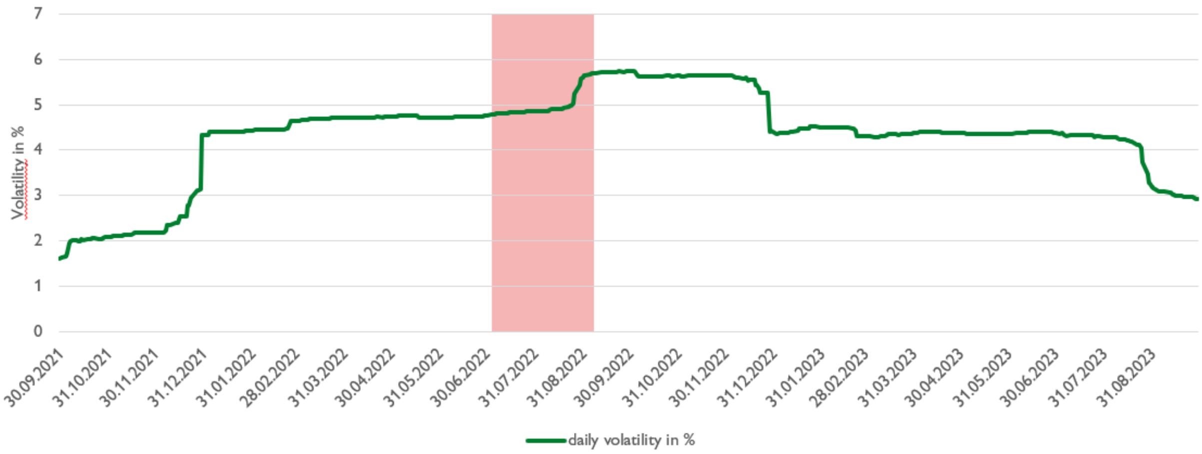



Figure 34: Daily volatility (30.9.2022 – 30.9.2023) of the portfolio of open futures positions, which represent the underlying hedge portfolio for production capacities in market area Germany [calculated by the ior/cf-HSG based on data from the ECC].

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 35). The initial margin and the variation margin refer to a short 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:

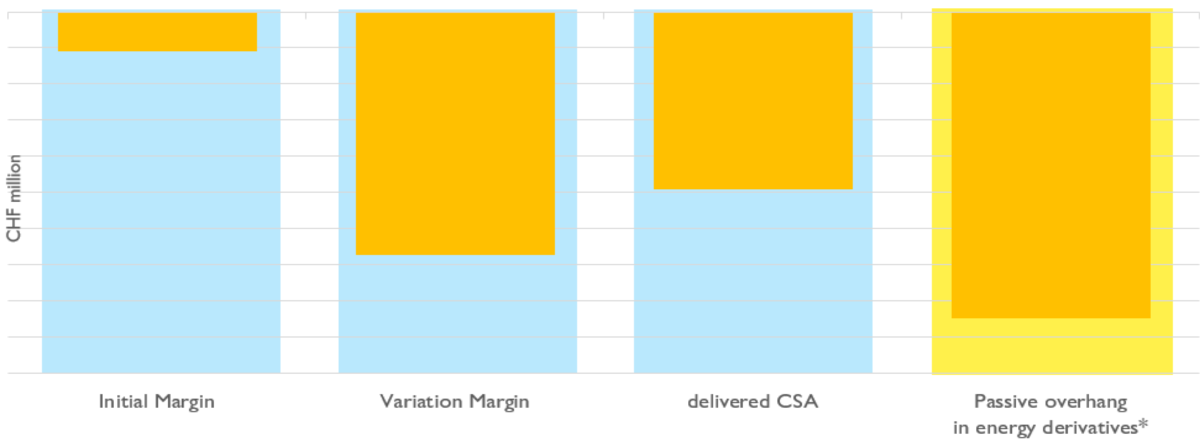



Figure 35: Primary risk factors for liquidity and equity capital in energy trading.

- 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[10].

The first three balance sheet items are colored blue, the fourth is colored yellow in Figure 35. 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 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.

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

[10] Passive overhang = $\max(0,$ negative FV changes – positive FV changes$)$;
active overhang = $\max(0,$ positive FV changes – negative FV changes$)$.

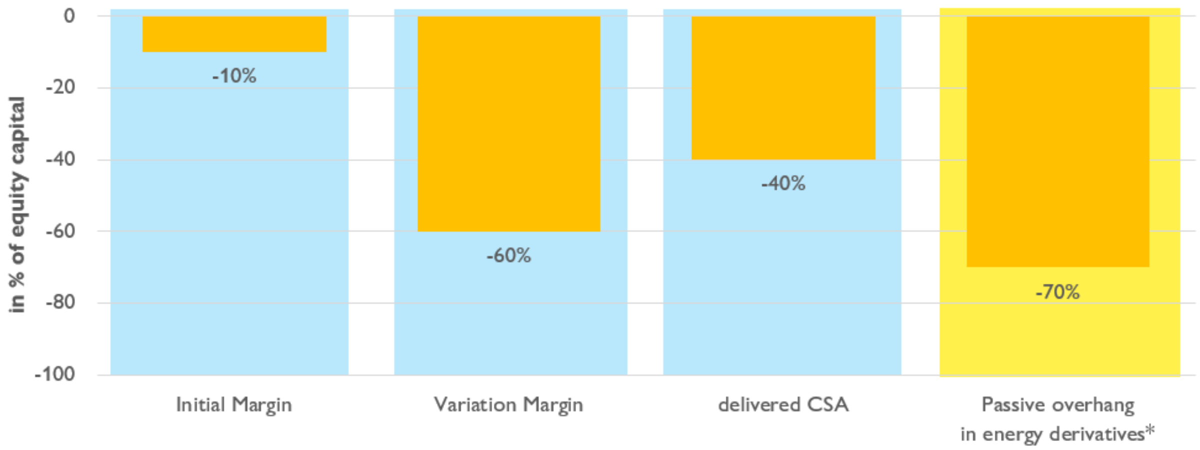



Figure 36: Benchmark for the risk exposure of the distinguished short hedge portfolio on 30th June 2022.

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 36.

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 increase does wipe out the equity reported as of the last balance sheet date and result in over-indebtedness amounting to *minus* 10% [=100%-110%] 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 almost quadrupled 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 may consider 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 (Schwintowski et al., 2018) the collaboration and information exchange between internal audit and risk control become critical. This collaboration forms the foundation for the BoD to fulfill its supervisory responsibilities.

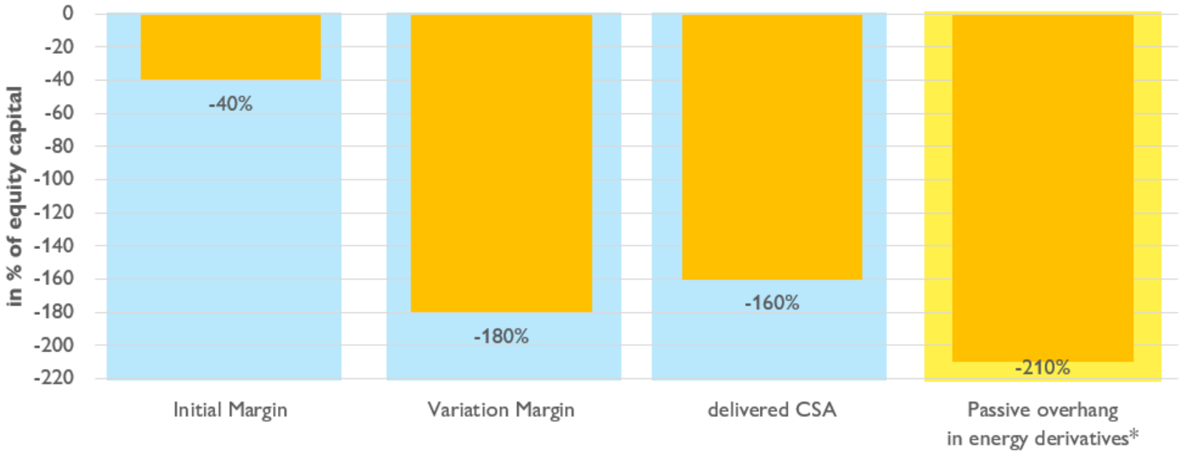



Figure 37: Risk exposure (estimated by the ior/cf-HSG, based on benchmark per 30th June 2022) of the selected short hedge portfolio on 26th August 2022.

We now know from futures market data that between 30th June and 26th August 2022, liquidity risk rose quadrupled, 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 37):

- The liquidity outflow to the energy exchanges for the initial margin will amount to approximately 40% of equity per 26th August 2022, as the liquidity risk has almost quadrupled between 30th June and 31st August 2025 (see Figure 33 and the further explanations on page 59).
- The liquidity outflow to the energy exchange for the variation margin will amount to estimated to 180% of equity per 26th August 2022, as futures prices have tripled, and a short hedge loses value accordingly.
- The CSAs provided to counterparties will now amount to estimated 160% of equity per 26th August 2022, also due to the tripling of futures prices, provided that the contractual agreements remain unchanged.[11]
- The passive overhang in energy derivatives will now amount to 210% of equity per 26th August 2022, 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% [=100%-210%] 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% [=100%-430%] of the equity reported as of the last balance sheet date: the initial margin contributes with

[11] 160% = 3 * 60% – (60% – 40%), where the first term is the FV change. Recall from page 49 that guarantees are due if the risk limit of 20% is exceeded, which explains the second term in parenthesis.

*minus* 40%, the variation margin contributes with *minus* 180%, the change in passive overhang contributes with *minus* 210% (see Figure 37).[12] 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 sound relationship with liquidity and equity capital.
- Aggressive hedging strategies are only justifiable if sufficient liquidity is available.

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 a kind of an X-ray picture of energy trading for the current fiscal year.

[12] 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.

# 7 Insights for the market area Switzerland

Due to the missing eletcricity aggrement between Switzerland and the EU, Switzerland has been excluded from participation with the launch of Single Intraday Coupling (SIDC, formerly XBID) on 12th June 2018. This introduced a platform for continuous cross-border intraday electricity trading based on continuous allocations of border capacities. After the conclusion of negotiations with the EU on institutional issues at the end of year 2024, this will require adoption by the Swiss legislature and possibly a vote. As long as the agreement between the EU and Switzerland is not ratified, Switzerland's access to the liberalized European electricity market is still strongly limited.

Being excluded from SIDC has the consequence that ID trading for the Swiss market area takes place exclusively within the Swiss control area from the start of ID trading at 3:00 p.m. of the previous day until GC, currently up to 5 minutes before the start of delivery of the respective trading product (if not capacity is explicitly allocated via a separate procurement). Thus, similar conditions apply for Switzerland over the entire trading period as for the four control areas in Germany during the last 25 minutes of trading.

Figure 38 illustrates the drop in trading volume in the Swiss intraday market before and after the introduction of SIDC on 12th June 2018 (for the delivery date 13th June). In return, the trading volumes of Swiss market participants on the intraday markets in Germany and France have increased. Figure 39 shows an increase in the trading volumes of Swiss market participants for the German IDM since the introduction of SIDC to approximately twice the trading volume that Swiss market participants contributed before the introduction of SDIC on this market.

With the collapse of trading volume in the Swiss intraday market by 90–95%, it can also be anticipated that the quality of the order book for the Swiss market area has deteriorated. Due to the lack of data, we limit ourselves to qualitative statements: The frictions in the order books of the individual trading products are likely to have significantly increased with decreased liquidity and sharply rising spreads. This not only reduces the potential value-added for flexible capacities in the Swiss intraday market, but the decline in order book quality also contributes to an increase in the demand for automatic and manual frequency restauration reserve in the Swiss control area, leading to higher balancing energy prices.

The lower liquidity in intraday trading in the TransnetBW control area leads to a 15% lower revenue potential for flexible generation compared to positive control energy and a 40% lower revenue potential for flexible consumption compared to negative control energy. Greater revenue potential for providers of flexible capacity in the control energy market means higher costs for the end consumer. If the revenue potential for flexible capacity in the intraday market exceeds that of the balancing energy market, as in the case of flexible generation capacities within the control areas of Amprion, Tennet, and 50Hertz in 2023, we consider this to be uncritical, as the revenue potential in ID trading is generated and financed by market participants.

Since Switzerland is excluded from SIDC trading, it would be expected that the revenue potential for flexible generation capacity within Switzerland's intraday trading would be significantly lower than 15% of the revenue potential for positive balancing energy, or that the revenue potential for flexible consumption would be significantly lower than 40% of the revenue potential for negative balancing energy. This eliminates the incentives for systemically important Swiss electricity companies to participate in intraday trading in the Swiss market area as liquidity providers. End customers finance the high revenues in the balancing power and balancing energy market. This places an additional burden on the quality of the Swiss intraday market.

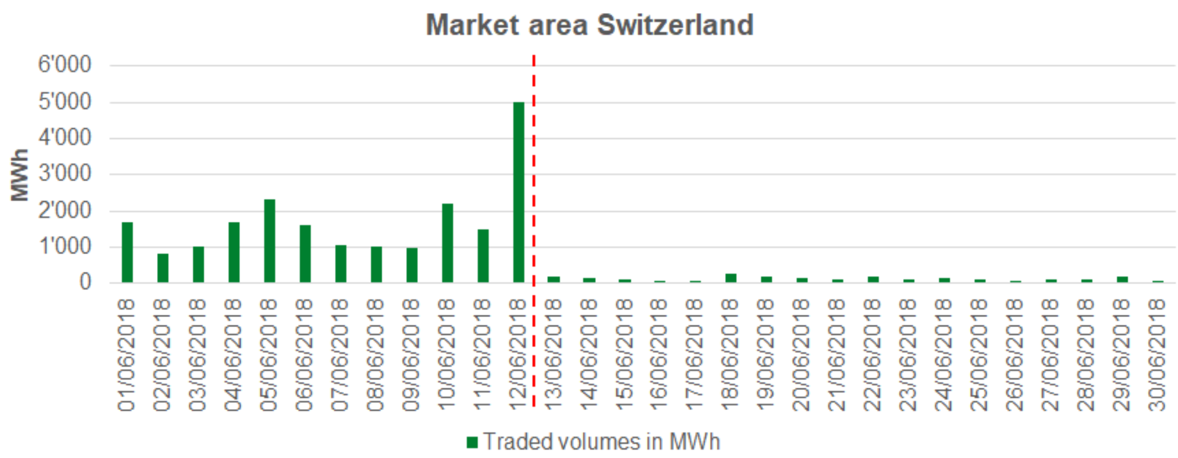



Figure 38: Traded volume in the Swiss intraday market before and after the introduction of SIDC (according to ElCom, 2019, p. 49).

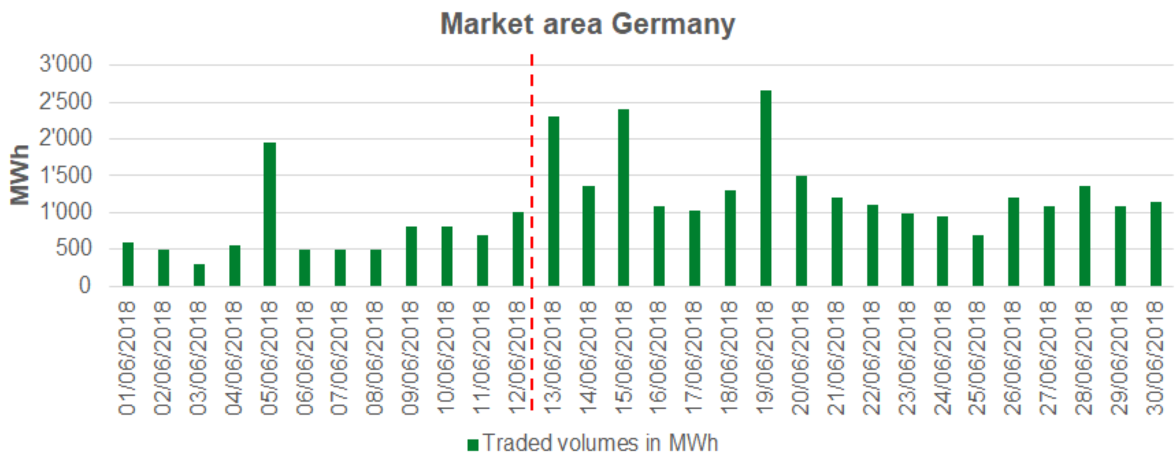



Figure 39: Trading volumes of Swiss market participants in the German intraday market before and after the introduction of SIDC (according to ElCom, 2019, p. 50).

One should keep in mind that the market design of liquid intraday trading in the liberalized electricity market is aimed at reducing the demand for control energy and thus the costs for end customers. If there is no fair competition in intraday trading in Switzerland, fair pricing in intraday trading within the Swiss market area, which can serve as the basis for bids in the control energy market, is not guaranteed. Therefore, from our perspective, it can currently be assumed that the interplay between the intraday market (IDM) and the balancing energy market (BEM) within Switzerland, which would generate welfare gains under fair competition, is lacking. Being aware of the upcoming *Heimfall* events it is our perception that the Swiss power market faces the risk that the market power of a few large power producers could be strengthened. Whether the market power gets more balanced with the *Heimfall* events depends on the priorities of the concessionary municipalities. It is our intention to sensitize the decision makers to support a framework for sound and fair competition.

Based on the achieved results for the four control areas of Germany we recommend for market area Switzerland the assessment of the

- economic value of flexible capacities (+/-) in the intraday market CH
- earnings potential (+/-) in the BEM CH
- effectiveness (+/-) of the economic decision rule
- relevance (+/-) of perfect information
- explanatory power of the factors driving ID-prices
- evolvement of activation and control area balance
- impact of PICASSO on market area CH
- effectiveness of ElCom's cap (+/-) for bids on aFRR
- market power in market area CH
- welfare effects for Switzerland
- compliance with antitrust law
- impact of distinguished *Heimfall* events on market power

The value creation potential in the IDM as well as in the BEM of the Swiss control area could be quantified analogously to those value creation potentials for the IDM in the four control areas in Germany and for the German BEM. The prerequisite for this lies solely in the availability of data. As a direct consequence, the welfare effect for the Swiss market area could be verified as well as the impact on market power and the compliance with antitrust law.

Finally, extreme surpluses for electricity producers caused by market power and/or exogenous factors mean extreme burdens for electricity-intensive industries in Switzerland. The Swiss legislator could 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.

# 8 Conclusions and outlook

In this study, we examined the earnings potential of flexible capacities marketed on the intraday or balancing energy market. Since in the current market design a flexible capacity cannot be at the same time offered in the balancing energy market and the intraday market, a provider must decide on which market an offer should be placed before the gate closure of the balancing energy market (T – 25). We developed an economic decision rule to offer the capacity in the market with the higher revenue potential, which is estimated with an option valuation model, and assume that the decision which market to choose is made at T – 30, when the intraday trading is split into the four individual control areas.

We also analyzed the liquidity during the last 30 minutes of intraday trading differs between the control areas. To this end, order books were reconstructed from all bids during the last 30 minutes of trading from data for the year 2023. It turned out that the liquidity (offered volumes, bid-ask spreads) in the control areas is very different. This leads to different volume-dependent transaction prices and, thus, different revenues that can be achieved from offering on the intraday market. In the three more liquid control areas (Amprion, Tennet, 50Hertz) the revenues are quite similar to the balancing energy market, only in the TransnetBW area the intraday market offers significantly lower revenues due to the low liquidity and high bid-ask spreads.

Next, we described as a use case a possible integration of the intraday market and the balancing energy market for automatic frequency restauration reserve (aFRR). The German market is appropriate for this application because the markets are sufficiently liquid, and data availability is good. Specifically, it was assumed that before the splitting of ID trading into the individual control areas and, thus, before the gate closure of the balancing energy market, qualified bids from the intraday market's order book are transferred into the bid list for balancing energy. The potential earnings in both markets were modeled as financial options. Because of the different liquidity in the individual control areas, intraday trading was analyzed separately by area. Because the capacity can only be offered for one application, it had to be examined whether, from the perspective of an exemplarily chosen provider (gas-fired power plant), a transfer of bids from the intraday to the balancing energy market would be economically attractive at all, or whether additional premiums need to be offered. Due to the comparable earnings opportunities in both markets, this does not seem necessary for the three more liquid control areas.

When the options model is used as a decision rule as to which market a provider should submit a bid in, the earnings do not improve in every case. Apparently, the model does not predict the earnings potential of positive balancing energy sufficiently well. A problem is that the data required for a forecast of the activation durations of balancing energy in a time slot with an imminent gate closure are only published with a delay. Further research is needed to analyze whether the model's forecast accuracy and the potential earnings improve if the time between the gate closure on the balancing energy market and delivery is shortened, and/or the activation data are published immediately after the end of the completed time slot.

Considering the volume available for a possible transfer from the intraday market's order book at T – 31, it appears at first glance small compared to the free bids on the balancing energy market. Nevertheless, by inserting all bids with a minimum size of 1 MW, the merit order for balancing energy would shift significantly, thereby reducing the costs for activating a certain amount of balancing energy. It remains open how many bids from the intraday market's order book could actually be transferred into the balancing energy market. Balancing energy can in principle only be provided by pre-qualified providers, and the origin of a bid in the intraday market's order book is not transparent. Moreover, many bids on the intraday market come from operators of renewable generation plants that hedge against forecast errors from previous marketing in order to avoid paying the imbalance price. Even if such facilities were (in the future) qualified to offer reserve power, these providers would not be indifferent between marketing on the intraday market and providing balancing energy, since in the latter case the activated quantity is unknown and costs for imbalance energy could arise.

We 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 years 2021 and 2022, empirical limit order book analyses are applied for identifying frictions of trading products. The focus was 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 consider an adequate buy surcharge and sell discount onto an index price (e.g., ID1 or ID3 published by the Epex-Spot 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 modeling jointly price and forecast variations over preselected short time horizons, which cover nonlinear dependencies.

The analyzed the effects of the PICASSO platform on the German intraday market. PICASSO, a European balancing platform introduced in year 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 balancing energy bids 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, aFRR 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.

Further, 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 Bord of Directors in its supervisory duties.

Extreme surpluses for electricity producers caused by exogenous factors mean extreme burdens for electricity-intensive industries in national economies. Legislators could 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.

While the quantitative analyses in this study concentrated on the German market, we gave a brief qualitative assessment how the value of flexible capacities in the Swiss market area can be assessed. Since Switzerland is not coupled with the spot markets of the other European countries, trading is limited to the own control area. The frictions in the order book (low volumes, high bid-ask spreads) restrict the potential value-added for flexibly capacities in the intraday market. Due to the lack of short-term marketing on the intraday market, open positions cannot be closed, which increases the demand for balancing energy.

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# 10 Appendix A

| DE (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. |
|---|---|---|---|---|---|---|---|---|
| 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) 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. |
|---|---|---|---|---|---|---|---|---|
| 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 6: 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) 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 | 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) 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 | 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 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 TransnetBW area.

| AMP (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 | 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) 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 | 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 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 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 9: 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) 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 | 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) 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 | 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 10: 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.

# 11 Appendix B

| Amprion | | Order Size [MW] | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Type** | **Phase** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** |
| Call | [T-30,T-5) | 33.22 | 32.33 | 31.70 | 31.21 | 30.78 | 30.29 | 29.88 | 29.55 | 29.24 | 28.98 |
| (HardCoal) | [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 | [T-30,T-5) | 57.47 | 57.37 | 57.20 | 57.11 | 56.98 | 56.94 | 56.92 | 56.91 | 56.44 | 54.43 |
| (HardCoal) | [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 | [T-30,T-5) | 43.11 | 42.05 | 41.29 | 40.69 | 40.17 | 39.57 | 39.07 | 38.67 | 38.29 | 37.98 |
| (Gas) | [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 | [T-30,T-5) | 41.93 | 41.84 | 41.69 | 41.61 | 41.49 | 41.43 | 41.39 | 41.36 | 41.05 | 39.16 |
| (Gas) | [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 11: 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 | [T-30,T-5) | 16.02 | 15.58 | 15.32 | 15.11 | 14.93 | 14.71 | 14.50 | 14.35 | 14.21 | 14.07 |
| (HardCoal) | [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 | [T-30,T-5) | 46.08 | 45.88 | 45.68 | 45.57 | 45.49 | 45.51 | 45.43 | 45.39 | 44.88 | 44.03 |
| (HardCoal) | [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 | [T-30,T-5) | 28.60 | 27.96 | 27.54 | 27.23 | 26.91 | 26.58 | 26.30 | 26.06 | 25.85 | 25.64 |
| (Gas) | [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 | [T-30,T-5) | 29.27 | 29.09 | 28.91 | 28.78 | 28.69 | 28.64 | 28.53 | 28.45 | 28.21 | 27.35 |
| (Gas) | [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 12: 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 | [T-30,T-5) | 44.84 | 42.93 | 41.94 | 41.24 | 40.68 | 39.93 | 39.31 | 38.82 | 38.36 | 37.98 |
| (HardCoal) | [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 | [T-30,T-5) | 42.11 | 42.26 | 42.28 | 42.29 | 42.24 | 42.27 | 42.40 | 42.58 | 42.38 | 39.88 |
| (HardCoal) | [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 | [T-30,T-5) | 47.42 | 45.46 | 44.44 | 43.70 | 43.12 | 42.33 | 41.68 | 41.18 | 40.69 | 40.30 |
| (Gas) | [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 | [T-30,T-5) | 39.66 | 39.79 | 39.80 | 39.81 | 39.78 | 39.84 | 39.97 | 40.13 | 39.94 | 36.99 |
| (Gas) | [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 13: 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 | [T-30,T-5) | 23.48 | 22.57 | 21.83 | 21.28 | 20.84 | 20.48 | 20.10 | 19.77 | 19.48 | 19.23 |
| (HardCoal) | [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 | [T-30,T-5) | 48.28 | 46.41 | 46.27 | 44.65 | 44.61 | 44.55 | 44.47 | 44.45 | 44.43 | 44.39 |
| (HardCoal) | [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 | [T-30,T-5) | 31.31 | 30.15 | 29.24 | 28.55 | 28.01 | 27.56 | 27.10 | 26.69 | 26.33 | 26.01 |
| (Gas) | [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 | [T-30,T-5) | 35.09 | 33.34 | 33.19 | 31.68 | 31.62 | 31.55 | 31.45 | 31.41 | 31.36 | 31.31 |
| (Gas) | [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 14: 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 | [T-30,T-5) | 8.94 | 8.43 | 8.09 | 7.85 | 7.67 | 7.52 | 7.37 | 7.24 | 7.13 | 7.03 |
| (HardCoal) | [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 | [T-30,T-5) | 36.52 | 35.10 | 34.75 | 33.90 | 33.68 | 33.46 | 33.29 | 33.23 | 33.15 | 33.05 |
| (HardCoal) | [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 | [T-30,T-5) | 18.09 | 17.30 | 16.79 | 16.43 | 16.17 | 15.95 | 15.73 | 15.54 | 15.36 | 15.19 |
| (Gas) | [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 | [T-30,T-5) | 22.69 | 22.00 | 21.66 | 20.85 | 20.65 | 20.45 | 20.28 | 20.21 | 20.13 | 20.03 |
| (Gas) | [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 15: 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 | [T-30,T-5) | 35.61 | 34.49 | 33.55 | 32.84 | 32.27 | 31.78 | 31.27 | 30.79 | 30.39 | 30.03 |
| (HardCoal) | [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 | [T-30,T-5) | 39.90 | 38.27 | 38.78 | 36.88 | 37.07 | 37.21 | 37.32 | 37.43 | 37.54 | 37.64 |
| (HardCoal) | [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 | [T-30,T-5) | 38.57 | 37.40 | 36.38 | 35.61 | 34.98 | 34.45 | 33.89 | 33.37 | 32.93 | 32.55 |
| (Gas) | [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 | [T-30,T-5) | 36.82 | 34.71 | 35.18 | 33.05 | 33.21 | 33.34 | 33.43 | 33.53 | 33.63 | 33.72 |
| (Gas) | [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 16: Standard deviations of option values as function of order sizes with data for the whole year 2023 for the TransnetBW con-trol area.

# 12 Appendix C

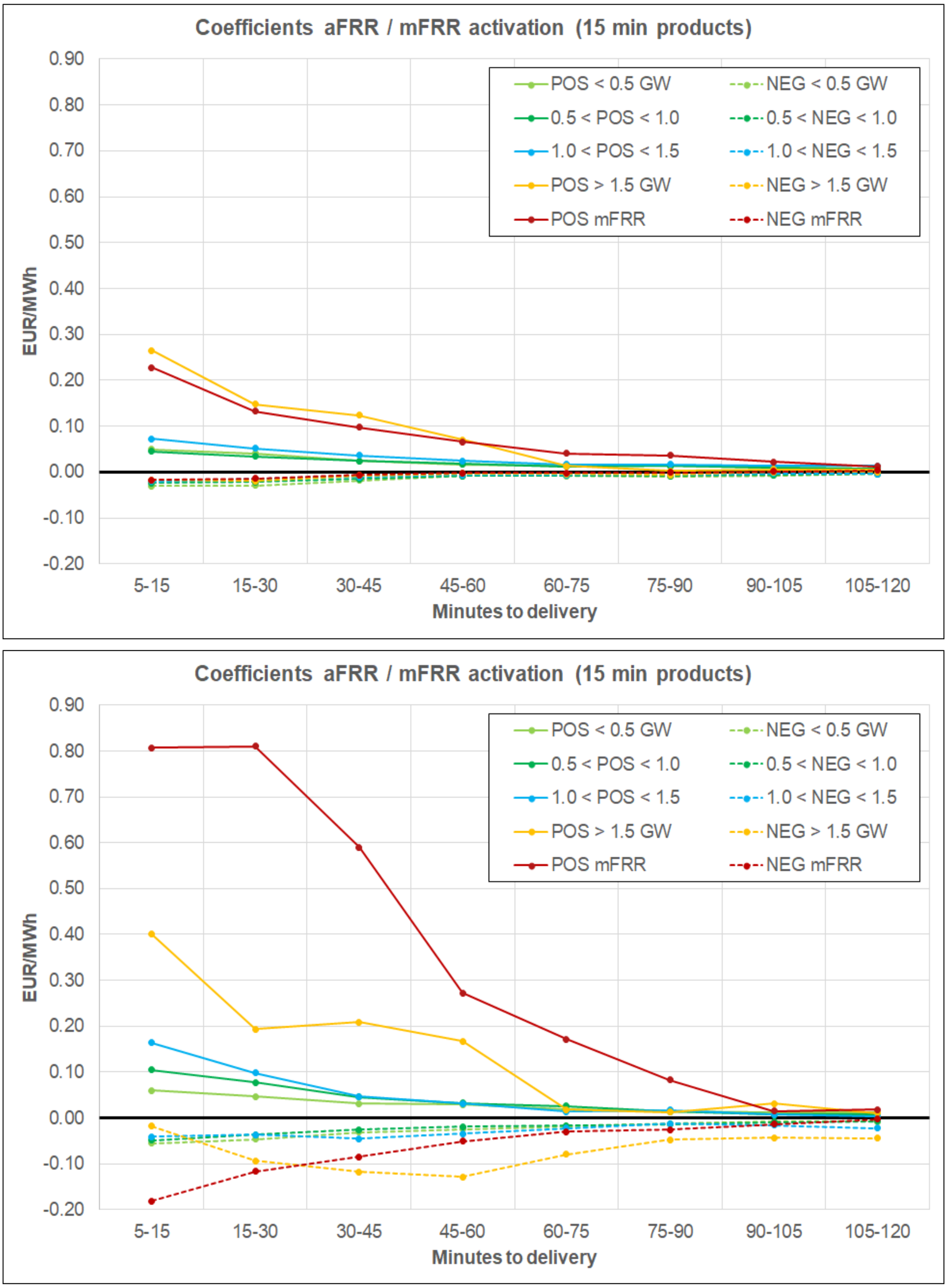


Figure 40: Coefficients of the variables for aFRR and mFRR activation from the estimation of the full model for the sample periods 2021 (upper panel) and 2023 (lower panel). Different magnitudes of aFRR activation were modeled as individual variables to take into account a nonlinear relationship between price and activated energy. A similar differentiation was not possible for mFRR due to the much smaller number of occurrences.

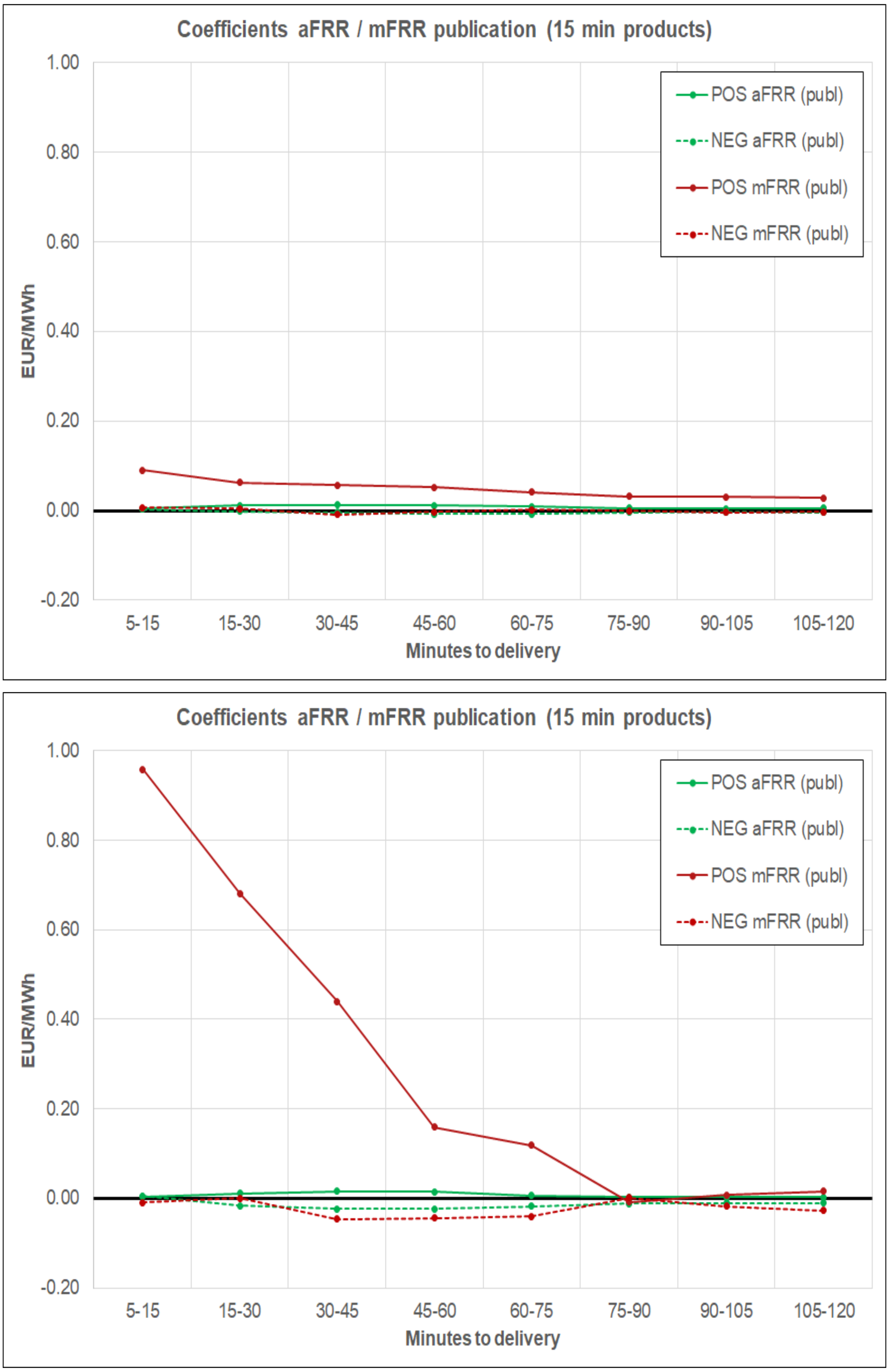


Figure 41: Coefficients of the factors *published aFRR* and *published mFRR* (aggregated activations after the end of a previous 15-min time slice) in case the *full model* is applied for the sample periods year 2021 (upper panel) and year 2023 (lower panel).

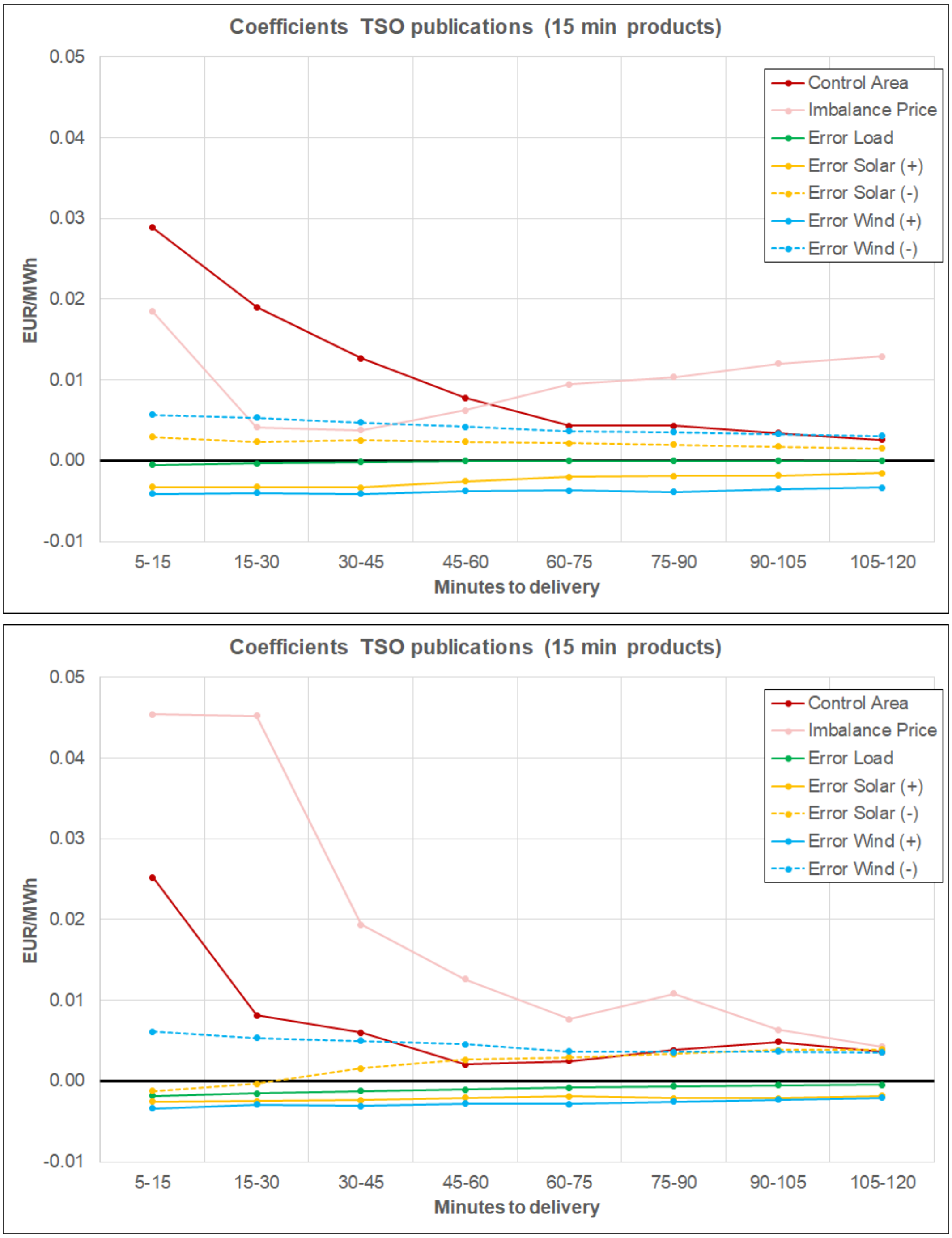


Figure 42: Coefficients for the listed factors, published by the TSO (after the end of a previous 15-min time period) in case the *full model* is applied to the sample periods year 2021 (upper panel) and year 2023 (lower panel). “Error” refers to the difference between the realized value and its day-ahead 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 fore-casted. Note that the coefficients of “Error Solar (-)” for the two products closest to delivery are not signif-icant for the sample period 2023 (p-value 11%). The factor *control area balance* is characterized by 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