Report

Trading based on balancing power activation

An empirical analysis of the temporal relationship between balancing power activation signals and electricity prices on the German intraday market

This is a machine translated version of a study originally published in German. The original is available at neon.energy/intraday-regelleistung

Final version from October 14, 2021

On behalf of BayWa r.e. Energy Trading, MVV Trading, Quadra Energy, Sunnic Lighthouse and Trailstone

Authors:
Lion Hirth (hirth@neon.energy)
Jonathan Mühlenpfordt (muehlenpfordt@neon.energy)

Trading based on balancing power activation

An empirical analysis of the temporal relationship be-tween balancing power activation signals and electricity prices on the German intraday market

This study is available at neon.energy/intraday-regelleistung-EN

For the German version see neon.energy/intraday-regelleistung

Neon Neue Energieökonomik is an energy industry consultancy based in Berlin. As a boutique, we have specialized in sophisticated quantitative and economic-theoretical analyses of the electricity market since 2014. With consulting projects, studies and training courses, we support decision-makers with the current challenges and future issues of the energy transition. Our clients include governments, regulatory authorities, grid operators, energy suppliers and electricity traders from Germany and Europe.

Contact:

Neon Neue Energieökonomik GmbH
Karl-Marx-Platz 12
12043 Berlin

Prof. Dr. Lion Hirth
hirth@neon.energy
+49 157-55 199 715

Summary

Summary

Background. The system balance ("NRV Saldo") is an important price driver on the intraday market. The activated quantity of balancing power, which allows conclusions to be drawn about the system balance, is not published in real time in Germany and is therefore only known to the providers of balancing energy. If they use this information advantage to trade on the electricity market ("*frontrunning*"), other market participants suffer an economic disadvantage.

Research question. This study empirically examines whether trading takes place on the German intraday market on the basis of the activation of balancing power. The investigation is carried out by evaluating price movements in relation to the activation signal.

Methodology. For this purpose, all 80 million transactions with quarter-hour and hourly contracts on the EPEX intraday trading platform and all 50 million SRL and MRL calls in the period from the beginning of 2020 to mid-2021 were analyzed as part of multiple regression analyses with a time resolution of 1 minute. This allows us to examine the direct temporal correlation. We can also statistically control for other price drivers, for example for generation forecasts and the later publication of activations. The extremely large number of observations allows us to examine a variety of specifications, control variables, temporal structures and non-linear effects as well as differentiate between products and trading times.

Result. We find a statistically significant, quantitatively significant and extremely robust correlation between balancing power calls and intraday prices. After SRL and MRL calls, there are systematic price movements for all products with a delivery time in the following two hours. The price movements are so conspicuous for many products that we can rule out the possibility of random fluctuations with a confidence level of well over 99.99%.

Example. If, for example, a positive SRL activation of 1000 MW takes place over 15 minutes from 11:30, we estimate that the electricity price at 11:46 for delivery from 12:00-12:15 is on average €34/MWh higher than without a activation. In addition, the price for all other nine hourly and quarter-hourly contracts with delivery starting between 12:00 and 14:00 also increases.

Robustness. The effect tends to be greater the shorter the interval until the start of delivery and the higher the activation. The effect is also greater for quarter-hourly products than for hourly products, greater for positive balancing energy calls than for negative ones and greater for MRL calls than for SRL. Since the introduction of the balancing energy market, the influence has become even stronger. These differences are to be expected and result in a coherent overall picture. However, even in cases with a smaller effect, we often find a statistically highly significant correlation. These results suggest that market players use the information from the balancing power activation for trading decisions.

1 Introduction

Market design for the energy transition. The short-term intraday wholesale market and the balancing energy system are two core elements of the German and European electricity market design. They are essential for supply and system security and the integration of renewable energies, and their importance in the context of system transformation is constantly increasing. The intraday market and balancing energy are also of great economic importance for many electricity producers and direct marketers. Smooth interaction between the two systems and the trust of market players in both market segments are essential for the continued success of the energy transition.

Fair conditions. Competitive markets serve the good of society if certain conditions are met, such as the absence of abuse of market power. Another key prerequisite is fair and equal conditions for market players. Information asymmetries, i.e. some players having more knowledge than others, undermine market activity. On financial markets, but also on wholesale electricity markets, this means in particular that all market players have access to price-relevant information at the same time. This principle is the starting point for a large number of regulations, including the REMIT Regulation.

Short-term pricing. In short-term electricity trading, a few hours to minutes before the start of delivery, only a few systems are able to adjust electricity generation or consumption. Additional demand for electricity (shortage) or additional supply (surplus) therefore often have a strong impact on the price, even for small volumes. At the same time, generation and consumption are subject to considerable short-term uncertainty, especially in unusual weather situations, partly because real-time data is not available from many producers and consumers. This applies in particular to standard load profile customers. Any information on the system balance, i.e. the difference between generation and consumption, therefore has a significant impact on the short-term electricity price.

Information content of the balancing power activation. The balancing power activation contains information about the current system balance and, where applicable, the system balance expected by the TSOs (under/over-generation). Neither the system balance nor the balancing power activation are published in real time in Germany. However, the providers of balancing energy are of course aware of the activation. As a rule, these companies are also active as traders on the intraday market. This means that balancing power providers receive exclusive information about the system balance before all other traders, which they can use profitably by buying or selling earlier than others.

Price effect of the activation. Such trading would influence the price on the intraday market. If such trading were to take place, a price effect would have to be observed in direct temporal connection with the activation of balancing capacity, even before other market players become aware of the changed situation through adjusted generation forecasts or publications by the TSOs. An upward price jump should therefore be observed shortly after the activation of positive balancing capacity. The effect is reversed for negative balancing power.

This study. The subject of this brief report is an empirical analysis of whether trading transactions are carried out on the German wholesale market for electricity on the basis of the activation of balancing power. The analysis is based on an evaluation of intraday price movements in relation to the activation of balancing power. We are particularly interested in whether systematic price changes can be found after the activation of balancing power, but before the publication of these activations. If this is the case, it can probably only be explained by the fact that market participants with knowledge of the calls, i.e. providers of balancing power or grid operators, use this information for trading decisions.

No legal examination. A legal classification, in particular an examination of whether the above-mentioned trading strategy constitutes insider trading within the meaning of REMIT, is not the subject of this report. Nor is this report intended to identify which market players engage in such trading transactions; this is not possible with the methodology used in any case.

2 Background

This section explains the background to our analyses: the functioning of German intraday trading, the activation of control power and the question of which possible trading strategies result from this.

2.1 Intraday trading

Importance of ID trading. Intraday (ID) trading refers to the short-term market segment on the European wholesale markets for electricity. It comprises trading that takes place after the day-ahead auction, which is held at 12:00 noon for the following day. Intraday trading takes place until just before delivery and comprises trading in quarter-hour products. This high-resolution short-term trading is of fundamental importance for the energy transition. While traditional electricity systems are closely aligned with rigid schedules, wind and solar energy, as well as new consumers such as heat pumps and battery-powered electric vehicles, are much more exposed to short-term weather fluctuations. Flexibility resources such as batteries offer the short-term possibility of balancing supply and demand. A functioning, liquid intraday market, whose prices are seen by market players as reliable signals for the use of systems, is essential for the continued success of the energy transition.

Auction and continuous. Intraday trading takes place over-the-counter and on various exchange platforms. The vast majority of this is processed via the EPEX SPOT exchange. There, the ID market consists of two segments, an opening auction at 3 p.m. and continuous trading from 4 p.m. - contrary to what the name suggests, intraday trading opens the day before. Around 15% of the trading volume is accounted for by the auction and 85% by continuous trading. The opening auction is a two-sided auction with the exchange as auctioneer, similar to the day-ahead auction. Continuous trading is similar to the trading of shares, bonds and other securities. Here, market participants can submit buy and sell offers at any time in the form of prices and quantities, which are published in anonymized form in order books. Other market participants can then accept these offers at any time. This means that each individual transaction has its own volume and price.

Products. Hourly and quarter-hourly contracts are traded on the German intraday market, which relate to different delivery periods. The hourly products are conceptually equivalent to block bids for four quarter-hour products. Although half-hourly and block products also exist, they play virtually no role in practice. This means that 120 different products are traded each day, 24 hourly products and 96 quarter-hourly products. Consequently, a large number of products are traded in parallel at any given time, with the number decreasing over the course of trading as more and more products are delivered. At 11:50, for example, traders can still trade twelve different hourly products and 48 quarter-hourly products for the current day. In this case, the arrival of price-relevant information can therefore have an effect not on "the" intraday price, but on the price of 60 different contracts. Over the year, this results in 43,800 different delivery periods and thus the same number of products, each of which is traded over a period of nine to 33 hours. Unlike the prices from day-ahead auctions (or the prices of shares or bonds), intraday prices are therefore not to be understood as a single continuous time series, but as a large number of short, overlapping time series. Figure 1 shows an example of the price time series of six products traded in parallel.

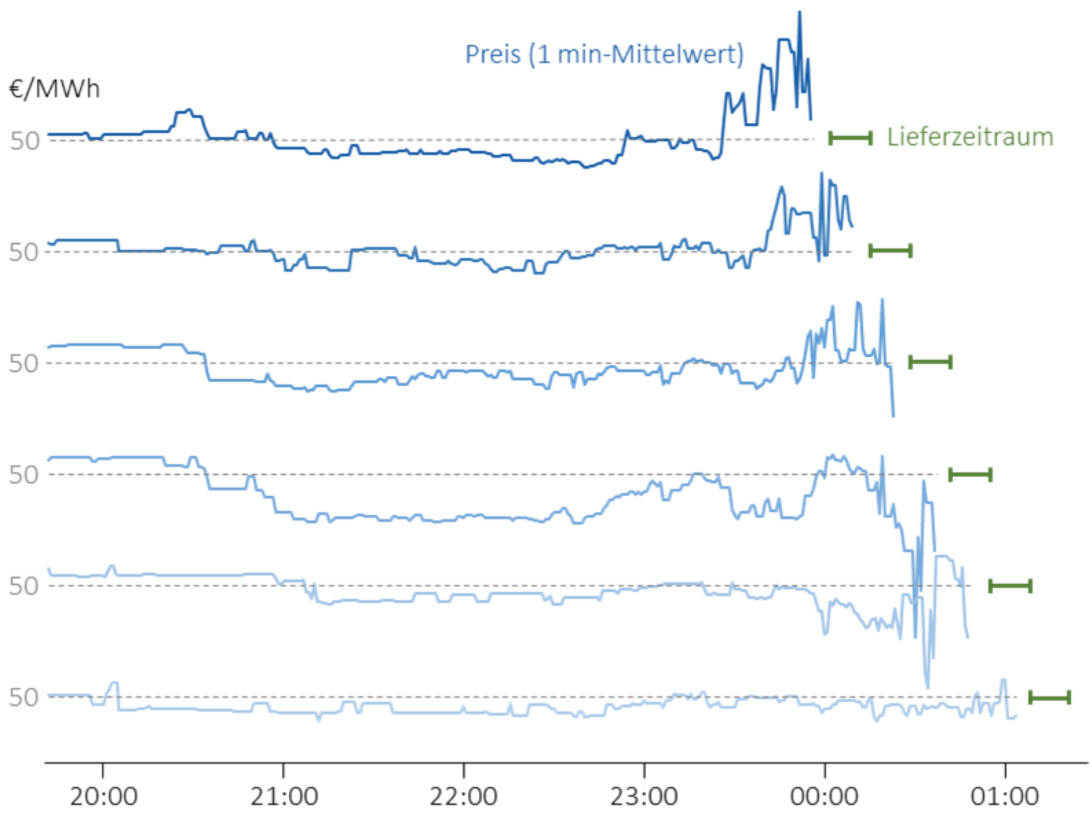

Figure 1. Prices of six quarter-hourly contracts traded in parallel on June 2, 2020: volume-weighted average prices per minute (blue) and delivery period (green). As is typical on the intraday market, price movements are similar but not identical, and the strongest price movements are observed shortly before the end of trading.

Transactions. The German intraday market is characterized by a large number of transactions with small volumes. Many traders rely on algorithm-based automated trading (bots). On average, 1.7 transactions are carried out per second with an average volume of two to three MWh. However, the transactions are spread across a large number of products and are also concentrated in the last few hours of trading, meaning that individual contracts are often hardly traded for several hours. In addition to price and volume, each transaction is characterized by two time parameters: the trading time and the delivery period. Figure 2 illustrates the trading transactions in a three-hour period on 21 October 2020. Nine quarter-hour products are shown (i.e. only some of the products currently traded), which are differentiated by color. The trading time is plotted on the x-axis and the price on the y-axis. The transaction volume is represented by the dot size. Any kind of aggregation of these prices into a single time series does not seem to make much sense.

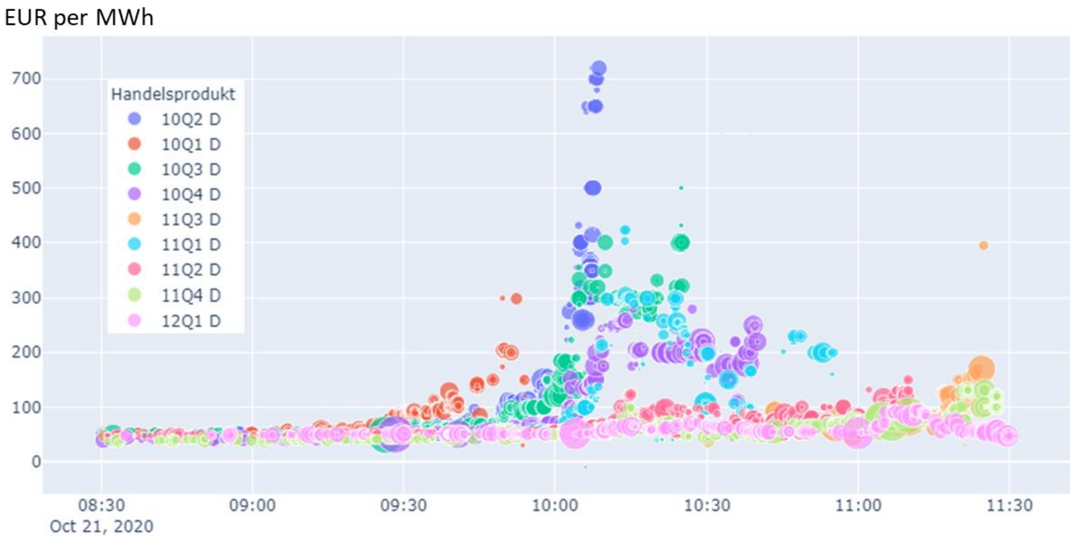

Figure 2. Individual transactions for nine products in a three-hour period on October 21, 2020.

Gate closure. Similar to the day-ahead auction, intraday trading in Europe is also implicitly coupled, i.e. imports and exports are processed as part of normal trading. Cross-border trading is processed via the so-called "Single Intraday Coupling" (SIDC) platform and takes place up to 60 minutes before the start of delivery (so-called gate closure). Germany-wide trading is still possible up to 30 minutes before delivery, after which trading is still possible within the four German control areas. This trading, known as "Single Delivery Area Trading" (SDAT), is possible on EPEX SPOT up to 5 minutes before the start of delivery. Around two thirds of all transactions take place in the period two hours before delivery. Within this period, there is again a concentration of trading activity in the minutes shortly before the three gate closure times mentioned (Figure 3).

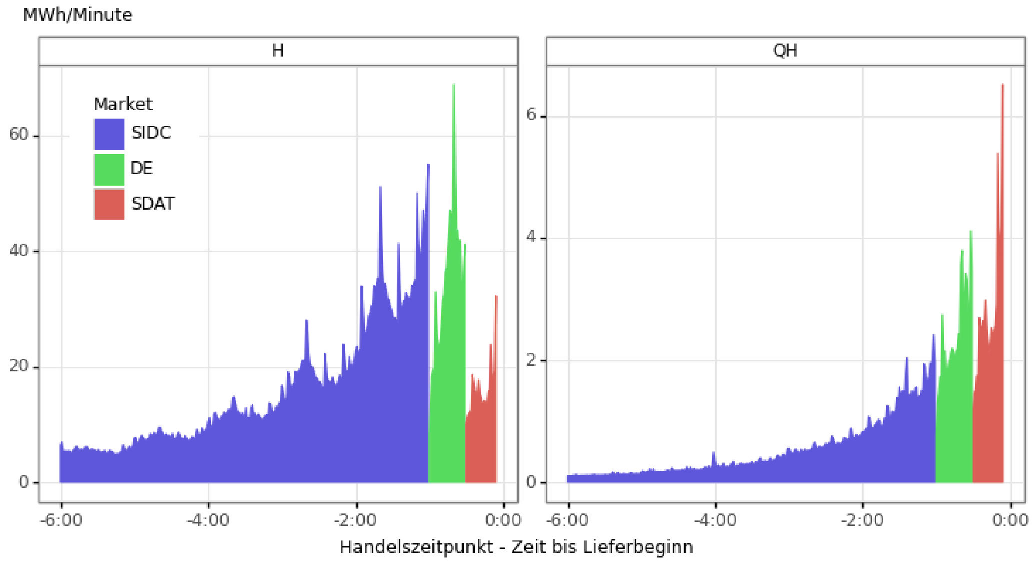

Figure 3. Trading volume relative to the beginning of the delivery period for hourly (left) and quarter-hourly products (right).

2.2 Balancing power activation

How balancing energy works. Control energy is used to maintain the balance between the physical generation and consumption of electricity at all times. This balance should be maintained both at the level of the synchronous area and at the level of the control area (or grid control network) in order to keep the grid frequency at 50 Hz and the area control error at zero.

types. Three types of balancing energy are used for this: *Frequency Containment Reserve* (FCR) and *automatic* and *manual Frequency Restoration Reserve* (aFRR, mFRR). In electricity trading, the outdated terms primary control reserve (PRL), secondary control reserve (SRL) and minute reserve (MRL) are still in use today, which is why we also use them in this study.

Procurement. All three types of balancing energy are procured as an operational reserve (balancing *power)* by the transmission system operators through auctions on the previous day and then called up at short notice as required. Suppliers of balancing power are thermal and pumped storage power plants in particular, often also in a network. The bids in the procurement auction are published in anonymized form. Since November 2020, it has also been possible to offer balancing energy outside of the power auction (balancing energy market), although market players have made little use of this to date.

Polling. The PRL is called up as a function of the locally measured grid frequency. SRL and MRL are activated by the TSOs via an electronic signal. The SRL activation takes place in the form of a target value updated every second, the MRL activation as a schedule product for whole quarters of an hour at the latest seven and a half minutes before the start of delivery. The aim of activation is to reduce the German system balance (NRV balance), i.e. the balance of electricity generation and consumption. In contrast to the PRL activation, an SRL or MRL activation therefore provides information about the current system balance or the system balance expected by the TSOs in the short term. When activating the SRL and MRL, the TSOs apply the merit order principle, i.e. the systems with the lowest energy charge are activated first. However, grid operators can deviate from this principle in order not to further increase the flow of electricity on congested lines. Furthermore, grid operators can also compensate for imbalances in Germany within the framework of the international TSO cooperation "International Grid Control Cooperation"; not every deviation from the balanced system balance necessarily leads to the activation of balancing capacity.

Publication. Unlike in other European countries, the German TSOs do not publish the system balance or control reserve activations in real time. Instead, the quarter-hourly values for SRL and MRL activations and the control area balances are published separately by the four TSOs between zero and eleven minutes after the end of each quarter-hourly delivery period. In addition, the second-hourly SRL setpoint is published on the following day.

Planned changes. As part of the implementation of the international MARI and PICASSO platforms for MRL and SRL, there will be a number of changes in the coming months. For example, providers can release their MRL offers for direct activation instead of schedule activation, providers can submit complex offers and marginal pricing will replace pay-as-bid as the price rule. In addition, German suppliers of balancing energy can then be activated to cover balancing energy requirements abroad, so that it will be more difficult to draw conclusions about the German system balance. However, this has no impact on the period under review.

2.3 Trading strategies based on balancing power activation

Information content of the balancing power activation. The activation of SRL and MRL therefore contains information about the current system balance and, if applicable, the system balance expected by the TSOs in the short term. The activation of positive control reserve means that the system tends to be under-balanced; the activation of negative control reserve indicates over-balancing. This information is only known in real time to the providers of balancing energy called upon, but not to all other market parties.

Price effect. The system balance has an influence on the intraday price as an indicator of under/over-generation. If the system is under-balanced, this indicates an increase in demand for electricity. In the short to medium term, purchases by the under-covered balancing groups are to be expected. These are accompanied by rising intraday prices. An electricity shortage indicated by the system balance or the activation of positive balancing energy can mean, for example, lower than forecast generation or higher than expected demand for electricity. The affected market players will then (have to) buy additional electricity on the intraday market as soon as they notice the shortfall in order to keep their own balancing group balanced. This additional demand causes the intraday price to rise. Conversely, the activation of negative balancing energy indicates an overcovered system and, as a result, additional sales activities and falling intraday prices.

Frontrunning. Market players who receive information about the current system balance before other market players can use this exclusive knowledge profitably by buying or selling earlier than the competition. However, this information asymmetry does not only affect direct marketers, but every market participant who receives a signal to call on balancing capacity, as it allows profit opportunities through long or short selling. These trading strategies are referred to as "*frontrunning*". If such trading strategies are used, this should lead to systematic intraday price movements shortly after the activation of balancing capacity.

redistribution. Unlike other trading transactions, these trading strategies do not create any economic added value compared to a situation in which all market participants receive the relevant system information at the same time. Rather, it is purely a redistribution due to asymmetric information: while the market parties with the information advantage benefit financially from it, the rest of the market suffers financial disadvantages to the same extent.

3 Methodology

The aim of this study is to empirically identify possible trading on the basis of balancing power calls. In the following, we outline our basic methodological approach, present the regression models used and then discuss data and data aggregation.

3.1 Overview

Regression analyses. We use multiple OLS regression analyses with high-resolution temporal data to empirically test whether a price movement can be observed on the intraday market as a result of a activation of balancing capacity. In this context, "multiple" means that when calculating the correlation between price and activation signal, we simultaneously statistically control for a large number of other possible variables that have an influence on the price and could be correlated with the control power activation. These include changes in the forecasts of wind and solar generation and load as well as the publication of SRL and MRL activations and control area balances by the TSOs after the end of each delivery period.

Observation period. Our analyses cover the period from January 1, 2020 to June 30, 2021, i.e. exactly one and a half years. During this period, there were almost 80 million transactions on the EPEX intraday trading platform as well as around 47 million SRL setpoints per second and 53,000 MRL calls. The extremely large number of observations allows us to examine a large number of specifications, control variables, temporal structures and non-linear effects as well as to differentiate between products and trading times.

Limitations of the methodology. Only publicly available (albeit not always free of charge) data and information was used for this study. In particular, we do not have any trading or balancing capacity data that can be assigned to individual market participants. It is not possible to identify individual market participants who trade on the basis of the balancing power activation with the data available to us.

3.2 Regression models

We estimate different variants of the regression model

$$P_t = \beta_0 + \beta_1 SRL_t^+ + \beta_2 SRL_t^- + \beta_3 MRL_t^+ + \beta_4 MRL_t^- + \boldsymbol{\beta_5' Pr_t} + \boldsymbol{\beta_6' V_t} + \beta_7 P_{t-15} + \varepsilon$$

where P_t is the intraday price, SRL_t^+ the activation of positive secondary control power and SRL_t^- that of negative, MRL_t^+ and MRL_t^- the activation of the minute reserve, $\boldsymbol{Pr_t}$ a vector of wind- , solar and load forecasts and $\boldsymbol{V_t}$ a vector of publications of SRL and MRL calls and the control area balance by the TSOs, and P_{t-15} the price delayed by 15 minutes. We focus in particular on the coefficients of the control reserve activations β_1 to β_4 (highlighted in blue), our variables of interest. Forecasts and publications are included as control variables to allow for a faithful estimation of these coefficients. We include the lagged price as a regressor since it is publicly known and incorporates a large amount of unobserved information. The native temporal resolution of MRL activations, publications and forecasts is quarter-hourly, while the SRL signal is available in second resolution. For the regressions we use a temporal resolution of one minute. t of one minute. Data sources and aggregation methods are described below.

3.3 Data and data aggregation

Price. The intraday price is the variable to be explained in our regression model. All price data comes from EPEX SPOT. We use the deviation of the intraday price from the previous day's auction - for hourly products we refer to the day-ahead auction, for quarter-hourly products to the intraday opening auction. The reason for this is that the system balance can have an effect on short-term price changes, but not on the price level, which fluctuates over the course of the year. Almost 80 million transactions took place during the observation period, i.e. around 1.7 per second. We concentrate our analyses on the closing phase of trading from 2 hours before the start of delivery, which accounts for around 60% of the observations. For trading taking place earlier, the information on the current system status should be of little significance. We aggregate the approximately 47 million observations of individual transactions into 5.4 million volume-weighted 1-minute averages, separately for each product. We exclude periods in which no trading transactions took place (31% of all minutes) from the analysis. A total of 5.4 million observations are therefore included in our regressions.

Products and pooling. There are around 66,000 hourly and quarter-hourly products in the observation period; the price data therefore consists of just as many separate time series, each with a length of two hours, of which ten overlap at any given time. We pool the observations for all quarter-hourly and hourly products separately. Furthermore, we divide the two-hour trading period under consideration, i.e. the time interval between the transaction and the start of the delivery period, into time periods of 15 minutes. In total, we divide the price data into 16 different data sets (eight trading periods each for quarter-hourly and hourly products), for which we perform separate regressions. These 16 data sets are never pooled, i.e. they are never included together in a regression. This allows us to use up to around 197,000 (hourly) or 788,000 (quarter-hourly) observations per regression, minus missing observations, e.g. due to a lack of trading activity.

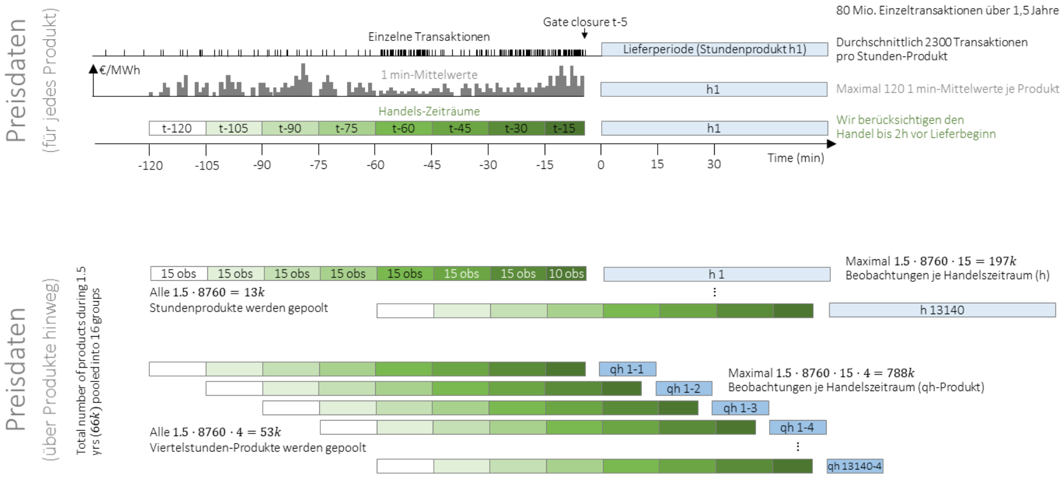

Figure 4. Price data and their aggregation.

SRL target value. We take into account the activations of SRL and MRL, which are each available as a continuous time series over the entire observation period. The data source is the internet platform Regelleistung.net, on which the TSOs publish this data on the following day.[1] The SRL target signal is a time series with a resolution of every second in the value range between approx. -2000 and +2000 MW, with significant changes generally only occurring every four seconds. The investigation period consists of a good 47 million seconds, for which the SRL target value is available in 79% of cases. We aggregate this time series to 1-minute rolling averages of the last 15 minutes, so that the resolution corresponds to that of the prices.

MRL activation. The MRL activation is scheduled in steps of 15 min. We assume that the MRL activation takes place 7 min before the start of delivery. The observation period consists of almost 53,000 quarter hours, in which, however, MRL was only called in 2.6% of cases. Figure 5 summarizes the aggregation of the control reserve activation.

[1] https://www.regelleistung.net/apps/cpp-publisher/api/v1/series/data?periodFrom=2020-01-01&periodTo=2021-06-30&exportFilename=exportedValues.csv&exportFormat=csv&seriesGroupName=GERMANY_aFRR_SETPOINT_MW_PT1S

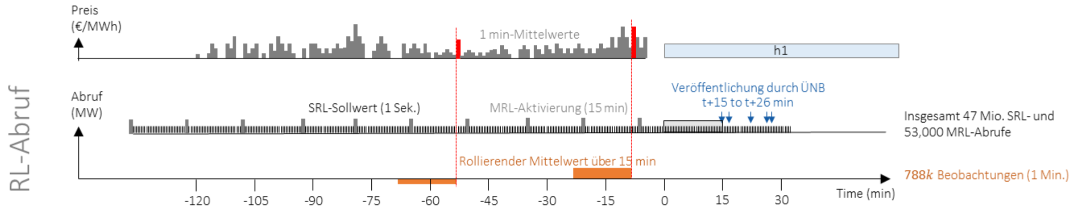

Figure 5. Balancing power activation data and their aggregation.

Forecasts. As control variables, we use the wind and solar generation forecasts from the forecasting provider Energy Meteo System as well as load forecasts from the provider TESLA (Europe) Ltd. All forecasts are available for each quarter-hourly delivery period and are also updated every quarter of an hour until delivery. We adjust the data to the minute-by-minute resolution of the prices by updating the current forecast for each delivery period until the next update arrives.

Publications. Another group of control variables are the publications of the TSOs, from which conclusions can be drawn about the system status. These include the quarter-hourly MRL activation, the quarter-hourly average value of the SRL activation and the control area balance. These are published by the TSOs at different times, first for each control area and then aggregated for the entire grid control network on Regelleistung.net (Table 1). The mean values of positive and negative balancing power calls are published separately here and are also included separately in our regressions. We control for all individual publications separately in order to adequately reflect their temporal structure. As with the forecast data, we also update the published control reserve data to a resolution of 1 minute.

Table 1 . Publications by TSOs (minutes after the start of the delivery period).

	Transnet	50Hertz	Amprion	TenneT	NRV
RZ Balance	19 min	21 min	25 min	26 min	26 min
SRL	19 min	21 min	25 min	26 min	26 min
MRL	15 min	15 min	15 min	15 min	15 min

Price. The last control variable to be included is price as an autoregressive term, i.e. the variable to be explained with a 15-minute time lag.

3.4 Possible disruptive factors in the identification strategy

Identification strategy. Systematic price movements on the intraday market shortly after the activation of balancing power suggest that market players use the information from the activation for trading decisions. However, there are also other theoretical explanations for such a correlation.

Power plant outages. We have not included unplanned power plant outages as regressors due to the lack of availability of correspondingly processed time series. To the extent that power plant outages are reported to the market in the form of *Urgent Market Messages* and at the same time cause an SRL call due to the physical effect in the grid, the regression model attributes the price effect to the SRL call, although in reality part of the effect could be due to the outage report (*omitted variable bias* due to a confounding variable). However, given the rarity of power plant outages compared to control reserve calls, we consider this effect to be negligible. Furthermore, power plant outages cannot, of course, explain the price effect of the activation of *negative balancing* capacity.

RE generation. A similar mechanism could exist if wind and solar producers have real-time measurements from their own plants that go beyond the forecast data used: Trading activity that is in reality motivated by these measurements would be incorrectly attributed by the model to the SRL activation taking place at virtually the same time. Short-term changes in generation could be caused by the weather or the curtailment of plants as part of feed-in management. As we control for RE generation forecasts and these contain a large number of real-time measured values, we also consider a possible bias (*omitted variable bias*) to be of secondary importance here.

Robustness analysis. As an additional robustness analysis, we examine in Section 4.6whether a correlation with the intraday prices can also be demonstrated with 1-minute aggregation of the SRL target values. This makes the direct temporal relationship between SRL call and price reaction even more accurate, which should avoid possible bias due to omitted variables. In principle, if all fundamental variables were known to all market participants in real time, a balancing power call would not contain any additional information and would therefore have no effect on the price. However, if there is a temporal relationship between the balancing power activation and the intraday price, the information about the activation has a potential economic value for the trader.

3.5 Evaluation metrics

Metrics. To assess the influence of the balancing power call on the intraday price, we look at three types of results in particular: (1) the magnitude of the coefficients, i.e. whether there is an economically significant influence; (2) the statistical significance of the coefficients, i.e. whether a correlation could stem from purely random price fluctuations; (3) the explanatory power of the models with and without balancing power call. For the latter, we compare the adjusted R^2 of otherwise identical models in which the SRL and MRL activation is included as a regressor or is not included.

Robustness. In addition, we assess the robustness of the results based on whether the metrics (1), (2) and (3) are stable when model specifications are changed, as well as on the consistency and internal plausibility of the results as a whole, i.e. the structure of the coefficients of balancing power activation and control variables.

4 Results

We first discuss the results of our basic specification, followed by a series of further analyses and robustness tests.

4.1 Basic specification

The basic specification uses all the control variables mentioned, the positive and negative SRL and MRL activations and the price delayed by 15 minutes. The balancing power activation is included linearly and the entire data range of one and a half years is used for estimation. As always, we estimate hourly and quarter-hourly contracts and the eight trading periods separately.

4.1.1 Shortest-term trading

Shortest-term trading. First, we show the influence of the balancing power call on the price in the shortest-term trade. For these regressions, only those trades were taken into account that took place between 15 minutes and 5 minutes before the start of delivery of the respective product. Only the trading of the respective front product is considered here.

Illustration. Figure 6 shows the coefficients of the SRL and MRL activation on the price of hourly (left) and quarter-hourly products (right), which originate from two separate regressions. The bars show the size of the coefficients, the brackets represent the 99% confidence interval.

SRL activation. This estimate suggests that a positive SRL activation of 15 minutes duration amounting to 1000 MW raises the electricity price of the hourly product about to be delivered by an average of €14/MWh and the price of the quarter-hourly contract by €34/MWh. These coefficients are statistically highly significant. With a confidence level of well over 99.99%, we can rule out the possibility that this estimate is due to random price movements.[2] Our estimates identify a much smaller, but also highly statistically significant effect when calling on negative SRL. The immediate effect of a GW activation is -8 €/MWh on the hourly contract and -16 €/MWh on the quarter-hourly contract.

MRL retrieval. The effect of a activation of positive MRL is even more pronounced than that of SRL. A GW activation increases the price of the quarter-hourly contract shortly before delivery by around € 104/MWh. However, the confidence intervals here are much wider than for SRL, and the effect on hourly contracts is not statistically significant at the 99% level. For this reason, and because MRL calls are much less frequent than SRL calls, we will nevertheless

---

[2] The P-value of the coefficients is $1.3\text{-}10^{-161}$ or lower.

focus on the latter in the following sections. The lesser importance of MRL as a price driver is also reflected in the only slight improvement in the explanatory power of the model when MRL is included as a regressor (see Figure 12 below).

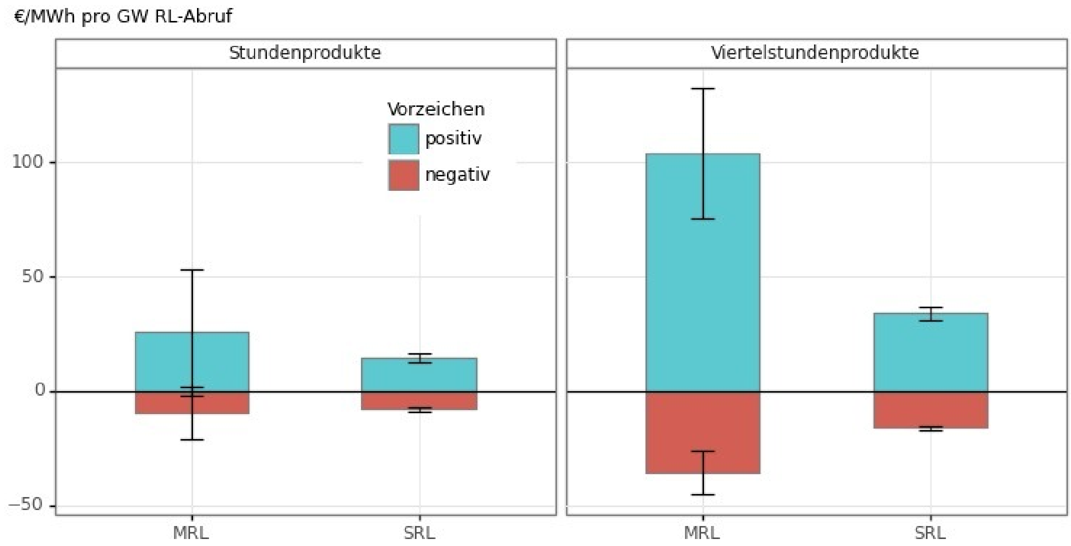

Figure 6. Effect of balancing power calls on the intraday price of front products. The coefficients of the SRL and MRL calls are shown as bars ($\widehat{\beta_1}$ to $\widehat{\beta_4}$) from two separate regressions for hourly (left) and quarter-hourly products (right) . The brackets represent the 99% confidence interval. There is a statistically highly significant correlation, except in the case of MRL for hourly products. A 15-minute positive SRL activation of 1000 MW increases the QH price by €34/MWh and the H price by €15/MWh.

Structure of the results. The structure of the results is plausible:

- The effect on quarter-hourly products is stronger than that on hourly products. This is obvious, as the control reserve activation transports information about the *current* system status and the delivery period for hourly products extends further into the future.
- The effect of an MRL activation is stronger than that of an SRL activation. This is plausible, as MRL is rarely activated and only in the event of major system imbalances due to the higher balancing energy prices during the observation period. This is also consistent with the result that a large SRL activation has a disproportionate effect (Section 4.2): A positive MRL activation has roughly the same price effect per MW as a large SRL activation per MW.
- A positive activation causes a greater price effect than a activation of negative SRL. This can be explained by the fact that a negative activation means an oversupply of electricity to the system. Unlike conventional power plants, wind and solar generators can be scaled down easily, quickly and at no cost. If the electricity price falls below the negative market premium, it is advantageous for direct marketers to shut down plants instead of selling electricity. Direct marketers can therefore refrain from selling electricity when prices are very negative. There is no analogous option in the event of a shortfall in the system, as thermal power plants cannot be ramped up in the short time available.

- The coefficients of most of the control variables are statistically highly significant and plausible in terms of sign and magnitude (Table 2). For example, if the wind or solar forecast increases by 1 GW, the intraday price falls by €0.6/MWh. The coefficients of the TSO publications do not provide an entirely consistent picture and are also statistically insignificant in some cases, which we attribute to the large number of publications in quick succession and the high correlation between them. As a robustness analysis, we have removed the publications individually and completely from the regression (Section 4.6). As a consequence, the coefficients of the SRL retrieval are slightly larger, so the result is robust.
- In absolute terms, the coefficients of the control reserve activation are around two orders of magnitude larger than the generation forecasts, although in both cases they indicate a system over/shortfall of 1 GW. This indicates that the control reserve activation is perceived by market participants as a much more robust information signal.

Table 2 . Regression coefficients for the front-quarter hourly product based on 342,349 observations.

Variable		Estimated effect on the ID price (€/MWh)	P-value
RL activation (GW)	Positive SRL activation	33,9	<0,0001
	Negative SRL activation	-16,2	<0,0001
	Positive MRL activation	104,0	<0,0001
	Negative MRL activation	-35,8	<0,0001
Forecasts (GW)	Wind forecast	-0,6	<0,0001
	Solar forecast	-0,6	<0,0001
	Load forecast	-0,2	<0,0001
TSO publications releases (GW)	Positive SRL activation TBW	-4,8	0,0239
	Positive SRL activation TBW+50H	6,0	0,0007
	Positive SRL activation TBW+50H+AMP	0,0	0,0220
	Positive SRL activation NRV	-1,6	0,2136
	Negative SRL activation TBW	-0,3	0,7413
	Negative SRL activation TBW+50H	-2,8	<0,0001
	Negative SRL activation TBW+50H+AMP	0,0	<0,0001
	Negative SRL activation NRV	2,1	<0,0001
	Positive MRL activation NRV	-33,8	<0,0014
	Negative MRL activation NRV	18,9	<0,0001
	Positive NRV balance	5,7	<0,0001
	Negative NRV balance	-5,2	<0,0001
Other	$Price_{t-15}$ (€/MWh)	0,7	<0,0001
	Constant (€/MWh)	-1.7	<0,0001

4.1.2 Total trading period

Trading times. While previously only the shortest-term trading was considered, we now discuss the effect of balancing power calls on electricity prices for trading times up to two hours before the start of delivery. The balancing power activation transports information about the current and expected short-term system status. It is therefore to be expected that the effect on prices will be greater with a short delivery period. For example, if the start of delivery is still two hours in the future, information about the current system status has little significance for the system status during delivery.

Methodology and presentation. We divide the price data into eight time windows of 15 minutes each. As always, hourly and quarter-hourly products are estimated separately, so that a total of 16 regressions are calculated. Figure 7 shows the coefficients of the SRL activation. The X-axis shows the effects on prices of a range of products that are available for different lengths of time before delivery.

Results. An SRL call has a statistically highly significant effect on intraday prices in all short-term trading of products up to two hours before delivery. In other words, a 15-minute positive SRL call of 1000 MW not only raises the price of the front quarter-hour contract by €34/MWh, but also the product with delivery afterwards by €20/MWh, the contract behind it by €14/MWh, etc. - and even the product with delivery in two hours by €3/MWh. In addition, the same activation not only raises the price of the front hourly contract by €8-17/MWh, but also that of the downstream product by €2-4/MWh. Figure 7 shows that an SRL call simultaneously influences the price of all 10 currently traded contracts with delivery start in the next two hours. All coefficients are statistically highly significant.

Structure of the results. The results confirm the assumption: if the delivery is even further in the future, the SRL activation has a quantitatively smaller effect.

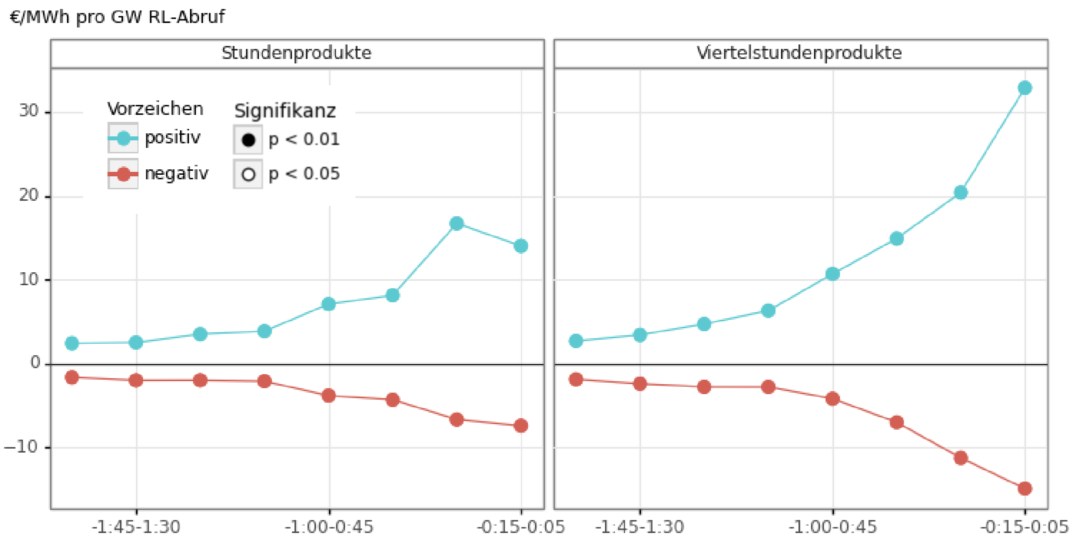

Figure 7. The effects of the SRL call on the intraday price at different trading times for hourly and quarter-hourly products. The coefficients of the SRL call ($\widehat{\beta_1}$ and $\widehat{\beta_2}$) from 16 different regressions. Filled circles indicate significance at the 1% level. An SRL call has a statistically highly significant influence on

all 16 intraday products considered, i.e. all contracts with delivery start in the next two hours. The prices of contracts about to be delivered react most strongly.

Summary. There is a statistically highly significant correlation between balancing power calls and the intraday price. The price rises when positive balancing power is called up and falls when negative balancing power is called up. This correlation is verifiable, although we statistically control for a large number of other price drivers. The price effect exists not only for the front product, but also for products whose delivery start is up to two hours in the future. In other words, an SRL activation is a price driver for a whole range of currently traded intraday products.

4.2 Non-linear effect

Non-linear effects. In the baseline specification, the SRL and MRL activations are linear, i.e. we assume that each MW activation always has the same €/MWh effect on the price, even if the effect may occur with a time lag and differs for different currently traded products. In this section, we investigate whether (a) a larger activation has a disproportionately large price effect and whether (b) switching from a negative to a positive activation, and vice versa, has an additional price effect.

Size of the activation. The absolute size of the activation could therefore play a role, as the energy charge merit order is generally highly non-linear. As a consequence, the (expected) reBAP rises disproportionately when a large volume activation is made. Table 3 shows the frequency of SRL calls by size during the observation period.

Table 3 . Number of 1-minute rolling 15-minute averages of SRL activations by size.

Range	Quantity	Share
< -1500	192	0.03%
-1500 to -1000	2905	0.41%
-1000 to -500	31285	4.41%
-500 to 0	328229	46.29%
0	0	0.00%
0 to 500	315878	44.55%
500 to 1000	26260	3.70%
1000 to 1500	3780	0.53%
>1500	500	0.07%
Total	709029	100.00%

Results. Figure 8 shows the price effect differentiated according to the size of the SRL activation. The results show that large activations of positive SRL have a disproportionately high price effect. On average, a small activation has a price effect of €26/MWh per GW activation on the quarter-hour front product (far right in the Figure), while a very large activation has an effect of €118/MWh. This means that the price increases by €3.90/MWh as a result of a 150 MW activation, but by €177/MWh as a result of a 1500 MW activation. No significant non-linear effect can be determined for the activation of negative SRL - if there is any difference at all, a larger activation tends to have a disproportionately low price effect.

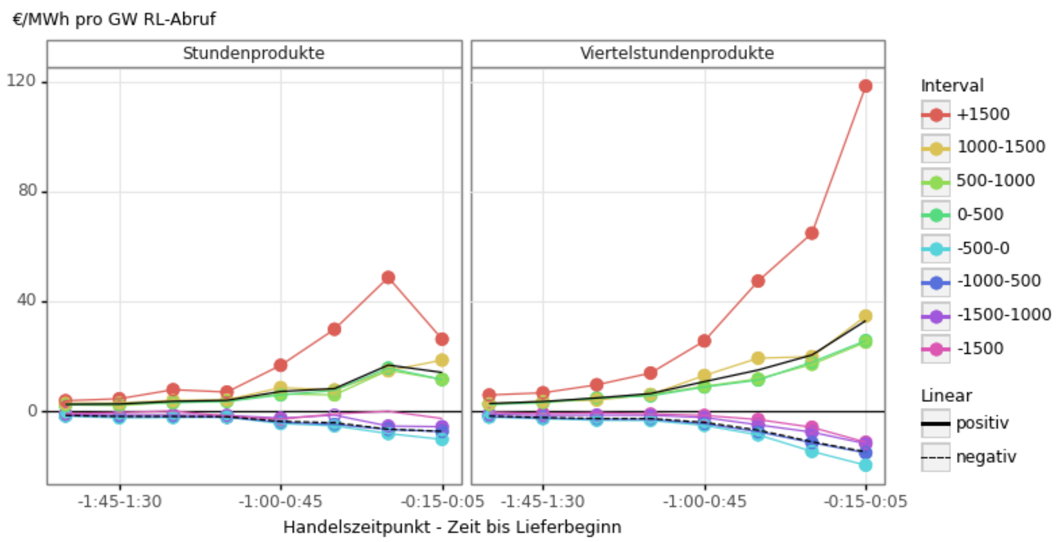

Figure 8. Effect of an SRL activation differentiated according to the size of the activation. Large-volume calls of positive SRL have a strongly disproportionate effect. However, small SRL calls also have a measurable and significant price effect at the 1% level in almost all trading periods considered.

Change of sign. It is conceivable that in certain situations a balancing power activation carries more price-relevant information than in others. One case could be the switch from positive to negative balancing power and vice versa. This indicates a change in the system. Figure 9 shows the coefficients of an additionally inserted binary variable "sign change", which indicates whether the 15 min average value of the SRL activation changes from negative to positive or vice versa. There is a statistically significant effect in some trading periods. This shows that the intraday price reacts more strongly to a sign change than the activation would suggest based on its absolute size. This effect is in addition to the "normal" effect of the SRL call. However, the size of the coefficients is rather small at € 1-2.

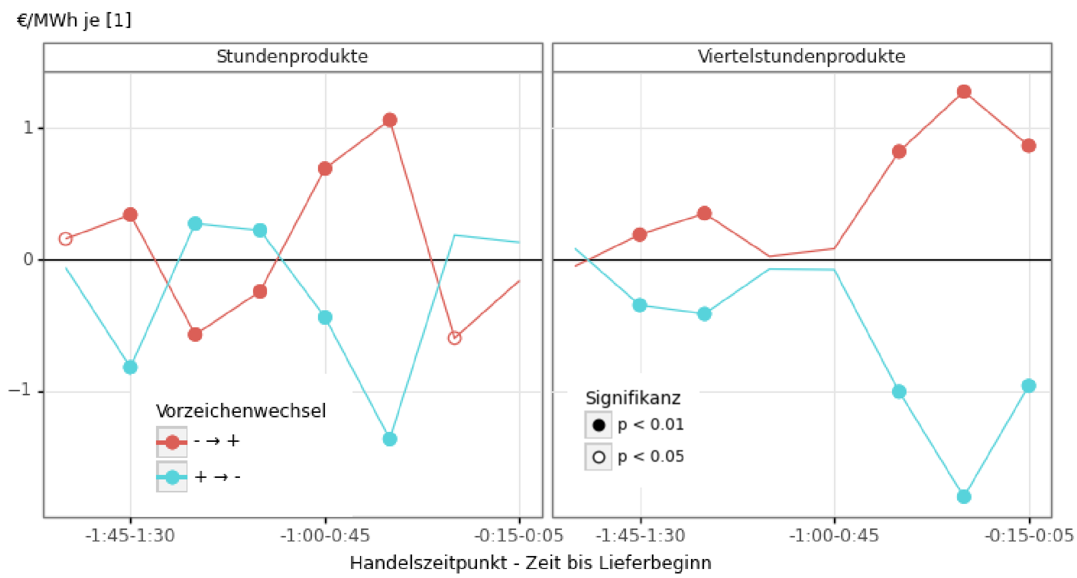

Figure 9. Effect of a change in the sign of the SRL activation on the front quarter-hour product. A change of sign has a statistically significant but quantitatively small additional effect on the intraday price.

4.3 Influence of the balancing energy market

Influence of the balancing energy market. On November 3, 2020, the balancing energy market ("Regelarbeitsmarkt"/RAM) was introduced in Germany, i.e. the option to offer balancing energy in the balancing energy auction without prior award. Contrary to the intention of the reform, prices for balancing energy in particular rose as a result. Higher balancing energy prices translate into higher balancing energy prices, which in turn could have an impact on the importance of balancing energy activation signals for short-term trading.

Analyses. In order to investigate a possible influence, we divided the period into two sections - up to November 2, 2020 and from November 3, 2020 - and examined these separately using a regression in the base specification, analogous to section 4.1.2. In all three time periods - before the introduction of RAM, after the introduction of RAM and in the overall period - we find a statistically significant effect of SRL activation on intraday price in the entire trading period two hours before delivery (Figure 10). In fact, the introduction of the RAM has strengthened the correlation in short-term trading.

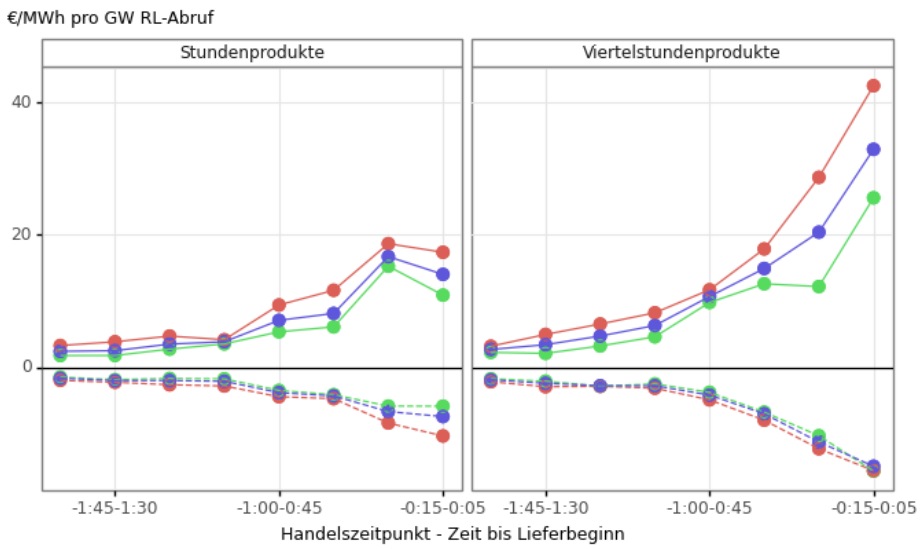

Figure 10. Price effect of the SRL call ($\widehat{\beta_1}$ and $\widehat{\beta_2}$) on hourly and quarter-hourly contracts at various trading times before and after the introduction of the standard labor market. Since the introduction of the RAM, the correlation is even stronger, but was already statistically significant in all cases considered before that.

4.4 Auto-regressive price

Analyses. In the regressions shown so far, the price is included with a time lag of 15 minutes. In the following, we now examine the role of price by (a) delaying it by 60 minutes or (b) not including it at all as a regressor in the model. Figure 11 shows a comparison of the coefficients of the SRL call in the three regression models. The inclusion of price as a regressor and the choice of time lag have only a minor influence on the size of the coefficients. Without price as an explanatory variable, the coefficients are slightly higher than previously estimated, especially for hourly contracts.

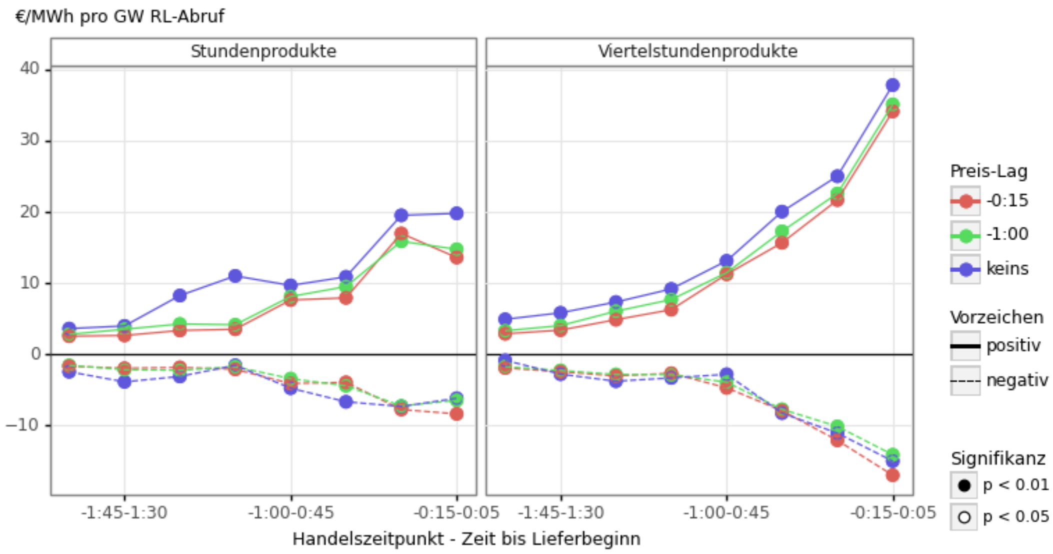

Figure 11. Price effect of the SRL call on hourly and quarter-hourly contracts at different trading times in regression models with and without time-delayed price as regressor and with 15min or 60min time delay. The red lines are identical Figure 7. Overall, the price as a regressor has only a minor influence on the coefficients of the SRL call, so the results are robust.

4.5 Explanatory power

Model fit. Instead of looking at the size and statistical significance of the coefficients of SRL and MRL activation, the explanatory power of the regression model as a whole can also be compared. In particular, we are interested in whether the explanatory power of the regression model increases when control reserve activation is included as a regressor. To this end, we consider the adjusted R^2 - the proportion of the variance of the intraday price that can be explained by the model - for four regression models, which differ only in that the balancing power activation is taken into account in the model in different forms: not at all, only MRL, only SRL and MRL and SRL. Unlike the (unadjusted) R^2, the adjusted R^2 is suitable for comparing models with a different number of regressors.

Results. Figure 12 shows the results, two of which are essentially relevant. Firstly, the explanatory power of the models increases significantly when balancing power is included. The increase is strongest in short-term trading. For trading up to 15 minutes before the start of delivery, the inclusion of balancing power calls in the regression model raises the adjusted R^2 from 64% to 75% (hourly contract) and from 51% to 55% (quarter-hourly contract). This considerable increase in the model fit shows that a significant proportion of the price changes in short-term trading are caused by balancing power calls. On the other hand, this increase can be explained almost exclusively by the SRL activation. The MRL activation only leads to a marginal improvement in the model fit, which can be explained by the fact that MRL was only activated in 2.6% of all quarter-hours.

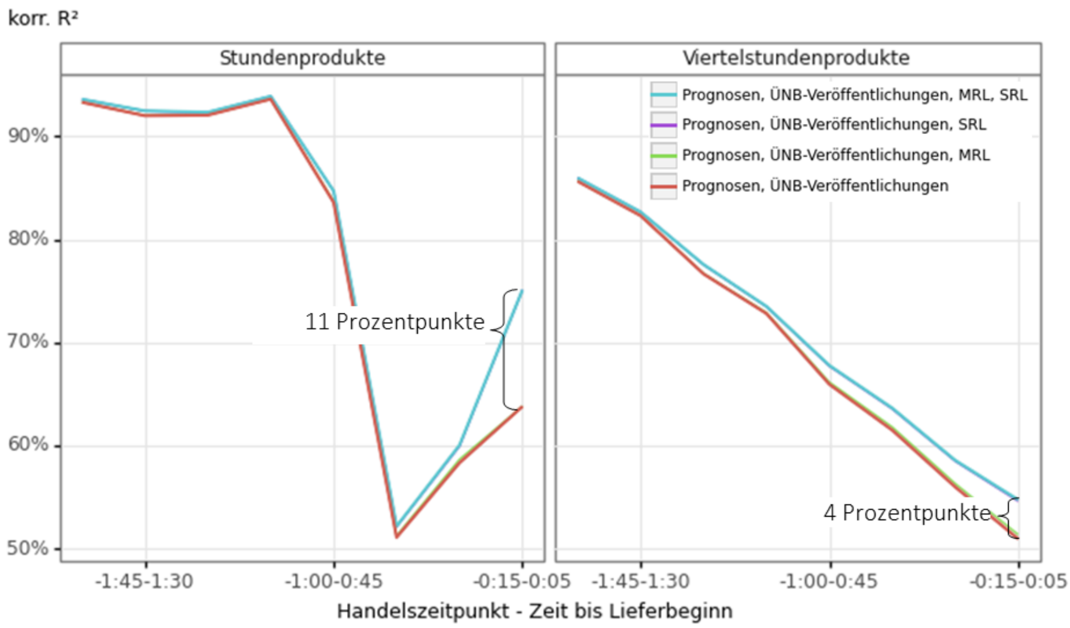

Figure 12. Explanatory power of otherwise identical regression models with and without MRL/SRL activation. The adjusted R² from a total of 64 regressions is shown. The inclusion of the balancing power activation as an explanatory variable significantly increases the R² value of the models, from 64% to 75% for short-term trading of hourly products. The inclusion of the SRL activation as an explanatory variable results in a much more significant increase in the adjusted R² than the MRL activation. This is another reason why we concentrate on the SRL call.

Differences in R². Figure 13 shows the *difference* in the adjusted R² between models with and without balancing power as regressors. This shows the *increase in* the adjusted R² due to the inclusion of SRL and MRL as explanatory variables. This shows that the model fit is substantially improved, especially in short-term trading, i.e. that the balancing power activation is an important price driver. This difference is also shown for various autoregressive price terms. It can be seen that this improvement is largely independent of whether a time-delayed price is included in the model (and by how much time-delayed). In other words, our central result is robust - the activation of balancing power is an important price driver in short-term intraday trading.

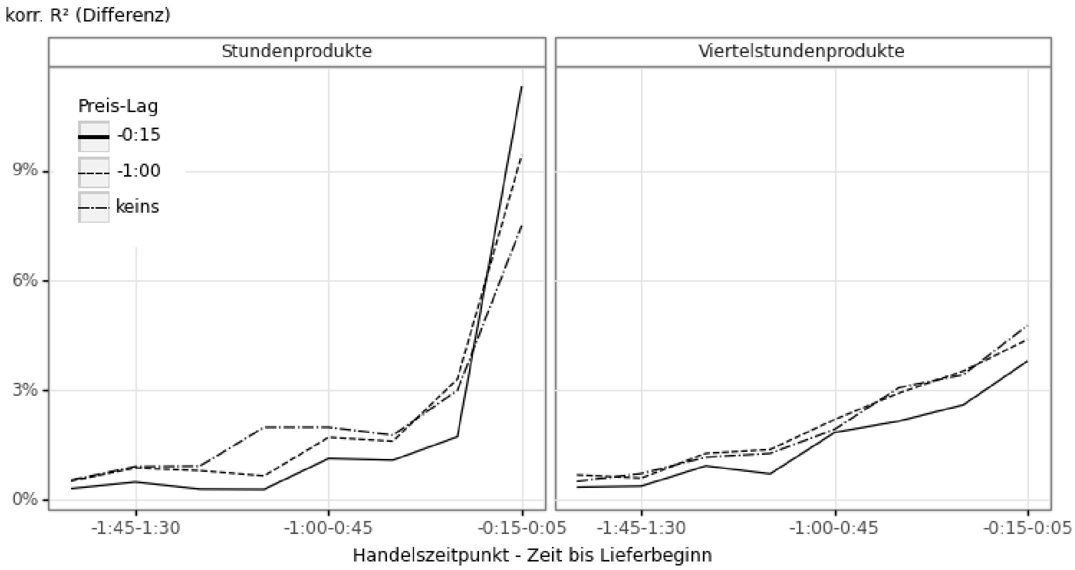

Figure 13. Difference in the adjusted R^2 between models with and without balancing power activation. The inclusion of the variables explaining the RL activation increases the R^2 by 8-11 percentage points (hourly product) or 4-5 percentage points (quarter-hourly product) for products shortly before delivery. This increase in R^2 is found in models that include the time-delayed regressor as well as in the baseline specification without autoregressive price. Our results are therefore robust: balancing power activation is a relevant price driver in short-term trading.

4.6 Further robustness analyses

1 min-SRL. Instead of averaging 15 minutes, we use the 1 min average of the SRL signal as a regressor. This has the advantage that the direct temporal relationship between SRL activation and price reaction can be mapped even more accurately, which should avoid possible distortion due to omitted variables. On the other hand, only those price effects that are realized in a short period of time can be measured in this way. If trading decisions are not made in the same minute or trading activity takes place later, a correlation is overlooked. As a result, the regression coefficients of the SRL call are around a third lower than for the basic specification. For example, a positive SRL activation of 1000 MW with a duration of *one minute has an* estimated price effect on the quarter-hour front product of €21/MWh, while a *15-minute* activation has an estimated effect of €34/MWh. Calculated per minute, the price effect is therefore even nine times stronger for 1-minute averages.

Reduced regression models. The coefficients of some control variables have unexpected signs. This applies in particular to the TSO publications, which we explain by the high collinearity of the values published in close temporal sequence. As the publications are of course also strongly correlated with the balancing power activation, we remove them individually and jointly from the regression model as a robustness analysis. The coefficients of the control reserve call remain stable in terms of sign, size and statistical significance, meaning that the result is robust. The SRL coefficients are even larger in absolute terms in the model with quarter-hourly products.

5 Conclusions

Results. We find a statistically significant, quantitatively significant and extremely robust correlation between balancing power calls and intraday prices. Shortly after SRL and MRL calls, there are systematic price movements, with prices moving upwards after the call of positive balancing power and downwards after the call of negative balancing power. These price movements can be observed for all hourly and quarter-hourly products whose delivery is a maximum of two hours in the future. The results are so striking that we can rule out the possibility that price jumps are due to random fluctuations in a large number of specifications with a confidence level of more than 99.99%.

Example. If, for example, an SRL activation of 1000 MW takes place at 11:35 and lasts 15 minutes, we estimate that the electricity price at 12:50 for delivery from 12:00-12:10 is on average €34/MWh higher than if the activation does not take place. This SRL activation also has an impact on the prices for all other hourly and quarter-hourly contracts with delivery starting between 12:00 and 14:00.

Differences. The effect tends to be greater the shorter the interval between the time of the activation and the time of trading, the shorter the trading period before the start of delivery and the higher the activation. The effect is also greater for quarter-hourly products than for hourly products, greater for positive balancing energy calls than for negative ones and greater for SRL calls than for MRL calls. Since the introduction of the balancing energy market, the influence has become even stronger. However, even in cases with a quantitatively smaller effect, we often find a statistically significant correlation.

Interpretation. The result is a consistent picture of robust correlations. These correlations suggest that market players use the information from the balancing power activation for trading decisions.

Appendix

The results of further analyses carried out are presented below.

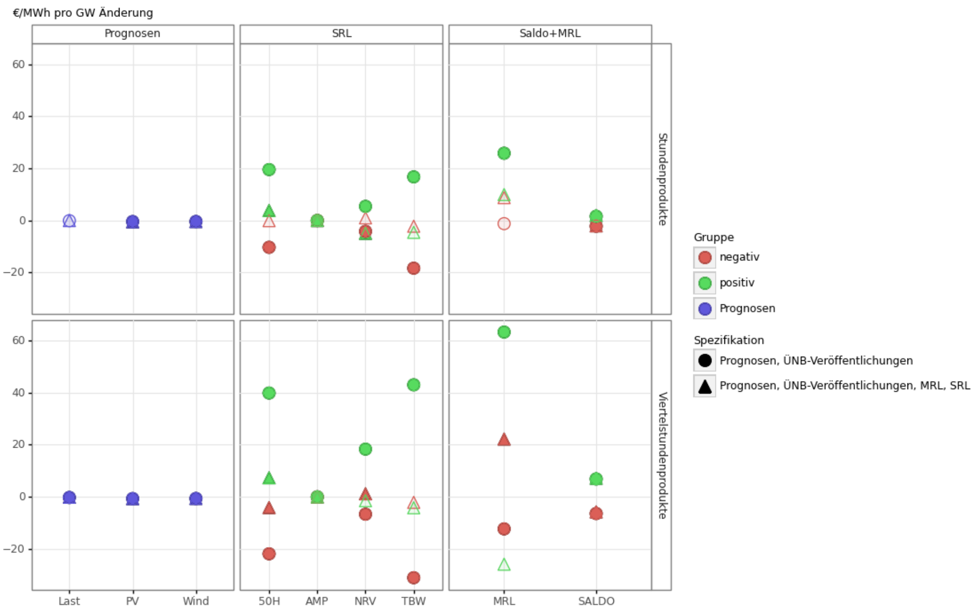

Figure 14. Coefficients of the control variables in the regressions with and without balancing power activation. Unfilled coefficients are not significant at the 99% level.

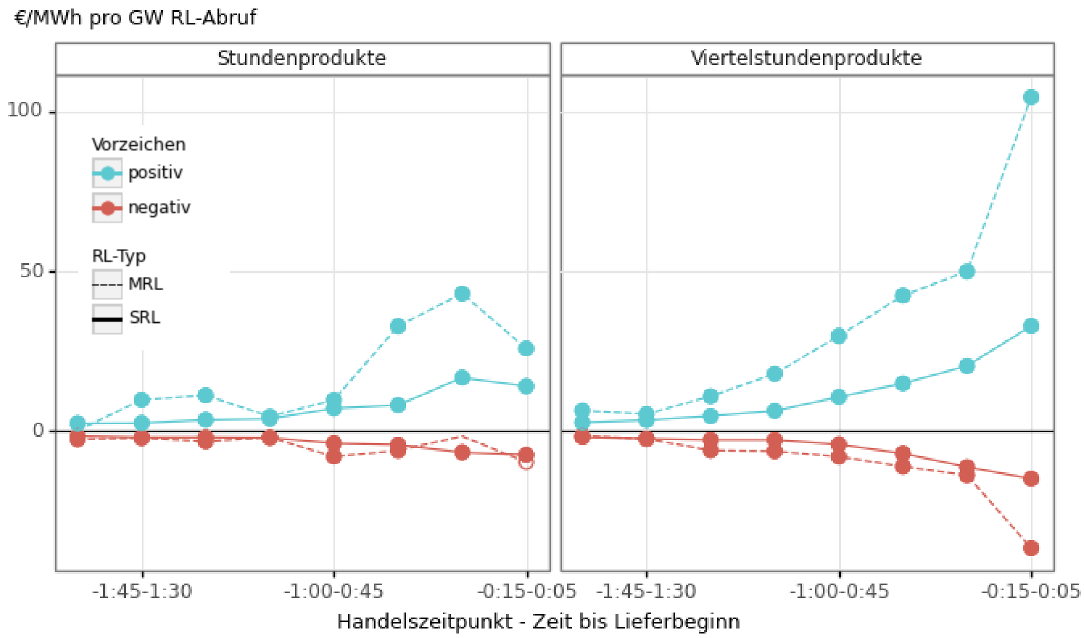

Figure 15. The effects of SRL and MRL activations on the intraday price at different trading times for hourly and quarter-hourly products. (Like Figure 7 incl. coefficients for MRL)

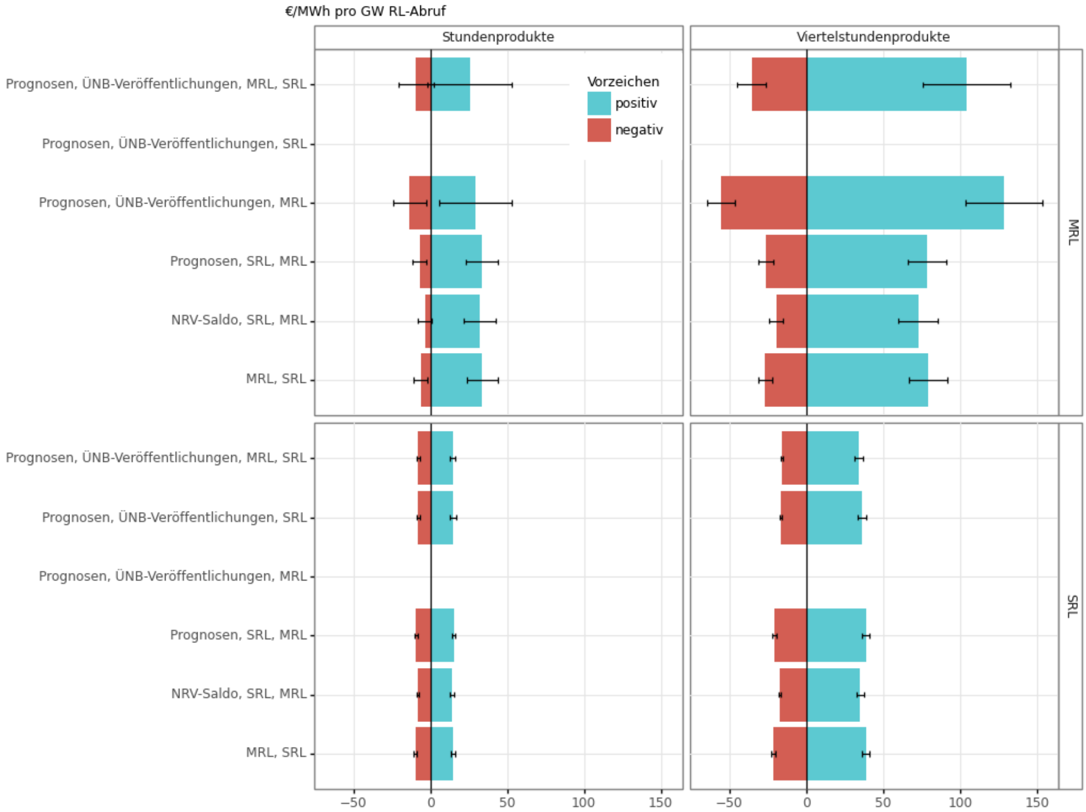

Figure 16. Effect of balancing power activation on the intraday price of front products in different regression specifications. The first bar from each panel corresponds to Figure 6.

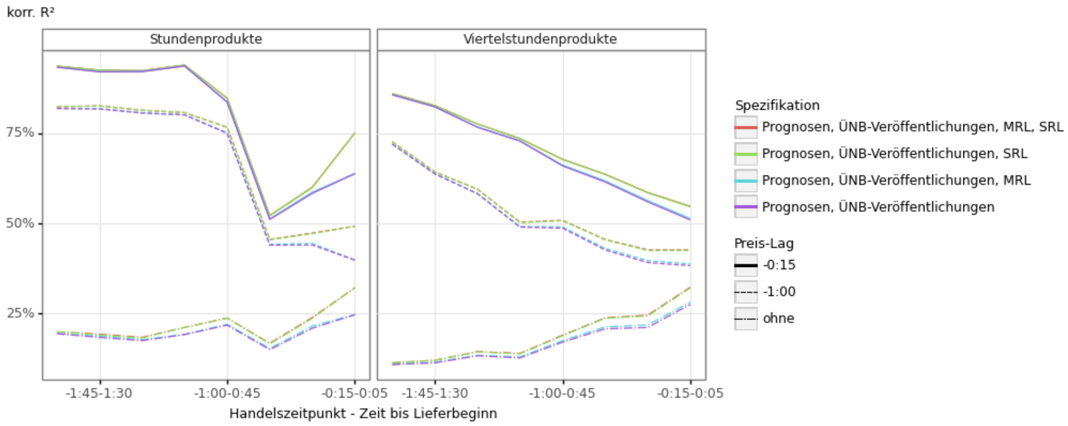

Figure 17. Adjusted R^2 for models with and without time-delayed price (time delay 15 or 60 min) as regressor and with and without control reserve activation (SRL, MRL, both) as regressor.

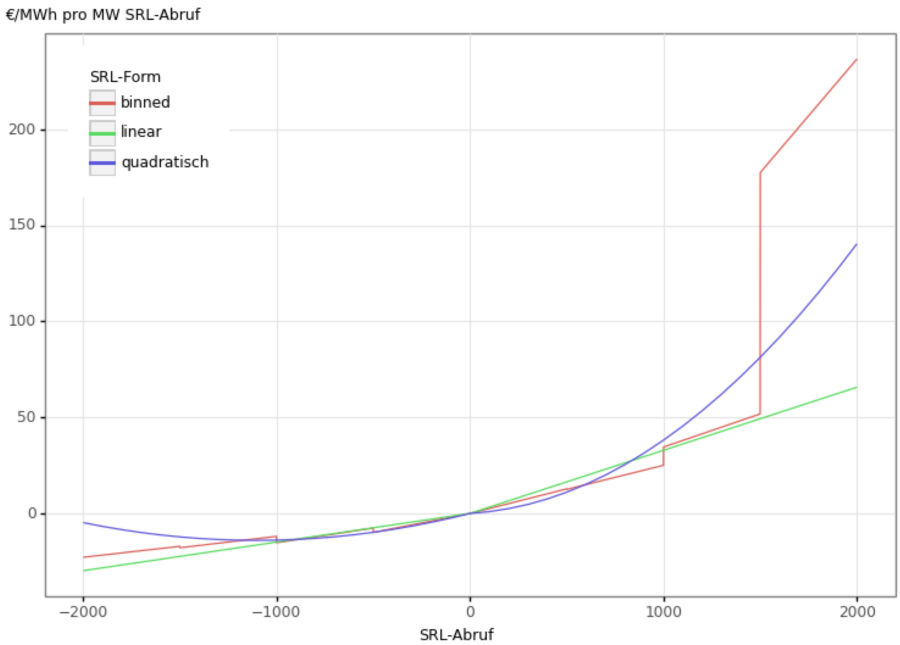

Figure 18. Alternative implementations of a non-linear relationship between the level of SRL activation and price: linear, intercept linear and quadratic relationship.

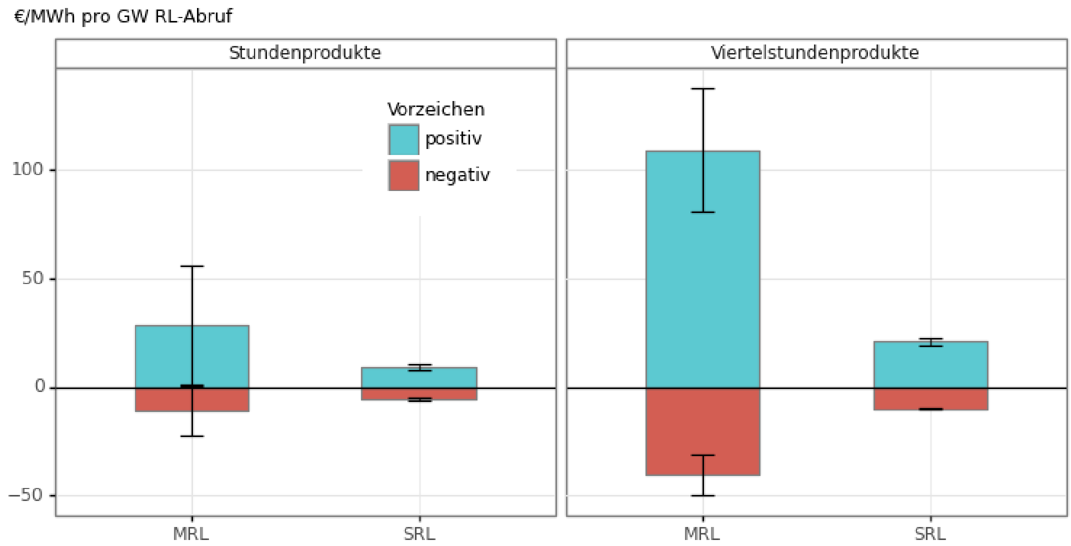

Figure 19. Effect of control reserve activation on the intraday price of the front products with 1-minute aggregation of the SRL setpoints.