The impact of varying system flexibility on market prices for electricity and balancing reserves

Hendrik Kondziella[a,*], Diana Böttger[a,b,**], Thomas Bruckner[a]
[a]Institute for Infrastructure and Resource Management (IIRM), Leipzig University, Leipzig, Germany
[b]Energy Economics and System Design, Fraunhofer Institute for Energy Economics and Energy System Technology IEE, Kassel, Germany

***Abstract*— The goal of this paper is twofold. At first, we provide a modeling framework to derive a consistent view on spot and balancing reserve markets. Secondly, we use this approach to determine the impact of increasing system flexibility via scenario analysis for day-ahead electricity and capacity reservation for balancing reserves, focusing particularly on the German electricity system for the year 2030. While fundamental modeling of spot market prices in the mid-term or long-term has been well established, it is quite ambitious to derive a consistent view on future balancing reserve markets. To achieve this goal, we use a two-step modeling approach to determine the equilibrium on both markets. Minimizing the opportunity costs for capacity reservation of the supply-side, we determine balancing reserve market bids that are consistent with spot market prices. The scenario analysis reveals a strong market position for battery storage regarding Frequency Containment Reserve (FCR) and positive automatic Frequency Restoration Reserve (aFRR). Due to the lower opportunity cost compared to fossil-fueled power plants, capacity prices for these market segments are diminished by battery storages.**

***Index Terms*-- Balancing reserves, Electricity market, Energy transition, Flexibility, Market prices**

I. INTRODUCTION

Against the background of the decarbonization of the energy sector to reach the climate protection targets there is a continuing debate on how much flexibility is required to cope with a significant share of variable renewable energy sources (RES) from wind and solar facilities, particularly for the electricity system. Several research and demonstration projects focus on displaying technical solutions to meet future needs on flexibility [1]. The business models behind the technical solutions are often based on energy sector coupling, e.g. electricity for heat or mobility purposes, often combined with an energy management system to adjust the energy service locally or temporarily along with supply from RES [2]. In order to determine the market-based flexibility demand, a consistent view on the financial revenue potential is essential for the evaluation of innovative business models in the energy sector. Since wholesale electricity markets typically include short-term trading opportunities, i.e. day-ahead and intraday, the corresponding volatility of the settlement price indicates the flexibility demand. Balancing reserve markets could offer additional revenues for the business models. Handling the price risk of two markets could become an issue for market participants. Moreover, modifying the market design by state regulation could deteriorate the business model.

Focusing on capacity prices for Frequency Containment Reserve (FCR) in Germany from January 2019 to May 2020, the arithmetic mean of the settlement price was 8.45 €/MW/h, ranging between 3.54 and 18.64 €/MW/h. Since July 2019, the product length has been reduced from an entire week to 24 hours to offer enhanced market access for flexibility providers. A comparison of the periods before and after the change in product design suggests a trend towards lower mean prices that reduces from 9.80 before to 7.72 €/MW/h after the regulative adjustment, but along with higher volatility (see Appendix, Figure 6).

In this paper, we provide an in-depth analysis of the development of the day-ahead market for electricity and the market for balancing reserves, focusing particularly on the German electricity system for the year 2030. Comparing two scenarios for the future market state, we isolate the effect of additional flexibility by several technology options on market prices. While fundamental modeling of spot market prices has been well established in recent years backed by the scientific community as well as consulting companies, it is still challenging to derive a consistent view on balancing reserve markets [3, 4]. To achieve this goal, we use a two-step modeling approach. At first, the equilibrium on the spot market is fixed by running the fundamental electricity market model *MICOES-Europe*[1]. In a second step, the spot market prices are fed into a second model aiming at detailed modeling of the balancing reserve market (*MICOES-Barometer*[2]). By calculating the opportunity costs for balancing capacity of single units of a provider´s portfolio, we determine balancing reserve market bids that are consistent with spot market prices.

Recently, several papers contributed to the topic with enhanced methods for electricity market modelling. To account

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* Corresponding author email address: kondziella@wifa.uni-leipzig.de
** https://orcid.org/0000-0002-9225-0271

[1] Mixed-Integer Cost Optimization of Electricity Systems for Europe

[2] Balancing Reserve Optimization and Metering

978-1-7281-6919-4/20/$31.00 ©2020 IEEE

for the probabilistic nature of the balancing reserve market, statistical methods are generally applied to explain the outcome of the bidding process. Reference [4] deploys approaches originating from econometrics and artificial intelligence and set up a forecasting framework based on auto-regressive and exogenous factors to forecast FCR prices. They identified the exogenous factors with most explanatory power as the price range of the previous auction, the future prices of the German-Austrian and the French market area, the load in the German-Austrian and the French market area and the planned unavailable capacity in Germany and France. In [5] a quantile regression model with natural cubic splines is proposed, which is back-tested with historical prices from the German secondary reserve market. Historical auction data from 2013 to 2018 serve for the regression to guarantee consistence in market design. Reference [6] analyzes the impact of voluntary bids as a design element for balancing reserve markets from a game-theoretical perspective and discuss interactions with other electricity market segments. As it is stated, the observed prices are above competitive levels, which leads to both permanent market design discussions and constant changes in the market design. They conclude that voluntary bids are suitable to realize market outcomes close to the Bayes-Nash-Equilibrium as they enable competition for the merit order positions for activation.

The econometric approaches discussed so far are appropriate for identifying explanatory variables of historic pricing schemes whereas mid-term to long-term price projections have not been covered by scientific literature to a similar extent. Moreover, statistical methods could hardly explain price effects due to structural changes, e.g. regarding the market design and substantial shifts of demand and supply curve. Thus, our approach aims to fill this gap by applying fundamental modeling. References [7, 8] follow comparable fundamental approaches for modeling balancing reserve markets. However, their research focus is more on costs, market concentration and bidding strategies than on future market prices. Moreover, we demonstrate the proof of concept with a scenario analysis for the year 2030 that deals with additional flexibility supply in the day-ahead and the balancing reserve market.

The remainder of the paper is structured as follows: in section II the applied models are presented qualitatively. We further elaborate on the assumptions for the case study in section III, which paves the way for the discussion of the results in section IV. Finally, section V encompasses the summary and conclusions.

II. METHODOLOGY

In this paper, we sequentially apply two fundamental power market models. In a first step, *MICOES-Europe* solves the unit commitment problem for the European power plant fleet. As a result, it determines the day-ahead electricity prices for each market zone. Moreover, the demand for balancing reserve capacity has also to be satisfied at this stage of the modeling procedure in a simplified way. The model output regarding the spot market prices of step one serves as major input for *MICOES-Barometer*. The second market model then calculates the opportunity costs per bidding pool for the provision of balancing reserves in Germany based on the foregone revenues compared to the pure spot market dispatch including potential start-up and shut-down costs [9]. The basic idea of this two-step modeling approach is shown in Figure 1. The subsequent subsections elaborate on both models and highlight the key features.

A. *MICOES-Europe*

The power market model *MICOES-Europe* is a fundamental unit commitment model with focus on European power markets. An extended documentation of the modelling concept with core equations is provided by [10–12]. Exemplary case studies that use the underlying mixed-integer optimization technique to project mid-term to long-term spot market prices are presented in [13–15]. For each hour of the projected years, the model identifies those power plants that meet the power demand and the demand for balancing power at minimal cost.

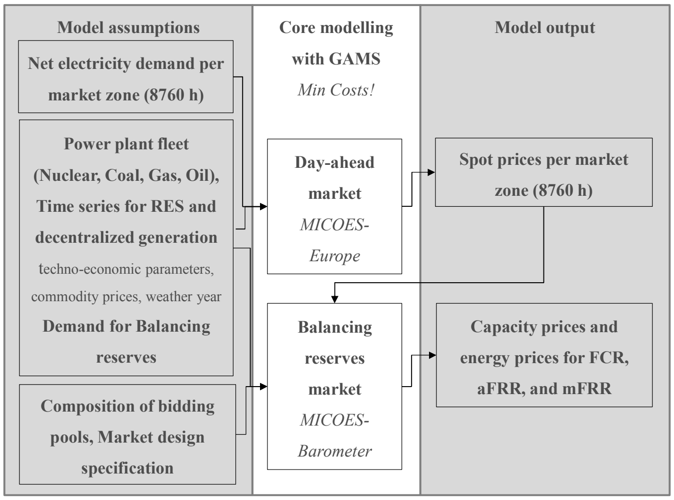

Figure 1: Sequential application of fundamental market models for the day-ahead market (*MICOES-Europe*) and the balancing reserve market (*MICOES-Barometer*).

The data pertaining to the hourly power demand of each country and the demand for balancing power serve as input for the model. In addition, a database containing the most important technical characteristics for power plants located in Europe is used. The power generation from variable RES is derived from synthetic time series for all countries related to the weather conditions of one reference year. We use weather data for the considered countries from [16]. In addition, the hourly electricity generation of heat-directed and decentralized co-generation plants is estimated as a function of ambient temperature, day-type, and hour, as well as the season. We consider the capacity of the interconnections according to net transfer values for the power transfer between the modeled twenty European market zones. To account for structural changes of electricity markets due to enhanced coupling of energy sectors and additional flexibility supply from technology innovation, we explicitly consider the additional electricity demand for heat pumps and electric cars. We apply the electricity demand profile from [17] for heat pumps and car usage profiles of [14] to figure out the additional hourly power consumption that adds to net electricity demand. By that approach, both technologies are assumed as price-inelastic consumers. However, bulk battery storage and demand-side management could provide additional flexibility endogenously. In addition, we assess the structural modification of the load profile from PV self-consumption of private households [18].

B. *MICOES-Barometer*

For the purpose of modeling the German balancing reserve market, we propose a fundamental modeling approach. The model considers individual pool operators who optimize their bids for offered capacity as well as capacity and energy prices for balancing reserves [19, 20]. Consequently, they can bid into the balancing reserve market and choose to distribute the capacity reservation among their plants. The balancing reserve market in *MICOES-Barometer* consists of three reserve types, namely frequency containment reserve (FCR), automatic and manual frequency restoration reserves (aFRR, mFRR)[3]. To account for modeling different market designs, the product length is a model parameter, which must be specified by the model user. Unlike most of the literature that deals with statistical approaches the central idea of the model is based on calculating opportunity cost as proxy for capacity prices for each of the balancing reserve types. In that way, the model compares the revenue streams for the operator when selling the entire portfolio on the spot market with a mixed strategy of bidding at spot and reserve markets. As a result, an incremental megawatt for balancing reserve implies foregone revenue at the spot market for the operator.

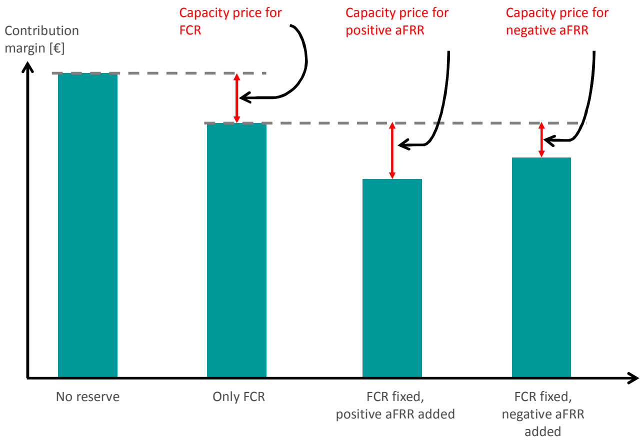

Figure 2: Schematic modeling approach to calculate opportunity cost as estimate for capacity prices in balancing reserve markets as fundamentally modeled in MICOES-Barometer

The optimization proceeds as follows: At first, power plant operators maximize their profits given the spot market prices as provided by the model *MICOES-Europe* (perfect foresight). Thus, the best-case solution represents the benchmark for calculating potential losses when offering FCR as symmetric product in a second step. Moreover, the entire bids for FCR must cover the given demand for FCR. Hence, the model chooses those pools that could offer FCR in the cheapest way. Finally, the financial loss divided by the product length and the capacity reservation gives the capacity price bids in Euro per Megawatt per hour. The accepted bids for FCR are than fixed for each pool owner for the rest of the product duration. The modelling procedure succeeds for aFRR in an equivalent manner. As before, the demand has to be covered from bids of all pools. However, the optimization considers both positive and negative reserve to get capacity prices for all aFRR products. Accepted bids are again fixed. Finally, capacity prices are calculated for mFRR analogously. Figure 2 summarizes this modeling approach.

It has to be noticed that pool operators have to guarantee a certain security level for their capacity reserve to comply with regulative prerequisites. Thus, the failure of the largest single unit might not affect the availability of reserve capacity (n-1 criterion). So far, we do not consider the n-1 criterion for the model. Furthermore, the bidding process does not include strategic behaviour of bidders, apart from rational choice.

III. CASE STUDY

We determine the energy economic framework for two scenarios for the year 2030 (see Table 1).

TABLE 1: SELECTED EXOGENOUS MODEL PARAMETERS THAT DETERMINE THE SCENARIO SPECIFICATION.

Selected key parameters	**Scenario 1**	**Scenario 2**
Model year	2030	
Weather year	2012	
RES capacity and fossil-fueled power plants in Germany	B2030 German Grid development plan [21]	
European RES capacity	TYNDP 2018 DG [22]	
European power plants	EU28: Reference scenario [23]	
Commodity prices	World Energy Outlook 2017: New Policies Scenario [24]	
Market penetration with additional technologies for energy sector coupling and flexibility	Heat pumps, electric cars, demand-side management, PV-battery systems, bulk battery storage, power-to-gas [21]	w/o additional technologies

The main assumptions for the German electricity market are based on the current national grid development plan [21] that represents a highly probable future state of the market environment due to its broad discussion by relevant stakeholders. For this scenario, the power plant fleet to be modeled endogenously for the unit commitment in *MICOES-Europe* encompasses about 50 GW of fossil-fueled power plants[4].

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[3] For the German market, the balancing reserve types are often referred to as primary, secondary, and tertiary reserve.

[4] The grid development plan consists of additional capacity declared as operated by industrial sites. We assume the exogenous scheduling of these units with constant operation.

Coal or gas fired power plants contribute almost equally to the installed capacity in the model[5]. Apart from that, ca. 72 % of these large units are operating in co-generation mode in 2030[6].

Additionally, the installed capacity of RES in Germany is projected with 203 GW, thereof nearly 100 GW originate from wind power plants and 91 GW of solar photovoltaics. Given the climate conditions of the year 2012, we derive feed-in profiles for RES (incl. supply from biomass, run-of-river, and geothermal facilities) that lead to an annual electricity generation of 391 TWh. Thus, a RES share of 65 % of gross electricity demand could be reached corresponding to the target of the German federal government [25].

The remaining power plant fleet outside the German market is modelled with an installed capacity of 473 GW [23], mostly contributing with natural gas (169 GW), hydro storage (133 GW), and nuclear power plants (104 GW)[7]. Net electricity demand for these market zones is assumed with 2,731 TWh, whereas the supply from RES amounts to 41 % (see also Appendix, Table 3). According to [24] commodity prices reflect the projections of the “New policies scenario”: European Union Emission Allowances prices are assumed to equal 29.4 €$_{2016}$/t, whereas fuel costs are given with 5.6 €$_{2016}$/MWh$_{th}$ for lignite, 8.4 €$_{2016}$/MWh$_{th}$ for hard coal, 26.4 €$_{2016}$/MWh$_{th}$ for natural gas, and 48.3 €$_{2016}$/MWh$_{th}$ for crude oil.

Beside the classical top-down approach of forming consistent demand-side scenarios for fundamental electricity market modeling, we present a way for the integration of so-called sector coupling and additional system flexibility. The net electricity demand is assumed to be 543.9 TWh in Germany Regarding the demand-side this includes electricity consumption for heating and mobility purposes in 2030.

For the German market zone, we consider 2.6 million heat pumps and six million electric vehicles, contributing with 18 TWh and 15 TWh, resp. [21]. This affects the hourly profile of net electricity demand as visualized for the weekly average in Figure 3. The peak demand raises by 5-8 GW in the morning and evening hours on average working days. Evidently, the effect is more pronounced in the winter term due to the prevailing heat demand. On the other hand, off-peak demand is also increasing by a minor extent with around 2 GW. We further elaborate on the quantitative effects of additional electricity demand for heat and mobility by modelling a scenario without this kind of sector coupling.

Beyond the flexibility that is typically provided by conventional power plants, pumped-hydro storage or the coupling of market zones, additional technologies are considered according to [21]. These comprise the market penetration with PV-battery-systems (8 GW), bulk battery storage (2 GW), demand-side management (DSM, 4 GW), and power-to-gas facilities (2 GW)[8].

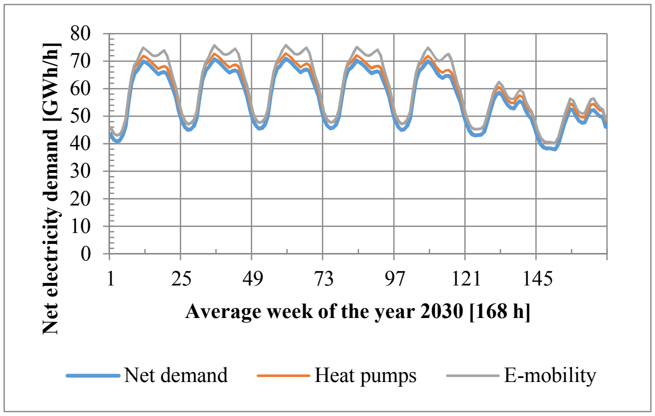

Figure 3: Impact of additional electricity demand from heating and mobility purposes on net electricity demand in Germany for the year 2030. For visualization purposes we show a weekly average of 8760 hours (one year).

Regarding the modelling of the balancing reserve market, further assumptions are required. According to [26] the total demand for FCR and FRR for Germany is 4,950 MW. We distribute that demand on the single products as follows: 600 MW for FCR, 2,175 MW for aFRR, and 2,175 MW for mFRR. This allocation corresponds approximately to the current state. The market design for the case study is proposed with symmetric four-hour products for FCR and asymmetric one-hour products for FRR. For the year 2030, we assume a pre-qualification for offering bids by conventional power plants, biomass plants, wind power plants, pumped-hydro storage plants, and bulk battery storages in *MICOES-Barometer.*

IV. RESULTS

In this section, we present the results of the model-based analysis for German market prices for electricity in 2030. Firstly, the price structure and its determinants for the day-ahead market are explicated. Secondly, we focus on the balancing reserve capacity prices.

A. Day-ahead spot market prices

As described in section III, scenario 1 includes additional electricity demand for heat and mobility as well as additional flexibility supply. To quantify the associated effect, we subsequently evaluate a model run without these drivers in scenario 2. The general view on the average price level for the German market zone reveals a range between 42.58 €/MWh (scenario 1) and 39.04 €/MWh (scenario 2). Figure 4 shows that 25 % of the hourly spot prices for the first scenario are lower than 27.31 €/MWh compared to 17.56 €/MWh for the second scenario. However, similar values are derived for the remaining quantiles[9]. These results suggest the overall effect of two determinants: the outward shift in demand amplifies the peak-

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[5] To give an estimate of the reduction of conventional power stations with respect to the selected primary energy sources the net capacity was 79 GW per end of 2016.

[6] The coal phase-out was not legally binding at the time of designing the scenarios. Nonetheless, the assumption on lignite capacity corresponds to the legal target for 2030 (9 GW).

[7] Specific power plant sites are determined by a former version of the Platts database enhanced by own desktop research.

[8] See Appendix, Figure 7, for exemplary scheduling of bulk battery storages and DSM in the model.

[9] Other European market zones show a wider range of spot market prices, especially in case of scarcity situations.

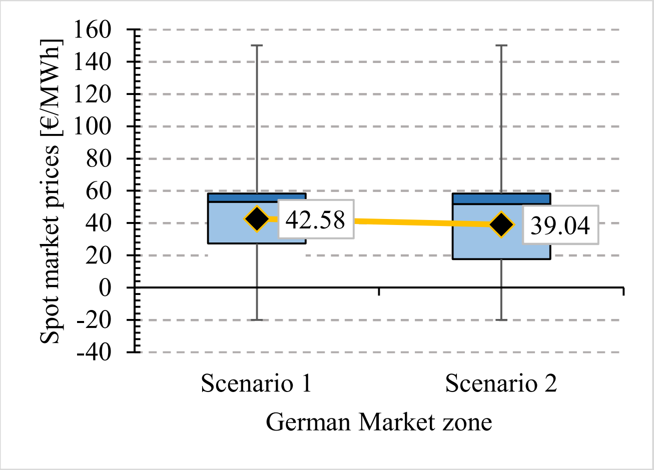

Figure 4: Modeling results – boxplot of projected day-ahead base price in Germany in 2030. The colored areas show the interquartile range, 25-50 % quantil (light blue) and the 50-75 % quantil (dark blue).

hours that drives wholesale prices up whereas the additional availability of flexibility in the market reduces the price spread. The price elasticity of the supply curve (merit order) then determines the aggregate of both factors. For the case of Germany, the price curve shows a stronger impact for off-peak hours (see Appendix, Figure 8) that reflects the stronger sensitivity for low-cost supply from RES and lignite power plants.

B. Balancing reserve prices

To be concise, we take one exemplary week of the model year 2030 to explain the effects on the balancing power market in more detail. Thus, we propose the results for one week at the end of March. Figure 5 depicts hourly values of the calculated capacity prices compared to the spot price curve for scenario 1. Evidently, the spike in FCR prices occur in parallel with the maximum spot price, which reflects the high opportunity costs for battery storage. Given scenario 2, the lower capacity of battery storage requires fossil-fueled plants to bid for FCR (see Appendix, Figure 9). These plants feature higher opportunity costs in comparison to battery storages in terms of short-run marginal costs. As a result, average FCR capacity prices are higher in the second scenario. Unlike the first scenario, marginal FCR prices peak corresponding to low spot prices, showing the opportunity costs of fossil units, which have to remain online for FCR provision. Conventional plants with high marginal cost could provide positive balancing reserve with low opportunity cost, in case of operation. Nevertheless, given their high marginal cost, operational hours are limited. For positive aFRR it is observable that capacity price peaks follow spot market price peaks in both scenarios. This is because opportunity costs of fossil plants are higher the higher the spot market prices are.

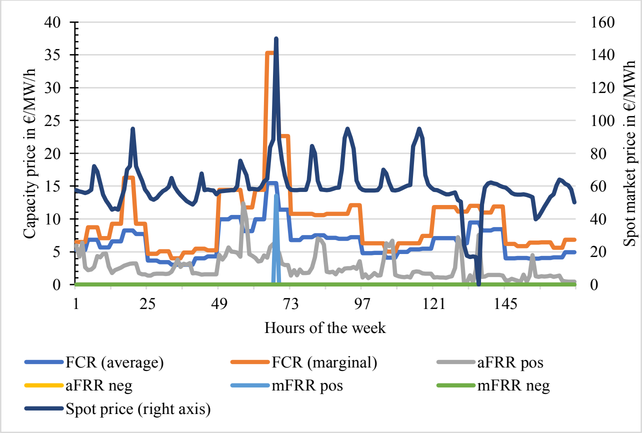

Figure 5: Modeling results - Capacity prices versus spot market prices for scenario 1 for an exemplary week at the end of March.

Table 2 summarizes the average volume-weighted capacity prices for FCR, aFRR and mFRR. For FCR also the marginal capacity price is presented according to the current market design with marginal pricing for FCR in contrast to FRR. The higher installed capacity of bulk battery storage in scenario 1 in comparison to the second scenario is able to offer comparably low-cost FCR (see also Appendix, Figure 10 and Figure 11 displaying the capacity reservation per technology type). Moreover, the spread between average and marginal capacity price is 3.33 €/MW/h in scenario 1. In scenario 2 this metric becomes remarkable (41.04 €/MW/h). The average capacity price for positive aFRR in scenario 1 is also lower in comparison to the second scenario. In contrast, the average capacity price for positive mFRR is almost negligible in both scenarios (0.08 €/MW/h). Concerning negative aFRR and mFRR capacity prices are also not specific to the scenario. Prices for negative FRR types are zero due to sufficient capacity provision from biomass, co-generation plants, and wind power plants. We assume that these technologies would bid without opportunity costs as they are in operation either for a given subsidy scheme. As these technologies are in operation due to exogenous conditions (weather, feed-in tariff), their capacity price bids equal zero. Nevertheless, energy price bids are non-negative.

TABLE 2: OVERVIEW OF AVERAGE CAPACITY PRICES IN EXEMPLARY WEEK

Capacity price in €/MW/h	**Scenario 1 with flexibility**	**Scenario 2 w/o flexibility**
FCR (average)	6.46	18.93
FCR (marginal)	9.77	59.97
aFRR positive	2.60	6.40
aFRR negative	0.00	0.00
mFRR positive	0.08	0.08
mFRR negative	0.00	0.00

Additionally, Figure 12 (in the Appendix) depicts exemplarily the merit order of all pool bids for FCR in scenario 1, given those time intervals with maximum and minimum spot market prices. It suggests that the capacity price bid curve depends on the level of the spot market price. Furthermore, one bid is accepted with 35.31 €/MW/h that leads to the highest capacity price in this week.

V. SUMMARY AND CONCLUSION

This research paper has investigated the effect of an increase in flexibility by distinct technology options joint by additional electricity demand for heating and mobility purposes on wholesale market prices for spot electricity and balancing reserve capacity for the year 2030. For the analysis of the simultaneous equilibrium conditions on both markets, we applied two fundamental market models. Thus, the equilibrium on the spot market covers also the demand for balancing reserve. Vice versa, the individual bids for balancing reserve are calculated recognizing the spot market prices. By that approach, we are able to manage alternative assumptions on key parameters describing the demand-side and the supply-side. Moreover, expectations on the future market design of the balancing reserve markets are covered. This accounts primarily for the duration the capacity must be reserved, i.e. the product length. For the day-ahead spot market in Germany, we expect a slight increase for the base price due to the additional demand. On the other hand, additional flexibility would smooth the price escalation by increasing electricity supply or a reduction in demand in peak hours whereas storage capacity is refilled or consumption has made up leeway in off-peak hours. As a result, the daily variance in day-ahead prices could be reduced primarily by utilizing electricity supply with comparatively low marginal costs, e.g. RES, raising off-peak prices significantly. The modeling of the balancing reserve market reveals a strong market position for battery storage regarding FCR and positive aFRR. Due to the lower opportunity cost compared to fossil-fueled power plants, capacity prices for these market segments are diminished by battery storages. Moreover, we expect hardly any reward for negative aFRR and mFRR while sufficient capacity is available from running co-generation units and wind power plants. The results are valid within a rational choice framework since the capacity prices are determined sequentially after clearing the spot market model-based. This approach is principally suited to explain the price effects in a competitive market environment. Furthermore, the price level reflects a lower bound for the pool operator when designing and submitting his bids. Clearly, historical market conditions that were characterized by fewer competition and complex product requirements could hardly be reproduced by the presented method. Further research should substantiate the findings by a wider range of the scenario assumption, in particular regarding commodity prices.

ACKNOWLEDGMENT

This research is part of the project "WindNODE" (03SIN540), funded by the German Federal Ministry of Economic Affairs and Energy. The authors gratefully acknowledge the support from Philipp Siegfried for supporting the data analysis.

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VII. APPENDIX

TABLE 3: CAPACITY OF CONVENTIONAL POWER PLANTS IN MEGAWATTS [MW] FOR THE EUROPEAN MARKET ZONES TO BE MODELLED ENDOGENEOULSY FOR THE UNIT COMMITMENT IN MICOES-EUROPE.

Market zone	**Installed capacity of conventional power plants [MW]**
Austria	17,859
Belgium	10,562
Switzerland	13,615
Czech Republic	15,388
DE	50,846
DKe	2,047
DKw	1,559
ES	55,908
FI	11,450
FR	88,809
GB	52,496
HU	7,414
IT	68,108
NL	17,269
NO	28,514
PL	30,762
PT	15,030
SE	27,609
SI	2,059
SO	6,682
Sum	**523,984**

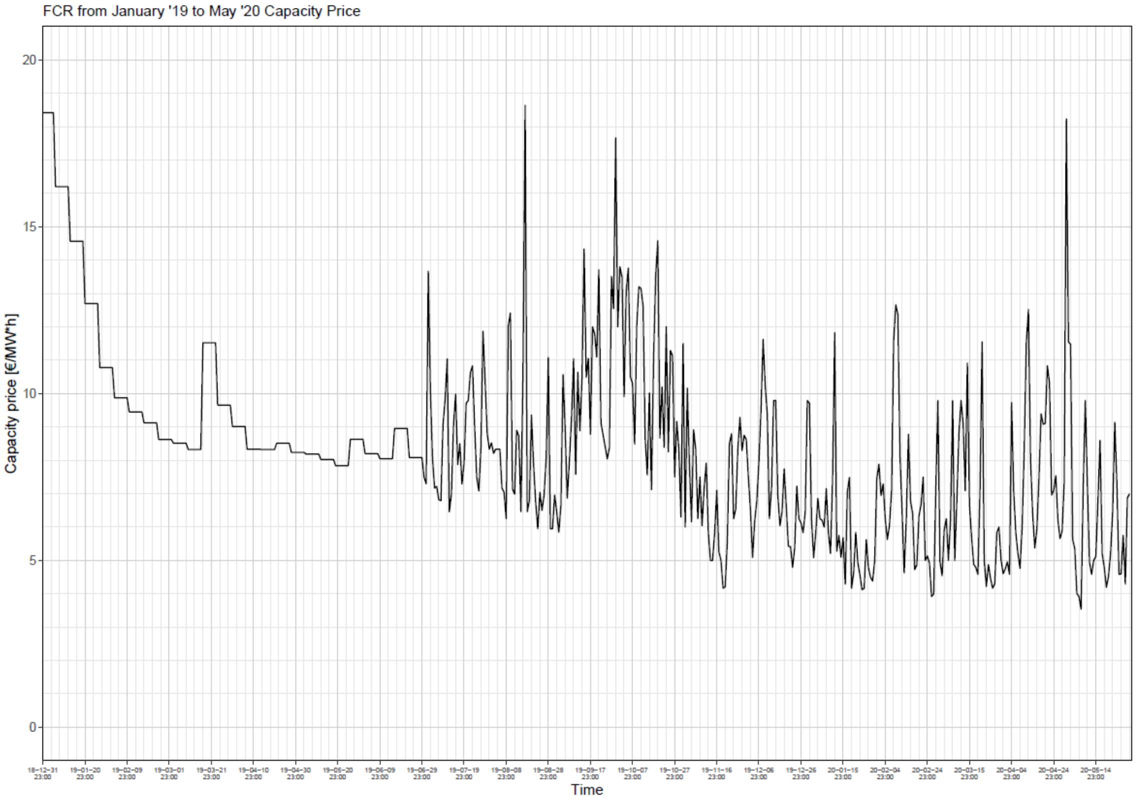

Figure 6: Capacity prices for Frequency Containment Reserve (FCR) as procured by German TSO from 01-2019 to 05-2020 (with data from regelleistung.net).

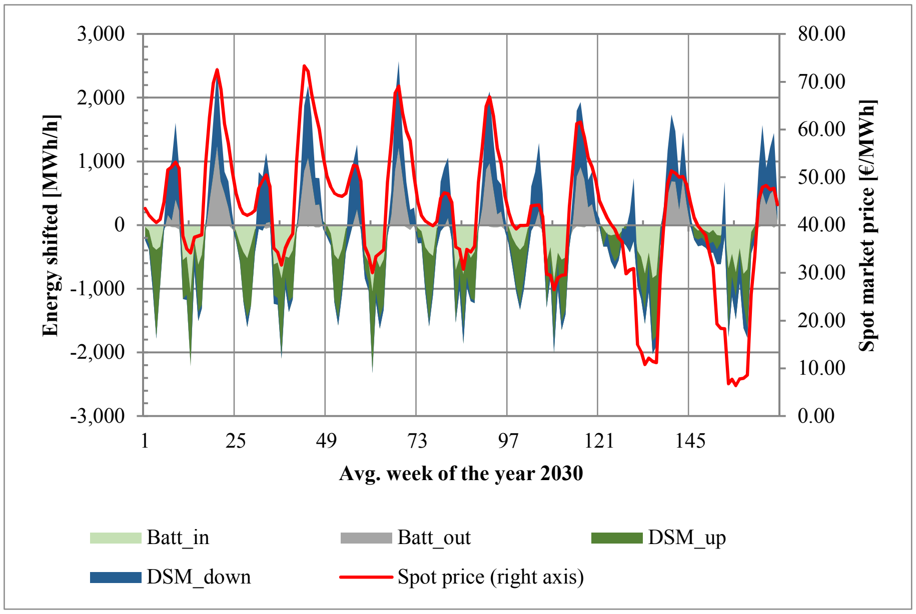

Figure 7: Flexibility supply of exemplary technologies in scenario 1.

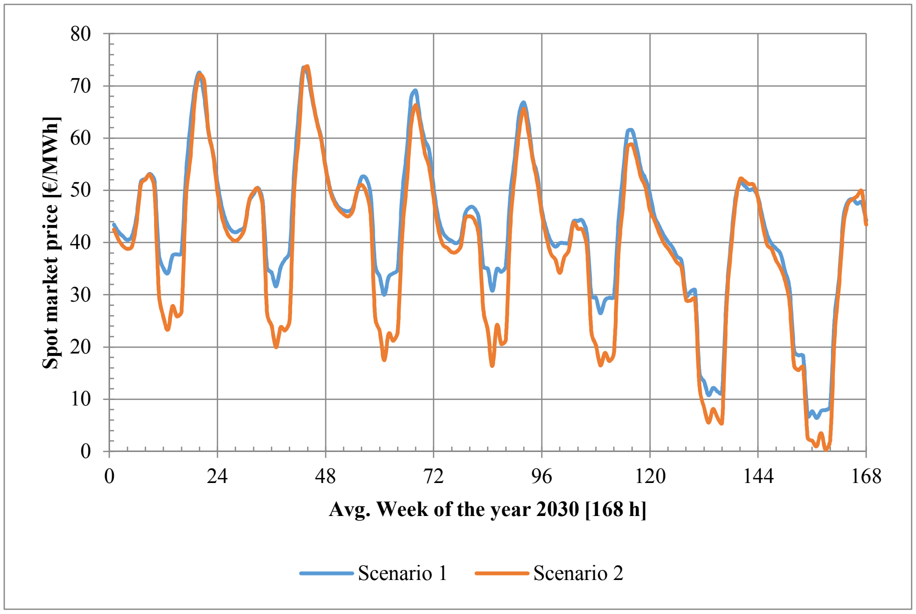

Figure 8: Day-ahead prices for the German market zone in 2030 – average week for scenario 1, and scenario 2 without additional demand for heat and mobility as well as flexibility supply.

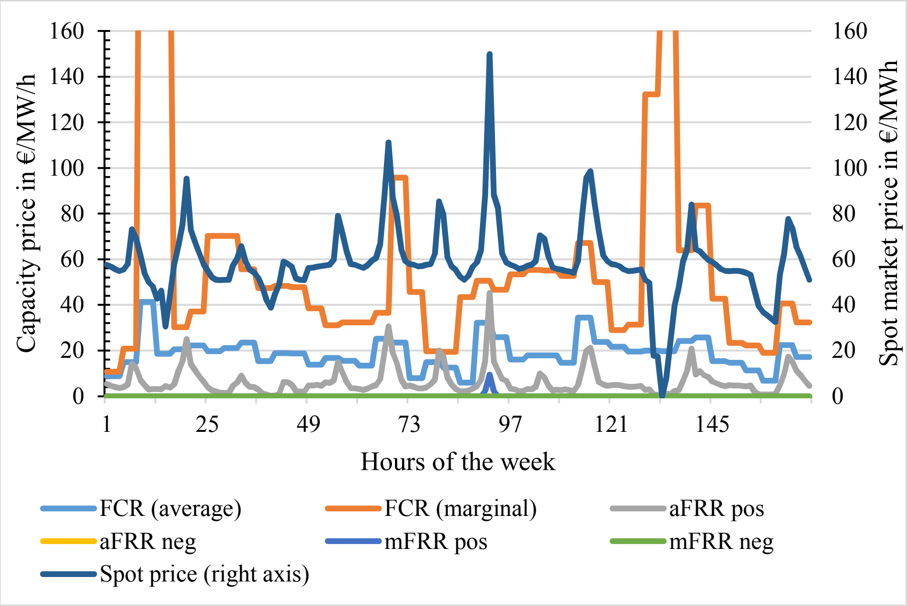

Figure 9: Capacity prices and spot market prices for scenario 2 showing a week at the end of March.

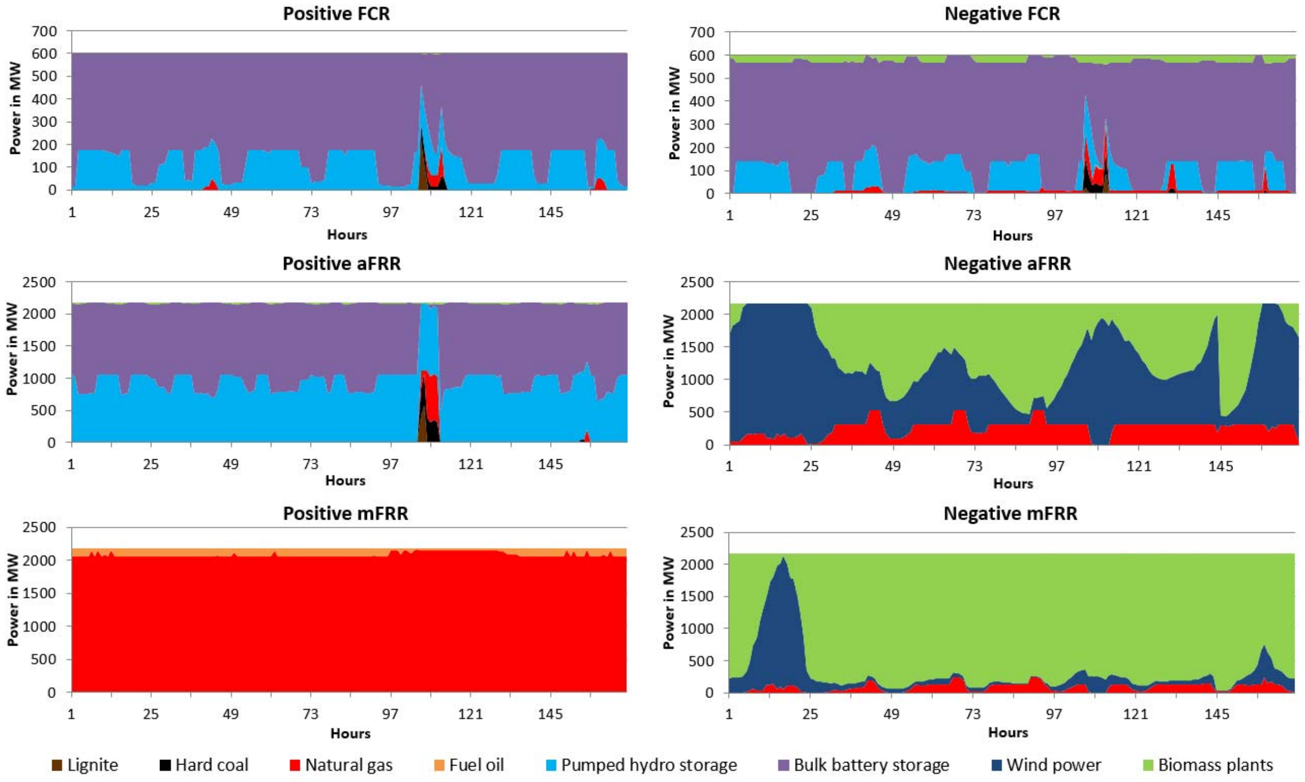

Figure 10: Hourly capacity reservation of different technologies for balancing reserve types for exemplary week in March 2030 for scenario 1.

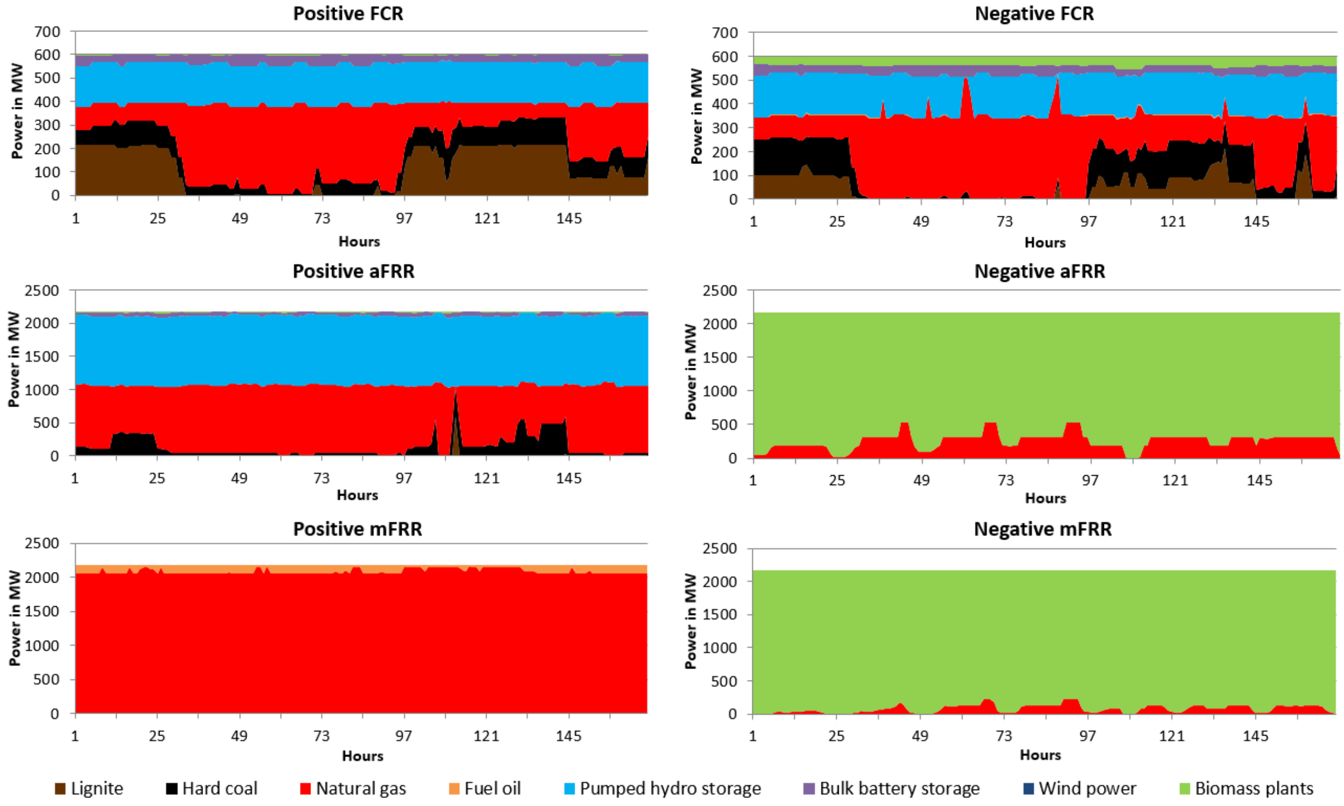

Figure 11: Hourly capacity reservation of different technologies for balancing reserve types for exemplary week in March 2030 for scenario 2.

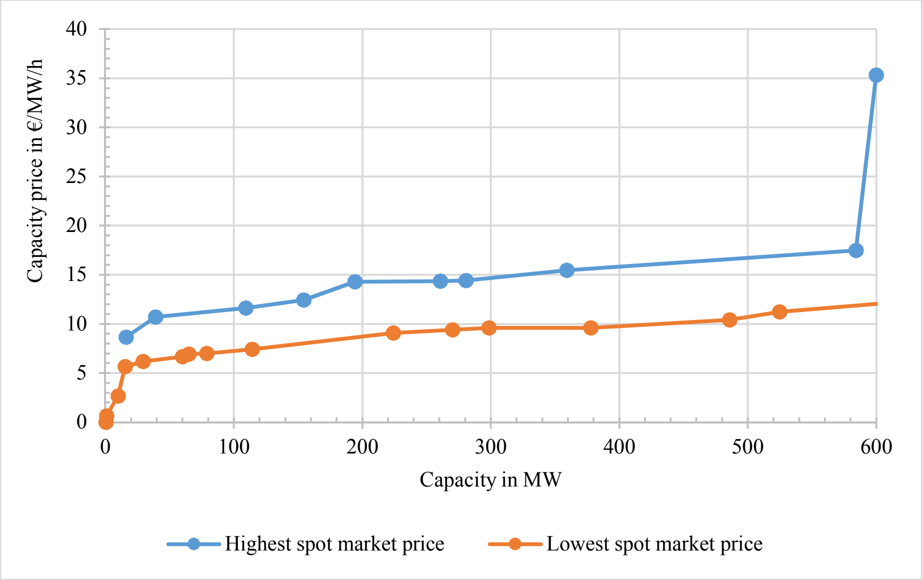

Figure 12: Merit order of all bids for FCR in scenario 1 for time interval with highest and lowest spot market prices.