

Ehrhart, Karl-Martin; Ocker, Fabian

Article — Published Version

Design and regulation of balancing power auctions: an integrated market model approach

Journal of Regulatory Economics

Provided in Cooperation with:

Springer Nature

Suggested Citation: Ehrhart, Karl-Martin; Ocker, Fabian (2021) : Design and regulation of balancing power auctions: an integrated market model approach, Journal of Regulatory Economics, ISSN 1573-0468, Springer US, New York, NY, Vol. 60, Iss. 1, pp. 55-73, <https://doi.org/10.1007/s11149-021-09430-7>

This Version is available at:

<https://hdl.handle.net/10419/287065>

Standard-Nutzungsbedingungen:

Die Dokumente auf EconStor dürfen zu eigenen wissenschaftlichen Zwecken und zum Privatgebrauch gespeichert und kopiert werden.

Sie dürfen die Dokumente nicht für öffentliche oder kommerzielle Zwecke vervielfältigen, öffentlich ausstellen, öffentlich zugänglich machen, vertreiben oder anderweitig nutzen.

Sofern die Verfasser die Dokumente unter Open-Content-Lizenzen (insbesondere CC-Lizenzen) zur Verfügung gestellt haben sollten, gelten abweichend von diesen Nutzungsbedingungen die in der dort genannten Lizenz gewährten Nutzungsrechte.

Terms of use:

Documents in EconStor may be saved and copied for your personal and scholarly purposes.

You are not to copy documents for public or commercial purposes, to exhibit the documents publicly, to make them publicly available on the internet, or to distribute or otherwise use the documents in public.

If the documents have been made available under an Open Content Licence (especially Creative Commons Licences), you may exercise further usage rights as specified in the indicated licence.



<https://creativecommons.org/licenses/by/4.0/>



Design and regulation of balancing power auctions: an integrated market model approach

Karl-Martin Ehrhart¹ · Fabian Ocker¹

Accepted: 1 June 2021 / Published online: 11 June 2021

© The Author(s) 2021

Abstract

We present an integrated market model which considers the dependencies between the wholesale market and the highly regulated balancing power markets. This fosters the understanding of the mechanisms of these markets and, thus, allows the evaluation of the designs of these markets and their interplay. In contrast to existing literature, in our model the prices on the different markets are interdependent and endogenously determined, which also applies to the switch from inframarginal suppliers to extra-marginal suppliers. Linked to this, the implementation of a specific assignment of the suppliers to the different markets is according to their production costs and their ability to provide balancing power. We prove the existence of a market equilibrium, analyze its outcome and contrast this with German market data. Based on this model, we assess design changes, partly stipulated by recent European regulation. This includes uniform pricing as a common settlement rule (effect: no truthful bidding in general), standardized prequalification criteria (promising measure for cost reduction), market flexibilization via “free energy bids” (no increased competition) and the alternative score “mixed-price rule” (no effect on the equilibrium).

Keywords Balancing power · Market design and interdependence · Scoring rule · Settlement rule

JEL Classification D2 · D4 · D5 · D6 · L1 · L5

✉ Fabian Ocker
fabian.ocker@googlemail.com

Karl-Martin Ehrhart
ehrhart@kit.edu

¹ Karlsruhe Institute of Technology (KIT), Germany, Neuer Zirkel 3, 76131 Karlsruhe, Germany

1 Introduction

To ensure a proper working of the electricity system, ancillary services are used. The most important short-term service is balancing power (henceforth abbreviated as *BP*, see Appendix¹): it balances demand and supply deviations in real-time. This ensures a stable grid frequency in alternating current grids. BP procurement is carried out by the system operator entity, e.g. transmission system operators (*TSO*) in Europe (ENTSO-E 2020). The mechanism on the BP markets are procurement auctions, i.e., prequalified suppliers compete for BP provision (Ocker et al. 2016).

Prequalified suppliers can act on different electricity markets (wholesale market and BP markets), and the suppliers, who provide BP, must run their plant at a minimal load and sell this electricity on the wholesale market. This causes interdependencies between the wholesale market and the BP markets (Just and Weber 2008). This is a major focus of our research. We provide a stylized integrated market model to identify and examine the characteristics of the different markets and their interdependencies. This approach does not only foster the understanding of the interdependent markets, but it also allows to examine and evaluate elements and changes of the market designs. Thus, our paper contributes to the field of electricity regulation.

In Europe, the “Electricity Balancing Guideline” states the framework conditions for a pan-European BP market with a harmonized structure (European Commission 2017a). This includes a harmonized settlement rule (uniform pricing) to incentivize truthful bidding and increase efficiency, and market flexibilization (“free energy bids”) to ease the integration of volatile renewable energy sources. With the same intention, the “System Operation Guideline” sets requirements for prequalification (European Commission 2017b). In addition, there were changes in the auction design stipulated by the regulatory authority “Bundesnetzagentur” in Germany. In 2018, the scoring rule (rule for winner determination) changed to the so-called “mixed-price rule,” aiming at BP cost reduction (Bundesnetzagentur 2018). While the intentions of these design changes are clear, so far, their effects on the interlinked wholesale and BP markets have not been assessed. We close this gap by applying our model to examine and evaluate these design changes.

The theoretical foundations for BP auction design are laid by Bushnell and Oren (1994) who analyze bidding strategies for different scoring rules and settlement rules. They derive conditions for efficient equilibria. Chao and Wilson (2002) show that a scoring rule consisting only of the capacity bid suffices the efficiency condition if incentive compatibility is imposed. The latter yields that suppliers energy bids reveal their variable cost, and energy bids are paid the wholesale market price. Müsgens et al. (2014) transfer this to the German BP markets. Here, the proposed scoring rule of Chao and Wilson (2002) is applied, but energy pricing is based on bids. They argue that a switch from pay-as-bid to uniform pricing ensures efficient activation. We relate to these contributions and present an equilibrium model for the wholesale and BP markets, considering different scoring and settlement rules.² The distinguishing

¹ The appendices are available in Ehrhart and Ocker (2021).

² The scoring rule proposed by Chao and Wilson (2002) is applied in many European countries (Ocker et al. 2016) and will be implemented in future harmonized European BP auctions (European Commission 2017a).

feature of our model is that we consider the dependencies between the markets endogenously: prices are not exogenously given, but the result of the interplay between the markets. In contrast, Müsgens et al. (2014) assume an exogenous wholesale market price, which yields two classes of suppliers: suppliers with production units which have variable cost below the wholesale market price (inframarginal), and suppliers with variable cost above the wholesale market price (extramarginal). This distinction is crucial for the cost of BP provision: inframarginals include opportunity costs of not trading at the wholesale market, extramarginals cover their expenses by BP profits. In our model, the market interplay induces a specific assignment of the suppliers to the different markets according to their production costs and their ability to provide BP. Thus, inframarginality and extramarginality are endogenously determined.³

Building on our market model, we prove the existence of an equilibrium and analyze its allocation, costs and prices. A central result is that all suppliers of negative BP are inframarginal, while in the positive market suppliers are inframarginal and extramarginal, depending on their production cost. We also consider empirical market data by comparing our theoretical results with German market results of 2015. Furthermore, we prove that lowering BP prequalification criteria is a promising means to reduce total costs. The mixed-price rule, however, does not impact the market equilibrium, although it may incentivize suppliers to change their bidding behavior. We also show that energy bids are not expected to foster competition, and that a switch of the settlement rule to uniform pricing does not incentivize truthful bidding in general.

The paper is structured as follows. Section 2 discusses related literature, Sect. 3 illustrates the electricity market design and Sect. 4 introduces our model. Section 5 presents equilibrium results, and Sect. 6 analyzes market design changes. Finally, Sect. 7 concludes.

2 Related literature

The first formalization of the economic conditions for BP markets is provided for California in the course of the electricity sector unbundling in the 1990s (e.g. Kirsch and Singh 1995; Borenstein et al. 1995; Kahn et al. 2001). Opportunity costs between markets, the effects of market power and of a change of the settlement rule are investigated. With focus on auction design, efficiency properties and incentive compatibility are examined, focusing on the scoring rule and equilibrium bidding strategies (e.g. Kamat and Oren 2002). There are several contributions dealing with regulatory aspects: increased renewables' penetration, information feedback schemes and further design variables, such as auction lead time and learning (e.g. Vandezande et al. 2010; Müsgens and Ockenfels 2011; Van der Veen and Hakvoort 2016; Borne et al. 2018; Doraszelski et al. 2018).

In Germany, there is an ongoing discussion on regulation and market imperfections since the liberalization of the auctions in 2002. Market entry barriers due to

³ Endogeneity is also incorporated in the model of Just and Weber (2008): BP suppliers cannot offer their entire capacity on the wholesale market, but have to run their units at a minimal load. However, the methodology for solving differs: Just and Weber (2008) apply a numerical solving procedure, whereas our model is solved analytically.

prequalification (Müller and Rammerstorfer 2008), dynamics of the reserve prices (Rammerstorfer and Wagner 2009) and strategic capacity withholding of suppliers with market power are assessed (Heim and Götz 2013). Recently, a number of market modifications were implemented, e.g. the aggregation of the four regional German BP markets to a single market and the shortening of the reservation period. Literature on BP auction design also widens, e.g. an examination of arbitrage opportunities between the wholesale market and the BP markets (Haucap et al. 2014; Just and Weber 2015; Ocker et al. 2018a). The massive subsidization of wind and solar generation yields to an investigation of renewables and the BP market. The “German Paradox” is presented: balancing reserves reduced by 15%, while wind and solar capacity tripled since 2008. The reasons are shorter intraday trading products and grid control cooperations (Hirth and Ziegenhagen 2015; Ocker et al. 2017).

3 Electricity markets

3.1 Electricity wholesale market

Electric energy (henceforth energy) is traded at forward markets and at spot markets (e.g. Ströbele 2013; KU Leuven Energy Institute 2015; Zweifel et al. 2017). At forward markets trading is more long-term, whereas at spot markets the point of delivery is instantaneous. Spot markets include a “day-ahead” and an “intraday” market. The day-ahead auction is considered as the central market place for electricity trading for the following day. On the contrary, intraday trading is done close to real-time and its main purpose is adjusting to changing circumstances, e.g. weather forecast or unplanned outages of units (Ocker et al. 2020).

3.2 Balancing power auctions

Traded volumes at the wholesale market usually differ from the actual production. The reason is that contracted volumes are based on predictions of supply and demand. A deviation which persists until real-time has a direct influence on the grid frequency in alternating current systems: if too much (little) energy is supplied, the grid frequency increases (decreases), which can lead to blackouts. To avoid this, system operators apply BP for stabilization (Zweifel et al. 2017).

Three different BP qualities can be distinguished: Primary BP (*PBP*), Secondary BP (*SBP*), and Tertiary BP (*TBP*) (e.g. ENTSO-E 2016).⁴ They differ in the reaction time.⁵ Each of the BP qualities comprises a separate procurement auction (Ocker et al. 2016). We focus on the weekly SBP and TBP auctions because they include the scoring rule proposed by Chao and Wilson (2002).

⁴ PBP is also referred to as “Frequency Containment Reserve (FCR)”, SBP as “automatic Frequency Restoration Reserve (aFRR)” and TBP as “manual Frequency Restoration Reserve (mFRR).” We refer to the German terms.

⁵ First, PBP is activated to limit deviations from the grid frequency, then SBP is utilized to restore frequency and, finally, TBP is activated as long-term measure. In Germany, PBP must be available after 30 s until 5 min, SBP after 5 min until 15 min, and TBP after 15 min until 60 min after an imbalance.

The deviation of the contracted production is separated in an overproduction (e.g. from wind plants during a storm) or an underproduction (e.g. from solar plants during a cloudy day). Thus, BP needs to provide an increased and decreased energy supply, which is implemented via two BP products: for the “positive product” (negative product) suppliers provide upward (downward) regulation (e.g. ENTSO-E 2016; Ocker et al. 2016). BP provision requires a prequalification, which leads to a highly invariant and limited supplier set.⁶ Suppliers encounter two types of cost: “capacity cost” for reserving balancing capacity [megawatt, MW], and “energy cost” for the delivery of balancing energy [megawatt hour, MWh]. In Germany, capacity costs are part of the grid tariff, whereas energy costs are accounted to the imbalanced party (see Sect. 3.3).

Suppliers submit three-dimensional bids: a capacity offer [MW], a capacity bid [Euro/MW], and an energy bid [Euro/MWh].⁷ Based on these bid information, scores of suppliers are calculated and those with the lowest scores are awarded. Until the regulatory intervention in 2018, the scoring rule in the German SBP and TBP markets was based on the capacity bid; then, it included also the energy bid (mixed-price rule). For settlement, pay-as-bid (*PaB*) pricing or uniform pricing (*UP*) is applied. If *PaB* is used, awarded suppliers are paid their submitted bids, if *UP* is used, all awarded suppliers are paid a uniform price. In the German SBP and TBP markets *PaB* is applied. Ultimately, the delivery of balancing energy is activated according to a merit-order of energy bids, i.e., suppliers with the lowest energy bids are utilized first and, thus, for the longest timespan.

3.3 Imbalance settlement scheme

BP procurement is the physical means to cope with imbalances. The financial settlement is done via the imbalance price. A market party’s difference between the contracted volumes and the actual physical position multiplied with the imbalance price gives her penalty payment in a certain timeframe (Koch and Hirth 2019). In Germany, the imbalance price is directly linked to the activated balancing energy bids. Thus, the German imbalance price can be interpreted as a levy for the balancing energy costs incurred to those responsible for activation (regelleistung.net 2021). To avoid the penalty payment, market parties can close open positions by trading short-term.

4 Stylized market model

4.1 Basic model

There are three energy markets: a wholesale market, a positive BP market and a negative BP market. We consider a certain period (e.g. year). The average demand on the wholesale market in this period is denoted by D and measured in gigawatt (GW).

⁶ For prequalification see regelleistung.net (2021) and for market concentration see Kaut et al. (2017).

⁷ This is the crucial difference to the German PBP market because here suppliers solely submit capacity bids.

The capacity demand on the positive and negative BP market is fixed and given by B^+ and B^- (with $B = B^+ + B^-$).

There is a set of energy suppliers, each with one power plant, which have the same capacity but differ in their variable energy production cost c between \underline{c} and \bar{c} . We assume that UP is implemented on all considered markets, which is the common settlement rule on the wholesale market and the planned rule for future European BP auctions (European Commission 2017a). Thus, all awarded suppliers receive the marginal price. On the BP markets, the uniform price for balancing energy is repeatedly determined within a pre-defined period of time – the “Balancing Energy Pricing Period” (BEPP). That is, uniform price for each BEPP is determined by the highest activated balancing energy bid within the BEPP. The application of UP allows to assume that the suppliers reveal their cost in their bids, which is the usual assumption for the wholesale market. For the BP markets, see Sect. 6.4. Thus, the supply function $S : [\underline{c}, \bar{c}] \rightarrow \mathbb{R}^+$ and its inverse $S^{-1} : \mathbb{R}^+ \rightarrow [\underline{c}, \bar{c}]$ are strictly increasing.

There are two different types of suppliers: BP-capable *BP suppliers* and non-BP-capable *nBP suppliers*. nBP suppliers only participate on the wholesale market, while BP suppliers can participate on the wholesale market and the BP markets. For the latter, they must run their plant on a minimal load (share of capacity) $m \in [0, 1)$ and sell this energy on the wholesale market. The total supply includes both the BP and the nBP suppliers: $S(c) = S_{BP}(c) + S_{nBP}(c)$, where $S_{BP} : [\underline{c}, \bar{c}] \rightarrow \mathbb{R}^+$ and $S_{nBP} : [\underline{c}, \bar{c}] \rightarrow \mathbb{R}^+$ denote the supply functions of BP and nBP suppliers. We assume that BP suppliers are uniformly distributed among all suppliers: at each cost level c , the BP suppliers’ share of the supply $S(c)$ is $\delta \in (0, 1]$ and the nBP suppliers’ share is $1 - \delta$.

Discrepancies between demand and supply are balanced by calling BP. The functions

$$\begin{aligned} z^- &: (0, B^-] \rightarrow [0, 1] \\ z^+ &: [0, B^+] \rightarrow [0, 1] \end{aligned} \tag{1}$$

describe the cumulated relative frequency of the differences between demand and supply in the period: $z^-(x)$ is the relative frequency of an excess supply of at least x GW and, thus, refers the call of negative balancing capacity of at least x GW. Analogously, $z^+(y)$ applies to an excess demand of at least y GW and, thus, to the call of positive BP.⁸ The z -functions (1) also describe the relative calling frequencies (abbrev.: rcf): $z^-(x)$ or $z^+(y)$ is the share of time within the period where a minimum of x negative or y positive balancing capacity is called, respectively. For example, the rcf in the German SBP market of 2015 is shown in Fig. 1. The interval $[-2000; 0]$ MW belongs to the negative market (note that the curve of z^- is shown reversely in the figure), while the interval $[0; 2000]$ MW belongs to the positive market. That is, $B^- = 2$ GW and $B^+ = 2$ GW.

The z -functions (1) are strictly decreasing with $z^-(B^-) = z^+(B^+) = 0$ and $z^-(x) + z^+(y) \leq 1$ for $x \in (0, B^-]$ and $y \in [0, B^+]$. The integrals

⁸ Discrepancies are only caused by production deviations, which can be justified by the increasing renewables share.

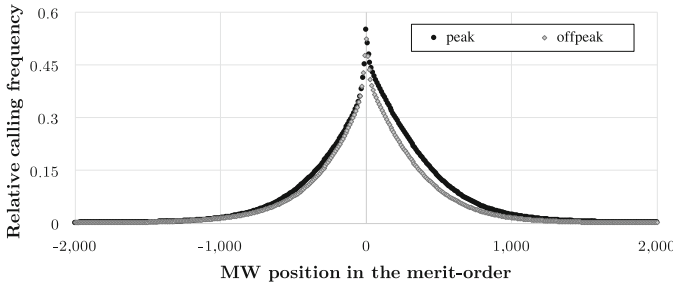


Fig. 1 Empirical functions for the rcf in the German positive (interval [0; 2000] MW) and negative (interval [-2000; 0] MW) SBP market (peak and offpeak period) (Hertz 2021)

$$\tilde{B}^- = \int_0^{B^-} z^-(x)dx \text{ and } \tilde{B}^+ = \int_0^{B^+} z^+(y)dy \tag{2}$$

are the expected total negative balancing capacity and the expected total positive balancing capacity that are needed to balance the excess supply and excess demand. Thus, $\gamma^- = \tilde{B}^-/B^-$ and $\gamma^+ = \tilde{B}^+/B^+$ are the fraction of provided negative balancing capacity and of positive balancing capacity, i.e., the fraction of the balancing capacities for the delivery of balancing energy demand (with $\tilde{B} = \tilde{B}^+ + \tilde{B}^-$). We call the BP markets symmetric if the difference between demand and supply on the wholesale market is symmetrically distributed, i.e., $B^- = B^+ = \frac{B}{2}$ and $z^-(x) = z^+(y)$ for $x = y$. In this case, $\tilde{B}^- = \tilde{B}^+$ and the average demand and average supply are equal.

Let c_0^+ (c_0^-) denote the lowest variable cost of all suppliers on the positive (negative) BP market and c_1^+ (c_1^-) the highest variable cost.⁹ The merit-order in the BP markets maps a supplier (according to her cost c) onto a merit-order position on the positive market by the bijective function $r^+ : [c_0^+, c_1^+] \rightarrow [0, B^+] =: R^+$ and on the negative market by $r^- : [c_0^-, c_1^-] \rightarrow [0, B^-] =: R^-$, with the derivatives $r_c^+(c) > 0$ and $r_c^-(c) < 0$. Each rank is assigned a rcf by the mappings $a^+ : R^+ \rightarrow [a_{min}^+, a_{max}^+]$ and $a^- : R^- \rightarrow [a_{min}^-, a_{max}^-]$, with the derivatives $a_r^+(r) < 0$ and $a_r^-(r) < 0$. The rcf determines the average share of time in which the supplier delivers BE. The values a_{max}^+ and a_{max}^- (a_{min}^+ and a_{min}^-) denote the highest (lowest) rcf in the two BP markets. The rcf are determined by the z -functions (1), where

$$\begin{aligned} a_{min}^+ &= z^+(B^+) = 0, & a_{max}^+ &= z^+(0) \in (0, 1), \\ a_{min}^- &= z^-(B^-) = 0, & a_{max}^- &= \lim_{x \downarrow 0} z^-(x) \in (0, 1), \\ a_{max}^+ + a_{max}^- &\leq 1. \end{aligned} \tag{3}$$

⁹ Any supply fluctuation requires BP activation and the costs are accounted to the suppliers. However, we do not account for these additional costs in the model because they reflect on average around 0.1% of the suppliers' variable cost (see Appendix, available in Ehrhart and Ocker 2021). Instead, we assume that all wholesale market suppliers deviate identically and dc denotes the average cost of balancing energy per MW for supply fluctuations ($c + dc$ represents the imputed variable cost).

On the wholesale market, suppliers constantly produce energy and are remunerated for each unit by the wholesale market price p_W . On the BP markets, suppliers receive the balancing capacity price p_{BC}^+ or p_{BC}^- , and, if they are called, additionally a balancing energy price $p_{BE}^+(c)$ or $p_{BE}^-(c)$. The balancing capacity prices p_{BC}^+ and p_{BC}^- are the same for all suppliers and are determined by the highest accepted capacity bid in the positive and the negative BP market, respectively. The balancing energy price $p_{BE}^+(c)$ ($p_{BE}^-(c)$) is determined by the associated costs of the highest merit-order position that is needed to cover the demand within the BEPP. Thus, the length of the BEPP influences a supplier's balancing energy prices: the longer the BEPP, the higher is the number of draws for balancing energy demand, and, thus, the higher (lower) are the cost of the last supplier on the positive (negative) market. We model the average supplier's balancing energy price in dependence of factor $\vartheta \in [0, 1]$ that corresponds to the length of the BEPP:

$$p_{BE}^+(c) = c(1 - \vartheta) + c_1^+ \vartheta, \quad (4)$$

$$p_{BE}^-(c) = -c(1 - \vartheta) - c_0^- \vartheta. \quad (5)$$

The case $\vartheta = 1$ models the longest possible BEPP, in which the balancing energy price p_{BE}^+ (p_{BE}^-) is always determined by the highest (lowest) supplier's cost c_1^+ (c_0^-).¹⁰ The smaller ϑ (i.e., the shorter the BEPP), the closer moves the supplier's average balancing energy price to her cost c .

Suppliers' profit per produced energy unit on the wholesale market π_W , on the positive BP market π_{BP}^+ , and on the negative BP market π_{BP}^- are given by¹¹

$$\pi_W(c) = p_W - c, \quad (6)$$

$$\pi_{BP}^+(c) = m(p_W - c) + (1 - m)[p_{BC}^+ + a^+(r^+(c))(p_{BE}^+(c) - c)], \quad (7)$$

$$\pi_{BP}^-(c) = (p_W - c) + (1 - m)[p_{BC}^- + a^-(r^-(c))(c + p_{BE}^-(c))]. \quad (8)$$

In the positive BP market, the suppliers' profit (7) consists of the profit from selling the minimal load on the wholesale market and the profit from providing BP, that is, balancing capacity and energy. In the negative BP market, suppliers are continuously paid the wholesale market price p_W for their entire capacity, although they may decrease the load level. The provision of negative BP has no impact on their trading on the wholesale market. The first part of (8) is the margin of selling the entire capacity at the wholesale market and the second part is the BP profit.

4.2 Efficient activation of balancing power

Within the interval $[\frac{B^-}{1-m}, \frac{B}{1-m}]$, which applies to the positive BP market, the rcf decreases from a_{max}^+ to $a_{min}^+ = 0$, and thus, the suppliers' active capacities decrease from $m + (1 - m)a_{max}^+$ to m . Due to the condition $a_{max}^- + a_{max}^+ \leq 1$, $1 - (1 - m)a_{max}^- \geq$

¹⁰ Note that suppliers submit negative energy bids in the negative market, see (8).

¹¹ The wholesale market price fluctuates and, thus, the supplier's profit, i.e., p_W and $\pi_W(c)$ are average values.

$m + (1 - m)a_{max}^+$ and, thus, the curve of active capacities is strictly decreasing within $[0, \frac{B}{1-m}]$. Applying the z -functions (1) together with (3), the curve of the BP suppliers' active capacities for providing energy for the BP markets and the wholesale market is given by the strictly decreasing function $j(q)$:

$$j(q) = \begin{cases} m + (1 - m) (1 - z^-(B^- - q(1 - m))) & : q \in [0, \frac{B^-}{1-m}) \\ m + (1 - m) z^+(q(1 - m) - B^-) & : q \in [\frac{B^-}{1-m}, \frac{B}{1-m}] \end{cases} \tag{9}$$

Using the maximum rcf a_{max}^+ leads to

$$j(q) = \begin{cases} 1 & : q = 0 \\ m + (1 - m) a_{max}^+ & : q = \frac{B^-}{(1-m)} \\ m & : q = \frac{B}{1-m} \end{cases} \tag{10}$$

The integral

$$J(m, B) = \int_0^{\frac{B}{1-m}} j(q) dq \tag{11}$$

is the average active capacity of all BP suppliers. With (2) we get

$$J(m, B) = \frac{B^-}{1 - m} - \tilde{B}^- + \frac{mB^+}{1 - m} + \tilde{B}^+ \tag{12}$$

The symmetric case is given by $j(\frac{B}{2(1-m)}) = \frac{1+m}{2}$, $j(\frac{B}{1-m} - q) = 1 + m - j(q)$ for $q \in [0, \frac{B}{2(1-m)}]$, and

$$J(m, B) = \frac{B(1 + m)}{2(1 - m)} \tag{13}$$

That is, in the symmetric case (see Fig. 2), $J(m, B)$ is independent of the shape of the j -curve. Since the asymmetry in the German markets is small (see Fig. 1 for the SBP market), we restrict the following analysis to the symmetric case.

An efficient allocation on the BP markets requires that suppliers with low variable cost have higher production volumes than those with high variable cost (see also Müsgens et al. 2014). From the j -function (10), illustrated by Fig. 2, the efficiency condition follows directly:

$$(A0) \text{ Rank of costs } c_0^- < c_1^- = c_0^+ < c_1^+$$

In the negative BP market, c_0^- belongs to the supplier on the last rank in the merit-order with $a_{min}^- = 0$. This supplier continuously produces with her entire capacity. The supplier with c_1^- has a rcf of a_{max}^- . This supplier operates with the load $m + (1 - a_{max}^-)(1 - m) < 1$. Thus, efficiency requires $c_0^- < c_1^-$. In the positive BP market, c_0^+ belongs to the supplier on the first rank in the merit-order with rcf a_{max}^+ . This supplier

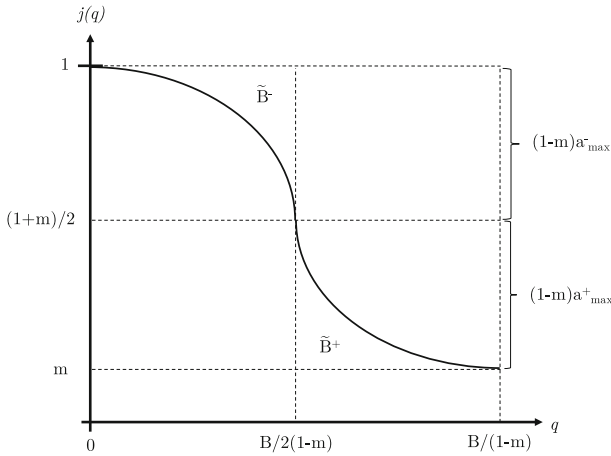


Fig. 2 Example of a j -function in a symmetric BP market

operates on the load level $m + a_{max}^+ (1 - m) \leq m + (1 - a_{max}^-) (1 - m)$ because of $a_{max}^+ + a_{max}^- \leq 1$. Thus, $c_1^- = c_0^+$. The supplier with c_1^+ is on the last rank of the merit-order and never provides BP, but runs the plant on the load level m on the wholesale market.

Since BP suppliers only use the share $1 - m$ of their capacities to provide BP, together they need the capacity $\frac{B}{1 - m}$ to cover B . To cover B^- , a total capacity of $\frac{B^-}{1 - m}$ is needed, which is provided by the BP suppliers with costs between c_0^- and c_1^- . The BP suppliers in the subsequent cost interval $[c_0^+, c_1^+]$ with $c_0^+ = c_1^-$ together provide $\frac{B^+}{1 - m}$ for covering B^+ . Hence, the interval $[c_0^-, c_1^+]$ corresponds to cumulated BP capacities in the interval $[0, \frac{B}{1 - m}]$, where $[c_0^-, c_1^-)$ corresponds to $[0, \frac{B^-}{1 - m})$ and $[c_0^+, c_1^+]$ to $[\frac{B^-}{1 - m}, \frac{B}{1 - m}]$. Within the interval $[0, \frac{B^-}{1 - m})$, the rcf increases from $a_{min}^- = 0$ to a_{max}^- . Thus, in the negative BP market, the suppliers' (expected) active capacities for providing energy for the BP markets and the wholesale market decrease from 1 to $1 - (1 - m)a_{max}^-$.

4.3 Stability and market clearing

BP suppliers either participate only in the wholesale market or simultaneously in a BP market and the wholesale market. For an allocation to be stable, the first and last position in the merit-orders are crucial. The supplier with c_0^- has to be indifferent between her last position in the merit-order of the negative BP market and a switch to the wholesale market. The supplier with c_1^+ must be indifferent between her last position in the merit-order of the positive BP market and not participating at all. The suppliers with c_1^- (c_0^+) has to be indifferent between a switch to the positive (negative) BP market. These requirements lead to the following conditions.

(M0)Between – market $(p_W - c_0^-) + (1 - m)p_{BC}^- \stackrel{!}{=} p_W - c_0^-$

(M1)Market – entrance $m(p_W - c_1^+) + (1 - m)p_{BC}^+ \stackrel{!}{=} 0$

(M2)BP – markets $(p_W - c_1^-) + (1 - m)(p_{BC}^- + a_{max}^-(c_1^- + p_{BE}^-(c)))$
 $\stackrel{!}{=} m(p_W - c_0^+) + (1 - m)(p_{BC}^+ + a_{max}^+(p_{BE}^+(c) - c_0^+))$

If one of these conditions is violated, either producing suppliers have an incentive to switch markets or non-producing suppliers have an incentive to enter the BP market.

Market clearing and energy balance require the following conditions:

- (S0) **Wholesale market** $D = S_{nBP}(p_W) + S_{BP}(c_1^-) + \frac{mB^+}{1-m}$
- (S1) **Positive BP market** $B^+ = (1 - m)(S_{BP}(c_1^+) - S_{BP}(c_0^+))$
- (S2) **Negative BP market** $B^- = (1 - m)(S_{BP}(c_1^-) - S_{BP}(c_0^-))$
- (S3) **Energy balance** $D - S_{nBP}(p_W) + S_{BP}(c_0^-) + \tilde{B}^- - \tilde{B}^+ + J(m, B) = 0$

Demand D on the wholesale market is met by the contracted supply, provided by nBP and BP suppliers. The supply $S_{nBP}(p_W)$ includes all nBP units with cost between \underline{c} and p_W . The supply of the BP units consists of $S_{BP}(c_1^-)$, i.e., the negative BP suppliers with cost between \underline{c} and c_1^- , and of $\frac{mB^+}{1-m}$, i.e., the positive BP suppliers with cost between c_0^+ and c_1^+ who only supply m . The demand for positive and negative balancing capacity is provided by the $(1 - m)$ th share of BP units within the interval $[c_0^+, c_1^+]$ and $[c_0^-, c_1^-]$ (S1, S2). Condition (S3) requires that total supply meets demand D also in case of deviations. Positive deviations \tilde{B}^+ and negative deviations \tilde{B}^- are balanced by the BP suppliers with cost between c_0^- and c_1^+ , whose active capacities are given by $J(m, B)$.

4.4 Total system costs

Total system costs C with a linear supply function $S(c) = \alpha c + \beta$, $\alpha \in \mathbb{R}^+$ and $\beta \in \mathbb{R}^+$, are

$$C = \int_{(1-\delta)\beta}^{D-q_{BP}-q_0} S_{nBP}^{-1}(q) dq + \int_{\delta\beta}^{q_0} S_{BP}^{-1}(q) dq + \int_0^{\frac{B}{1-m}} j(q) S_{BP}^{-1}(q + q_0) dq, \quad (14)$$

with $q_0 = S_{BP}(c_0^-)$ and $q_{BP} = J(m, B)$. Equation (14) gives the total costs for the wholesale market and the BP markets. The first integral are the costs of nBP suppliers in the interval $[0, D - q_{BP} - q_0]$, the second integral are the costs of BP suppliers in the interval $[0, q_0]$, and the third integral are the costs for the BP markets, given by the costs of BP suppliers in the interval $[q_0, q_0 + \frac{B}{1-m}]$ weighted with the average active capacity of function $j(q)$.

5 Market equilibrium and empirical results

5.1 Allocation, costs and prices

The propositions in this section are derived under (A0), (M0), (M1), (M2), (S0), (S1), (S2), (S3), symmetric BP markets, and a linear supply function $S(c) = \alpha c + \beta$, $\alpha, \beta \in \mathbb{R}^+$, and

$$S_{BP}(c) = \delta(\alpha c + \beta), \quad (15)$$

$$S_{nBP}(c) = (1 - \delta)(\alpha c + \beta). \quad (16)$$

Proposition 1 *There exists an equilibrium of the wholesale market and the BP markets with the following prices:*

1. Wholesale market price: $p_W = \frac{D - \beta}{\alpha} \leq m c_1^+ + (1 - m) c_0^+$
2. Balancing capacity price in the positive market: $p_{BC}^+ = \frac{m}{1 - m} (c_1^+ - p_W) = \frac{\frac{B}{2} \frac{m}{1 - m}}{\delta \alpha}$
3. Balancing capacity price in the negative market: $p_{BC}^- = 0$

See Appendix¹² for the proof. The wholesale market price p_W is determined by the inverse supply function at demand D . Condition $p_W \leq m c_1^+ + (1 - m) c_0^+$ ensures stability since a higher p_W induces suppliers of positive BP to switch into the wholesale market. The capacity price p_{BC}^+ in the positive BP market covers the wholesale market loss of the supplier with $c_1^+ > p_W$ caused by her costs of supplying the minimal load m and a rcf of zero. The capacity price p_{BC}^- is zero.

Proposition 2 *In the equilibrium of the wholesale market and both BP markets the following holds for c_0^- , c_1^+ , c_0^+ , and c_1^- :*

1. The cost c_0^- of the supplier on the last rank in the negative BP market is given by

$$c_0^- = \frac{D - \beta}{\alpha} - \frac{\frac{B}{2} \frac{1+m}{1-m}}{\delta \alpha} = p_W - \frac{\frac{B}{2} \frac{1+m}{1-m}}{\delta \alpha} < p_W.$$

2. The costs c_1^- and c_0^+ of the suppliers on the first rank in both BP markets are given by

$$c_1^- = c_0^+ = \frac{D - \beta}{\alpha} - \frac{\frac{B}{2} \frac{m}{1-m}}{\delta \alpha} = p_W - \frac{\frac{B}{2} \frac{m}{1-m}}{\delta \alpha} = p_W - p_{BC}^+ \leq p_W.$$

3. The cost c_1^+ of the supplier on the last rank in the positive BP market is given by

$$c_1^+ = \frac{D - \beta}{\alpha} + \frac{\frac{B}{2}}{\delta \alpha} = p_W + \frac{\frac{B}{2}}{\delta \alpha} > p_W.$$

See Appendix¹³ for the proof. Since the cost c_1^- of the last supplier of negative BP is determined by $p_W - p_{BC}^+$, $c_1^- \leq p_W$. Thus, all suppliers of negative BP are inframarginal. This also applies to the suppliers of positive BP with low cost, beginning

¹² The appendices are available in Ehrhart and Ocker (2021).

¹³ The appendices are available in Ehrhart and Ocker (2021).

with $c_0^+ = c_1^-$, while the suppliers with higher cost are extramarginal. According to Proposition 2 (2.), if the minimum load m converges to zero, the line between suppliers of negative BP and those of positive BP, given by c_1^- , converges to the line between inframarginals and extramarginals, given by p_W . That is, $c_1^- = c_0^+ = p_W$ for $m = 0$.

Proposition 3 *In the equilibrium of the wholesale market and both BP markets the following holds for the profits of the suppliers:*

1. $\pi_W(c)$ and $\pi_{BP}(c)$ decrease in c .
2. $\pi_W(c) \geq 0$ for $c \in [\underline{c}, p_W]$ and $\pi_{BP}(c) \geq 0$ for $c \in [c_0^-, c_1^+]$.
3. $\pi_W(c) \geq \pi_{BP}(c)$ for $c \in [\underline{c}, c_0^-]$ and $\pi_{BP}(c) \geq \pi_W(c)$ for $c \in [c_0^-, c_1^+]$.

See Appendix¹⁴ for the proof. On all markets, suppliers' profits are greater than zero and decrease with their variable cost. For low cost $c < c_0^-$ the profit is higher in the wholesale market than in the BP markets, while for higher cost $c > c_0^-$ it is the other way round.

Proposition 4 *The equilibrium of the wholesale market and both BP markets ensures overall market efficiency, i.e., it minimizes the total system costs C .*

See Appendix¹⁵ for the proof.¹⁶

5.2 Comparison with German market data

We calibrate our model to the German wholesale market and SBP markets in 2015.¹⁷ Details are provided in the Appendix¹⁸. Table 1 shows that total BP costs of 2013 (403 Mio. Euro) nearly halved in 2015 (205 Mio. Euro). Hence, costs move towards our model result of 137 Mio. Euro.¹⁹

Balancing capacity costs decreased from 345 Mio. Euro in 2013 to 141 Mio. Euro in 2015. Our model predicts costs of 123 Mio. Euro for 2015, which are accounted entirely to the positive market. In the negative market costs decreased around 80% since 2013 (from 202 Mio. Euro to 39 Mio. Euro) and move towards our prediction of 0 Mio. Euro. The development of the balancing energy costs is not uniform: they reduced by 8 Mio. Euro from 2013 to 2014 and then increased by 14 Mio. Euro from 2014 to 2015. Thus, there is a difference between the observed balancing energy costs and our model prediction of 50 Mio. Euro in 2015.²⁰ We discuss this in Sect. 6.3.

¹⁴ The appendices are available in Ehrhart and Ocker (2021).

¹⁵ The appendices are available in Ehrhart and Ocker (2021).

¹⁶ Note that in case of asymmetric BP markets or a non-linear supply function, efficiency is not guaranteed.

¹⁷ We focus on the SBP market because it has a higher demand than the TBP market and, thus, is regarded as the most important BP quality (e.g. Borne et al. 2018). We consider the market of 2015 because since July 2016 the Austrian and German TSOs procure a common SBP merit-order, i.e., activation is linked within the two countries. Note that the conclusions drawn for the SBP market can be transferred to the TBP market because they share the same market design and have similar market characteristics (see Sect. 3.2).

¹⁸ The appendices are available in Ehrhart and Ocker (2021).

¹⁹ Note that balancing capacity demand remained nearly constant since 2013, while balancing energy demand declined continuously since 2013 (Bundesnetzagentur 2016a, b, 2017).

²⁰ It is noted that our predicted balancing energy costs are a lower bound in our model (see Appendix, available in Ehrhart and Ocker 2021).

Table 1 Empirical and model results for the German SBP market with unit Mio. Euro

Cost parameter	Observed 2013	Observed 2014	Observed 2015	Model 2015
Balancing capacity costs	345	210	141	123
Positive market	143	132	102	123
Negative market	202	78	39	0
Balancing energy costs	58	50	64	14
Positive market	95	65	72	40
Negative market	-37	-15	-8	-26
Total BP costs	403	260	205	137

6 Market design changes

We analyze four relevant and topical design changes. These were either already introduced (lowering BP prequalification criteria, free energy bids) or already withdrawn (mixed-price rule) or will be implemented in the near future (uniform pricing) by the regulator.

6.1 Lowering balancing power prequalification criteria

First, we consider the measure of increasing the set of BP suppliers by lowering prequalification criteria (e.g. [regelleistung.net 2021](#)). An increasing share of prequalified BP suppliers δ has the following effects: By Proposition 1, p_{BC}^+ decreases, while p_W and p_{BC}^- do not change. By Proposition 2, the interval $[c_0^-, c_1^+]$ becomes smaller because c_0^- increases and c_1^+ decreases. The reduction of the interval length is caused by a higher density of BP suppliers. More precisely, the difference between $p_W = \frac{D-\beta}{\alpha}$ and c_0^- , between p_W and $c_1^+ = c_0^+$, and between c_1^+ and p_W decreases.

Proposition 5 *The total costs (14) decrease in δ .*

The proof is in the Appendix²¹. This result recommends to lower prequalification criteria.

6.2 Free energy bids

The European Commission (2017a) foresees so-called “free energy bids:” BP suppliers can submit only energy bids close to real-time (i.e., no capacity payment), if they did not participate or were not awarded in the regular (capacity bid) auction. In Germany, free energy bids were introduced on November, 03, 2020. The rationale is to increase competition and, thus, to reduce costs for BP activation (German TSOs 2020). However, our analysis does not support this hypothesis.

²¹ The appendices are available in Ehrhart and Ocker (2021).

Proposition 6 *The extension of our model by allowing suppliers, who were not allocated on a BP market, to submit free energy bids does not change the equilibrium results in Sect. 5.1.*

The proof is in the Appendix²². The reason is that it is not profitable for suppliers to enter the BP markets or to switch between the BP markets with free energy bids. This results is supported by the market outcome in Germany: nearly no additional free energy bids are submitted and an increase in liquidity since November is not observed (Bundesnetzagentur 2020).

6.3 Switch of the scoring rule: the mixed-price rule

In Germany, the trend of increasing energy bids, particularly in 2018, caused very high imbalance prices. As a reaction, the German regulator decided to change the scoring rule to the so-called “mixed price rule” in late 2018 (Bundesnetzagentur 2018). While the prior score was determined only by the capacity bid b_{BC} (see Sect. 3.2), the mixed price score b is determined by a combination of b_{BC} and the energy bid b_{BE} : $b = b_{BC} + \varrho b_{BE}$ with $\varrho > 0$. The rationale behind this modification was to incentivize a changed bidding behavior to prevent extreme energy bids. However, the mixed-price rule has no effect on the equilibrium in our model.

Proposition 7 *The equilibrium results in Sect. 5.1 also hold under the mixed-price rule.*

See Appendix²³ for the proof.

Yet, market results changed because some suppliers submitted lower energy bids and higher capacity bids (regelleistung.net 2021). Transferred to our model, where $*$ denotes the equilibrium bids under the prior scoring rule and mp under the mixed price rule, this means

$$b_{BC}^{mp} > b_{BC}^* \quad \text{and} \quad b_{BE}^{mp} < b_{BE}^*. \quad (17)$$

In the Appendix²⁴ we show by means of a micro-economic model that the mixed-price rule generates incentives for (17), if the suppliers think “myopically” and do not adapt their beliefs about their opponents’ bidding behavior to the new rule. However, in our model in Sect. 4, these changed bids cannot establish an equilibrium because, for example, higher capacity bids lead to higher capacity payments, which violates Condition (M1). We therefore expected that these changes would have disappeared in the course of time. Before this could have happened, after some months the regulator returned to the prior scoring rule because of a drawback of the new rule: high and frequent imbalances occurred as a result of low imbalance prices (see Sect. 3.3),

²² The appendices are available in Ehrhart and Ocker (2021).

²³ The appendices are available in Ehrhart and Ocker (2021).

²⁴ The appendices are available in Ehrhart and Ocker (2021).

which did not incentivize market parties to close open positions (Higher Regional Court Düsseldorf 2019).²⁵

6.4 Switch of the settlement rule: uniform pricing

The European Commission (2017a) further foresees UP because it should induce suppliers to report their true costs in their bids (e.g. Müsgens et al. 2014).²⁶ However, we do not attribute this property to UP. Only for a specific ϑ a bidder with cost c is incentivized to truthfully reveal her cost. Hence, incentive compatibility does not apply in general.

Proposition 8 *A supplier's optimal energy bid b_{BE}^* depends positively on her cost c and negatively on the length ϑ of the BEPP. For the positive [negative] BP market the following applies: (i) $\vartheta = 0$: $b_{BE}^* > c[-c]$, (ii) $\vartheta = 1$: $b_{BE}^* < c[-c]$, (iii) there exists a $\vartheta \in (0, 1)$: $b_{BE}^* = c[-c]$.*

See Appendix²⁷ for the proof. We provide an intuitive explanation. The time a supplier delivers balancing energy depends on her merit-order position. Hence, the length of the BEPP has an impact on the suppliers' bidding strategy. The longer the BEPP, the more bids are taken into account for the determination of the price. This induces suppliers to reduce their energy bids, even below their costs, for the sake of a better merit-order position (Ocker et al. 2018a, b). In our model, the case $\vartheta = 1$ corresponds to UP for only one BEPP, and the case $\vartheta \in (0, 1)$ to UP for several BEPPs. Assuming that the last accepted bid determines the uniform price, a short BEPP increases the probability that a bidder's own bid sets the price. Thus, $\vartheta = 0$ corresponds to PaB and suppliers have an incentive to exaggerate their costs in their bids. Note that the ϑ that induces $b_{BE}^* = c[-c]$ depends on c . Generally, a unique ϑ that induces truthful bidding to all suppliers does not exist. However, since the differences between the incentive-compatible ϑ are expected to be small, we take the freedom and assume truthful bidding in our model.

In practice, we doubt that suppliers understate their costs in their bids in case of a long BEPP. Moreover, UP may also be prone to manipulation by large suppliers submitting multiple bids, which is not captured by our model. These suppliers have an incentive to exaggerate some of their bids or even reduce their offered capacity to increase the bid that determines the uniform price and, thus, to increase their payment and profit (Haufe and Ehrhart 2018).

²⁵ The intraday market prices were around 500 Euro/MWh and imbalance prices around 100 Euro/MWh. This resulted in an undersupply of balancing capacity of nearly 10 GW, which could not be met by the contracted SBP and TBP volumes of 3 GW. As a relieving measure, German TSOs procured additional balancing capacities, which caused capacity bid prices of over 37,000 Euro/MW (German TSOs 2019).

²⁶ In Germany, UP will be introduced at the end of 2021 (regelleistung.net, 2021).

²⁷ The appendices are available in Ehrhart and Ocker (2021).

7 Conclusion

We present an integrated market model which considers the dependencies between the wholesale and BP markets. We prove the existence of a market equilibrium, analyze its outcome and contrast this with German market data. Moreover, we show that the mixed-price rule does not impact the market equilibrium but may incentivize suppliers to change their bidding behavior in an undesirable way. Free energy bids do not foster competition, and a switch to UP does not lead to truthful bidding in general. Lowering BP prequalification criteria is a promising means to reduce costs.

Section 6.3 illustrated that if the imbalance price is too low, there are insufficient incentives to close open positions. As a reaction, German TSOs changed the imbalance scheme: the imbalance price is now linked to the intraday market price, in accordance with the European target design (ACER 2021). In case of an electricity undersupply (oversupply) and the necessity for positive (negative) BP, the imbalance price will be at least as high (low) as a certain intraday index. This sets the right incentives: BP activation is more costly than self-balancing in the intraday market.

Some of our assumptions may be relaxed in an extended model: the linear supply, the same share of BP production units in the supply, or the homogeneous must-run capacities for all units. Further extensions may include suppliers with multiple plants and those with market power. Finally, experimental studies may help to test and foster our theoretical findings.

Acknowledgements We thank Jörg Rosenberg for the technical support in terms of data collection.

Funding Open Access funding enabled and organized by Projekt DEAL.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- 50Hertz. (2021). Regelenegie Downloadbereich. Retrieved March 26, 2021, from <https://www.50hertz.com/de/Markt/Regelenegie>.
- ACER. (2020). Public consultation on harmonising the imbalance settlement. Retrieved March 26, 2021, from https://acer.europa.eu/Official_documents/Public_consultations/Pages/PC_2020_E_07.aspx.
- Borenstein, S., Bushnell, J., Kahn, E., & Stoft, S. (1995). Market power in California electricity markets. *Utilities Policy*, 3(4), 219–236.

- Borne, O., Korte, K., Perez, Y., Petit, M., & Purkus, A. (2018). Barriers to entry in frequency-regulation services markets: Review of the status quo and options for improvements. *Renewable and Sustainable Energy Reviews*, *81*, 605–614.
- Bundesnetzagentur. (2016a). Kraftwerksliste Bundesnetzagentur (bundesweit; alle Netz- und Umspannebenen)—Stand 10.05.2016. Retrieved March 26, 2021, from https://www.bundesnetzagentur.de/DE/Sachgebiete/ElektrizitaetundGas/Unternehmen_Institutionen/Versorgungssicherheit/Erzeugungskapazitaeten/Kraftwerksliste-kraftwerksliste-node.html.
- Bundesnetzagentur. (2016b). Monitoringbericht 2015. Retrieved March 26, 2021, from https://www.bundesnetzagentur.de/SharedDocs/Downloads/DE/Allgemeines/Bundesnetzagentur/Publikationen/Berichte/2015/Monitoringbericht_2015_BA.pdf;jsessionid=1CFAAB5566000E812220C7431B6EFE8C?__blob=publicationFile&v=4.
- Bundesnetzagentur. (2017). Monitoringbericht 2016. Retrieved March 26, 2021, from https://www.bundesnetzagentur.de/SharedDocs/Mediathek/Monitoringberichte/Monitoringbericht2016.pdf?__blob=publicationFile&v=2.
- Bundesnetzagentur. (2018). Festlegungsverfahren zur Änderung der Ausschreibungsbedingungen und Veröffentlichungspflichten für Sekundärregelung und Minutenreserve. Retrieved March 26, 2021, from https://www.bundesnetzagentur.de/DE/Beschlusskammern/1_GZ/BK6-GZ/2018/BK6-18-019/BK6-18-019_Konsultation_zuschlagsmechanismus.pdf?__blob=publicationFile&v=2.
- Bundesnetzagentur. (2020). Beschluss zur Änderung der Modalitäten für Regelreserveanbieter, Az.: BK6-20-370. Retrieved March 26, 2021, from https://www.bundesnetzagentur.de/DE/Beschlusskammern/1_GZ/BK6-GZ/2020/BK6-20-370/BK6-20-370_Beschluss_vom_16.12.2020.pdf?__blob=publicationFile&v=1.
- Bushnell, J. B., & Oren, S. S. (1994). Bidder cost revelation in electric power auctions. *Journal of Regulatory Economics*, *6*, 5–26.
- Chao, H. P., & Wilson, R. (2002). Multi-dimensional procurement auctions for power reserves: Robust incentive-compatible scoring and settlement rules. *Journal of Regulatory Economics*, *22*, 161–183.
- Doraszelski, U., Lewis, G., & Pakes, A. (2018). Just starting out: Learning and equilibrium in a new market. *American Economic Review*, *108*, 565–615.
- Ehrhart, K.M. & Ocker, F. (2021). Design and regulation of balancing power auctions—an integrated market model approach. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3852495.
- ENTSO-E. (2016). Survey on ancillary services procurement and electricity balancing market design. Retrieved March 26, 2021, from <https://www.entsoe.eu/publications/market-reports/ancillary-services-survey/Pages/default.aspx>.
- ENTSO-E. (2020). Entso-e member companies. Retrieved March 26, 2021, from <https://www.entsoe.eu/about/inside-entsoe/members/>.
- European Commission. (2017a). Electricity balancing guideline. Commission Regulation (EU) 2017/2195 of 23 November 2017 establishing a guideline on electricity balancing. Retrieved March 26, 2021, from <http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32017R2195>.
- European Commission. (2017b). System operation guideline. Commission Regulation (EU) 2017/1485 establishing a guideline on electricity transmission system operation. Retrieved March 26, 2021, from <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=LEGISSUM%3A4309265>.
- German TSOs. (2019). Untersuchung von Systembilanzungleichgewichten in Deutschland im Juni 2019. Retrieved March 26, 2021, from https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&ved=2ahUKEwj_m4ug3IXpAhWisaQKHS72AwEQFjAAegQIBBAB&url=https%3A%2F%2Fwww.regelleistung.net%2Fext%2Fdownload%2FSTUDIE_JUNI2019&usg=AOvVawIjp4Mg28YrOa-m13A7rmR.
- German TSOs. (2020). Regelarbeitsmarkt in Deutschland startet. Retrieved March 26, 2021, from <https://www.50hertz.com/de/News/Details/id/7178/regelarbeitsmarkt-in-deutschland-startet>.
- Haucap, J., Heimeshoff, U., & Jovanovic, D. (2014). Competition in Germany's minute reserve power market: An econometric analysis. *The Energy Journal*, *35*, 137–156.
- Haufe, M. C., & Ehrhart, K. M. (2018). Auctions for renewable energy support—Suitability, design, and first lessons learned. *Energy Policy*, *121*, 217–224.
- Heim, S., & Götz, G. (2013). Do pay-as-bid auctions favor collusion? Evidence from Germany's market for reserve power. ZEW—Centre for European Economic Research Discussion Paper No. 35.
- Higher Regional Court Düsseldorf. (2019). Beschluss vom 22.07.2019—3 kart 806/18 (v). Retrieved March 26, 2021, from <https://openjur.de/u/2179540.html>.

- Hirth, L., & Ziegenhagen, I. (2015). Balancing power and variable renewables: Three links. *Renewable and Sustainable Energy Reviews*, *50*, 1035–1051.
- Just, S., & Weber, C. (2008). Pricing of reserves: Valuing system reserve capacity against spot prices in electricity markets. *Energy Economics*, *30*, 3198–3221.
- Just, S., & Weber, C. (2015). Strategic behavior in the German balancing energy mechanism: Incentives, evidence, costs and solutions. *Journal of Regulatory Economics*, *48*, 218–243.
- Kahn, A. E., Cramton, P. C., Porter, R. H., & Tabors, R. D. (2001). Uniform pricing or pay-as-bid pricing: A dilemma for California and beyond. *The Electricity Journal*, *14*, 70–79.
- Kamat, R., & Oren, S. S. (2002). Rational buyer meets rational seller: Reserves market equilibria under alternative auction designs. *Journal of Regulatory Economics*, *21*, 247–288.
- Kaut, A., Obermüller, F., & Weiser, F. (2017). Tender frequency and market concentration in balancing power markets. Institute of Energy Economics at the University of Cologne (EWI) Working Paper 17/04 (pp. 242–259).
- Kirsch, L. D., & Singh, H. (1995). Pricing ancillary electric power services. *Electricity Journal*, *8*, 28–36.
- Koch, C., & Hirth, L. (2019). Short-term electricity trading for system balancing: An empirical analysis of the role of intraday trading in balancing Germany's electricity system. *Renewable and Sustainable Energy Reviews*, *113*, 109275.
- KU Leuven Energy Institute. (2015). The current electricity market design in Europe. EI-FACT SHEET 2015-01.
- Müller, G., & Rammerstorfer, M. (2008). A theoretical analysis of procurement auctions for tertiary control in Germany. *Energy Policy*, *36*, 2620–2627.
- Müsgens, F., & Ockenfels, A. (2011). Information feedback design in balancing power markets. *Zeitschrift für Energiewirtschaft*, *35*, 249–256.
- Müsgens, F., Ockenfels, A., & Peek, M. (2014). Economics and design of balancing power markets in Germany. *International Journal of Electrical Power & Energy Systems*, *55*, 392–401.
- Ocker, F., Braun, S., & Will, C. (2016). Design of European balancing power markets. In *Proceedings of the 13th international conference on the European energy market* (pp. 1–6).
- Ocker, F., & Ehrhart, K. M. (2017). The “German paradox” in the balancing power markets. *Renewable and Sustainable Energy Reviews*, *67*, 892–898.
- Ocker, F., Ehrhart, K. M., & Belica, M. (2018a). Harmonization of the European balancing power auction: A game-theoretical and empirical investigation. *Energy Economics*, *73C*, 194–211.
- Ocker, F., Ehrhart, K. M., & Ott, M. (2018b). Bidding strategies in the Austrian and German secondary balancing power market. *Wiley Interdisciplinary Reviews - Energy and Environment*, *7*(6), e303.
- Ocker, F., & Jaenisch, V. (2020). The way towards harmonised electricity intraday auctions in Europe—Status quo and future developments. *Energy Policy*, *145*, 111731.
- Rammerstorfer, M., & Wagner, C. (2009). Reforming minute reserve policy in Germany: A step towards efficient markets? *Energy Policy*, *37*, 3513–3519.
- regelleistung.net. (2021). Internetplattform zur Vergabe von Regelleistung. Retrieved March 26, 2021, from <https://www.regelleistung.net>.
- Ströbele, W., Pfaffenberger, W., & Heuterkes, M. (2013). *Energiewirtschaft: Einführung in Theorie und Politik*. Oldenburg (Munich).
- Vandezande, L., Meeus, L., Belmans, R., Saguan, M., & Glachant, J. M. (2010). Well-functioning balancing markets: A prerequisite for wind power integration. *Energy Policy*, *38*, 3146–3154.
- Van der Veen, R. A., & Hakvoort, R. A. (2016). The electricity balancing market: Exploring the design challenge. *Utilities Policy*, *43*, 186–194.
- Zweifel, P., Praktiknjo, A., & Erdmann, G. (2017). *Energy economics*. Berlin: Springer.