The value of intraday electricity trading –

Evaluating situation-dependent opportunity costs of flexible assets

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Abstract

As electricity generation in Germany is shifting to volatile PV and wind power generation, intraday trading becomes more important to ensure power balance in the energy system. Market participants already have various opportunities of distributing their power at different markets. A realistic forecast of revenues in continuous intraday trading is a crucial factor for an optimized electricity dispatch. Our study assesses the value of intraday revenues based on a superimposed, normal distribution function that represents the characteristics of deviations between continuous intraday prices and prices in the intraday auction. Empirical analyses based on data from 2018 lead to situation-dependent functions depending on the residual load forecast. The validation based on real intraday revenues, which could be generated by exemplary power plants, shows a much better performance of forecasting with the situation-dependent, superimposed distributions compared to a standard normal distribution. This approach results in an improved evaluation of revenues in continuous intraday trading, leading to an optimized operation of flexible assets.

Keywords

continuous intraday trading; intraday revenue forecasting; opportunity costs; bidding behavior; normal distributed prices

JEL codes: C53, D4, F37

1 Introduction

1.1 Motivation

Keeping the energy transition in Europe in mind, there is a shift to decentralized volatile generation units resulting in more bottlenecks regarding the grid. An opportunity to decrease these congestions is the integration of local flexibility markets adapting the generation or consumption of flexible assets [1]. Alternatively, redispatch of flexible power plants can decrease these congestions. In addition to local flexibility markets or redispatch, such flexible assets have the opportunity of trading at short-term electricity markets [2]. Sufficient forecasting of revenues in all available markets is a crucial factor to a successful integration of these flexible units into the energy system. This paper develops an approach to analyze the opportunity costs of units that distribute e.g. in local flexibility markets or evaluate a schedule change because of redispatch. Therefore, it focuses on the continuous intraday market in Germany.

1.2 Analysis of intraday trading in Germany

Trading on the intraday market supplements day-ahead trading with the shorter-term intraday market with partly shorter products. In continuous trading, both hourly and quarter-hourly products are tradable within Germany up to 30 minutes before physical delivery and within a German control area even up to 5 minutes before delivery. The trading volume has risen sharply in recent years. Figure 1 shows the annual trading volume of the years 2012 to 2018 in the quarter-hourly intraday auction, as well as the continuous quarter-hourly and hourly trading based on data of EPEX Spot[1] [3]. The continuous, hourly intraday market by far offers the largest volumes. However, in all markets the volumes traded have increased consistently in recent years. While in 2012 the volumes traded were around 13 TWh, the volumes in 2018 reached 52 TWh, which corresponds to an increase of 300 %. The liquidity of the intraday market has thus increased a lot, which leads to a higher attractiveness of the market.

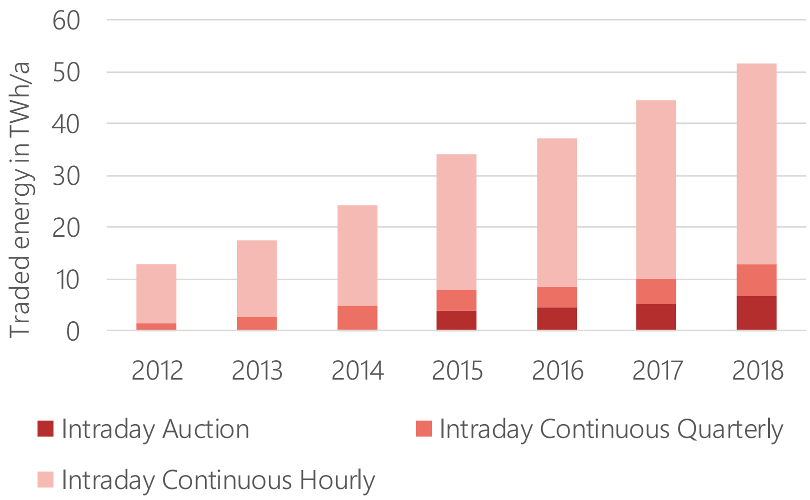

Figure 1: Intraday trading volumes for the years 2012 to 2018 in Germany

In addition to the strong increase in trading volumes on the intraday market, the price characteristics have also changed in recent years. Figure 2 shows the frequency distribution of the average price of the last three hours before delivery for quarter-hourly, continuous intraday trading. It can be seen that both the average electricity price and in particular the dispersion of electricity prices have risen sharply in the last three years. This means that even assets with very high marginal costs have increased distributing opportunities in continuous intraday trading leading to a higher relevance of the intraday market.

[1] The data are proprietary, but can be obtained via the EPEX Spot website [3].

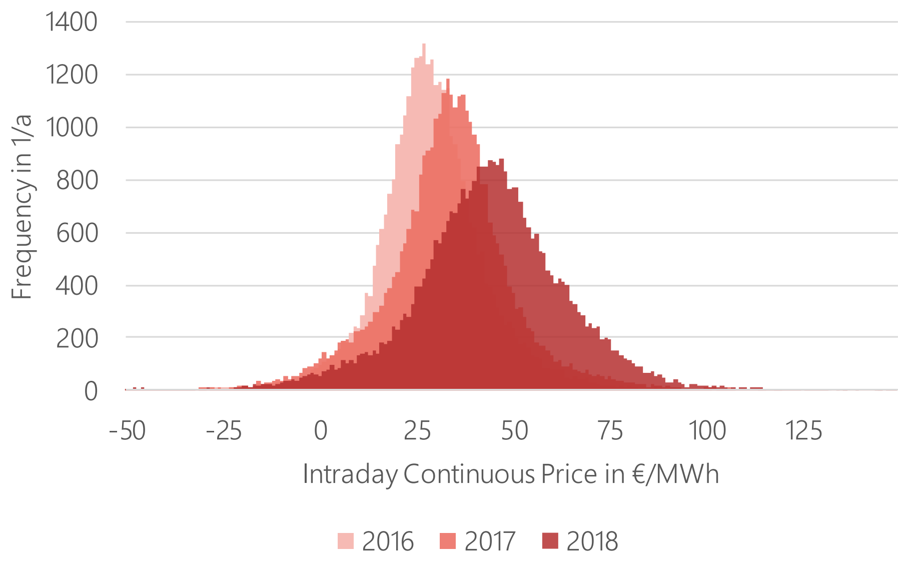

Figure 2: Frequency distribution of continuous intraday prices in Germany for the years 2016 to 2018

2 General approach

In this paper, a basic existing methodology for assessing opportunity costs in the intraday market is extended. This chapter first presents and analyzes the methodology, whereupon Chapter 3 introduces the extension of the methodology to a situation-dependent approach.

2.1 Approach of evaluating opportunity costs

The price development of the continuous intraday price affects the potential revenues of flexible asset. Continuous, quarter-hourly intraday prices, modelled in a simplified way as Brownian motion, result in normally distributed values with a mathematical expectation value of the intraday auction price and a standard deviation [4].

Based on [4], the value of intraday options, meaning potential intraday revenues, depends on four different parameters:

- The expectation value of the continuous intraday price μ at time of evaluation of the option
- The standard deviation σ of the continuous intraday prices indicating the distribution of prices around the expectation value μ
- The marginal costs c for a power output of a flexible asset
- The amount of power to be distributed

The unit-specific and statistical parameters result in the value of intraday options as illustrated in Figure 3. If marginal costs of an asset c_2 are higher than the intraday auction price, it will not distribute its electricity at this market. Yet, there is still a chance for higher continuous intraday prices as the prices are assumed to be normally distributed around the expectation value. Distributing electricity with these higher continuous intraday prices will lead to revenues. The nearer the marginal costs get to the expectation value, the higher the value of the intraday call option will get. If otherwise marginal costs of an asset c_1 are lower than the price in intraday auction trading, it will sell its electricity at these markets. Consequently, a continuous intraday price that is lower than the marginal costs will lead to revenues resulting from the purchase of electricity instead of producing itself. Possible revenues weighted with their probabilities lead to the value of the intraday put option.

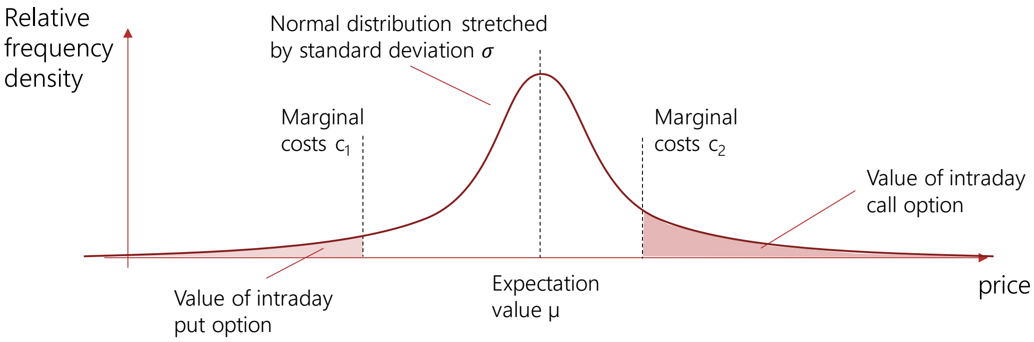

Figure 3: Evaluation of the value of intraday options

Consequently, the shape of the normal distribution determined by expectation value and standard deviation is crucial for the value of intraday options.

2.2 Analysis of considered distribution function

This paper focuses on data of the intraday market in Germany. In a first step, the deviation between the continuous intraday price *id_cont_3h* and the intraday auction price *id_auc*, following referenced as *id_diff_3h*, is analyzed for a normally distributed characteristic. The evaluated value *id_cont_3h* represents the volume-weighted average price of all transactions in continuous intraday trading within 3 hours before delivery.

Standardized test algorithms like Kolmogorow-Smirnow test [5] or Shapiro-Wilk test [6] reject the hypothesis that the data represents a normal distribution, meaning that the data is not normally distributed. As both tests tend to be very sensitive for rejecting the hypothesis for large sample sizes [7], one can use graphical tests by plotting the histogram of the empirical distribution and corresponding fitted normal distribution function.

Figure 2 shows the empirical probability distribution of *id_diff_3h* for all quarter hours of 2018. The normal distribution fitted to the empirical values is added as a red dashed line. The normal distribution is fitted by using the maximum likelihood estimation [8], except that the estimate of the sigma parameter is the square root of the unbiased estimate of variance. By graphical plausibility check, not all ranges of the distributions seem to be represented well by the function. One possibility of a different representation of the distribution corresponds to a superimposed normal distribution displayed as a red solid line. The superimposed function corresponds to the additive mapping of two normal functions fitted again by maximum likelihood estimation. The first one has a very small standard deviation as a representation of the steep range at low price deviations. The second function has a higher standard deviation to represent the higher values on the tails of the normal distribution. However, the Kolmogorow-Smirnow and Shapiro-Wilk test still reject the test if the empirical data could have come from the superimposed distribution function.

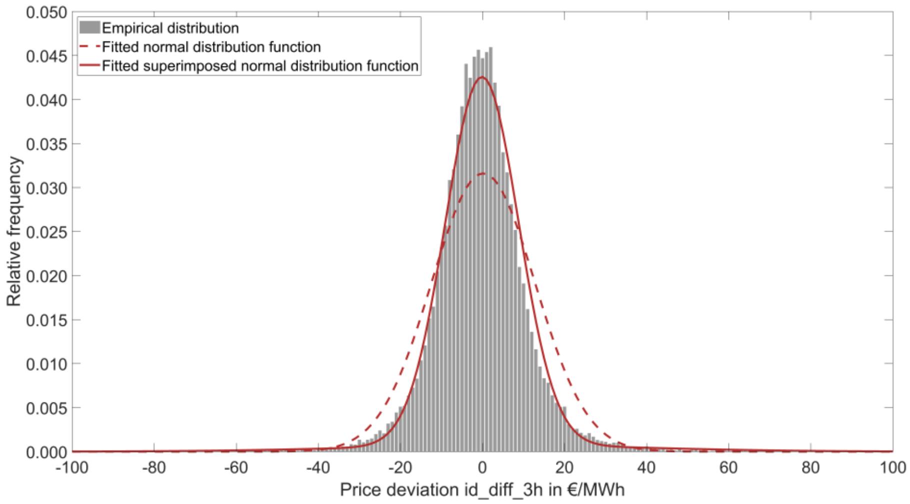

Figure 4: Comparison of empirical distribution to fitted distribution functions

In order to evaluate the quality of the functions, a graphical analysis of the probability density functions, as used in the Kolmogorow-Smirnow test, leads to a more detailed investigation. Figure 5 shows that the superimposed normal distribution matches much better with the empirical distribution than the normal distribution. The maximum deviation of the superimposed normal, cumulative distribution from the empirical, cumulative distribution is 1.6 % (1.8 % in 2017) and is thus considerably lower than the maximum deviation of normal and empirical, cumulative distribution with 8,3 % (9,4 % in 2017). Consequently, a higher quality and a better representation of the empirical distribution can be assumed for the superimposed normal distribution function. Therefore, further investigations include both, the superimposed normal distribution and the normal distribution.

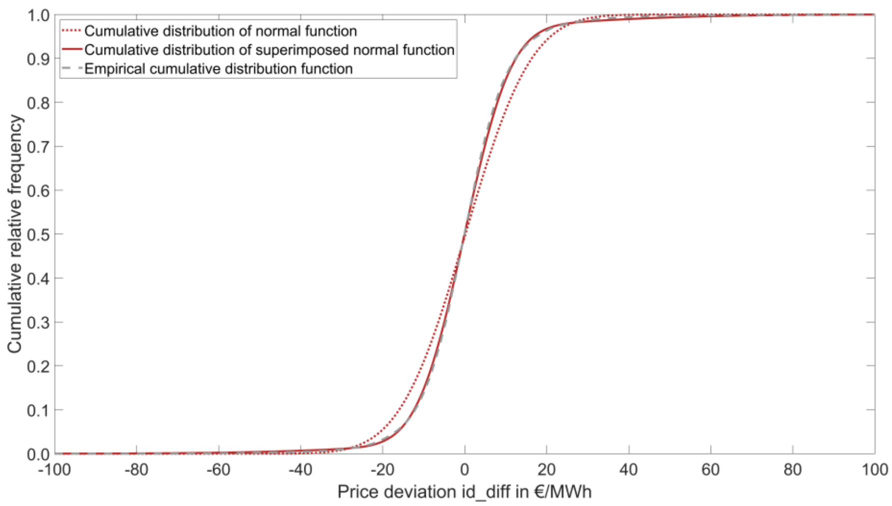

Figure 5: Comparison of cumulative empirical, normal and superimposed normal distribution function

2.3 Evaluation of intraday price distribution in 2018

Evaluating intraday prices in 2018 in Germany, the fitted functions have the same expectation value and standard deviation compared to the empirical data. For the empirical distribution, the normal distribution and the superimposed, normal distribution, the standard deviation is 12.62 €/MWh and the expectation value is 0.17 €/MWh. By drawing a sufficiently large set of random values from the distribution functions, their standard deviation and expectation value are determined. A slightly positive mean value represents a slightly lower intraday auction price than the average continuous intraday price of the last three hours before delivery. The standard deviation stands for the uncertainty of price developments in continuous intraday trading, meaning a higher standard deviation refers to a higher uncertainty. Modelling continuous intraday prices with one standard deviation assumes the same uncertainty for every considered quarter hour in a year. As the electricity generation becomes more volatile because of an increase of renewable generation units, one can suppose that the uncertainty of continuous intraday prices has a situation-dependent differentiation. This assumption leads to the investigations in the following chapter of a situation-dependent analysis of standard deviation and mean for the difference of continuous intraday price and intraday auction price.

3 Situation-dependent intraday options

Considering the electricity generation shifting to more volatile generation units leads to the assumption that continuous intraday prices become more uncertain. This chapter discusses main influencing factors on the price uncertainty and quantifies situation-dependent characteristics of intraday prices.

3.1 Discussion of main influencing factors for situativeness of intraday price deviations

For identifying possible influencing factors for situation-dependence of intraday prices, two criteria are important. Firstly, a factor in general must have a systematical influence on electricity prices. Secondly, there has to exist day-ahead data to evaluate this influencing factor. It is crucial to use available day-ahead data because the uncertainty of continuous intraday prices has to be evaluated at the time of the intraday auction, meaning 15:00 the day before.

At this stage of investigations, the influence of a factor on intraday prices is limited to simply comparing the mean intraday auction price with different characteristics to show a general price dependence on the influencing factor. The next chapter continues analyzing the influence of these factors on price deviations *id_diff_3h*. Table 1 displays the main identified influencing factors based on the analysis of their influence on intraday auction prices and data availability. Because entso-e data for PV and wind generation forecast is missing for some days of 2018, the following investigations are limited to 34,400, instead of 35,040 data points. Considering the factors wind generation forecast, PV generation forecast, load forecast and residual load forecast, high and low characteristics are separated by the median forecast value of the factor. For simplicity, this paper defines residual load as load minus PV and wind generation. For the wind generation forecast in Germany in 2018, for example, the median value is 9.9 GW, which means that the term "low wind" in Fehler! Verweisquelle konnte nicht gefunden werden. represents data points with wind generation forecast lower than 9.9 GW and the term “high wind” all others.

Although the influencing factors are only clustered in two to three different characteristics, there are clear price dependencies except for the factor residual load gradient. Since the residual gradient affects intra-hourly price differences [9], the influence of the factor on the continuous intraday price is to be analyzed in further investigations. Therefore, in the next chapter, situation-dependent investigations of the deviations of continuous intraday price and intraday auction price concentrate on all seven discussed influencing factors.

Table 1: Analysis of main factors on uncertainty of intraday auction prices

Factor	Influence on intraday auction price	data
Wind generation	High wind: 38 €/MWh Low wind: 51 €/MWh	[10][2]
PV generation	High PV: 44 €/MWh Low PV: 51 €/MWh	[10]
Load	High load: 36 €/MWh Low load: 52 €/MWh	[10]
Residual load	High residual load: 34 €/MWh Low residual load: 55 €/MWh	[10]
Residual load gradient	Positive residual load gradient: 44 €/MWh Negative residual load gradient: 45 €/MWh	[10]
Day time	0:00 to 8:00: 37 €/MWh 8:00 to 20:00: 48 €/MWh 20:00 to 24:00: 47 €/MWh	-
Week day	Monday to Friday: 47 €/MWh Saturday: 40 €/MWh Sunday: 34 €/MWh	-

3.2 Quantifying situation-dependent standard deviation and expectation value of intraday price deviations

For describing the empirical distribution of intraday price deviations, statistical parameters include the standard deviation and the expectation value. Relating the deviation between continuous prices and expectations of intraday auction to day-ahead forecasts of previous discussed influencing factors results in a situation-dependent standard deviation displayed in Figure 6. It shows the comparison of standard deviations for the deviation of continuous intraday price and intraday auction price based on different specifications of all seven influencing factors. For this purpose, two different price deviations are defined:

- *id_diff_1h:* Average price of all transactions in continuous intraday trading within one hour before delivery minus intraday auction price
- *id_diff_3h:* Average price of all transactions in continuous intraday trading within three hours before delivery minus intraday auction price

[2] The data are proprietary, but can be obtained via the entso-e website [10].

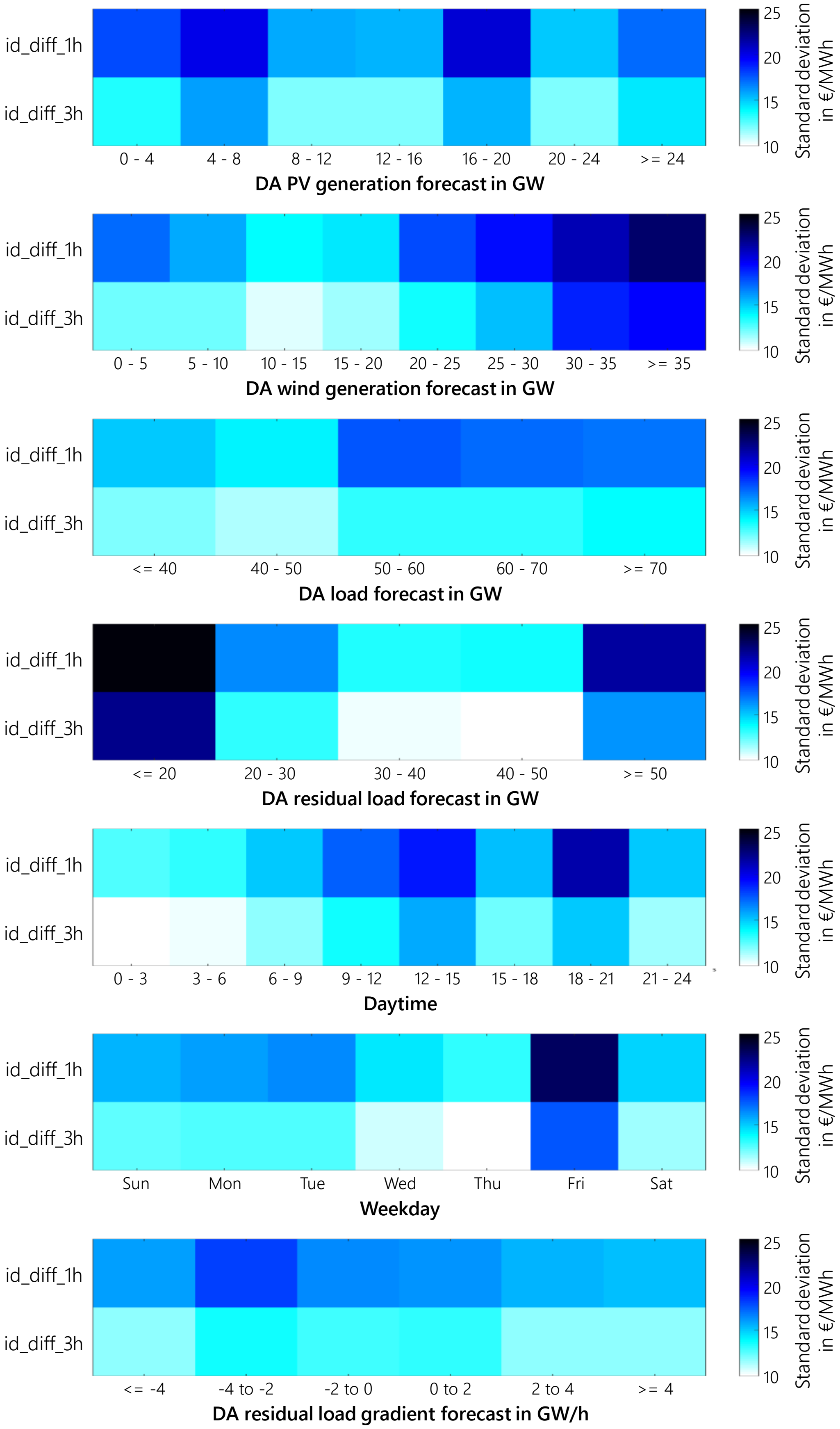

Figure 6: Comparison of standard deviation for intraday price deviation based on different specifications of influencing factors

Regarding the mean standard deviation for different specifications of the influencing factors, some factors stand out with high situational dependencies; others come along with a random uncertainty of price deviations. In the following analysis, the term cluster refers to the different specifications of the influencing factors.

Influencing factor PV generation forecast excludes all time steps during nighttime with a forecast of no generation. All other factors use all quarter hours from 2018. The standard deviations vary from 12.0 to 15.6 €/MWh for *id_diff_3h* and 15.0 to 20.5 €/MWh for *id_diff_1h*. As there is no intuitive explanation, why e.g. cluster "4-8 GW" is much more uncertain than cluster "0-4 GW" and "8-12 GW", one cannot assume a systematical situational dependence here.

The standard deviation for influencing factor wind generation forecast varies from 10.5 to 19.5 €/MWh for *id_diff_3h* and 13.9 to 22.8 €/MWh for *id_diff_1h*. The diagram shows a systematic dependence of price uncertainty and wind generation forecast. In situations with a moderate wind generation forecast of 10-15 GW, the continuous intraday price deviates less from intraday auction price than with a very high wind generation forecast. If e.g. a very high wind generation leads to curtailment of wind power plants, this will cause a more uncertain continuous intraday price.

For a variation of load forecasts, the standard deviation shows only a slight dependence on the demands level. Standard deviations are between 11.9 and 13.9 €/MWh for *id_diff_3h* and between 14.0 and 17.5 €/MWh for *id_diff_1h*.

The residual load combines the previous three influencing factors. Standard deviations vary from 10.2 to 22.0 €/MWh for *id_diff_3h* and 13.4 to 26.2 €/MWh for *id_diff_1h*. The spread between maximum and minimum standard deviation is larger than for all other evaluated influencing factors. Intraday price deviations between continuous and auction trading are much more uncertain for very low and very high residual load forecasts than for moderate residual load forecasts. A big advantage of using residual load as an influence factor is the consideration of interdependencies of PV and wind generation forecasts as well as load forecasts.

For further investigations, the fifth diagram in Figure 6 shows the standard deviation of intraday price deviations for different residual load gradient forecasts. Here the standard variation varies from 11.8 to 13.6 €/MWh for *id_diff_3h* and 15.2 to 18.0 €/MWh for *id_diff_1h*. As it is quite similar and does not differ systematically with higher, lower, positive or negative residual load gradients, this influence factor is unsuited to show situational dependencies.

Lastly, an investigation of the standard deviation at specific times shows some situational dependence. Depending on the time of the day, there is a minimum mean standard deviation at night and a maximum one at midday, ranging from 10.3 to 15.7 €/MWh for *id_diff_3h* and 12.7 to 21.5 €/MWh for *id_diff_1h*. Time steps at midday correlate to time steps with low residual load, when there is high wind and PV generation, leading to a higher standard deviation. The influencing factor daytime often is an indirect representation of influence factor residual load.

Dependence on the weekday leads to a mean standard deviation of 9.8 to 17.6 €/MWh for *id_diff_3h* and 13.2 to 23.1 €/MWh for *id_diff_1h*. Although the variances of the standard deviation depending on the weekday are large, there is no reasonable explanation for a much higher uncertainty on Friday compared to the one on a Thursday.

In Weber et al. [4], the expectation value of quarter-hourly continuous intraday trading assumes the intraday auction price at the time of the auction. This is a reasonable assumption because otherwise there would be opportunities of making arbitrage profits. If there was a positive expectation value, meaning a higher mean continuous intraday price compared to the mean auction price, traders would consistently buy at intraday auction and sell in continuous intraday trading to generate profits on average.

Nevertheless, the expectation value of continuous intraday trading dependent on the different specification of considered influencing factors is analyzed to support or reject this hypothesis. Figure 7 therefore shows the expectation value of *id_diff_1h* and *id_diff_3h* for all seven influencing factors separated in the factors specifications. An expectation value of zero, displayed in black, represents a continuous intraday price that is equal to the average auction price. Positive expectation values, shown in red, and negative expectation values, displayed in green, point out a mean price deviation between continuous intraday price and intraday auction price.

Several influencing factors, like PV generation forecast, load forecast, daytime, weekday and residual load gradient, only have minor, non-systematic, or non-explainable deviations of expectation value zero. These slight differences do not seem appropriate to deduce a deviant expectation value.

For a variation of the wind generation forecast on the other hand, there seem to be systematic deviations of the expectation value. For a wind generation forecast higher 25 GW, there is a mean expectation value of 2.3 to 2.9 €/MWh for *id_diff_3h* and 2.1 to 3.4 €/MWh for *id_diff_1h*. In Germany, curtailment of wind power plants correlates to the amount of wind power generation. Therefore, a reasonable explanation for systematic higher continuous intraday prices is the decreased electricity generation offered, resulting from curtailed wind power plants, when there is a general high wind power generation. However, market participants should anticipate that, as it is an opportunity of making systematic profits.

The influencing factor residual load forecast once again is a representation of wind generation forecast, PV generation forecast and load forecast and consequently includes the previous discussed impacts of high wind generation forecasts represented in a low residual load forecast. The expectation value is around 2.2 €/MWh for low residual loads and -1.1 €/MWh for high residual loads for both *id_diff_1h* and *id_diff_3h*. The fact that there is a systematic lower continuous intraday price for high residual load forecasts is very interesting, as it cannot be observed in the separate depictions of wind generation, PV generation and load forecast. A reasonable explanation could be many conventional power plants running, leading to a high flexibility and a high supply in continuous intraday trading.

In summary, the analysis of the influencing factors showed that the standard deviation and even the expectation value are situation-dependent. A separation by specifications of influencing factors is suitable to represent that. The clearest and most reasonable situational dependency of price deviations shows the influence factor residual load forecast. Since this factor simultaneously includes the influencing factors wind generation forecast, PV generation forecast and load forecast, this influencing factor is excellently suited and used in the following investigations for the evaluation of the value of intraday options.

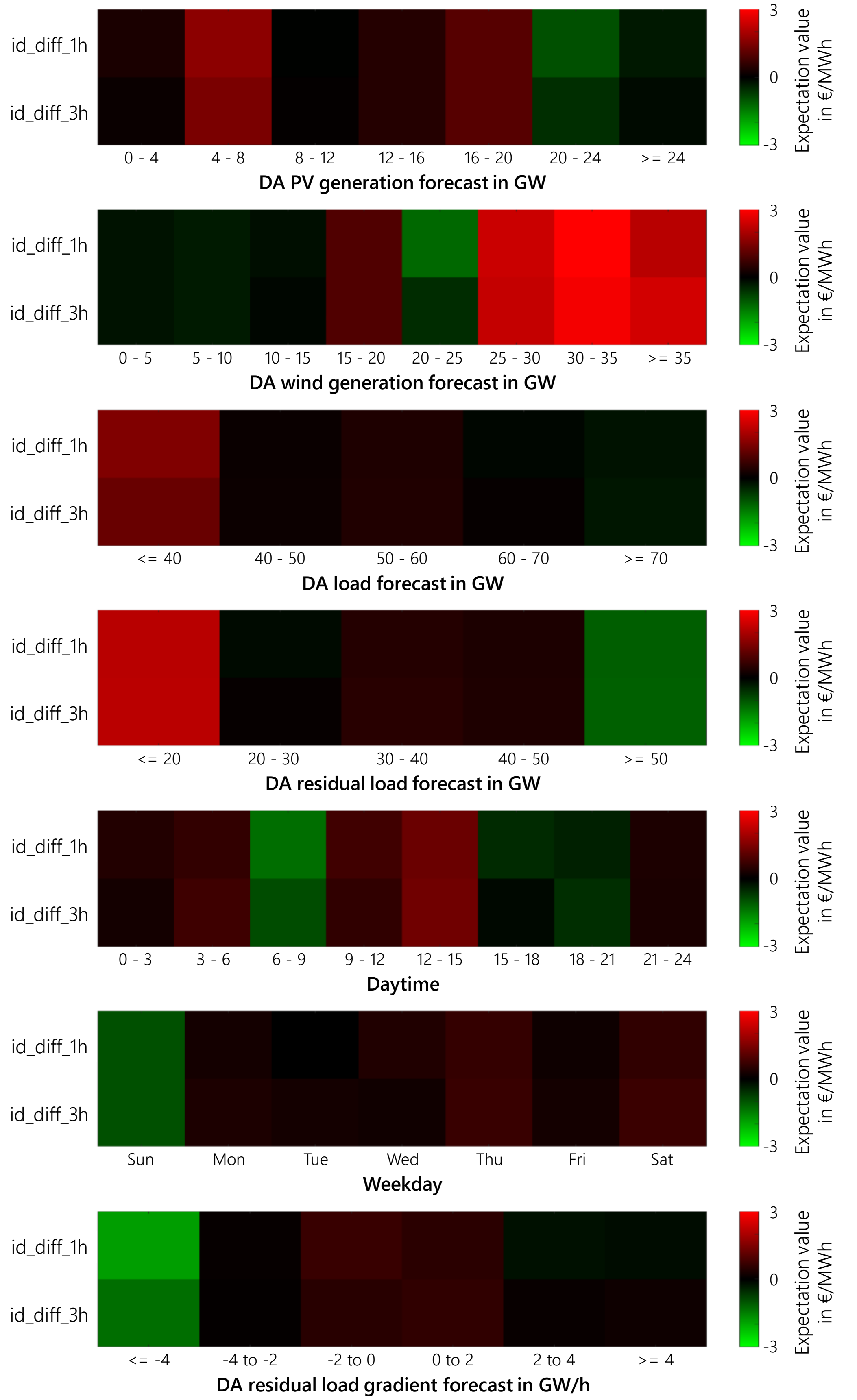

Figure 7: Comparison of expectation value for intraday price deviation based on different specifications of influencing factors

4 Evaluation of intraday options in 2018

Based on situation-dependent standard deviations and expectation values of intraday price deviations, this chapter evaluates intraday opportunity costs for the year 2018 for two exemplary power plants. As described in chapter 2.1, for a calculation of intraday opportunity costs, a distribution function of continuous intraday prices, marginal costs of a unit and the amount of distributed power have to be parametrized. The exemplarily investigations assume the following parameterization:

- *Considered distributions:*
    - Normal distribution function with standard deviation 13.52 €/MWh and expectation value of 0.01 €/MWh based on data of 2017
    - Situation-dependent distribution functions (normal compared to superimposed) based on data of 2017 with the following parameters:

Function	Residual load in GW	Standard deviation in €/MWh	Expectation value in €/MWh
1	<= 20	26.2	3.3
2	20 – 30	14.8	0.2
3	30 – 40	9.8	0.1
4	40 – 50	8.4	0.1
5	>= 50	18.4	-1.0

- *Exemplary marginal costs based on [11]:*
    - 30 €/MWh, representing a lignite power plant
    - 60 €/MWh, representing a gas power plant
- *Exemplary amount of evaluated power:*
    - 1 MW

Considering the time period January to December in 2018, firstly, the residual load forecast leads to a selection of the situation-dependent distribution function, as illustrated in Figure 8 for an exemplarily week in July, 2018. There are five different distribution functions, which are selected dependent on the residual load forecast. The depicted week is characterized by high PV generation, leading to the lowest residual load of 14 GW on July-07. Depending on the residual load forecast, the allocated, situation-dependent distribution function estimates the value of the intraday option.

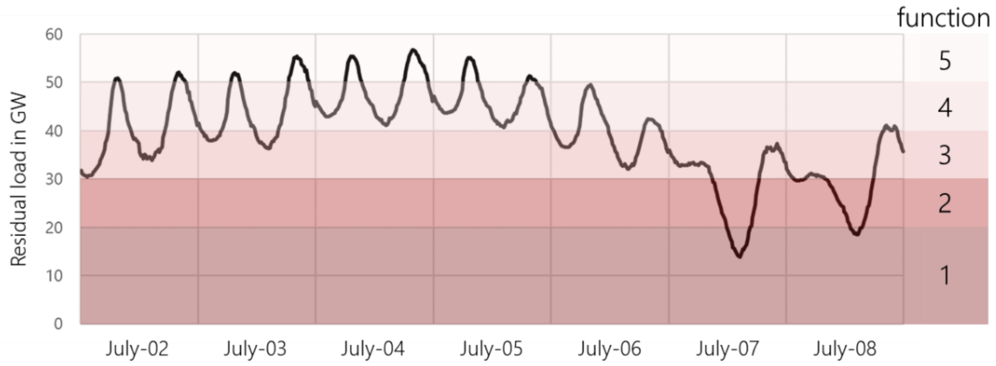

Figure 8: Selection of situation-dependent function

The intraday options consist of the described call and put options. Comparing the simulated value of the intraday options for 2018 to the real value results in a validation of the modelling approach. For the calculation of the real values, the average, quarter-hourly continuous intraday price within 3 hours before delivery *id3_price* represents possible revenues at continuous intraday trading. As it is the average price, most trading participants are able to offer or purchase electricity for that price. There are two options to generate profits for a flexible power plant. Whenever the *id3_price* is higher than the marginal costs of a power plant that did not offer at intraday auction because the auction price was lower than its marginal costs, there exist real revenues calculated by the *id3_price* minus the marginal costs, representing the call option. When otherwise the *id3_price* is lower than the marginal costs of a power plant that sold electricity at intraday auction because the auction price was higher than its marginal costs, there result real revenues calculated by the marginal costs minus the *id3_price*, representing the put option.

Simulating intraday options for the year 2018 results in the revenues shown in Fehler! Verweisquelle konnte nicht gefunden werden.. The real revenues are between 6,200 € and 6,400 € for the year of 2018 for both considered power plants. Simulating revenues with the situation-dependent superimposed distribution functions leads to revenues of 6,100 € and 7,000 € and consequently to a quite realistic forecast of revenues in continuous intraday trading. Revenues modelled by the situation-dependent normal distribution are 9,000 € and 9,300 €. Modelling intraday options with a normal, non-situation-dependent distribution generates revenues around 11,000 € and therefore, results in profits that are excessively high. Therefore, the situation-dependent, superimposed distribution function reflects the total revenues much better than normal distribution function (situation-dependent or non-situation-dependent).

Table 2: Real and modelled intraday revenues for 2018

Marginal costs of power plant	Modelled revenues			Real revenues
	Normal distribution	Situation-dependent normal distribution	Situation-dependent superimposed distribution	
30 €/MWh	11,300 €	9,300 €	7,000 €	6,400 €
60 €/MWh	11,200 €	9,000 €	6,100 €	6,200 €

As an additional evaluation, the real and modelled intraday revenues for the various residual load clusters are compared, shown in Figure 9. The average, volume weighted price deviation of real and modelled prices for a power plant with marginal costs of 30 €/MWh is 170 € for the situation-dependent, superimposed functions, 490 € for the situation-dependent, normal functions and 1,480 € for the normal distribution. For a power plant with marginal costs of 60 €/MWh, average, volume weighted price deviation of real and modelled prices is 410 € for the situation-dependent, superimposed functions, 970 € for the situation-dependent, normal functions and 1,320 € for the normal distribution. Once again, the situation-dependent, superimposed functions have advantages compared to the normal distribution and the situation-dependent, normal distribution by reflecting the real prices much better.

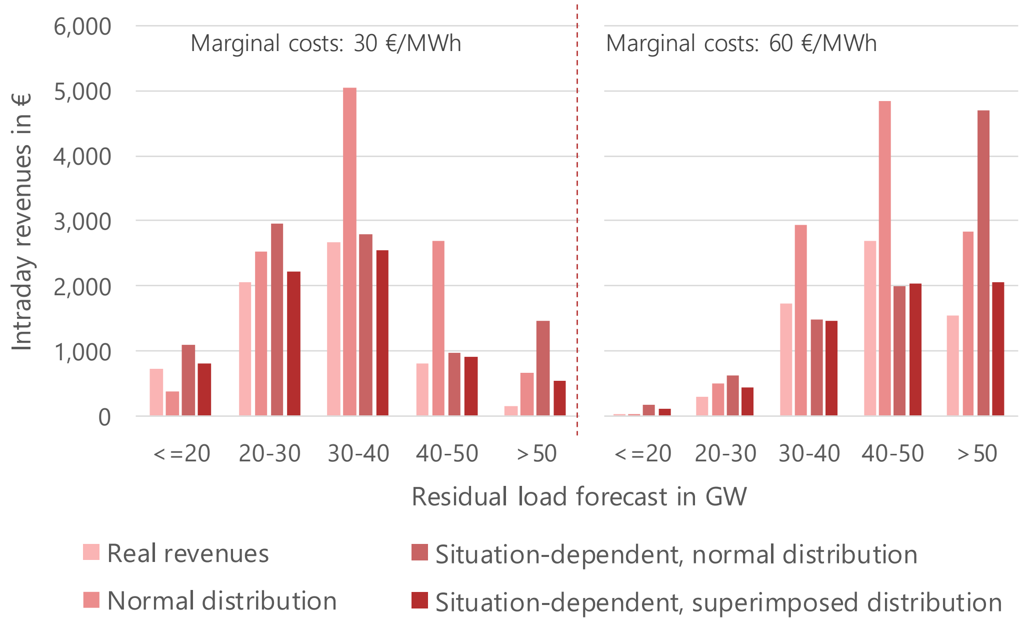

Figure 9: Real and modelled intraday revenues for the various residual load clusters

5 Conclusion

In this paper, we investigate average, expected revenues at the continuous intraday market. Considering a variety of dispatch opportunities for flexible generation units, e.g. at future local flexibility markets or redispatch offering, it is crucial to be capable of evaluating intraday opportunity costs realistically. The modelling of the deviation of continuous intraday price and intraday auction price with superimposed normal distribution functions that are dependent on the residual load leads to a realistic representation of possible intraday revenues.

These opportunity costs of the continuous intraday market added to the marginal costs of a power plant, consisting of fuel and carbon costs, lead to realistic marginal costs of the corresponding power plant and therefore an optimized evaluation of offering electricity at other markets. Our approach consequently promotes flexible assets to maximize their profit and even grid operators to evaluate realistic opportunity costs for power plants offering redispatch.

In the project C/sells, we use the average revenue forecasts for continuous intraday trading as opportunity costs for flexible power plants dispatching at a smart flexibility market. In further studies, offering at continuous intraday trading will be analyzed as a use case for electric vehicles that are able to charge bidirectionally. In addition to the analyzed quarter-hourly, average revenues for continuous intraday trading, in these studies we will also consider hourly continuous intraday trading.

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