Balancing Power Auctions

Theoretical and Empirical Analyses

Zur Erlangung des akademischen Grades eines
Doktors der Wirtschaftswissenschaften

(Dr. rer. pol.)

von der Fakultät für Wirtschaftswissenschaften
des Karlsruher Instituts für Technologie (KIT)

genehmigte

DISSERTATION

von

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Tag der mündlichen Prüfung: 19. Juli 2018
Referent: Prof. Dr. Karl-Martin Ehrhart
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Karlsruhe, 2018

Danksagung

Viele Personen haben mich in den vergangenen drei Jahren, in welchen diese Doktorarbeit angefertigt wurde, wohlwollend unterstützt. Bei diesen Personen möchte ich mich an dieser Stelle bedanken.

Mein erster Dank gilt meinem Doktorvater Professor Karl-Martin Ehrhart, der es mir ermöglichte bei ihm in der Forschungsgruppe zu promovieren. Hierbei hat er mich in den vergangenen drei Jahren (und bereits während meines Studiums) durchgehend bei meiner wissenschaftlichen Tätigkeit unterstützt und mir viele Freiheiten bei meiner täglichen Arbeit eingestanden. Hierfür möchte ich mich herzlich bei ihm bedanken. Ebenso möchte ich mich bei Professor Wolf Fichtner bedanken, der freundlicherweise als Korreferent für meine Doktorarbeit fungierte. Im Rahmen dieses Korreferats gab er mir mehrmals die Möglichkeit, meine Arbeit vor ihm und seinen Mitarbeitern zu präsentieren und zu diskutieren. Im Rahmen meines Promotionsverfahrens wirkten zudem Professor Christof Weinhardt als Prüfer und Professor Maxim Ulrich als Vorsitzender der Prüfungskommission mit, welchen ich hierfür danke.

Für die sehr angenehmen und spannenden drei Jahre in der Forschungsgruppe Strategische Entscheidungen möchte ich gerne meinen Kollegen danken. Zunächst bedanke ich mich herzlich bei Marie-Christin Haufe und Matej Belica, welche mir von Beginn meiner Tätigkeit inhaltlich aber auch organisatorisch mit Rat und Tat zur Seite standen. Des Weiteren möchte ich mich bei Jan Kreiss und Ann-Katrin Hanke bedanken, mit welchen ich viele spannende Diskussionen führte. Zudem bedanke ich mich bei Nayeli Gast Zepeda und Philipp Büchner, die im Rahmen ihrer Hiwi-Tätigkeit eine wertvolle Stütze des Teams darstellten.

Bei meinen Koautoren bedanke ich mich für die spannenden und lehrreichen Diskussionen. Neben meinen Kollegen sind dies zudem Sebastian Braun (TU München), Professorin Marion Ott (RWTH Aachen) sowie Christian Will (KIT). Außerdem bedanke ich mich bei Professor Timm Teubner, der mir im Rahmen meines Stipendiums an der Karlsruhe School of Services (KSOS) als Ansprechpartner zur Verfügung stand.

Bei Professor Reinhard Haas und seinem Team von der Energy Economics Group an der TU Wien möchte ich mich für die Ermöglichung meines Forschungsaufenthaltes bedanken. Der Forschungsaufenthalt wurde zudem vom Karlsruher House of Young Scientists (KHYS) finanziell gefördert, wofür ich mich ebenfalls bedanken möchte.

Meine Eltern, Ellen und Klaus-Martin Ocker, waren mir nicht nur in den vergangenen drei Jahren eine unentbehrliche Stütze. Ihnen gebührt ein ganz besonderer Dank – ohne euch wäre die Anfertigung dieser Arbeit nicht möglich gewesen. Meinem langjährigen Freund Erik van Schoor gilt für seinen stetigen Zuspruch zudem ein spezieller Dank. Meiner Frau, Corina Florentina Ocker-Nastase, widme ich diese Arbeit und bedanke mich für ihre warmherzige Unterstützung und Liebe.

Karlsruhe, im April 2018

Abstract

The shift towards renewable energy sources for electric energy production is accompanied by high volatility, demanding elaborated ancillary services for the power grid. Balancing power is the most crucial short-term ancillary service for securing the operability of the grid. In liberalized electricity markets, the procurement of balancing power is organized via auctions.

Game-theoretical modelling is the appropriate tool for a formal analysis of balancing power auctions. Such models, however, lack for any auction design that is currently applied in Europe. Moreover, the interplay of the electricity wholesale market and the balancing power market is neglected in most scientific work. Furthermore, balancing power auction data from Austria and Germany, which share the same design, reveal extremely high prices. Since the future European-wide auction is very similar to the current Austrian-German design, the understanding of the underlying auction mechanism is of particular importance.

This thesis presents three theoretical approaches for analyzing balancing power auctions. The first is an integrated market model for the electricity wholesale market and the balancing power market. The existence of an integrated market equilibrium is proven. The comparison of theoretical findings with German market data reveals costs above the equilibrium.

Game-theoretical models for the Austrian-German and the future European auction constitute the second approach. Both auction designs have desirable economic properties in their one-shot versions. A switch to uni-

form pricing does not induce truthful bidding, but leads to underbidding. A comparison of theoretical findings with German market data indicates non-competitive prices. A game-theoretical grounded explanation is given, which bases on the regular auction repetition and the limited supply side.

The third is a decision-theoretical model. It considers recent work that indicates that bidders adjust their bids to previous auctions results. The model is confronted with Austrian and German market data, which shows that the identified bidding strategies are actually applied.

Additional empirical analyses show that the increasing electricity production from volatile renewable energy was not accompanied by higher balancing power demands: grid control cooperations led to considerable savings and adaptations in the electricity market design were undertaken.

This thesis is based on six papers prepared at the Institute for Economics (ECON) in the Research Group for Strategic Decisions under the supervision of Professor Karl-Martin Ehrhart at the Karlsruhe Institute of Technology (KIT) and is written in English.

Kurzfassung

Die zunehmende Stromproduktion aus erneuerbaren Energieträgern erhöht die Volatilität der Stromversorgung erheblich. Daher bedarf es passgenauer Systemdienstleistungen für das Stromnetz, wobei Regelleistung die Funktionsfähigkeit des Stromnetzes kurzfristig sichert. Die Märkte für Regelleistung sind in liberalisierten Strommärkten als Auktionen organisiert.

Spieltheoretische Modellierung ist die geeignete Methode um Regelleistungsauktionen formal zu analysieren. Solch ein Modell existiert jedoch für kein aktuell implementiertes Auktionsdesign in Europa. In den meisten wissenschaftlichen Arbeiten werden zudem die Wechselwirkungen zwischen dem Großhandelsmarkt für Strom und dem Markt für Regelleistung vernachlässigt. Die Auktionsergebnisse für Regelleistung in Deutschland und Österreich, in welchen das gleiche Design verwendet wird, offenbaren zusätzlich extrem hohe Preise. Da sich die zukünftig europaweite Auktion stark am deutsch-österreichischen Design orientiert, ist das Verständnis des zugrunde liegenden Auktionsmechanismus umso wichtiger.

Die vorliegende Doktorarbeit legt drei theoretische Modelle für die Untersuchung von Regelleistungsauktionen vor. Das erste ist ein integriertes Modell für den Großhandelsmarkt für Strom und den Markt für Regelleistung. Es wird gezeigt, dass ein integriertes Marktgleichgewicht existiert. Der Vergleich theoretischer Ergebnisse mit deutschen Marktdaten legt offen, dass die empirischen Kosten über denen des Gleichgewichts liegen.

Spieltheoretische Modelle für die deutsch-österreichische sowie zukünf-

tig europaweite Auktion bilden den zweiten Modellansatz. Beide Auktionsdesigns haben wünschenswerte Eigenschaften bei einmaliger Durchführung. Das Einheitspreisverfahren induziert nicht wahrheitsgemäßes Bieten, sondern Unterbieten. Der Vergleich theoretischer Ergebnisse mit deutschen Marktdaten legt nicht wettbewerbliche Preise offen. Ein spieltheoretischer Erklärungsansatz wird präsentiert, welcher auf der regelmäßigen Wiederholung der Auktion und der begrenzten Angebotsseite basiert.

Der dritte Ansatz ist ein entscheidungstheoretisches Modell. Es berücksichtigt empirische Erkenntnisse, dass Bieter ihre Gebote an historischen Auktionsergebnissen ausrichten. Der Vergleich mit deutsch-österreichischen Daten zeigt, dass die identifizierten Bietstrategien Anwendung finden.

Weitere empirische Analysen erläutern, dass trotz der zunehmenden Stromproduktion durch erneuerbare Energieträger die Nachfrage für Regelleistung nicht stieg: Anpassungen im Strommarktdesign wurden vollzogen und Stromnetz-Kooperationen führten zu erheblichen Einsparungen.

Die Grundlage dieser Doktorarbeit sind sechs Papiere, welche am Institut für Volkswirtschaftslehre (ECON) in der Forschungsgruppe Strategische Entscheidungen unter der Betreuung von Professor Karl-Martin Ehrhart am Karlsruher Institut für Technologie (KIT) erarbeitet wurden. Die Arbeit ist in englischer Sprache verfasst.

Dissertation, genehmigt von der Fakultät für Wirtschaftswissenschaften des Karlsruher Institut für Technologie (KIT), 2018. Referent: Prof. Dr. Karl-Martin Ehrhart, Korreferent: Prof. Dr. Wolf Fichtner.

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List of abbreviations

aFRR	automatically-activated Frequency Restoration Reserve
ASYM	Asymmetric BP product
AT	Austria/Austrian
BE	Balancing Energy
BEPP	Balancing Energy Pricing Period
BP	Balancing Power respectively BP-capable bidders
CS	Consumer Surplus
DA	Daily procurement of BP
EEX	European Energy Exchange
Entso-E	European Network of Transmission System Operators
Euro/h	Euro per hour
Euro/MW	Euro per megawatt
Euro/MWh	Euro per megawatt hour
FCR	Frequency Containment Reserve
GAMMA	German-Austrian Manual Merit-order Activation
GER	Germany/German
GW	Gigawatt
GWh	Gigawatt hour
IGCC	International Grid Control Cooperation
MAN	Manual BP activation
MARI	Manually Activated Reserves Initiative
mFRR	manually-activated Frequency Restoration Reserve

MO	Monthly procurement of BP
M.-O.	Merit-order activation of BP
MW	Megawatt
MWh	Megawatt hour
n/a	Parameter not available
nBP	non-BP-capable bidders
PaB	Pay-as-bid pricing
PAR	Parallel (pro-ratio) activation of BP
PBP	Primary Balancing Power
PICASSO	Platform for the International Coordination of the Automatic Frequency Restoration Process and Stable System Operation
PS	Producer Surplus
SBP	Secondary Balancing Power
SP	Stochastic Programming
SYM	Symmetric BP product
TBP	Tertiary Balancing Power
TP	Total Price
TSO	Transmission System Operator
UP	Uniform Pricing
VRE	Volatile Renewable Energy Sources
WE	Weekly procurement of BP
YE	Yearly procurement of BP

List of functions and variables

α	Gradient of function S
β	Intercept of function S
γ^+	Fraction of provided B^+
γ^-	Fraction of provided B^-
δ	Share of BP bidders in function S
ϑ	Length of the BEPP
μ	Mean value
π	Bidder's profit function
π_E	Bidder's profit function of the BE bid
π_P	Bidder's profit function of the BP bid
π_W	Bidder's profit function on the wholesale market
π_{BP}	Bidder's profit function on the BP market
π_{BP}^+	Bidder's profit function on the positive BP market
π_{BP}^-	Bidder's profit function on the negative BP market
$E[\pi]$	Bidder's expected profit function
$E[\pi_E]$	Bidder's expected profit function of the BE bid
$E[\pi_W]$	Bidder's expected profit function on the wholesale market
$E[\pi_{BP}]$	Bidder's expected profit function on the BP market
ρ	Spearman's rank correlation coefficient
σ	Standard deviation
ϕ	BP bid
ϕ^*	Optimal BP bid

ϕ_{min}	Lowest awarded BP bid
ϕ_{max}	Highest awarded BP bid
ψ	BE bid
ψ^*	Optimal BE bid
ψ_{min}	Lowest BE bid
ψ_{max}	Highest BE bid
ψ_2	Voluntary BE bid
a	Calling probability function
a^+	Calling probability function for positive BP
a^-	Calling probability function for negative BP
a_{max}	Maximum calling probability for BP
a^+_{max}	Maximum calling probability for positive BP
a^-_{max}	Maximum calling probability for negative BP
a^+_{min}	Minimum calling probability for positive BP
a^-_{min}	Minimum calling probability for negative BP
b	Number of awarded BP bidders
B	BP demand (e.g., SBP demand)
B^+	Positive BP demand
B^-	Negative BP demand
$\tilde{B}$	BE demand
$\tilde{B}^+$	Positive BE demand
$\tilde{B}^-$	Negative BE demand
c	Variable energy production costs
c_0	Lower interval boundary for c
c_0^+	Lowest c of all bidders on the positive BP market
c_0^-	Lowest c of all bidders on the negative BP market
c_0^{-*}	c_0^- that minimizes function T

c_1	Upper interval boundary for c
c_1^+	Highest c of all bidders on the positive BP market
c_1^-	Highest c of all bidders on the negative BP market
C	Set of c
$C_{(i,n-1)}$	ith highest cost of $n-1$ bidders with density function $f_{(i,n-1)}$ and distribution function $F_{(i,n-1)}$
$c + dc$	Imputed variable energy production costs
d	Length of the reserve period
dc	Average cost of BE per MW caused by supply fluctuations
df	Degree of freedom
dw	Durbin-Watson test statistic
D	Wholesale demand
f	Density function of c
F	Distribution function of c
g	(Subjective) winning probability function (with ϕ)
g_2	(Subjective) winning probability function (with ψ_2)
h	Function of BP bidders' average active capacities
H	BP bidders' average active capacities (integral of h)
i	Parameter for order-statistics
j	Representative bidder
k	Calling costs per MW
l	Capacity costs per MW
m	Minimal load capacity
n	Number of BP bidders
o^+	Relative rank function in the positive BP merit-order
o^-	Relative rank function in the negative BP merit-order
O^+	Normalized rank function in the positive BP merit-order

O^-	Normalized rank function in the negative BP merit-order
p_W	Wholesale market price
p_{BE}	BE price
$p_{BE,2}$	BE price with voluntary BE bids
p_{BE}^+	Bidder's individual positive BE price function
p_{BE}^-	Bidder's individual negative BE price function
p_{BP}	BP price
p_{BP}^+	Uniform positive BP price
p_{BP}^-	Uniform negative BP price
p_{RES}	Reservation price per energy unit for a reliable power system
P^+	Normalized BE price function in the positive BP market
P^-	Normalized BE price function in the negative BP market
q	Power offer
r	Rank function in the BP merit-order
r^+	Rank function in the positive BP merit-order
r^-	Rank function in the negative BP merit-order
R^+	Set of positive BP merit-order ranks
R^-	Set of negative BP merit-order ranks
s	Argument value (quantity) of function h
s_0	Supply of BP bidders until c_0^-
s_0^*	s_0 that minimizes function T
s_1	Supply of BP suppliers until c_1^+
S	Supply function
S_{BP}	BP supply function
S_{nBP}	nBP supply function
S^{-1}	Inverse supply function
S_{BP}^{-1}	Inverse BP supply function

S_{nBP}^{-1}	Inverse nBP supply function
t	Parameter for exponential representation of function a
t^+	Parameter for exponential representation of function a^+
t^-	Parameter for exponential representation of function a^-
T	Total cost function of the power system
u	Integration variable in Chapter 5
v	Integration variable in Chapter 5
w	Integration variable in Chapter 5
x	Integration variable in Chapter 5
y	Minimum called BP capacity
z	Distribution of the difference between demand and supply

Chapter 1

Introduction

The European electricity sector undergoes tremendous changes in the last decades. At the centre is the establishment of liberalized and competitive electricity markets, which was initiated and promoted by several directives of the European Commission (European Commission, 2018). In the course of this endeavour, auctions have proven to be an appropriate mechanism for overcoming the regulated past and paving the way towards competitive markets. Recent prominent examples are the auctions for capacity mechanisms (Cramton and Ockenfels, 2012) and the auctions for the promotion of renewable energy sources (AURES project, 2018). Largely unnoticed, markets for ancillary services have been implemented as procurement auctions since the early beginnings of the liberalization. At the forefront are the auctions for balancing power (BP). In Germany, for example, liberalized BP auctions are conducted since 2001 (regelleistung.net, 2018a).

Despite the early liberalization of BP procurement, the establishment of competition in these auctions is complicated. The reason is that BP market participation requires an elaborate and expensive prequalification process in order to meet the high reliability criteria. Therefore, the number of prequalified bidders (i.e., suppliers) is relatively small and invariant over time (Hirth and Ziegenhagen, 2015). Although several actions to increase the competition level were taken, recent German auction data reveal extremely high prices: bids of 77,777 Euro per megawatt hour (Euro/MWh) were awarded on 17 October 2017, resulting in the highest recorded prices for securing of system stability, which are ultimately passed on to the consumers (Bundesnetzagentur, 2018a). These developments are of particular importance because the future European-wide BP auction is very similar to the current Austrian-German design.

1.1 Background

1.1.1 Volatility in the electricity system

Electric energy (henceforth energy) is usually traded at wholesale electricity markets that include forward markets and spot markets (e.g., Grimm et al., 2008; Ströbele et al., 2013; KU Leuven Energy Institute, 2015; Zweifel et al., 2017). Forward markets represent a possibility for long-term energy trading, whereas at spot markets the point of delivery is instantaneous, i.e., typically within the next 48 hours. Therefore, forward markets are mostly utilized for risk hedging and trading is often carried out bilaterally (so-called "over the counter"). Spot markets are organized as standardized auctions, and the most important auctions are the "Day-Ahead" auction and "Intraday Continuous" auction (Viehmann, 2017). In the Day-Ahead auction, trading is done for the following day for separate hours or blocks, whereas in the Intraday Continuous auction, trading is done only minutes before the actual delivery.

The European-wide goal of increasing the share of final energy consumption from renewable sources to 27% by 2030 substantially increases the volatility of the supply (European Commission, 2016). The reason is that the shift towards volatile renewable energy sources (VRE) such as wind and solar plants is accompanied by a less predictable production. Thus, the requirements for the electricity grid change considerably, in particular, it must react highly flexible on supply deviations. Therefore, ancillary services become increasingly important and mandatory. According to DENA (2014), ancillary services are defined as indispensable services that support the operability of the power supply. They include services for maintaining frequency stability and voltage stability, for the re-establishment of power supply and for operational management.[1] To distinguish the application of BP, i.e., for the maintaining of frequency stability, from other ancillary services and contingency situations, three support cases for supply reliability are illustrated in the following.

In the first case, the market clearing on the wholesale market fails because energy demand is higher than energy supply.[2] Then, capacity mechanisms (e.g., strategic reserves) ensure the supply reliability by activating standby plants (e.g., Cramton and Ockenfels, 2012).

In the second case, the market clearing on the wholesale market was successful, but grid restrictions do not allow a certain allocation, e.g., because of internal gird bottlenecks.[3] In this case, the allocation on the wholesale market must be changed (by a so-called "redispatch"), i.e., contracted energy producers who intend to transmit energy via the bottleneck must lower their supply. The missing energy supply is replaced by suppliers that are spatially behind the bottleneck (Ocker and Ehrhart, 2017b).

If the market clearing on the wholesale market was successful and the allocation is aligned with the grid restrictions, a third case may arise, and this is the case which is analyzed in this thesis: the predicted energy demand and supply do not match (e.g., because of a sudden underproduc-

[1] The actual implementation and classification of ancillary services depends on the specific country. For Germany, see for example Schweizer and Mattis (2016).

[2] A reason for this may be that the continuous penetration of renewable energy sources leads to a decline in wholesale market prices, which threatens the profitability of conventional power plants.

[3] In Germany, the energy production of wind power plants in the Northern Sea overextends the grid capacities to Southern Germany periodically, requiring a redispatch of energy production.

tion of a photovoltaic plant). The reason is that the volumes traded at the wholesale market usually differ from the actual production of energy because they are based on predictions of supply and demand. Then, demand and supply must be balanced instantaneously to stabilize the frequency in alternating current grids: If the frequency deviations are too extreme (higher than 0.2 Hertz), area-wide power outages occur and generators connected to the grid are damaged due to a disharmonious operation (Hirth and Ziegenhagen, 2015; Gawlik et al., 2017). This short-term operability of the grid is ensured by utilizing BP.

For integrating BP into the power system, there exist two implementation options with respect to the minimization of the expected energy costs: firstly, integrated or coupled co-optimization (usually applied in North America) and, secondly, decoupled co-optimization (usually applied in Europe). Co-optimization means that the allocations on the wholesale market and on the BP market are optimized simultaneously, whereas decoupled co-optimization means that the allocations on the two markets are determined separately (Ellison et al., 2012).

1.1.2 Balancing power markets

The "European Network of Transmission System Operators (Entso-E)" discerns three BP qualities ("three-quality pattern"): the Primary Balancing Power (PBP), the Secondary Balancing Power (SBP) and the Tertiary Balancing Power (TBP) (Entso-E, 2017).[4] These three qualities differ in their reaction time after an imbalance causing event: PBP is activated to limit deviations from the grid frequency, then SBP is utilized to restore the grid frequency, and as a final and more long-term measure, TBP is activated. For each of the three qualities there exist separate markets that are orga-

[4]PBP is also known as "Frequency Containment Reserve (FCR)", SBP as "automatically-activated Frequency Restoration Reserve (aFRR)", and TBP as "manually-activated Frequency Restoration Reserve (mFRR)". In this thesis, the Austrian-German expressions for the three BP qualities are used.

nized as procurement auctions (e.g., Bushnell and Oren, 1995; Chao and Wilson, 2002; Hirth and Ziegenhagen, 2015).

Imperfect predictions of energy demand and supply can either cause an overproduction (e.g., caused by a wind park during a storm) or an underproduction (e.g., caused by solar plants during cloudy weather). Thus, BP needs to provide an increased and a decreased supply. For this, there exist two different BP products: In the positive (negative) BP market, bidders provide upward (downward) regulation by, for example, increasing (decreasing) the load level of their power plants.

BP bidders face two cost types: costs for keeping BP capacities available to the grid (so-called "capacity costs"), and costs for the activation of BP (so-called "calling costs"), i.e., the actual delivery of balancing energy (BE). To mirror these cost types, there exist different bid components: a balancing power bid (BP bid, with unit Euro per megawatt, Euro/MW) and a balancing energy bid (BE bid, with unit Euro/MWh). Furthermore, bidders state their power offer (with unit megawatt, MW).[5] In Germany, for example, the costs of the BP bids are passed on to the consumers within the grid charge, whereas the costs of the BE bids are allocated among the energy suppliers under the cost-by-cause principle.

Based on these bids, the tendering authority, e.g., the regulator, the transmission system operator (TSO) or the Independent System Operator, determines which bidders are awarded. This is done by calculating scores for each bidder, i.e., a combination of the submitted bid components. The bidders with the lowest scores and, thus, the lowest (expected) costs for BP provision win the auction. For pricing the winners, either pay-as-bid pricing (PaB) or uniform pricing (UP) is applied: in the former case, all awarded bidders are paid the amounts of their bids, whereas in the latter case, all awarded bidders are paid a uniform price. For the delivery of

[5]Note that power offer and power bid are also referred to as capacity offer and capacity bid.

BE either a merit-order activation or pro-rata activation is applied. If a merit-order activation is utilized, awarded bidders with the lowest bids are activated first, whereas pro-rata activation implies that all awarded bidders are activated to the same extent.

1.2 Objective

In the light of the extremely high BP prices that are recently observed, the non-existence of an appropriate representation of BP auctions, i.e., a game-theoretical model because auctions are an application of game theory, in the scientific literature is surprising. Moreover, the interdependencies of the wholesale market and the BP market are not considered in most theoretical analyses: BP bidders cannot offer their entire capacity on the wholesale market, however, have to run their plants at a certain minimal load. Furthermore, recent literature points at empirical anomalies in the German BP markets. Hirth and Ziegenhagen (2015) present the so-called "German paradox" in the BP markets: while German VRE capacity tripled since 2008, the BP demand was reduced by 15%. In addition, they long for "a more rigorous evaluation of BP price developments" because the price volatility indicates that bidders individual behavior is not guided by fundamental influences only. A reason for this research gap might be that BP markets involve complex procurement auction mechanisms, which require a high model complexity and market insights.

The main objective of this thesis is the development of theoretical models for BP auctions. This includes the development of a) an integrated model of the wholesale market and the BP market, b) a game-theoretical model for the current Austrian-German SBP auction design and for the future European-wide SBP auction design, and c) a decision-theoretical model for the Austrian-German SBP auction. The findings of these models are confronted with empirical auction data. In addition, the thesis relates to recent scientific work, e.g., the German paradox by Hirth and Ziegenhagen (2015), by considering market changes and by systematically examining the bidding behavior in BP auctions.

In this thesis, I focus mostly on the analysis of SBP auctions. The reason for this is twofold: Firstly, SBP auctions have the highest market volumes in most European countries and, thus, are the most important short-term ancillary service (e.g., Hirth and Ziegenhagen, 2015; Bundesnetzagentur and Bundeskartellamt, 2017; Borne et al., 2018). Secondly, the imminent start of the European-wide SBP auction emphasizes the necessity for scientific examination: the harmonization will start in 2019 and must be executed no later than 2021 (European Commission, 2017).

1.3 Approach

Chapter 2 starts by giving an overview of BP market designs. For this, related literature is discussed and an overview of European BP markets is presented. Here, the focus rests on the Austrian-German and on the future European SBP auction design. Finally, general characteristics of BP bidders are discussed, i.e., the prequalification and cost structures.

Chapter 3 relates to the German paradox in the BP markets: it discusses that in spite of the increasing energy production from VRE, there is no need for a higher BP demand in Germany. National and international grid control cooperations as well as adaptations in the German energy market design are examined. Additionally, the price developments in the German SBP market in the time period from 2012 to 2014 are evaluated. For this, SBP demands and SBP prices are linked, and the bidding behavior of SBP auctions is investigated.

In Chapter 4, the interdependencies of the electricity wholesale market and the BP market are considered. For this, an integrated market model is presented, which relates to the future European-wide harmonization of BP markets. In particular, the allocation, prices and costs across the two markets are investigated. Furthermore, theoretical findings are contrasted with empirical market data from Germany of 2015, and implications regarding the harmonized BP market design are discussed.

Chapter 5 presents a game-theoretical model of the current Austrian-German SBP auction design and the future European-wide SBP auction. This includes an examination of the two pricing rules PaB and UP and the integration of an additional BE market. For this, the theoretical properties of the auction designs are investigated. The theoretical findings are compared with German auction data in the time period of 2013 to 2015. In addition, the SBP auction is categorized within the research field of repeated games and existing results are applied to this setting.

In Chapter 6, a bidder's decision-theoretical calculus for bidding in the Austrian and German SBP auctions is presented. The theoretic approach allows to derive optimal bidding strategies by integrating price expectations based on historic market data. The results are validated by a numerical application of the bidder's calculus. By relating to market data from Austria and Germany in the time period of 2014 to mid 2017, the decision-theoretic approach is confronted with actually applied bidding strategies.

The thesis concludes in Chapter 7. Here, overarching conclusions and implications are drawn from the results of the analyses, and an outlook for further directions of research is presented.

Chapters 2 to 6 are based on six papers, which have been edited slightly for consistency and coherence in this thesis. Table 1.1 illustrates the authors, title and reference for each paper.

Chapter	Authors	Title	Reference
2	Fabian Ocker	Design and performance of European balancing power auctions	Ocker (2017a)
	Fabian Ocker, Sebastian Braun, Christian Will	Design of European balancing power markets	Ocker et al. (2016a)
3	Fabian Ocker, Karl-Martin Ehrhart	The “German paradox” in the balancing power markets	Ocker and Ehrhart (2017a)
4	Karl-Martin Ehrhart, Fabian Ocker	Allocation, prices, and costs in the electricity wholesale market and balancing power market – an integrated approach	Ehrhart and Ocker (2018)
5	Fabian Ocker, Karl-Martin Ehrhart, Matej Belica	Harmonization of the European balancing power auction – a game-theoretical and empirical investigation	Ocker et al. (2017)
6	Fabian Ocker, Karl-Martin Ehrhart, Marion Ott	Bidding strategies in Austrian and German balancing power auctions	Ocker et al. (2018)

Table 1.1: Overview of the papers prepared for this thesis.

Chapter 2

Design of balancing power markets

BP markets involve complex procurement auction mechanisms that are challenging both to design for auctioneers and to take part in for bidders. Therefore, in this chapter, an overview of the design options for BP markets and short-term energy wholesale markets is provided.[1] It includes all 24 European member countries of the Entso-E that utilize BP auctions, and is mostly based on Ocker et al. (2016a) and Ocker (2017a).

The structure of the chapter is as follows. In Section 2.1 an overview of related literature is provided. Section 2.2 presents the overview of European markets, and Section 2.3 illustrates BP bidder characteristics.

2.1 Related literature

Since BP markets are organized as procurement auctions, most of the related literature originates from auction-theoretical research fields. Furthermore, specific literature on BP markets is presented.

2.1.1 Auction-theoretical literature

The BP procurement relates to the general research on *multi-unit auctions*. In a BP auction, the auctioneer (e.g., the TSOs in Austria and Germany)

[1]For the overview of applied market designs in Europe see Appendix A.

demands multiple goods (i.e., multiple units of reserved power).[2] The related literature on single-unit auctions is elaborated and many aspects are also relevant in the context of energy markets. Information acquisition (Gretschko et al., 2014), information disclosure (Bergemann and Wambach, 2015), collusion (Skrzypacz and Hopenhayn, 2004; Hortacsu and Puller, 2008), competing sellers (McAfee, 1993), sequential auctions (Hörner and Jamison, 2008) etc., are well-understood. However, compared to single-unit auctions, the bidders' strategy spaces are considerably larger and richer in multi-unit auctions. In particular, it is often challenging to find unique equilibria even with symmetric bidders, since strategic supply reduction must be considered.[3] Furthermore, the insights of single-unit auctions do often not extend to multi-unit auctions.

Secondly, BP auctions consider *scoring auctions*. In scoring auctions, other attributes than the price (multi-attributive) are considered for the evaluation of bids. For example, for the construction of highway roads, it may be of equal importance how fast and at what price a road is built (Herbsman et al., 1995). Therefore, a rule is to be defined that considers all parameters that are of relevance for winner determination. Che (1993) studies competition in government procurement by developing a two-dimensional auction design, i.e., firms bid on both price and quality. Branco (1997) studies the design of procurement auctions and allows for a correlation of firm's costs. Asker and Cantillon (2008) provide an analysis of equilibrium behavior in scoring auctions when suppliers' private information is multi-dimensional. Furthermore, they show that scoring auctions dominate other usually applied procedures for buying differentiated products, including beauty contests and price-only auctions. Asker and Cantillon (2010) characterize the buyer's optimal buying mechanism

[2]For examples of multi-unit auctions see Ausubel et al. (2014).
[3]For an overview see Ausubel et al. (2014), for the relevance in energy markets see Wolfram (1997) and for an laboratory experiment see Engelmann and Grimm (2009).

when she procures a good characterized by its price and its quality. Bichler and Kalagnanam (2005) represent such scoring auctions through integer programming problems. The effects of different payment rules and auction settings are analyzed in David et al. (2006). Ocker and Ehrhart (2017b) suggest a multi-attributive auction design for the German grid reserve.

Thirdly, BP auctions refer to the discussion of *pricing rules* in auctions. In multi-unit auctions, there are typically two rules for pricing the winners, namely PaB or UP. If PaB is applied, winning bidders pay (in sale auctions) or receive remunerations (in procurement auctions) that are equal to their bids. On the contrary, if UP is applied, winning bidders pay (receive) a uniform payment, which is usually based on either the lowest accepted bid or the highest rejected bid in sell-auctions, and vice versa in buy-auctions. In scientific literature, there is a controversial debate whether one of the pricing rules is superior (e.g., Milgrom and Weber, 1982; Kremer and Nyborg, 2009; Ausubel et al., 2014). This also transfers to energy markets. Kahn et al. (2001) examine whether a shift from UP to PaB is appropriate for the Californian power market, and argue that changing the pricing rule does not yield efficiency gains. Federico and Rahman (2003) investigate the change from an auction with UP to PaB in the wholesale market. Son et al. (2004) analyze UP and PaB mechanisms in an energy market by presenting the strategic behavior in a short-term auction game. Tierny and Schatzki (2008) access the advantages and disadvantages of a switch from UP to PaB in wholesale markets.

Fourthly, BP auctions are conducted regularly for many years. Therefore, it also relates to *repeated auctions* and *collusion in auctions*. In game theory, the "folk theorem" states that there exists a large set of subgame perfect equilibria in infinitely repeated games. This set contains equilibria that lead to higher payoffs for the players than the continuous repetition of the base game equilibrium, which can be achieved by a subgame perfect equilibrium in a repeated game (e.g., Abreu et al., 1994; Fudenberg et al., 1994; Dutta, 1995; Wen, 1994; Ely and Välimäki, 2002). Playing these equilibria in the repeated game is also referred to as tacit or implicit collusion (Friedman, 1971; Tirole, 1988; Vives, 1999).

There is a huge body of evidence for collusion in repeated auctions, both theoretically (e.g., Aoyagi, 2003, 2007; Fabra, 2003; Skrzypacz and Hopenhayn, 2004; Marshall and Marx, 2007; Hortacsu and Puller, 2008) and empirically. Feinstein et al. (1985) and Porter and Zona (1993) analyze bid-rigging in procurement auctions for highway construction. Ehrhart (2001) shows that the fixed rate tender for refinancing operations invites bidders to continually raise their bids in repeated auctions. Macatangay (2002) reports tacit collusion in repeated multi-unit uniform price auctions for energy wholesale in England and Wales. Cramton and Schwartz (2000) and Bajari and Yeo (2009) find collusive bidding in multi-round FCC spectrum auctions. Porter and Zona (2004) examine collusive behavior in the school milk market in Ohio. Ishi (2009) conducts an empirical study of repeated procurement auctions in Japan to study the effect of exchanging favor. Lu et al. (2014) consider the effects of transparency on collusion in Dutch flower auctions. Ishii (2014) examines the "roundness level" of bids, which are defined as the number of zeros at a bid's end, in public procurement auctions for Japanese construction works.

2.1.2 Specific literature on balancing power markets

In addition to the auction literature, other economic research approaches to BP markets have been conducted. Those are presented briefly in the following. Here, theoretical and empirical analyses are distinguished.

Bushnell and Oren (1995) and Chao and Wilson (2002) investigate different scoring auctions from a theoretical standpoint. In more detail, they describe essential elements for scoring rules to ensure an efficient allocation, however, without considering strategic interaction among the bidders. Wen and David (2002) present a stochastic optimization model that yields optimal bidding strategies and provide a numeric example. Kamat and Oren (2002) analyze efficiency properties of BP markets in the USA. Swider and Weber (2007) present an optimization based methodology for profit maximizing bidding under price uncertainty for BP. Müller and Rammerstorfer (2008) categorize several elements that can be used for the design of BP markets. Just and Weber (2008) model the interdependencies between BP markets and spot markets. Müsgens et al. (2014) discuss the economic fundamentals that govern market design and behavior in the German BP markets. They argue that UP is superior to PaB, since it minimizes strategic behavior of bidders. Just and Weber (2015) examine the incentives market participants are confronted with in the German BP mechanism. They find that strategic oversupply and undersupply are caused by stochastic arbitrage opportunities between the spot market and the BP mechanism. Ortner (2017) discusses fundamental modelling approaches and illustrates case studies under perfect competition.

Empirical analyses have also been conducted. Rammerstorfer and Wagner (2009) assess the effects associated with a reorganization of the German BP market. Flinkerbusch and Heuterkes (2010) investigate potential cost reductions in the BP markets by pooling all four German control areas and project savings of 17% in the period from 2007 to 2008. Bevrani et al. (2010) present an overview of the key challenges for BP regarding the integration of VRE units into the power system. Van der Veen (2012) examines to what extent multinational BP markets in Europe improve market efficiency without endangering security of supply. Holttinen (2012) examines experiences and future challenges of wind power integration and relates it to BP. Haucap et al. (2012) find that substantial costs savings were achieved in the German TBP market because of regulatory reforms. Heim and Götz (2013) present evidence for strategic capacity withholding by a bidder with market power.[4] Bessa et al. (2014) discuss how VRE variability and uncertainty in power systems operation can be handled, e.g., how system operators manage their systems based on forecasts of renewable generation. Brijs et al. (2015) statistically analyze negative prices in European BP markets. Wandelt et al. (2015) compare different technologies of power plants for their potential provision of BP. Hirth and Ziegenhagen (2015) connect VRE to BP markets and discuss several implications such as the increased volatility of energy supply caused by solar and wind power plants. Söder (2016) analyzes balancing challenges in sustainable and smart energy systems with 100% renewable energy supply. Jansen (2016) examines the economics of BP provision by VRE. Knaut et al. (2017) investigate the effects of varying tender frequencies on market concentration, and find that shorter time spans of procurement reduce costs substantially. Lorenz (2017) analyzes the future BP provision in a decarbonized electricity sector. Hoogvliet et al. (2017) model the benefits of electric vehicle owners when providing BP in the Dutch market. Maaz et al. (2017) develop an agent-based model for the analysis of strategic bidding in the German BP auctions and compare their findings with market outcomes. Borne et al. (2018) discusses barriers for market entry in the BP markets. Joos and Staffell (2018) study the short-term VRE integration costs and focus on wind curtailment and BP in Britain and Germany.

[4] Therefore, these markets may exhibit oligopolistic properties. A general discussion on oligopolistic market structures in electricity markets can be found in Borenstein et al. (1995) and Bompard et al. (2007, 2010).

2.2 Market overview

In this section, the overview of European market designs is presented. First, general design options are examined, then, the designs of 24 countries as of 2016 are illustrated.

2.2.1 Design options

It is examined whether the three-quality pattern of PBP, SBP and TBP is applied or if certain market qualities are non-existent. If existent, it is reported for each BP quality whether the provision is a compulsory service or an auction is used, and if it is activated manually (MAN).

If an auction is applied, the bid components (BP bid and/or BE bid) are presented and it is stated whether there exist positive and negative BP products (asymmetric product, ASYM) or just one symmetric (symmetric product, SYM). Additionally, the auction frequency (yearly, YE; monthly, MO; weekly, WE; daily, DA) and the activation strategy (merit-order, M.-O.; pro-ratio/parallel, PAR) is examined. Lastly, the reserve periods, their durations (e.g., 24x1h) and the minimum power offer are stated (e.g., 1 MW). Furthermore, pricing rules and scoring rules of the respective markets are discussed. Pricing options are UP and PaB or a combination of these. The scoring rule describes how the winners of the auction are determined (e.g., by a total price, TP, or by stochastic programming, SP). If no parameter is available, it is denoted with “n/a”.

In addition to these BP market design options, the latest possible trading option before physical delivery for Intraday trading is reported. If no Intraday market is available, it is stated “Day-ahead market”.

2.2.2 European markets

In the following, the most crucial results for the 24 European countries are presented. A more detailed overview can be found in Appendix A.

There are intraday trading options in 21 countries, which, however, do not imply equal levels of flexibility: More than half of these countries have trading options of 60 minutes or less before delivery, whereas particularly southern European countries such as Portugal, Spain and Italy must trade several hours in advance of the energy delivery. The respective market clearing price is mostly uniform (see also Grimm et al., 2008; Braun, 2018).

19 countries apply the three-quality pattern of the Entso-E. While SBP is part of many markets, PBP and TBP are not as frequently used. Particularly smaller countries often compel market players to supply PBP or rely on larger neighbouring countries (e.g., Russia for the Baltic states).

Regarding BP market design, nearly every constellation of BP bid and/or BE bid is applied throughout the three qualities. 23 countries distinguish positive from negative BP, especially for SBP and TBP. Only Italy is not distinguishing between the products at all. The auction frequency is highly diverse, ranging from a daily to a yearly procurement. The activation strategy for BE on the other hand is almost consistent throughout the European markets: Merit-order activation is used mainly, merely a few countries activate pro-ratio/parallel. The number of reserve periods, their duration and the minimum size of the power offer vary greatly between the countries and BP qualities. With regard to the applied pricing rule, the picture is also incoherent: In ten countries UP and in eleven countries PaB is used. If UP is applied for BP procurement, this price either depends on an exogenous market price or on the submitted bids. The scoring rule is either based on a TP for BP and BE, only on the BP bid or on SP.

2.2.3 Austrian and German markets

Since this thesis focuses on the BP markets in Austria and Germany, Table 2.1 highlights the characteristics of these markets.

The auctions for PBP, SBP and TBP are carried out on a daily or weekly basis. The PBP (SBP) tenders take place each Tuesday (Wednesday) for the subsequent week. The TBP tender is carried out on a daily basis (Monday to Friday) for the following day or weekend.[5] The procurement of PBP capacities is performed for the entire week, while the procurement of SBP and TBP capacities is divided into different reserve periods with separate markets. In the SBP market, there are two reserve periods: the main period from Monday to Friday from 8am to 8pm, and the sub-period for the rest of the time.[6] Thus, there are four SBP auctions each week. In the TBP market, each day is divided into six blocks with a period of four hours, resulting in 12 separate TBP auctions each day.

There are two crucial differences between the PBP auction and the SBP/TBP auctions. Firstly, bidders submit two-dimensional bids in the PBP auction (power offer, BP bid), while they submit three-dimensional bids in the SBP and TBP auctions (power offer, BP bid and BE bid).[7] Secondly, in the SBP and TBP auction, positive and negative capacities are procured separately, which is not the case in the PBP auction.[8]

In the PBP, SBP and TBP auctions, the scoring rule is based on the BP bid exclusively. Ties are resolved by considering the corresponding BE bids and power offers. Furthermore, PaB is applied as pricing rule, and the activation strategy for BE is a merit-order, i.e., in the PBP auction

[5] The TBP auction can also be organized on a weekly basis with an auction date on Thursday (regelleistung.net, 2018a; Austrian Power Grid, 2018).

[6] The main period (sub-period) is also referred to as "peak" period ("off-peak" period).

[7] In the PBP market, bidders integrate the capacity costs and the calling costs in the BP bid.

[8] Because of these two essential design differences, our theoretical analyses in the subsequent chapters – focusing on the current Austrian and German SBP auctions and the future European SBP auction – cannot be transferred to the PBP auction without adaptations.

	PBP market	SBP market	TBP market
Auction frequency	WE	WE	DA
Auction date	Tue.	Wed.	Mon.–Fri.
Reserve periods	1x168h	main-/sub-period[1)]	6x4h
Bid components	power offer, BP bid	power offer, BP & BE bid	power offer, BP & BE bid
Products	SYM	ASYM	ASYM
Scoring rule	BP bid	BP bid	BP bid
Pricing rule	PaB	PaB	PaB
Activation strategy	M.-O. of BP bids	M.-O. of BE bids	M.-O. of BE bids

1) The main period includes Monday to Friday from 8am to 8pm and the sub-period the rest of the time.

Table 2.1: Overview of the current Austrian-German PBP, SBP and TBP markets (regelleistung.net, 2018a; Austrian Power Grid, 2018).

based on the BP bids, and in the SBP and TBP auctions based on the BE bids (regelleistung.net, 2018a; Austrian Power Grid, 2018).

2.2.4 Harmonized European markets

This thesis also considers the future harmonization of European BP auctions (see chapters 4 and 5). Therefore, a brief overview of the harmonization efforts for the three BP qualities is presented in the following.

For the PBP market, a cooperation of eight European countries already exists since 2011. In the "International Grid Control Cooperation (IGCC)" the netting of demands for BP is enabled across the participating countries (regelleistung.net, 2018a; Entso-E, 2017).[9] Opposite and unnecessary activations of BP are avoided, resulting in financial benefits of around 300

[9]The IGCC refers to PBP. The participating countries in the IGCC are: Austria, Belgium, the Czech Republic, Denmark, France, Germany, the Netherlands, and Switzerland regelleistung.net (2017).

Mio. Euro since 2011 (Transnet BW, 2016).[10] Consequently, the PBP auction is already carried out on a European-wide level, and changes in the market design are not to be expected in the near future (Entso-E, 2017).

For the TBP market, two cooperation initiatives exist: the Austrian-German GAMMA project and the European MARI project.[11] Yet, a European TBP auction is not to be implemented before 2021 (Entso-E, 2017).

The harmonization of the SBP auction starts in 2019 and must be executed no later than 2021 (European Commission, 2017). Due to the imminent start of the harmonization process, 14 European TSOs started the so-called PICASSO project (Entso-E, 2017).[12] It aims at facilitating the upcoming transition towards a harmonized European SBP auction. The future European SBP market is similar to the current Austrian-German SBP design. Yet, it includes several modifications (see Table 2.2). Firstly, the procurement of SBP is conducted on a daily basis with six reserve periods, each for four hours. Secondly, UP is to be used for both the BP bid and BE bid. Thirdly, voluntary BE bids are to be introduced mandatorily, i.e., bidders that were not awarded or did not participate in the regular SBP auctions are allowed to submit additional BE bids and, thus, have a second chance to be part of the merit-order.

2.3 Bidder characteristics

In the following, BP bidder characteristics are discussed. This includes a brief discussion of the prequalification process and the cost structure.

[10] The IGCC does not encompass a fully integrated market, i.e., an Austrian bidder cannot offer BP in the French market boundlessly and across all BP qualities.

[11] GAMMA stands for German Austrian Manual Merit-order Activation, and MARI stands for Manually Activated Reserves Initiative.

[12] PICASSO stands for Platform for the International Coordination of the Automatic Frequency Restoration Process and Stable System Operation. The active member states are Austria, Belgium, France, Germany, and the Netherlands, and the observer states are Bulgaria, the Czech Republic, Denmark, Finland, Hungary, Norway, Poland, Sweden, and Slovenia (Entso-E, 2017).

	AT-GER market	European market
Joint design elements		
Bid components	power offer, BP bid, BE bid	
Products	ASYM	
Scoring rule	BP bid	
Activation strategy	M.-O. of BE bids	
Diverging design elements		
Market scope	Germany & Austria	Europe
Frequency	WE (Wed.)	DA
Reserve periods	main & sub-period	6x4h
Pricing rule	PaB	UP
Voluntary BE bids	no	yes
Gate closure BE bid	weekly	hourly

Table 2.2: Overview of the Austrian-German (AT-GER) and the future European SBP market (regelleistung.net, 2018a; Austrian Power Grid, 2018; European Commission, 2017).

2.3.1 Prequalification

Since the provision of BP requires a high degree of operational and technical flexibility, potential bidders must undergo an elaborate prequalification process for market participation. In consequence, the set of bidders is highly invariant and limited, i.e., usually the same bidders compete within the BP auctions (Knaut et al., 2017). For a better understanding of the prequalification process, the criteria set by the German TSOs are briefly illustrated (regelleistung.net, 2018b).

Bidders who intend to participate in the BP auction must ensure that their prequalified capacity exceeds the minimum power offer. For this, the responsible TSO concludes a framework agreement with the bidder, which includes information about the nominal capacity, minimum capacity and maximum capacity of a bidder's plant. As soon as all the required certificates, protocols and other documents have been submitted, the technical prequalification commences, which lasts at least two months.

Within this technical prequalification, a bidder demonstrates that her plant meets the load gradient requirements: the plant must ramp up and down within the predefined activation time. This procedure makes sure that a plant is able to stabilize the grid frequency if deviations occur. In addition to the technical prequalification, the proper provision of BP must be guaranteed under operational conditions. For this, systems for information communication must be installed and tested.

2.3.2 Cost structure

The costs of providing BP depend on the operation mode of a bidder's plant. If a plant runs independently of BP, a bidder is obliged to sell the respective energy on the wholesale market. If a plant is used for BP only, all costs (e.g., starting costs or usage costs) must be covered by the BP participation. To capture these differences in the cost structures, Müsgens et al. (2014) introduced so-called "inframarginal" and "extramarginal" bidders: A bidder is inframgarinal (extramarginal), if the variable costs of her plant are smaller (greater) than the wholesale market price. Hence, inframarginal plants can sell their energy on an alternative energy market, which determines their opportunity costs. Extramarginal bidders cannot participate profitably at an alternative energy market and, thus, must not consider opportunity costs, but costs for running the plant.

2.3.2.1 Capacity costs

The capacity costs include costs for keeping capacity available to the grid in the reserve period, and are included in the BP bid (unit Euro/MW). Here, the interdependenies with the wholesale market is important: a BP bidder cannot offer her entire capacity on the wholesale market, however, has to run her plant at a certain minimal load. Depending on whether a bidder is inframarginal or extramarginal and whether positive or negative BP is offered, different costs occur.

For positive BP, inframarginal bidders sell their minimal load at the wholesale market with a profit. Furthermore, they must consider opportunity costs, which are given by the margin between the wholesale market price and the variable costs multiplied with the reserve period and power offer. For an extramarginal bidder, there are no opportunity costs, but the costs for running the power plant at a minimal load capacity and selling the respective energy at a market price lower than the variable costs. In addition, starting costs and usage costs are of importance for extramarginal bidders. Therefore, the calculation of capacity costs for extramarginal bidders is complex and can differ substantially between different plant types.

For negative BP, there are no opportunity costs for inframarginal power plants. All of the energy produced is sold with a profit. An extramarginal bidder must run at a certain level above minimal load in order to be able to reduce its load. Hence, she generates losses, which depend on the difference between variable costs and the wholesale market price. Again, starting costs and usage costs only occur for extramarginal power plants.

2.3.2.2 Calling costs

The costs for delivering BE are assigned to the BE bid (unit Euro/MWh). These costs occur if BP is actually called by the tendering authority, and they vary for inframarginal bidders and extramarginal bidders.[13]

For positive BP, these costs equal the variable costs of a bidder's plant because she increases her load level. For negative BP, these costs are actual savings for both inframarginal bidders and extramarginal bidders.

[13] In the Austrian-German SBP markets, this is executed automatically according to the merit-order.

The reason for this is that bidders are still remunerated with the wholesale market price: If negative BP is needed, there is too much energy supplied to the power system. Therefore, a bidder must not generate traded energy herself. Additionally, a bidder saves the variable costs of running her plant because she must reduce its load level. Consequently, bidders are willing to pay the tendering authority for the provision of negative BP. The maximum willingness to pay is determined by the variable costs.

Chapter 3

The German paradox in the balancing power markets

The starting point of this chapter is the article by Hirth and Ziegenhagen (2015) who link VRE (wind and solar) to BP markets. They present the so-called German paradox: In spite of the extreme increase in energy production by VRE, BP demand has decreased. The authors qualitatively mention some possible reasons for this paradox and point to further investigations. We take this up, conduct quantitative analyses, and provide a plausible explanation for the paradox. Our argument is based on the combination of efficiency savings from national and international grid control cooperations and recent changes in the German energy market designs.

Hirth and Ziegenhagen (2015) also consider the development of the prices in the German BP markets and refer to some factors that may have an effect, but do not provide a quantitative evaluation. We systematically examine these markets and present a quantitative analysis of the market data. Here we focus on the development of the demands and of the prices in the German SBP markets. In our analysis, we concentrate on the German SBP market because it is the market with the highest market volume and, thus, is most important for overcoming deviations of the grid frequency (regelleistung.net, 2018a; Borne et al., 2018). Our analysis supports the hypothesis that bidders successfully coordinate on a high and non-competitive price level. This finding is an indication for collusive behavior that is facilitated by the weekly repetition of the auction.

This chapter is structured as follows: In Section 3.1 we present our plausible explanation for the German paradox. Section 3.2 analyzes price developments in the SBP market. Section 3.3 concludes.

3.1 The German paradox

Hirth and Ziegenhagen (2015) raise the question why the German BP demand did not increase in response to the immense growth of wind and solar energy production. They offer various reasons for this development, such as the German TSO cooperation in reserve sizing. A quantitative investigation of these possible influencing factors, however, is not presented. In the following, we argue that international and national TSO cooperations led to efficiency savings, which, together with adaptations in the German energy market, reduce the requirement for BP.

3.1.1 Savings through grid control cooperations

Efficiency savings that result from the cooperation of the German and the international TSOs provide a first plausible explanation for the German paradox. In the period of 2009 until 2010 the four German TSOs introduced a common BP market as part of the German grid control cooperation, the so-called “Netzregelverbund” (regelleistung.net, 2018a). Since the German TSOs are legally obliged to procure BP at the lowest possible costs, it would be highly inefficient if, for example, in one control area positive BP is called, while negative BP needs to be activated in another control area. A more cost efficient solution is to link both control areas and thereby avoid activating power plants for providing opposite BP.

Figure 3.1: Example for the national TSO cooperation (Netzentwicklungsplan, 2016).

This is illustrated in a simple example, which is based on Sprey et al. (2015). Figure 3.1 shows the four different control areas in Germany that are operated by the four TSOs (50 Hertz, Amprion, TenneT, TransnetBW) in Germany (Netzentwicklungsplan, 2016). In each of the four areas the demand for BP is indicated exemplarily by the amount of MW in the areas. In this example, the total demand for BP without a cooperation of the four TSOs would be 450 MW of negative BP and 150 MW of positive MW, i.e., 600 MW in total. By linking the different control areas, the BP demand drops to 300 MW (only negative), since the negative and positive BP demands can be canceled out. This simple example illustrates how the connection of different control areas substantially reduces the need for BP and is in line with the significant drop of dispatched BE after the introduction of the German grid control cooperation (Bundesnetzagentur and Bundeskartellamt, 2016).

Since these savings are not only possible by linking different German control areas, but also between different countries, the IGCC was founded in 2011 (Austrian Power Grid, 2016). Here, TSOs from Austria, Belgium, the Czech Republic, Denmark, France, Germany, the Netherlands and Switzerland participate. Since the introduction of the IGCC in 2011 until the end of 2014, 2,98 terawatt hours of negative and positive BP were saved (Fattler and Pellinger, 2015). For example, Germany saved about 25% of positive SBP and about 10% of negative SBP out of this cooperation. In total, this results in efficiency savings for Germany of about 12 Mio. Euro in 2012, 18 Mio. Euro in 2013, and 24 Mio. Euro in 2014.

3.1.2 Adaptations in the German energy market design

Recent changes in the German energy market design constitute the second part of our argument. In Germany, energy is generated by four large and many small municipal utilities. The spot market at the European Energy Exchange (EEX) in Leipzig, where most of the German energy trading takes place, consists of the Day-ahead market and the Intraday market (see also Section 1.1.1). In the latter, energy can be traded continuously until 30 minutes before delivery (EPEX Spot SE, 2016b). This is especially relevant for power plants that cannot plan their energy production for more than a few hours, such as wind and solar power plants. That is why with the increasing amount of wind and solar energy production, the market volume of the Intraday market should grow at the same pace. In Figure 3.2 the amount of energy traded at the Intraday market (European Energy Exchange, 2016) and the installed power of VRE (Federal Ministry for Economic Affairs and Energy, 2016) are depicted.

The graphs show that with the increasing installed VRE capacity the Intraday market volume increased as well. This growth in trading volume

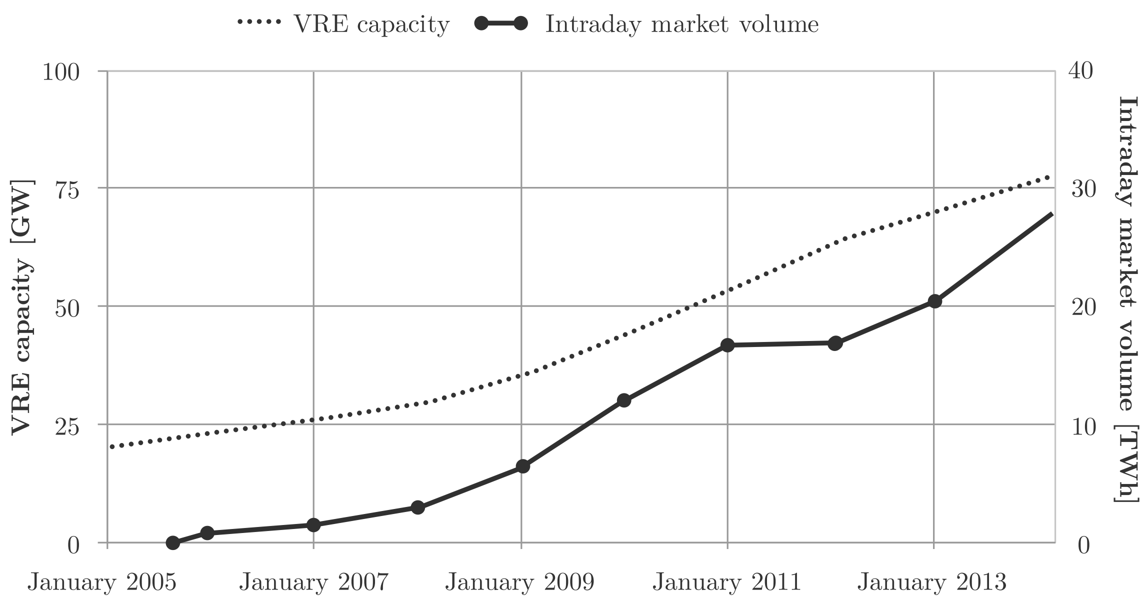

Figure 3.2: Development of the German Intraday market volume and the installed VRE capacities in Germany since December 2005 until December 2014 (European Energy Exchange, 2016; Federal Ministry for Economic Affairs and Energy, 2016).

in the Intraday market lead to a reduced need for BP due to more flexible allocation possibilities.

Additionally, the EEX market platform was expanded with a 15 minutes Intraday contract market in December 2014. Within this new 15 minutes market, the 96 quarter-hour contracts for energy delivery on the next day can be traded (EPEX Spot SE, 2016a). Since the market participants' energy supply needs to be balanced on a 15-minutes-basis, 60-minutes-contracts from the Day-Ahead market do not meet the VRE market participants' requirements. In Figure 3.3, this is illustrated for a load profile of a solar power plant. Here, the energy supply from 6am to 10am is depicted. Since the energy supply of a solar power plant depends on the weather conditions, the energy supply is not constant but volatile (see "cloudy period" in Figure 3.3). With the 60-minutes Day-ahead auction, a possible trading profile of the solar power plant is illustrated. The actual energy production and the traded energy volume differ substantially.

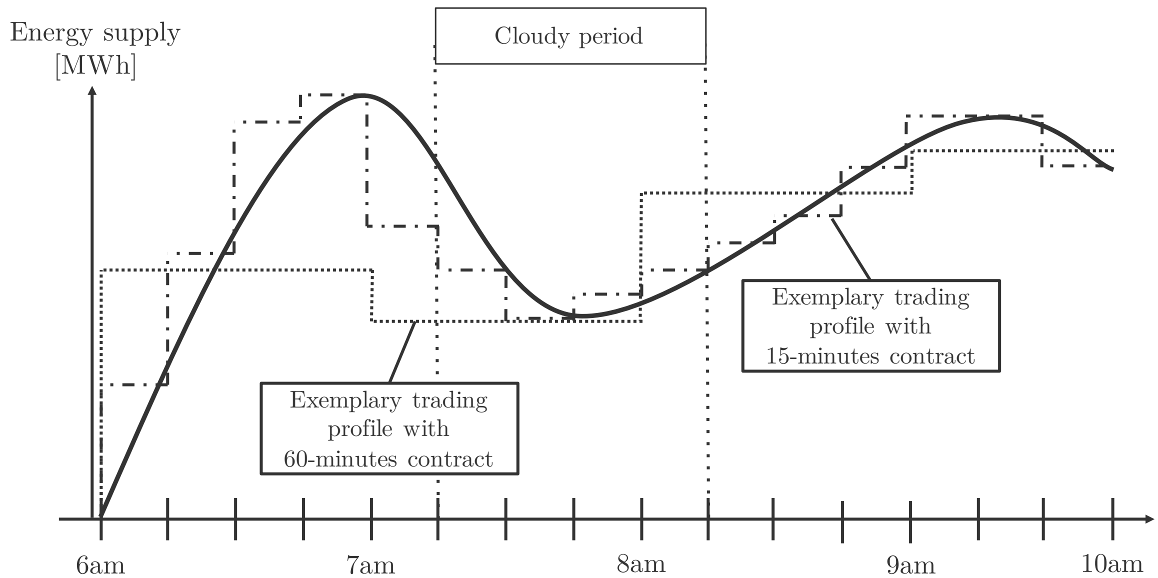

Figure 3.3: Exemplarily energy supply and trading profiles with 60-minutes and 15-minutes contracts.

With the 15-minutes contracts, the trading profile is much closer to the actual energy supply of the solar power plant. Hence, the actual energy production and the expected energy production converge. This leads to a lower BP demand (Braun and Brunner, 2018).

Concluding, we present two approaches to a resolution for the German paradox. Remarkable efficiency savings were achieved by the German TSO cooperation and the IGCC, which together with adequate adaptations of the German energy market design (i.e., integration of flexible energy trading in the continuous and in the contract Intraday market) lead to a lower demand of BP.

3.2 German Secondary Balancing Power market data

The price developments in the German BP markets are not trivial to comprehend. Hirth and Ziegenhagen (2015) present a number of “shocks” that could have an impact such as a contracted demand, supply shocks (e.g., nuclear phase-out), lower margins on the spot market or BP markets becoming more competitive. In the following, we analyze the impact of the demand on prices and investigate whether the participating bidders use previous auction prices as an orientation for their BP bids. The data is provided by the German TSOs and can be publicly accessed via regelleistung.net (2018a). Hereby, we concentrate on the SBP market. We analyze the period from January 2012 to December 2014. The reason for this is that in late 2011 changes in BP market design (Hirth and Ziegenhagen, 2015) and in December 2014 changes in spot market design were implemented (see Section 3.1.2). These changes in market design could have had significant influence on the behavior of the bidders and, thus, are not considered for our analysis. In consequence, our investigation is based on market data of 35 entire months with a total of 153 auctions.

3.2.1 Development of the market demands

Figures 3.4 and 3.5 depict the development of the demands in the positive and negative SBP markets (main period and sub-period) for the period from January 2012 until December 2014 (regelleistung.net, 2018a).

The demand on both negative SBP markets strongly fluctuates until August 2013. The reason for this is that the TSOs provided BP with their own capacities, the so-called “Kernanteil”, until August 2013 (a total of 87 auctions) (Consentec, 2014). The provision of BP out of the TSOs’ capacities led to a substantial reduction of demand for negative BP (regelleistung.net, 2018a). For the positive SBP markets, no BP capacities were exclusively supplied by the TSOs. Except of one outlier, the demand on both positive SBP markets is quite constant, which also applies to the demand on the negative SBP markets after August 2013.

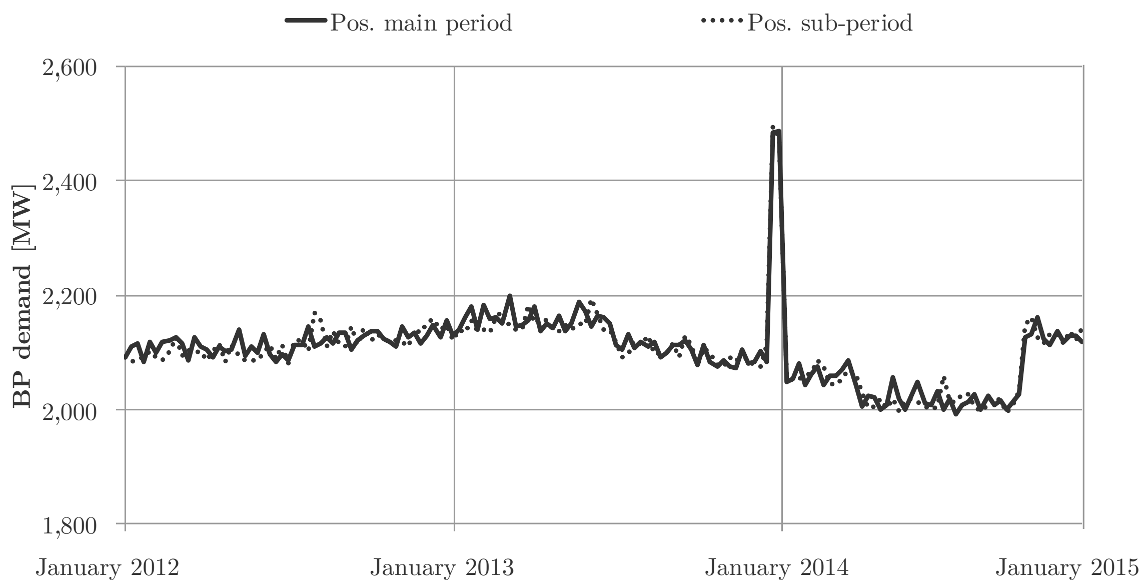

Figure 3.4: Development of the German positive SBP demand from January 2012 until December 2014 (regelleistung.net, 2018a).

Furthermore, interesting demand developments can be noticed. Firstly, there is a huge increase in demand for positive and negative SBP at Christmas and New Year's Eve in 2013. The reason for that could be a combination of two facts: While companies commonly don't produce at full capacity at this time, household energy consumption may be expected to rise because people are usually at home and use electrical devices such as light, computer, or television more often. Therefore, more BP in both directions is needed. However, such a demand peak did not appear at the end of the year 2012. Secondly, our analysis reveals that since August 2013 the demand for negative SBP is always below the demand for positive SBP. This is due to the fact that the TSOs fear an underproduction of energy more than an overproduction. Thirdly, the demand in all four markets increased at the end of 2014. This could be the result of a more variable household energy consumption due to changing weather conditions.

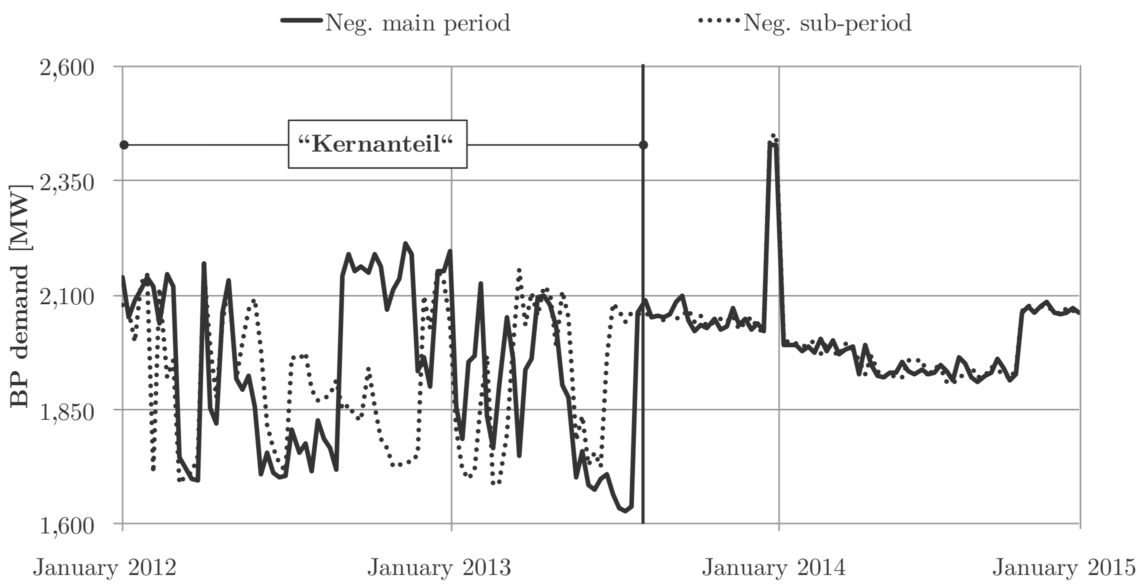

Figure 3.5: Development of the German negative SBP demand from January 2012 until December 2014 (regelleistung.net, 2018a).

Table 3.1 provides some statistical data for the development of the demand, denoted by B and measured in MW, in all four SBP markets. For the positive markets, all 153 auctions in the years 2012 to 2014 are taken into account, while for the negative markets, we restrict our analysis to the 66 auctions after August 2013, i.e., without the provision of the Kernanteil. Note that the demand maximum $\text{Max}(B)$ in each market is given by the mentioned outlier at the end of 2013. The relatively small standard deviation $\sigma(B)$ on each market indicates only slight demand fluctuations.

3.2.2 Development of the market prices

After illustrating the developments of SBP demand, we now examine the corresponding prices. In our analysis we focus on the BP bids because they are directly linked to the BP demand. Other than the demand for BP, the demand for BE is ex ante uncertain. However, we also take the BE bids

Market	# Auctions	$\mu(B)$	Min(B)	Max(B)	$\sigma(B)$
Pos. main period	153	2,104	1,992	2,487	65
Pos. sub-period	153	2,101	1,994	2,494	64
Neg. main period	66	2,009	1,911	2,429	91
Neg. sub-period	66	2,008	1,908	2,450	94

Table 3.1: Statistical data for the market demand B, measured in MW, in the German SBP markets from January 2012 until December 2014 (regelleistung.net, 2018a).

into account when analyzing and interpreting the development of the BP prices. For the positive and negative SBP markets, the development of the BP prices (i.e., weighted average of the awarded BP bids) is presented in figures 3.6 and 3.7 for the 153 auctions from January 2012 until December 2014. These data are published by the TSOs (regelleistung.net, 2018a).

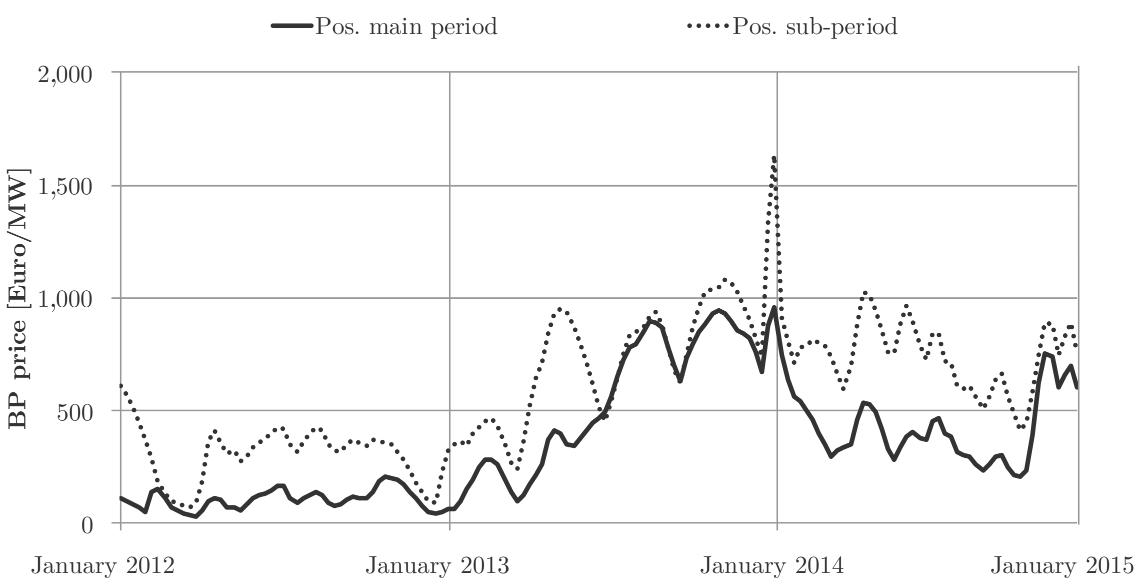

Figure 3.6: Development of the BP prices (weighted average of the awarded BP bids) on the German positive SBP market (main period and sub-period) from January 2012 until December 2014 (regelleistung.net, 2018a).

Table 3.2 provides some statistical data of the prices, which are denoted by p_{BP} and measured in Euro/MW. Again, we only consider the 66 auc-

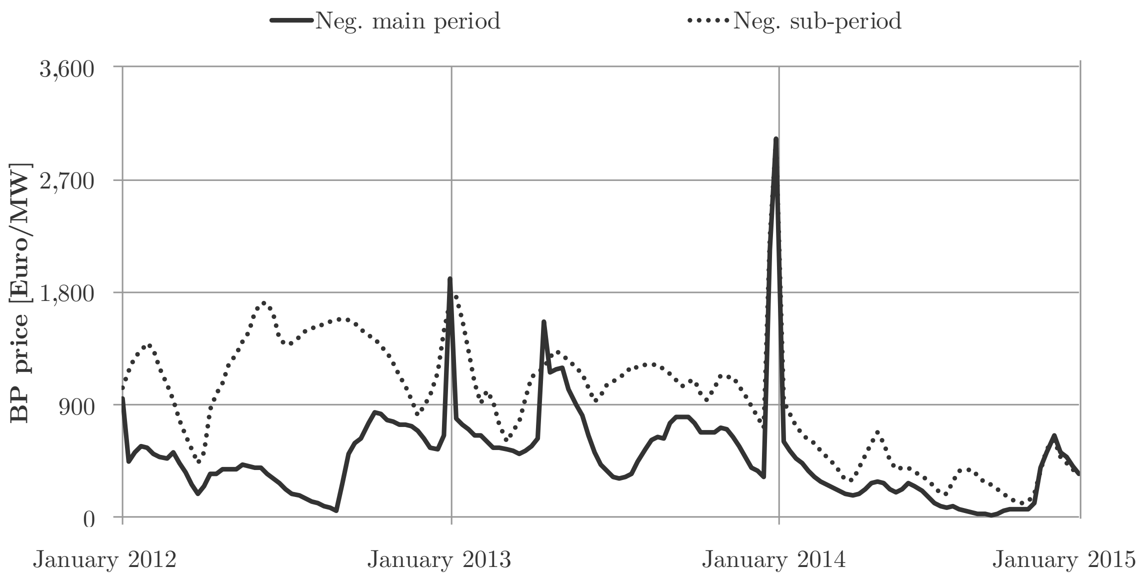

Figure 3.7: Development of the BP prices (weighted average of the awarded BP bids) on the German negative SBP market (main period and sub-period) from January 2012 until December 2014 (regelleistung.net, 2018a).

tions after August 2013 for the two negative markets. The high standard deviations $\sigma(p_{BP})$ in all four markets indicate a much higher fluctuation of the average BP prices than of the demand.

3.2.3 Linking prices with demand

Let us now examine the interdependence between prices and demand in the SBP markets. In order to illustrate whether changes in demand have

Market	# Auctions	$\mu(p_{BP})$	Min(p_{BP})	Max(p_{BP})	$\sigma(p_{BP})$
Pos. main period	153	356	27	957	270
Pos. sub-period	153	591	69	1,634	286
Neg. main period	66	412	17	3,029	451
Neg. sub-period	66	651	114	3,016	486

Table 3.2: Statistical data of the BP prices in Euro/MW in the German SBP markets from January 2012 until December 2014 (regelleistung.net, 2018a).

an impact on prices, we first generate scatterplots of demand and prices. The data of the positive SBP market are presented in figures 3.8 and 3.9 and of the negative SBP market in figures 3.10 and 3.11. As before, for the sake of comparability, we only consider the 66 auctions after August 2013 on the two negative markets.

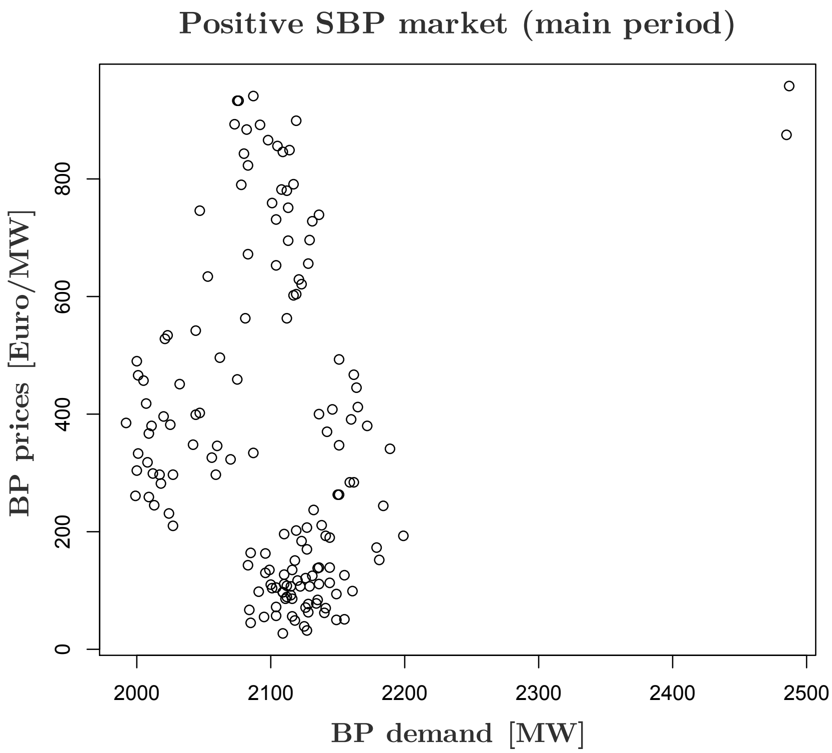

Figure 3.8: Scatterplots of market demand [MW] and prices [Euro/MW] for the positive SBP market in the main period (regelleistung.net, 2018a).

Under the same supply conditions, a higher demand should induce higher prices because a larger number of BP bids needs to be accepted to cover the higher demand. In order to examine whether there is a monotonic relationship between demand and prices, we compute Spearman's rank correlation coefficient ρ for each market. Surprisingly, for both positive markets the coefficient is negative ($\rho = -0.237$ for the main period, $\rho = -0.299$ for the sub-period), which can be interpreted as an indication

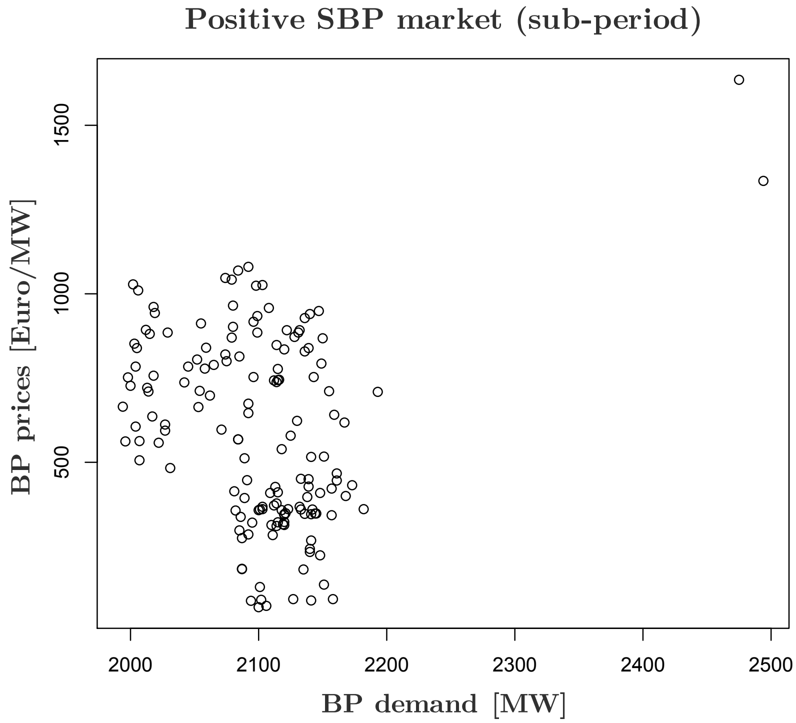

Figure 3.9: Scatterplots of market demand [MW] and prices [Euro/MW] for the positive SBP market in the sub-period (regelleistung.net, 2018a).

for a negative relationship between demand and prices.

The comparison of the price development in figures 3.6 and 3.7 with the demand development in figures 3.4 and 3.5 reveals that in both positive markets the price level strongly increases in 2013, although the demand remains on the same level. When splitting the considered period into two half-periods (first half-period from 01/02/2012 until 07/08/2013, second half-period from 07/15/2013 until 12/01/2014), the comparison of the average prices and average demands in the two half-periods supports our hypothesis of two different price levels: for the first (second) half-period of the main period the average price is 170 Euro/MW (561 Euro/MW) and the average demand is 2,129 MW (2,077 MW), and for the first (second) half-period of the sub-period the average price is 393 Euro/MW (808 Euro/MW) and the average demand is 2,124 MW (2,077 MW). That is,

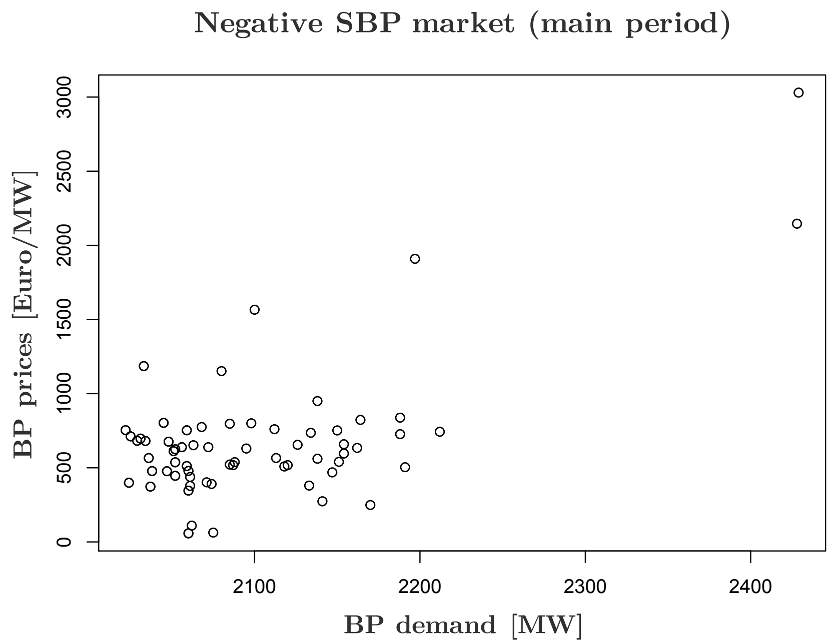

Figure 3.10: Scatterplots of market demand [MW] and prices [Euro/MW] for the negative SBP market after August 2013 in the main period (regelleistung.net, 2018a).

from the first to the second half-period the price level more than doubles in both positive markets, although the demand even slightly decreases.

Remarkably, the corresponding average BE bids also increase: 173 Euro/MWh (285 Euro/MWh) for the first (second) half-period of the main period and 180 Euro/MWh (287 Euro/MWh) for the first (second) half-period of the sub-period (regelleistung.net, 2018a). That is, both the price level for BP and the price level for BE increase. Bidders do not compensate their higher BP bids by lowering the BE bids. Moreover, the number of bidders in the SBP markets increased steadily (Hirth and Ziegenhagen, 2015). This in combination with the near-constant demand indicates an increased level of competition. Against this background, the higher price levels are counterintuitive. We take a closer look at this in Section 3.2.4.

The separate analysis of the two positive markets for the half-periods reveals significantly positive Spearman's rank correlation coefficients:

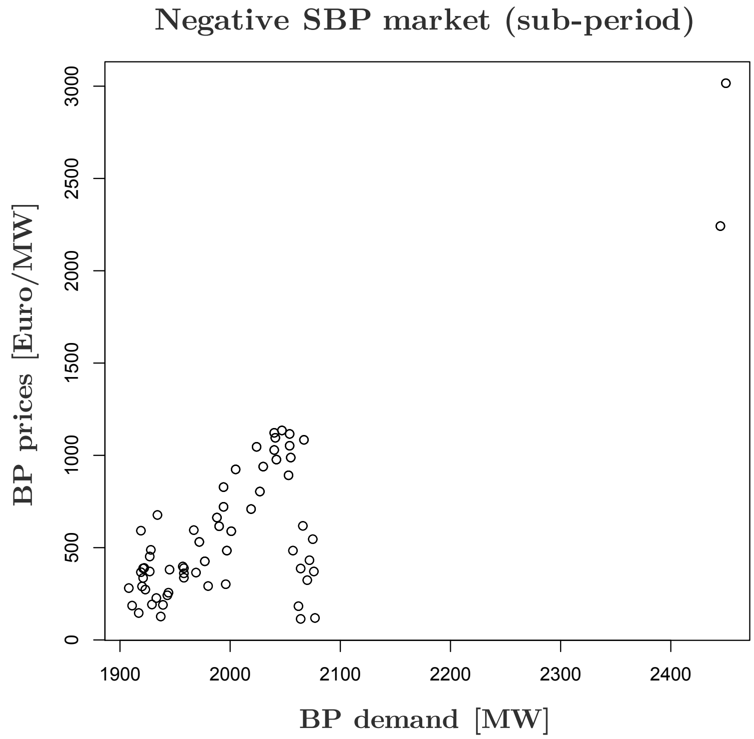

Figure 3.11: Scatterplots of market demand [MW] and prices [Euro/MW] for the negative SBP market after August 2013 in the sub-period (regelleistung.net, 2018a).

$\rho = +0.410$ ($\rho = +0.560$) for the first (second) half-period of the main period and $\rho = +0.264$ ($\rho = +0.210$) for the first (second) half-period of the sub-period.[1] This is a clear indication for the expected monotonic relationship between prices and demand within the two half-periods.

In the main period of the negative SBP market the relationship between demand and prices is weakly positive but not significant ($\rho = +0.054$), whereas for the sub-period in the negative SBP market we find a significantly positive relationship ($\rho = +0.537$).[2]

[1] Single-sided t-tests, $df = 80$ (first half-period), $df = 73$ (second half-period); main period: first half-period, test-value = 3.97, p-value < 0.001; second half-period, test-value = 5.70, p-value < 0.001; sub-period: first half-period, test-value = 2.42, p-value < 0.01; second half-period, test-value = 1.81, p-value < 0.05.

[2] Single-sided t-tests, $df = 66$; main period: test-value = 0.42, p-value > 0.3; sub-period: test-value = 5.09, p-value < 0.001.

3.2.4 Adjustment to previous auction results

The analysis in Section 3.2.3 indicates that in both positive SBP markets the price level in the second half-period is much higher than in the first half-period and (far) above the competitive price level. This indicates that bidders successfully coordinate on a high price level and are able to maintain it during the second half-period. Evidence for a coordination of bidders in the German SBP market was already found between 2009 and 2010: a supply reduction of the most dominant bidder caused a higher price level (Heim and Götz, 2013). As the number of bidders has continuously increased in the SBP market since 2010 (Hirth and Ziegenhagen, 2015), the influence of a single bidders on prices has decreased, which should make coordination even more difficult. Our hypothesis is that bidders yet manage to coordinate on a high price level by adjusting their bids to previous auction prices. Recent scientific work indicates that the most expensive accepted BP bid of the previous auctions could serve as a focal point for coordination (Müsgens et al., 2014).

To test our hypothesis that bidders adjust to previous price levels, we compute the autocorrelation of consecutive auction prices (weighted average of the awarded BP bids) by applying the Durbin-Watson autocorrelation test to the positive SBP markets.[3] The test results for the first five lags (i.e., the five preceding auction periods) are presented in Table 3.3. The strong positive autocorrelation in the main period and the subperiod of the positive SBP market is an indication that bidders try to establish a high price level. This might be an explanation for the observed non-competitive prices in the positive SBP markets (see Section 3.2.3).

[3] The Durbin-Watson test-statistic dw ranges from 0 to 4. As a rule of thumb, $dw \leq 1$ is an indication for a positive correlation, and $dw \geq 3$ for a negative correlation.

Lag	Main period		Sub-period	
	Autocorrelation	*dw*	Autocorrelation	*dw*
1	0.961	0.066	0.928	0.144
2	0.910	0.157	0.820	0.357
3	0.864	0.230	0.750	0.490
4	0.824	0.294	0.701	0.577
5	0.781	0.370	0.667	0.636

Table 3.3: Durbin-Watson autocorrelation test with test-statistic *dw* for the first five lags in the positive SBP market, auction data retrieved from regelleistung.net (2018a).

3.3 Conclusion

We offered an explanation for the German paradox in the BP markets in response to Hirth and Ziegenhagen (2015). We argued that the increasing energy production from VRE did not necessarily require an increase in BP demand. On the one hand, the German energy market was extended by two flexible trading options within the last five years. As a consequence, the increasing energy supply from VRE was flexibly traded and did not require a higher power reserve. On the other hand, national and international grid control cooperations for BP led to considerable efficiency savings. Thus, uneconomical activation of BP was avoided and the necessary demand for BP could be reduced.

Furthermore, we found evidence that the bidders successfully managed to coordinate on a high and non-competitive price level. The bidding practice of simple bid repetition is consistent with the observation that the high price level is maintained for a long time. Since the BP market mechanism is highly complex, adjusting the bids to previous auction results is an easy and obvious strategy.

Chapter 4

Allocation, prices, and costs in the electricity wholesale and balancing power market – an integrated approach

In most theoretical analyses, the interdependencies of the electricity wholesale market and the BP market are not appropriately considered. For example, Müsgens et al. (2014) and Hirth and Ziegenhagen (2015) assume that the wholesale market price is exogenous. This yields two classes of bidders: bidders with power plants that have variable cost below the wholesale market price, and bidders with variable cost above the wholesale market price. The former sell energy profitably on the wholesale market, while the latter do not participate in this market. Müsgens et al. (2014) denote these two types of bidders as inframarginal bidders and extramarginal bidders (see Section 2.3.2). This distinction has a direct impact on the costs for providing BP: inframarginal bidders must integrate opportunity costs of not trading at the wholesale market, and extramarginal bidders must cover their expenses by the BP profits.

To our knowledge, only Just and Weber (2008) address these interdependencies: BP bidders cannot offer their entire capacity on the wholesale market, however, have to run their plants at a certain minimal load. The authors focus on the identification of reservation pricing and the influence of reserve capacity on the supply function of the wholesale market. For this, they apply a complex numerical solution procedure.

Our approach relates to the work of Just and Weber (2008), however, we use a different methodology. We develop an integrated market model to analyze the interdependencies between the energy wholesale market and the BP market. The interplay between the markets induces a specific assignment of the energy producers (who differ in their production costs and their ability to provide BP) to the different markets. There exists a unique market equilibrium that ensures efficiency under certain assumptions. We also consider prices and costs in the markets as well as the distribution of surpluses. The comparison with German market data reveals that the actual costs are higher than predicted by our model. This holds particularly for the costs resulting from the BE bids: The gap between the predicted and observed BE costs increased over the years, although the costs of the BP bids substantially decreased at the same time. We consider this as an indication that the bidders successfully coordinated on a price-level above the theoretical equilibrium, which is facilitated by the regular repetition of the BP auctions and the limited number of bidders (Knaut et al., 2017).

The remainder of this chapter is structured as follows. Section 4.1 presents the integrated market model. Section 4.2 discusses the market equilibrium. Section 4.3 contrasts theoretical findings with German market data, and Section 4.4 considers empirical BE prices. Section 4.5 concludes.

4.1 Integrated market model

In this section we first illustrate how the markets interrelate and then present our model.

4.1.1 Interdependencies

BP is provided by prequalified bidders that have to meet specific technical requirements, i.e., a certain degree of technical flexibility regarding the operation mode of their plant (see Section 2.3.1). Since not all types of power plants are qualifiable, there is a coexistence of two distinct types of bidders on the wholesale market: bidders that exclusively offer their capacities in the wholesale market, and bidders who can offer their capacities on both the wholesale market and the BP market. Thus, there are fundamental interconnections between the two markets because BP bidders cannot offer their entire capacity on the wholesale market, however, must run their power plants at a certain minimal load. This results in must-run capacities that are sold on the wholesale market (Just and Weber, 2008).

4.1.2 The model

There are three energy markets: a wholesale market, a positive and a negative BP market. We consider a certain period (e.g., one year). The average demand on the wholesale market in this period is denoted by D and measured in gigawatt (GW). 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 bidders whose variable energy production costs lie in the interval $[c_0, c_1]$. We assume that bidders reveal their cost in their energy bids. This is justified by the implementation of UP, i.e., all awarded bidders receive the marginal price on all markets.[1] Thus, the supply function

[1]Game-theoretical results indicate that equilibrium bidding strategies converge towards bidders' true costs

$S : [c_0, c_1] \to \mathbb{R}^+$ is strictly increasing and $S(c)$ is the supply at price c. The inverse function is $S^{-1} : \mathbb{R}^+ \to [c_0, c_1]$. There are two types of bidders: BP-capable (BP) bidders and non-BP-capable (nBP) bidders. The nBP bidders only participate on the wholesale market, while BP bidders can participate on the wholesale market and the BP market. For the latter, they must run their plant on a minimal load (i.e., share of capacity) $m \in [0, 1)$ and sell this energy on the wholesale market. The supply includes BP and nBP bidders: $S(c) = S_{BP}(c)+S_{nBP}(c)$, where $S_{BP} : [c_0, c_1] \to \mathbb{R}^+$ and $S_{nBP} : [c_0, c_1] \to \mathbb{R}^+$ denote the strictly increasing supply functions of BP bidders and nBP bidders. We assume that BP bidders are uniformly distributed among all bidders: at each cost level c, the BP bidders' share of the supply $S(c)$ is $\delta \in [0, 1]$ and, thus, the nBP bidders' share is $1 - \delta$.

Discrepancies between demand and supply are balanced by calling BP, i.e., BP bidders deliver the required BE. The function

$$z : [-B^-, B^+] \to [0, 1] \tag{4.1}$$

describes the distribution of the difference between demand and supply in the period, where $z(y)$ for $y < 0$ refers to excess supply and, thus, to the call of negative BP, while $z(y)$ for $y \geq 0$ refers to excess demand and to the call of positive BP (see Figure 4.1). We assume that the discrepancies are only caused by supply fluctuations due to production deviations.[2]

Hence, (4.1) also describes the probabilities for calling BP (see Figure 4.4 as an example). That is, $z(y)$ for $y < 0$ ($y \geq 0$) is the frequency for an excess supply (excess demand) of at least $|y|$ GW and, thus, the share of time within the period where a minimum capacity of $|y|$ negative (positive)

under certain assumptions (see Chapter 5 and Ocker (2017b)). Furthermore, UP represents the usual market pricing mechanism on the wholesale market (see Section 2.2.2), and considers the future harmonized European SBP auction design (see Section 2.2.4).

[2]This can be justified by the increasing penetration of VRE into the power system because their energy production depends on the weather conditions and is therefore highly volatile.

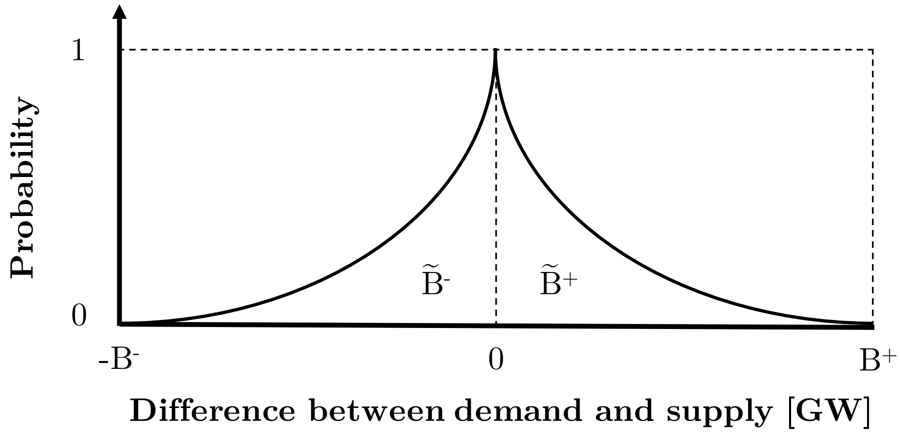

Figure 4.1: Visualization of the z-function.

BP is called. Function $z(y)$ is strictly increasing for $y < 0$ and strictly decreasing for $y \geq 0$ with $z(-B^-) = z(B^+) = 0$ and $z(y) + z(y') \leq 1$ for $y \in [-B^-, 0)$ and $y' \in [0, B^+]$. The integrals

$$\tilde{B}^- = \int_{-B^-}^{0} z(y)\,dy \quad \text{and} \quad \tilde{B}^+ = \int_{0}^{B^+} z(y)\,dy \tag{4.2}$$

are the total negative respectively positive BP capacity that are called in order to balance the excess supply and excess demand, i.e., the BE demand. Thus, $\gamma^- = \tilde{B}^-/B^-$ and $\gamma^+ = \tilde{B}^+/B^+$ are the fraction of provided negative BP and of positive BP, i.e., the fraction of the BP capacities for the delivery of BE 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 $z(-y) = z(y)$ for $y \in (0, \frac{B}{2}]$. 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 bidders on the positive (negative) BP market and c_1^+ (c_1^-) the highest variable cost.[3] The BP

[3] Any supply fluctuation demands the provision of BP. The respective costs are accounted to the bidders. In our theoretical model, we do not account for these additional costs since they reflect on average approximately 0.1% of the bidders variable cost (see Section 4.3.3). We assume that any supply fluctuation triggers BP and

merit-order maps a bidder (according to her cost c) onto a merit-order rank on the positive market by the bijective function $r^+ : [c_0^+, c_1^+] \to [0, B^+] =: R^+$ and on the negative market by $r^- : [c_0^-, c_1^-] \to [B^-, 0] =: R^-$. Each rank is assigned a calling probability by the mappings $a^+ : R^+ \to [a_{max}^+, a_{min}^+]$ and $a^- : R^- \to [a_{min}^-, a_{max}^-]$. The calling probability determines the average share of time in which the bidder delivers BE. The values a_{max}^+ and a_{max}^- (a_{min}^+ and a_{min}^-) denote the highest (lowest) calling probability in the two BP markets and are assumed to be exogenous with $a_{max}^+ + a_{max}^- \leq 1$, $a_{max}^+, a_{max}^- \in (0, 1]$, and $a_{min}^+ = a_{min}^- = 0$.

On the wholesale market, bidders constantly produce energy and are remunerated for each unit by the wholesale market price p_W. On the BP markets, a bidder receives the BP price p_{BP}^+ or p_{BP}^-, and, if she is called, additionally a BE price $p_{BE}^+(c)$ or $p_{BE}^-(c)$. The BP prices p_{BP}^+ and p_{BP}^- are the same for all bidders and are determined by the highest accepted positive respectively negative BP bid. The BE price $p_{BE}^+(c)$ ($p_{BE}^-(c)$) is determined by the associated costs of the highest merit-order rank in the positive (negative) market that is needed to cover the BE demand within a predetermined period of time – the "Balancing Energy Pricing Period (BEPP)." Hence, the length of the BEPP influences the bidder's BE prices: the longer the BEPP, the higher is the number of draws for BE demand, and, thus, the higher (lower) are the cost of the last bidder on the positive (negative) market. We model the average bidder's BE price in dependence of a factor $\vartheta \in (0, 1]$ that corresponds to the length of the BEPP:

$$p_{BE}^+(c) = c\,(1 - \vartheta) + c_1^+\,\vartheta\,, \tag{4.3}$$

$$p_{BE}^-(c) = -c\,(1 - \vartheta) - c_0^-\,\vartheta\,. \tag{4.4}$$

The case $\vartheta = 1$ models the longest possible BEPP, in which the BE price

that all bidders of the wholesale market deviate identically. For this, dc denotes the average cost of BE per MW caused by supply fluctuations. The sum $c + dc$ represents the imputed variable cost.

p^+_{BE} (p^-_{BE}) is always determined by the highest (lowest) bidder's cost c^+_1 (c^-_0).[4] The smaller ϑ (i.e., the shorter the BEPP), the closer moves the bidder's average BE price to her cost c.

A bidder's profit per produced energy unit on the wholesale market is[5]

$$\pi_W(c) = p_W - c\,, \tag{4.5}$$

on the positive BP market

$$\pi^+_{BP}(c) = m\,(p_W - c) + (1-m)\left[p^+_{BP} + a^+(r^+(c))\left(p^+_{BE}(c) - c\right)\right]\,, \tag{4.6}$$

and on the negative BP market

$$\pi^-_{BP}(c) = (p_W - c) + (1-m)\left[p^-_{BP} + a^-(r^-(c))\left(c + p^-_{BE}(c)\right)\right]\,. \tag{4.7}$$

Equation (4.5) states the difference of the wholesale market price and a bidder's variable cost. In the positive BP market, the profits consist of two parts. The first part of (4.6) represents the profits from selling the minimal load on the wholesale market, and the second part states the profits generated by the BP price and the BE price (depending on the calling probability). In the negative BP market, bidders are continuously paid the wholesale market price for their entire capacity. Recall that a bidder provides negative BP by decreasing the load level of her power plant, since there is an oversupply to the power system. Consequently, the provision of negative BP has no impact on her trading on the wholesale market. Therefore, the first part of (4.7) represents the margin of selling the entire capacity on the wholesale market. The second part states the BP profits, which consist of the payments for BP and BE.

[4] Note that bidders submit negative energy bids in the negative market (see (4.7)).

[5] The wholesale market price fluctuates and, thus, the bidder's profit, i.e., p_W and π_W are average values.

4.1.3 Conditions for efficiency, stability and market clearing

In this section we present crucial conditions for our model.

4.1.3.1 Efficient allocation on the balancing power markets

An efficient allocation on the BP markets requires that plants with low variable cost are preferred to plants with high variable cost for the production of an additional energy unit. Thus, plants with low variable costs must have higher production volumes than plants with high variable costs (Müsgens et al., 2014). This yields a unique order of c_0^+, c_0^-, c_1^+ and c_1^-.

In the negative BP market, c_0^- denotes the bidder on the last rank in the merit-order with a calling probability of $a_{min}^- = 0$, i.e., she continuously produces with her entire capacity. The bidder with c_1^- is assigned the calling probability of a_{max}^-, i.e., her plant operates with the load $m + (1 - a_{max}^-)(1 - m) < 1$. This yields $c_0^- < c_1^-$.

In the positive BP market, c_0^+ is assigned to the bidder on the first rank in the merit-order with calling probability a_{max}^+. Thus, her plant operates on the load level $m + a_{max}^+ (1 - m) \leq m + (1 - a_{max}^-)(1 - m)$ because of $a_{max}^+ + a_{max}^- \leq 1$. This yields $c_1^- = c_0^+$. The bidder with c_1^+ is on the last rank of the merit-order. She never provides BP, but runs her plant permanently on the load level m on the wholesale market. As a result, the following order is induced.

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

Note that (A0) in conjunction with (4.3) and (4.4) yields $|p_{BE}^-| < p_{BE}^+$.

4.1.3.2 Stability criteria

BP bidders either participate at the wholesale market or at the BP market. This raises the question about the stability of the efficient BP allocation.

That is, do prices exist such that the bidders are incentivized to choose the “right” rank of their own accord?

The conditions for the bidders on the first and last rank in the merit-orders are most crucial. The bidder with c_0^- has to be indifferent between her last rank in the merit-order of the negative BP market and a switch to the wholesale market. The bidder with c_1^+ must be indifferent between her last rank in the merit-order of the positive BP market and not participating at all. The bidders with c_1^- (c_0^+) need to be indifferent between a switch to the positive (negative) BP market. This leads to the following stability conditions.

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

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

(M2) BP-markets

$$(p_W - c_1^-) + (1-m)\left[p_{BP}^- + a_{max}^-\left(c_1^- + p_{BE}^-(c)\right)\right] \stackrel{!}{=} m\,(p_W - c_0^+) + (1-m)\left[p_{BP}^+ + a_{max}^+\left(p_{BE}^+(c) - c_0^+\right)\right]$$

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

4.1.3.3 Market clearing and energy balance

Since BP bidders only use the share $1-m$ of their capacities to provide BP, their total capacities to provide B^- and B^+ are $\frac{B^-}{1-m}$ and $\frac{B^+}{1-m}$. The curve of the BP bidders' active capacities for providing energy for the BP markets and the wholesale market is given by the strictly decreasing function $h(s)$, which is derived from the calling probability function (4.1):

$$h(s) = \begin{cases} m + (1-m)\left(1 - z\left(s\,(1-m) - B^-\right)\right) & : s \in [0, \frac{B^-}{1-m}) \\ m + (1-m)\, z\left(s\,(1-m) - B^-\right) & : s \in [\frac{B^-}{1-m}, \frac{B}{1-m}] \,. \end{cases}$$

Using the maximum calling probability a^+_{max}, we have

$$h(s) = \begin{cases} 1 & : s = 0 \\ m + (1-m)\, a^+_{max} & : s = \frac{B^-}{(1-m)} \\ m & : s = \frac{B}{1-m}\,. \end{cases} \tag{4.8}$$

The integral

$$H(m,B) = \int_0^{\frac{B}{1-m}} h(s) ds \tag{4.9}$$

is the average active capacity of all BP bidders. With (4.2) we get

$$H(m,B) = \frac{B^-}{1-m} - \tilde{B}^- + \frac{mB^+}{1-m} + \tilde{B}^+\,. \tag{4.10}$$

Figure 4.2 illustrates the symmetric case with $h(\frac{B}{2(1-m)}) = \frac{1+m}{2}$, $h(\frac{B}{1-m} - s) = 1 + m - h(s)$ for $s \in [0, \frac{B}{2(1-m)}]$, and

$$H(m,B) = \frac{B\,(1+m)}{2(1-m)}\,. \tag{4.11}$$

In the symmetric case, $H(m,B)$ is independent of the h-curve's shape.

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 $B^+ = (1-m)\big(S_{BP}(c_1^+) - S_{BP}(c_0^+)\big)$

(S2) Negative BP market $B^- = (1-m)\big(S_{BP}(c_1^-) - S_{BP}(c_0^-)\big)$

(S3) Energy balance $D - S_{nBP}(p_W) + S_{BP}(c_0^-) + \tilde{B}^- - \tilde{B}^+ + H(m,B) = 0$

The demand D on the wholesale market is met by the contracted supply, which refers to the case without deviations (S0). This supply is provided by nBP bidders and BP bidders. The supply $S_{nBP}(p_W)$ includes all nBP

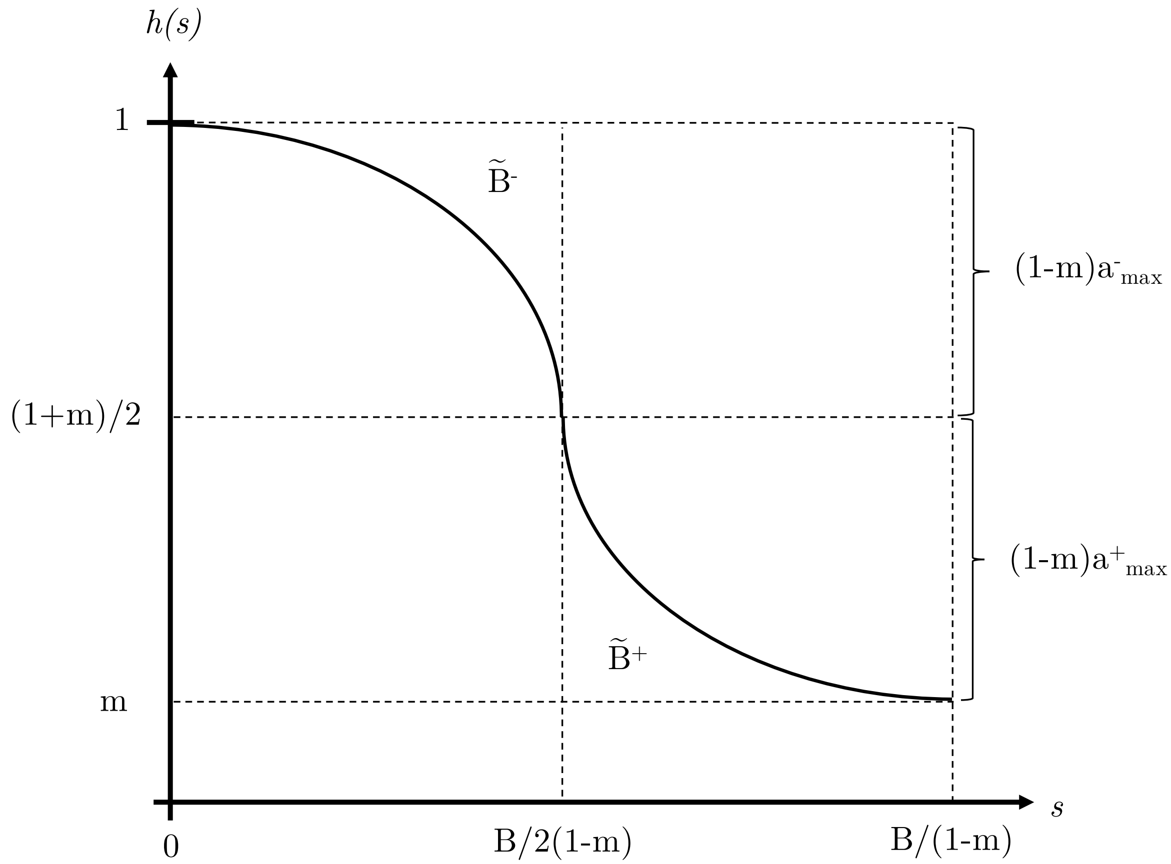

Figure 4.2: Example of a h-function in a symmetric BP market.

bidders with cost between c_0 and p_W. The supply of the BP bidders comprises of two groups: the contracted supply of the negative BP bidders with cost between c_0 and c_1^- is $S_{BP}(c_1^-)$ and that of the positive BP bidders with cost between c_0^+ and c_1^+, whose contracts only refer to the minimal load m, is $\frac{mB^+}{1-m}$. The demand for positive and negative BP is provided by the $(1-m)$th share of BP bidders 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 bidders with cost between c_0^- and c_1^+, whose active capacities are given by $H(m, B)$.

4.1.4 Total costs of the integrated power system

The total costs T of the power system are given by the following function

$$T = \int_0^{D-H(m,B)-s_0} S_{nBP}^{-1}(s)\, ds + \int_0^{s_0} S_{BP}^{-1}(s)\, ds + \int_0^{\frac{B}{1-m}} h(s)\, S_{BP}^{-1}(s+s_0)\, ds\,,$$

with $s_0 = S_{BP}(c_0^-)$, $s_1 = S_{BP}(c_1^+)$ and $B = (1-m)(s_1 - s_0)$. The function T includes the wholesale market costs and BP market costs. The first are determined by the costs of nBP bidders in the interval $[0, D-H(m,B)-s_0]$ and the costs of BP bidders in the interval $[0, s_0]$, while the costs for the BP markets are given by the costs of BP bidders in the interval $[s_0, s_0 + \frac{B}{1-m}]$ weighted with the average active capacity of function $h(s)$.

4.1.5 Welfare distribution

The producer surplus PS is given by

$$PS = D\, p_W + B^+\, p_{BP}^+ + B^-\, p_{BP}^- - T\,.$$

PS includes the profits of the wholesale market $D\, p_W$ and of the BP payments $B^+\, p_{BP}^+ + B^-\, p_{BP}^-$, while the total energy production costs T are subtracted. The BE costs do not effect PS because they are charged between the bidders (see Section 4.1.2).

For the consumer surplus CS, we apply the concept of a consumers' reservation price (per energy unit) for a reliable power system p_{RES} (e.g., Zolotarev, 2017), which leads to

$$CS = D\,(p_{RES} - p_W) - B^+\, p_{BP}^+ - B^-\, p_{BP}^-\,.$$

The consumer surplus CS incorporates the difference of the reservation price p_{RES} and the wholesale market price p_W for the demand D. The BP costs $B^+ p^+_{BP}$ and $B^- p^-_{BP}$ reduce CS because consumers bear the costs for keeping capacities available for BP (e.g., regelleistung.net, 2018a).

Note that the variables p_W, B^+, p^+_{BP}, B^-, and p^-_{BP} have opposed effects on PS and CS: PS increases and CS decreases in each variable.

4.2 Market equilibrium

The following propositions 1, 2, 3, and 4 are derived under the efficiency condition (A0), the micro-stability criteria (M1), (M2) and (M3), the conditions (S0), (S1), (S2) and (S3), symmetric BP markets, and a linear supply function $S(c) = \alpha\, c + \beta$ ($\alpha \in \mathbb{R}^+$, $\beta \in \mathbb{R}^+$).

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

1. *Wholesale market price:* $p_W = \dfrac{D - \beta}{\alpha} \leq m\, c_1^+ + (1-m)\, c_0^+$
2. *Positive BP price:* $p^+_{BP} = \dfrac{m}{1-m}\,(c_1^+ - p_W) = \dfrac{\frac{B}{2}\,\frac{m}{1-m}}{\delta\,\alpha}$
3. *Negative BP price:* $p^-_{BP} = 0$

Proof. See Appendix B. □

The wholesale market price p_W is determined by the inverse supply function at demand D. Condition $p_W \leq m\, c_1^+ + (1-m)\, c_0^+$ is necessary for stability because a higher p_W induces bidders of positive BP to switch into the wholesale market. The positive BP price p^+_{BP} is equal to c_1^+ because the calling probability of this bidder is zero and, thus, p^+_{BP} must cover her wholesale market losses caused by her costs of supplying the minimal load m. The negative BP price p^-_{BP} must equal zero (see also (M0)).

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^- is given by*

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

2. *The costs c_1^- and c_0^+ are given by*

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

3. *The cost c_1^+ is given by*

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

Proof. See Appendix B. □

The cost c_0^- of the first BP bidder is determined by the difference of the wholesale market price p_W and the cost of the BP supply, which implies $p_W \geq c_0^-$. Costs c_1^- and c_0^+ are equal and are determined by the difference of p_W and the positive BP price p_{BP}^+, which implies $p_W \geq c_1^- = c_0^+$. The cost c_1^+ of the last BP bidder is determined by p_W and half of the costs of the entire BP supply, which implies $p_W \leq c_1^+$.

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

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

Proof. See Appendix B. □

Bidders' profits decrease with their variable cost on all markets. The profits in all markets are (weakly) greater than zero, and a bidder's participation in the BP markets generates (weakly) higher profits than on the wholesale market.

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

Proof. See Appendix B. □

Here is an intuitive explanation. An upward shift of the interval $[c_0^-, c_1^+]$ has three effects: more expensive power plants provide BP, the supply of BP bidders on the wholesale market increases, which crowds out nBP bidders on this market. In the case of symmetric BP markets and a linear supply function, the three cost effects cancel each other out in the equilibrium. The reasons are that, due to the symmetric BP markets, the costs of BP supply only depend on c_0^- and c_1^+ but not on $h(s)$, and, due to the linear supply function, the cost savings of negative BP (i.e., shutting down expensive power plants due to an overproduction of cheaper plants) equal the increasing costs for positive BP (i.e., activating more expensive plants due to an underproduction of cheaper plants).[6]

4.3 Comparison with German market data

We compare the data of the German SBP market of 2015 with the results of our theoretical model adapted to the German SBP market.[7]

[6]Note that in case of asymmetric BP markets or a non-linear supply function, efficiency cannot be guaranteed because the three cost effects do not necessarily cancel each other out in the equilibrium.

[7]We investigate the market results of 2015 for two reasons: Firstly, 2015 is the most recent year for which publicly available data for SBP was made available by the German TSOs. Secondly, since July 2016, the Austrian and German TSOs procure a common SBP merit-order, i.e., activation of SBP is linked within the two countries. Therefore, an analysis of the year 2016 had to include also the Austrian supply side.

4.3.1 Asymmetric markets

The German SBP markets are asymmetric, which is reflected by the shape of the function $h(s)$ (see Figure 4.3). Now, $\gamma^+ \neq \gamma^-$ and $\tilde{B}^+ \neq \tilde{B}^-$. As a consequence, the effects of the positive and negative SBP market do not cancel each other out and the position of the interval $[c_0^-, c_1^+]$ has an impact on the total cost function T. However, c_0^-, $c_1^- = c_0^+$ and c_1^+ do not depend on γ^+ and γ^-.[8] Therefore, the market equilibrium with asymmetric SBP markets cannot guarantee efficiency. Yet, the results of the parametrized model with asymmetric SBP markets for the German SBP market of 2015 only slightly differ from the corresponding symmetric model because the asymmetry is small (see following sections). We use this as a justification of our theoretical model in which we restrict our analysis to symmetric SBP markets.

4.3.2 Parametrization of the model

We calibrate our model with the characteristics of the German wholesale market and SBP markets in 2015. Note that the results are presented in one hour with unit Euro/MWh, and that the current German positive and negative SBP markets are spilt into the two time periods, i.e., the main period and the sub-period (regelleistung.net, 2018a).

4.3.2.1 Demand

The demand on the wholesale market was 525,000 gigawatt hour (GWh) in 2015 (Federal Association of the German Energy and Water Industries and Federal Ministry for Economic Affairs and Energy, 2016), i.e., an average demand per hour of $D = 59.93$ GW. The average SBP demand on the positive and negative market were $B^+ = 2.053$ GW, $B^- = 2.027$ GW

[8] The market equilibrium depends on $B^+, B^-, \gamma^+, \gamma^-$, a^+_{max}, and a^-_{max} but none of the conditions presented in Section 4.1.3 depend on γ^+ or γ^-.

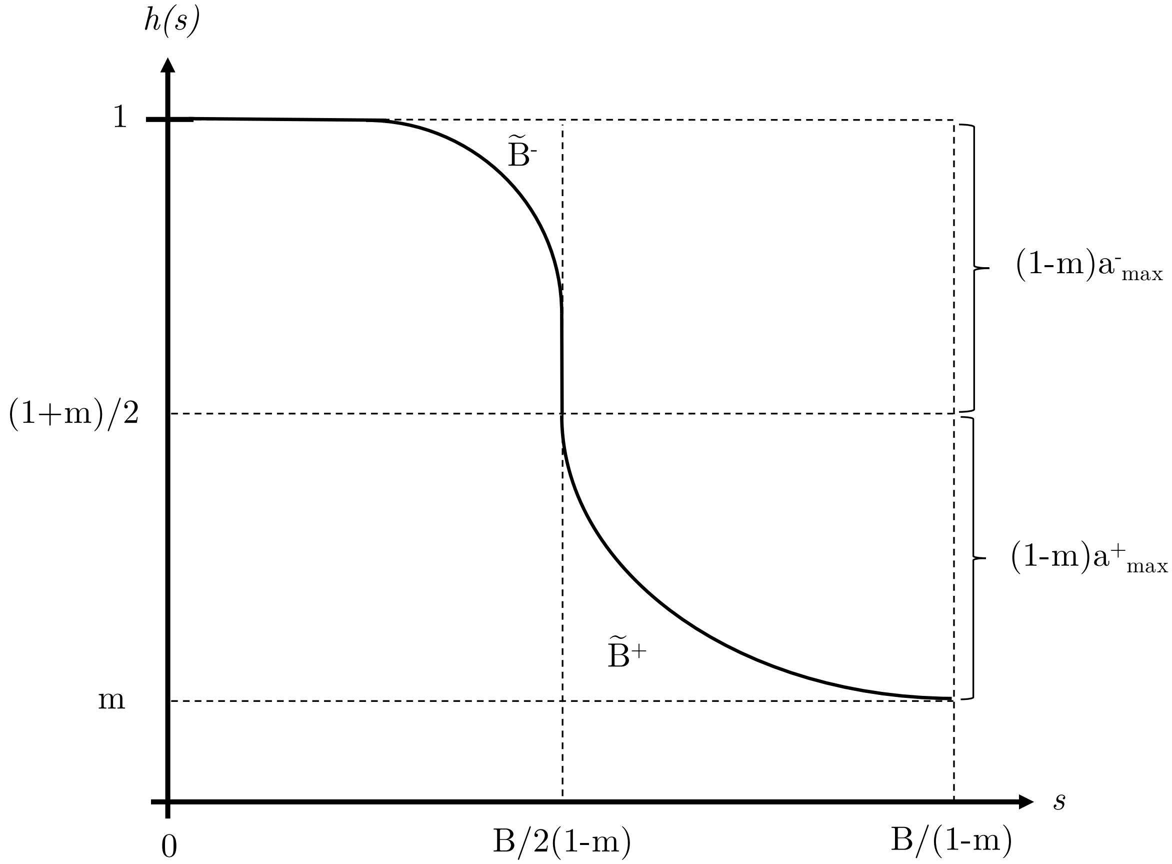

Figure 4.3: Illustration of asymmetric BP markets.

and the average percentage demands were $\gamma^+ = 0.078$ and $\gamma^- = 0.060$ (Bundesnetzagentur and Bundeskartellamt, 2017). This yields average activated SBP capacities of $\tilde{B}^+ = 0.160$ GW and $\tilde{B}^- = 0.122$ GW.

4.3.2.2 Market characteristics

The activated BE was 2,500 GWh in 2015. Hereof, 1,400 GWh were utilized for positive SBP and 1,100 GWh for negative SBP (Bundesnetzagentur and Bundeskartellamt, 2017). Thus, the demand for BE is not symmetric and positive SBP is used more frequently (56%) than negative SBP (44%). This yields maximum calling probabilities of $a^+_{max} = 0.56$ in the positive market and $a^-_{max} = 0.44$ in the negative market.

The calling probabilities of 2015 are shown in Figure 4.4. Here, the interval [-2,000, 0] MW belongs to the negative SBP market and the interval [0, 2,000] MW to the positive SBP market.

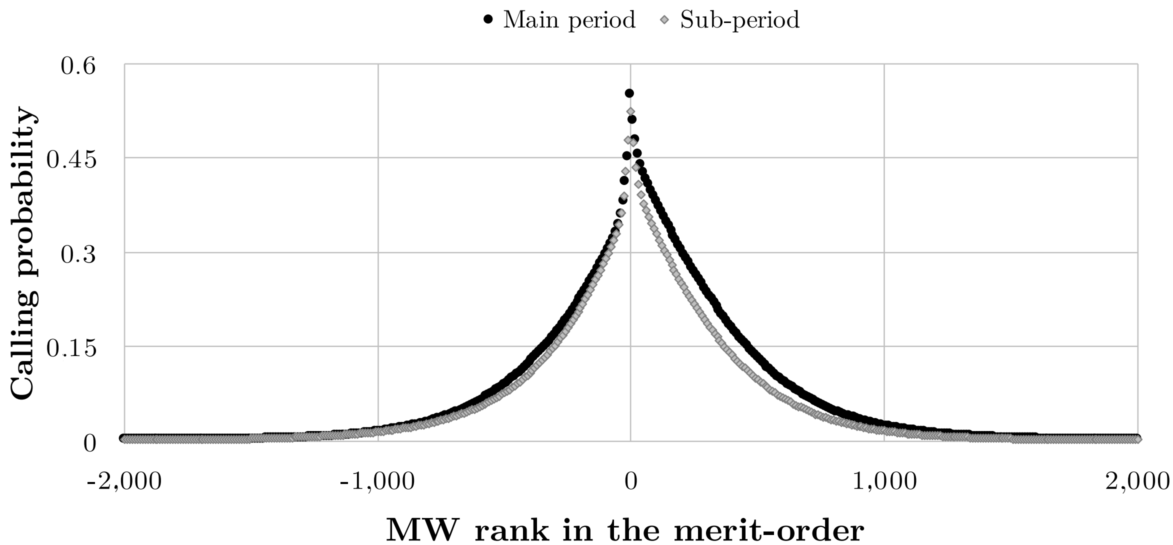

Figure 4.4: Empirical calling probability functions in the German positive (i.e., the interval [0, 2,000] MW) and negative (i.e., the interval [-2,000, 0] MW) SBP market (main period and sub-period) (50hertz, 2017).

We approximate these calling probabilities with an exponential function. For the positive BP market, for example, the function is given by

$$a^+(o^+(c)) = a^+_{max} \frac{e^{-t^+o^+(c)} - e^{-t^+o^+(c_1^+)}}{e^{-t^+o^+(c_0^+)} - e^{-t^+o^+(c_1^+)}} = a^+_{max} \frac{e^{-t^+o^+(c)} - e^{-t^+}}{1 - e^{-t^+}} . \quad (4.12)$$

This represents the normalized merit-order with $o^+(c) = \frac{c - c_0^+}{c_1^+ - c_0^+} \in [0, 1]$ for all $c \in [c_0^+, c_1^+]$, and gradient t^+. Integrating $a^+(o^+(c))$ yields the percentage positive BE demand

$$\gamma^+ = \int_0^1 a^+_{max} \frac{e^{-t^+o^+(c)} - e^{-t^+}}{1 - e^{-t^+}} \, do^+ = a^+_{max} \frac{1 - (t^+ + 1)\, e^{-t^+}}{t^+ \left(1 - e^{-t^+}\right)} .$$

Figure 4.5 illustrates (4.12) for the positive (negative) SBP market with $\gamma^+ = 0.078$, $a^+_{max} = 0.56$, $t^+ = 7.1$ ($\gamma^- = 0.060$, $a^-_{max} = 0.44$, $t^- = 7.2$).

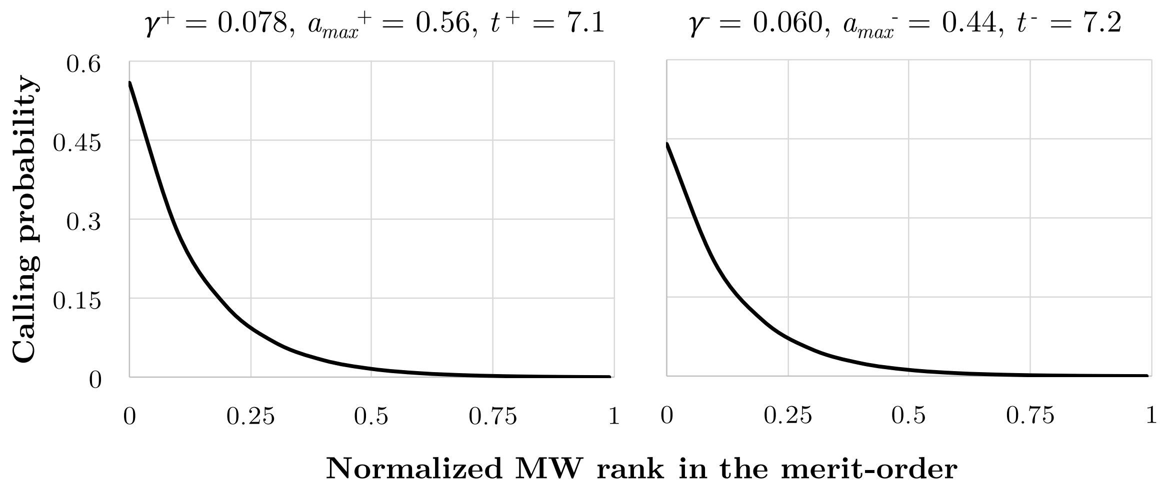

Figure 4.5: Approximation of the calling probabilities in the German positive and negative SBP market.

The (normalized) rank in the positive merit-order $O^+(c)$, for example, is then given by the function

$$O^+(c) = \frac{\int_c^{c_1^+} o^+ \, a^+(o^+(c))\, do^+}{\int_c^{c_1^+} a^+(o^+(c))\, do^+}, \forall c \in [c_0^+, c_1^+]\,,$$

which yields the (normalized) BE price function $P^+(c)$ in the positive market

$$P^+(c) = (1 - \vartheta)\, O^+(c) + \vartheta, \forall c \in [c_0^+, c_1^+]\,.$$

The pricing rule in the German SBP market is PaB not UP. Since there is no publicly available information about the extent of the markups on the variable costs under PaB, we neglect markups, i.e., $\vartheta = 0$. Thus, our calculation represents a lower bound for the BE costs. This yields $O^+(c) = P^+(c) = 0.14$ and $O^-(c) = P^-(c) = 0.14$. Regarding must-run capacities, we assume $m = 0.5$ for all types of power plants (Steck and Mauch, 2008; Just and Weber, 2008; Hundt et al., 2009).

4.3.2.3 Supply characteristics

For the wholesale market we refer to the Intraday Continuous auction with the average price $p_W = 33.31$ Euro/MWh in 2015 (Fraunhofer ISE, 2017).[9] We calibrate our model by this price p_W. We also consider renewable energy sources, which typically have variable cost close to zero and, thus, set the intercept of the supply function (Christoph et al., 2013; Nestle, 2014; Milojcic and Dyllong, 2016; Niedermeier et al., 2017). We use the official data on installed capacity provided by the German regulator (Bundesnetzagentur, 2016).[10] This yields $S(c) = 1.369\,c + 14.345$ in Figure 4.6, which includes the calibration point (33.31 Euro/MWh, 59,930 MW). Since 2017, the German TSOs publish the prequalified capacities: for positive SBP 22.32 GW and 22.38 GW for negative SBP (regelleistung.net, 2018a). Thus, we set $\delta = 0.22$.[11]

4.3.3 Results of the integrated market model

The model results are presented in tables 4.1 and 4.2.[12] The cost interval for the merit-order in the negative SBP market is [13.03, 26.49] Euro/MWh and [26.49, 40.13] Euro/MWh in the positive SBP market.[13] All bidders of negative SBP and about half of the bidders of positive SBP have lower variable cost than $p_W = 33.31$ Euro/MWh. The BP price in the positive

[9] The average price on the German Day Ahead Auction was 31.20 Euro/MWh, and 33.09 Euro/MWh on the Intraday Auction in 2015 (Fraunhofer ISE, 2017).

[10] According to Bundesnetzagentur (2016), the information includes: "The Bundesnetzagentur's list of power plants includes existing power plants in Germany with a net nominal electricity capacity of at least 10 MW. It also includes capacities feeding into the German grid from Luxembourg, Switzerland and Austria. In addition, the list shows generation facilities of less than 10 MW which are eligible for receiving payment under the Renewable Energy Sources Act (EEG), grouped by federal state and energy source. Generation facilities under 10 MW not eligible for EEG are grouped by energy source." These also include wind onshore and offshore and solar power plants. Since their production strongly depends on the weather conditions, we use their actual energy production (Federal Association of the German Energy and Water Industries, 2016) instead of their installed capacity.

[11] We do not differentiate with respect to the prequalified capacities per class of power plants, since it would not allow for a homogeneous δ.

[12] Note that the hourly cost of BE are 1,555 Euro. Thus, the BE cost that need to be considered by the bidders are $dc = 0.026$ Euro/MWh.

[13] Note that we state the imputed cost $c + dc$, and that the condition for p_W holds (see Proposition 2).

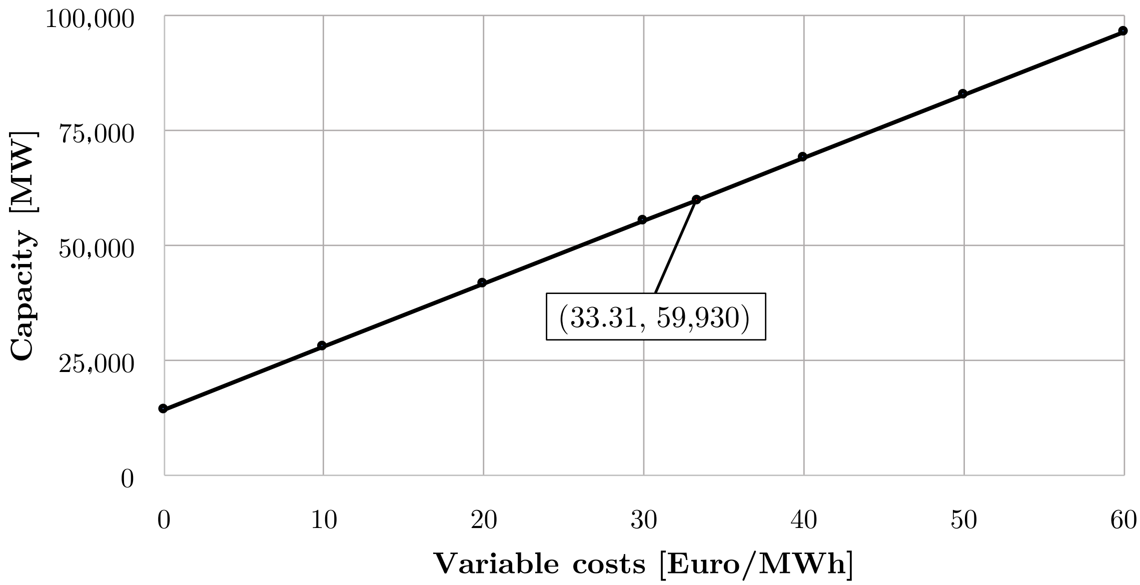

Figure 4.6: Linear approximation of the supply.

SBP market is $p^+_{BP} = 6.82$ Euro/MWh, while the BP price in the negative SBP market equals zero. The average BE price in the positive market is $p^+_{BE} = 28.40$ Euro/MWh and the average BE price in the negative market is $p^-_{BE} = -24.61$ Euro/MWh. The profits in the merit-orders are $\pi^-_{BP}(c^-_0) = 20.28$, $\pi^-_{BP}(c^-_1) = \pi^+_{BP}(c^+_0) = 6.82$, and $\pi^+_{BP}(c^+_1) = 0.00$.[14]

The power system total costs are 2,011,823 Euro per hour (Euro/h). Hereof, over 99% of the costs are due to the wholesale market, and less than 1% due to the SBP market (positive and negative). The costs for positive SBP are 18,547 Euro/h and -2,992 Euro/h for negative SBP.[15]

[14]The model results for a symmetric German SBP market of 2015, i.e., $B^+ = B^- = 2.00$, $\gamma^+ = \gamma^- = 0.07$, and $a^+_{max} = a^-_{max} = 0.5$, are as follows: $dc = 0.09$, $c^-_0 = 13.38$, $c^-_1 = c^+_0 = 26.67$, $c^+_1 = 39.95$, $p^+_{BP} = 6.64$, $p^-_{BP} = 0.00$, $p^+_{BE} = 28.53$, $p^-_{BE} = -24.81$, $\pi^-_{BP}(c^-_0) = 19.93$, $\pi^-_{BP}(c^-_1) = \pi^+_{BP}(c^+_0) = 6.64$, and $\pi^+_{BP}(c^+_1) = 0.00$.

[15]The model results for a symmetric German SBP market of 2015 are as follows: Hourly total system costs: 2,010,075, hourly wholesale market costs: 1,996,268, hourly SBP costs 13,807, hourly positive BP costs: 13,286, hourly negative BP costs: 0, hourly positive BE costs: 3,994, hourly negative BE costs: -3,473.

Parameter	Model GER 2015
c_0^-	13.03
$c_1^- = c_0^+$	26.49
c_1^+	40.13
p_W	33.31
p_{BP}^+	6.82
p_{BP}^-	0.00
p_{BE}^+	28.40
p_{BE}^-	-24.61

Table 4.1: Merit-order rank and prices with unit Euro/MWh.

Cost parameter	Model GER 2015
Total system	2,011,823
Wholesale market	1,996,268
SBP market	15,555
Positive SBP: BP	13,999
Positive SBP: BE	4,548
Negative SBP: BP	0
Negative SBP: BE	-2,992

Table 4.2: Hourly cost of the power system with unit Euro/h.

4.3.4 Model results and empirical market results

The German regulator publishes annual data for the SBP market (Bundesnetzagentur and Bundeskartellamt, 2016, 2017). For comparing our modelled results of Section 4.3.3 with the actual data of 2013, 2014 and 2015, we convert our results into annual values (see Table 4.3).

Note that our parametrized model only accounts for the SBP costs of 2015. Yet, we consider it valuable to also illustrate prior market results. Since the German TSOs do not provide detailed annual costs, we estimate the cost parameters based on the market data provided by the TSOs

Cost parameter	Real 2013	Real 2014	Real 2015	Model 2015
BP costs	**345**	**210**	**141**	**123**
Costs pos. BP	143	132	102	123
Costs neg. BP	202	78	39	0
BE costs	**58**	**50**	**64**	**14**
Costs pos. BE	95	65	72	40
Costs neg. BE	-37	-15	-8	-26
Total costs	**403**	**260**	**205**	**137**

Table 4.3: Empirical market results and asymmetric model results for the German SBP market of 2015 with unit Mio. Euro (regelleistung.net, 2018a; Bundesnetzagentur and Bundeskartellamt, 2016, 2017).

(regelleistung.net, 2018a). That is, we estimate the average BP costs per week and convert them into annual values.[16]

The costs for BE depend on two parameters: the BE bids and the actual demand for BE. On the one hand, the BE bids are very volatile, but on the other hand, if we assume for 2013 and 2014 the calling probabilities of 2015 (see Figure 4.5), then the average weighted BE bid of the activated plants is only slightly higher than the BE bid on the first rank in the merit-order (less than 1 %). Thus, as an approximation, we estimate the BE costs by using the average bid on the first position in the merit-order and convert these to annual values.[17]

[16] Average BP bids for positive SBP in the main period (sub-period) [Euro/MW]: 552 (740) in 2013, 456 (782) in 2014, 350 (585) in 2015 and for negative SBP: 726 (1,142) in 2013, 268 (491) in 2014, 102 (267) in 2015. We multiplied these numbers with the number of weeks: 52 in 2013 and 2014 and 53 in 2015 and with the average power demand for positive (negative) SBP [MW]: 2,122 (2,081) in 2013, 2,058 (1,987) in 2014, and 2,053 (2,027) in 2015. Our estimates for the aggregated annual costs differ slightly from the official values: 353 Mio. Euro in 2013, 228 Mio. Euro in 2014, 155 Mio. Euro in 2015 (Bundesnetzagentur and Bundeskartellamt, 2016, 2017).

[17] The average BE bid for positive SBP in the main period (sub-period) on the first position in the merit-order with unit Euro/MWh was: 67.79 (64.02) in 2013, 54.26 (56.57) in 2014, and 51.98 (50.50) in 2015. The average BE bid for negative SBP in the main period (sub-period) on the first position in the merit-order with unit Euro/MWh was: -22.20 (-12.51) in 2013, -16.20 (-5.30) in 2014, and -11.61 (-5.25) in 2015. We multiplied these numbers with the assigned hours per week for the main period (60h) and the sub-period (108h), the number of weeks: 52 weeks in 2013 and 2014, and 53 weeks in 2015 as well as with the average energy demand for positive (negative) SBP with unit MW: 166 (264) in 2013, 133 (184) in 2014, and 160 (122) in 2015.

The empirical results illustrate that almost all costs continuously decreased. The total costs of 2013 (403 Mio. Euro) nearly halved in 2015 (205 Mio. Euro). The modelled result of 137 Mio. Euro indicates that there is still potential for further cost reductions.

The total BP costs decreased from 345 Mio. Euro in 2013 to 141 Mio. Euro in 2015 although the BP demand was nearly constant during these years (Bundesnetzagentur and Bundeskartellamt, 2016, 2017). The model predicts 123 Mio. Euro. For positive and negative BP costs, the differences between the actual and the modelled results are larger. While our model predicts costs of 123 Mio. Euro for positive BP in 2015, the actual costs were 102 Mio. Euro. Remarkably, the actual costs are lower than the predicted costs. This indicates that bidders understate their opportunity costs in their BP bids. Ocker et al. (2018) offer an explanation: if bidders expect high BE prices, they submit low BP bids in order to increase the probability of winning and, thus, to benefit from the high BE prices. That is, bidders subsidize the BP bid with the expected profits of the BE bids (see Chapter 6). The difference between the actual positive (negative) BE costs of 72 Mio. Euro (-8 Mio. Euro) and the prediction of 40 Mio. Euro (-26 Mio. Euro) supports this hypothesis. The negative BP costs decreased more than 80% since 2013. In 2015, a difference of +39 Mio. Euro remains.

The development of the actual total BE costs is ambiguous and the development of positive and of negative BE costs differ. While the positive BE costs decreased from 95 to 72 Mio. Euro (with a small increase from 2014 to 2015), the negative BE costs increased from -37 to -8 Mio. Euro.[18] The large difference between the total BE cost level (50 to 64 Mio. Euro) and the prediction of 14 Mio. Euro is mainly due to the large difference of the positive BE costs (72 and 40 Mio. Euro), which we discussed before.[19]

[18] Note that the BE demand declined since 2013 (Bundesnetzagentur and Bundeskartellamt, 2016, 2017).

[19] The modelled costs of the symmetric German SBP market of 2015 with unit Mio. Euro are as follows:

4.4 Balancing energy prices

In this section we discuss empirical BE bids and the impact of the BEPP on BE prices.

4.4.1 Extreme balancing energy bids

Empirical data reveal extreme bidding behavior, particularly on higher ranks in the merit-orders. This result is supported by recent studies that find evidence for market imperfections in the German SBP markets (Heim and Götz, 2013; Ocker and Ehrhart, 2017a). We illustrate the high BE bids for the merit-order ranks 500, 1,000, and 1,500 of 2013, 2014, and 2015 for the positive and negative SBP market in Table 4.4.

	2013			2014			2015		
	500	1,000	1,500	500	1,000	1,500	500	1,000	1,500
Positive									
Main period	103	164	242	94	164	349	84	159	447
Sub-period	109	166	247	97	182	350	86	192	484
Negative									
Main period	-8	19	123	27	111	497	38	155	723
Sub-period	7	49	203	31	119	435	51	220	841

Table 4.4: Average energy bids with unit Euro/MWh for merit-order ranks 500, 1,000, and 1,500 in the positive and negative German SBP markets (main period and sub-period) of 2013, 2014, 2015 (regelleistung.net, 2018a).

In the negative SBP market, bids lower than zero disappeared from rank 500 onwards since 2014. Additionally, bids significantly increased over time on all ranks. In the positive market, bids particularly increased on the last merit-order ranks. Although the calling probability substantially decreases

116 for positive BP, 0 for negative BP, 35 for positive BE, -30 for negative BE, resulting in total costs of 121.

on higher ranks (see Figure 4.4), the empirical data illustrate the potential effect of increasing bids on costs.

4.4.2 Uniform pricing and length of the Balancing Energy Pricing Period

The extremely high BE bids are accompanied by very low BP bids (see Section 4.3.4). This reveals a major disadvantage of the applied scoring rule: since solely the BP bid is relevant for winner determination, competition for BE bids is undermined, and facilitates the coordination on (extremely) high prices (see Chapter 6). The European Commission (2017) implements UP in the future European SBP auction by arguing that it induces bidders to report their true cost in their bids and, thus, leads to efficient auction outcomes. In Chapter 5 we show that this reasoning only holds if the BEPP is short. Else, bidders are incentivized to understate their costs in their bids. Therefore, we advocate to set the BEPP to a short value.

However, we doubt that a switch to UP will change the bidding behavior in BP markets. There is empirical evidence that bidders abused their market power and coordinated on high price levels (Heim and Götz, 2013; Ocker and Ehrhart, 2017a). Changing the pricing rule will not impede collusion as long as the factors, which facilitate collusion, are not affected: the regular repetition of the auction with a limited set of bidders.[20]

If UP is applied, the length of the BEPP directly impacts the BE costs: the longer the BEPP, the higher is the rank in the merit-order that determines the uniform price. Our model allows the comparison of different BEPP figures. The results of the model in Section 4.3.4 refer to a value of $\vartheta = 0$, i.e., PaB without markups. If we set $\vartheta = 1$ (the longest BEPP), we find that the annual costs rise to 149 Mio. Euro, i.e., an increase of 9%.[21]

[20] The European Commission (2017) also intends to introduce voluntary BE bids, i.e., bidders that were not awarded within the regular SBP auction can submit an additional energy bid. The additional BE bids allow to be part of the merit-order without the power payment. This may increase the competition on the BE bids, and set an upper bound for BE prices (see Chapter 5).

[21] Setting $\vartheta = 1$ yields $P^{+}(c) = P^{-}(c) = 1$. The costs for BP reduce to 107 Mio. Euro, whereas the costs

4.5 Conclusion

We examined the interrelations of the energy wholesale market and the BP market. Our analysis was based on the market interdependencies that BP bidders cannot trade their capacities on the wholesale market, however, must run their plants at a minimal load. We developed an integrated market model for which we derived an equilibrium on all markets. Our market setting relates to the recently discussed harmonization of the European BP markets. We proved that there exists an integrated market equilibrium that guarantees efficiency on both markets under certain assumptions. By comparing the theoretical results with empirical German market data of 2015 we found considerable discrepancies: our theoretical results predicted lower total costs than the costs observed in the empirical market outcomes.

for BE increase to 42 Mio. Euro. The reason for this is the reduction of the BP price to 5.96 Euro/MWh, and an increase of the positive (negative) BE price to 39.46 Euro/MWh (-12.36 Euro/MWh).

Chapter 5

Harmonization of the European balancing power auction – a game-theoretical and empirical investigation

The previous chapters provided evidence for market imperfections in the German SBP markets. In particular, the regular repetition of the auctions and the required prequalification of bidders facilitates collusion. The German case becomes even more important because the future European market design is very similar to the current Austrian-German design.

Against this background, the European Commission (2017) implements two essential design modifications: Firstly, the pricing rule is to be switched from PaB to UP, and secondly, an additional market after the regular auction is to be implemented. The former shall incentivize bidders to report their true costs in their bids, and therefore – in comparison to PaB – generate more efficient auction outcomes. The latter shall guarantee a higher degree of competition for the BE bids (e.g., German Federal Ministry for Economic Affairs and Energy, 2015; Morch and Wolfgang, 2016; European Commission, 2017).

In order to assess whether the future market design is appropriate, the understanding of the auction mechanism is crucial. Since auctions are a subfield of game theory, a game-theoretical model is necessary. However, such a model seems to be lacking for any (European) BP market design. Therefore, we present such a model for both the current Austrian-German auction and the future European auction. We analyze the market institutions with regards to their game-theoretical equilibria, and hereby concentrate on the two essential policy targets: efficiency and market prices. We find that the market equilibrium in the applied Austrian-German auction has all desirable theoretical properties. The modifications in the future European auction have no impact on this equilibrium. In particular, UP does not induce bidders to truthfully report their costs in their bids. On the contrary, UP incentives bidders to understate their costs in their bids. The additional market after the regular auction, however, is sensible to foster competition and, thus, impede collusive behavior.

The remainder of this chapter is structured as follows. Section 5.1 presents our game-theoretical model. In Section 5.2, we discuss the theoretical properties of the one-shot auction under different market designs. Section 5.3 confronts theoretical findings with empirical data from Germany, and Section 5.4 extends the analysis to results of repeated games. Section 5.5 concludes.

5.1 Game-theoretical model

In this section we provide the basis for our game-theoretical model. Furthermore, we discuss conditions for an overall efficient market outcome. For the sake of presentation and since the positive and negative BP market are analyzed separately, we do not differentiate the notation for positive and negative BP in this chapter.

5.1.1 The model

Consider a BP market (e.g., for positive or negative BP) with n bidders. Each bidder participates with one power plant. All plants have the same power offer q [MW]. Without loss of generality, we set $q = 1$.[1] The BP demand B is given by the number of awarded bidders $|B| = b$, $b < n$. These b bidders are awarded according to their BP bid ϕ and a merit-order activation strategy, i.e., awarded bidders are activated in increasing order of their BE bids ψ. We consider the two pricing rules UP and PaB for both the BP bid and the BE bid. The length of the reserve period is denoted by d. Let p_W denote the wholesale market price and $a_{max} \in [0, 1]$ the maximum calling probability, i.e., the share of time which the bidder with the lowest submitted BE bid will be demanded. Bidders independently draw their private variable energy production costs $c \in [c_0, c_1]$ from a probability distribution $F : [c_0, c_1] \to [0, 1]$ with density $f : [c_0, c_1] \to \mathbb{R}^+$. For a representative bidder, let $C_{(i,n-1)}$ denote the ith order statistic of her opponents' costs, i.e., the ith highest cost of the other $n-1$ bidders with the distribution function $F_{(i,n-1)}$ and density $f_{(i,n-1)}$. If there is no danger of confusion, we write $F_{(i,n-1)} = F_{n-1}$ and $f_{(i,n-1)} = f_{n-1}$. Bidders' profit function is denoted by π, i.e., the function π_{BP} on the BP market and the function π_W on the wholesale market.

5.1.2 Assumptions

We impose the following additional assumptions on the BP market model.

- (A1) b, p_W and a_{max} are exogenously given and common knowledge.
- (A2) The positive and the negative BP markets are investigated separately and are assumed to be independent.

[1] In addition, we assume indivisible bids and that none of the bidders has market power.

- (A3) Only inframarginal bidders are considered, that is $c_1 \leq p_W$.
- (A4) The calling probability of an awarded bidder decreases linearly with her rank within the merit-order from a_{max} to 0.

Assumptions (A1) and (A2) are simplifications that are in line with recent literature on BP markets.[2] The assumption of an exogenous wholesale market price can be found in Müsgens et al. (2014), the separate analysis of the positive and the negative markets in Hirth and Ziegenhagen (2015).[3] We are aware that Assumption (A3) might be critical for the external validity of our model. We decided to include this assumption for three reasons. Firstly, it is crucial to theoretically analyze the auction in general. Since the cost structures of inframarginal and extramarginal plants differ substantially (see Section 2.3.2), we had to consider an asymmetric auction-theoretical model. However, the literature on these type of models shows the difficulties of their analysis concerning the existence and uniqueness of equilibria and the generality of the results (Maskin and Riley, 2000; Landsberger et al., 2001; Krishna, 2002). We therefore decided to develop a model with symmetric bidders, which provides a first benchmark for an idealized market with only inframarginal plants. Secondly, the theoretical results of our integrated market model in Chapter 4 indicate that a substantial share of BP bidders is inframarginal. Furthermore, this assumption is in line with current research (e.g., Just and Weber, 2008; Müsgens et al., 2014). Thirdly, the assumption is supported by the publicly available data on the technologies of the prequalified bidders in Germany.[4] Assumption (A4) accounts for the fact that the calling probability is decreasing in the merit-order rank of awarded bids. We

[2]Information regarding the demand and calling probabilities of previous auctions are provided by the TSOs.
[3]Wen and David (2002) and Braun and Burkhardt (2015) discuss optimized trading across different markets.
[4]According to the German TSOs, the prequalified capacities for the SBP (around 22 GW for the positive and negative market) relate to the following types of plants: around 2 % nuclear, 6 % lignite, 7 % hard coal, 12 % gas-fired, less than 1 % oil, 6 % biomass, 61 % hydro, and 5 % others (regelleistung.net, 2018a).

are aware that the empirical calling probability function does not have a linear shape (see Chapter 4). Yet, the assumption of a linear relationship between merit-order rank and calling probability is of technical nature and facilitates the computation of the conditional calling probability.

5.1.3 Market efficiency

Before we present our theoretical results, we define conditions for an efficient market outcome. As elaborated in Chapter 4, the provision of BP influences the generation on the wholesale market. In consequence, an overall efficient allocation of capacities requires that the aggregated generation costs on both markets are minimized (e.g., Müsgens et al., 2014).

Due to our assumptions of only considering inframarginal plants and a maximum calling probability equal to 1, an efficient market outcome requires that the bidders with the highest variable energy production costs are selected. This holds for both the positive and negative provision of BP. The reason for this is that on the wholesale market, in contrast to the BP market, producers continuously generate energy.

Regarding an efficient delivery of BE, the positive and negative market differ. An efficient provision of positive BP is ensured if bidders are activated in an increasing order with respect to the variable costs. The reason is that positive BP bidders supply additional energy to the power grid. Hence, BP costs are minimized if bidders with the lowest variable costs are activated first. On the contrary, an efficient provision of negative BP demands that bidders are activated in an decreasing order with respect to the variable costs. The reason for this is that if negative BP is required, too much energy is supplied to the power grid and, consequently, the energy supply has to be reduced. Thus, costs are minimized if those bidders with the highest variable costs are activated first.

5.2 Theoretical analysis of the base game

In this section we provide the game-theoretical analysis of the current Austrian-German and future European SBP market in their one-shot versions, i.e., the base game. First, we investigate the theoretical implications of switching the pricing rule from PaB to UP for all four combinations of BP bid and BE bid. Then, we discuss the introduction of voluntary BE bids. Hereby, we differentiate between the positive and negative market.

5.2.1 Different applied pricing rules

In this section we discuss the effects of switching the pricing rule from PaB to UP. For this, we derive symmetric Bayesian Nash equilibria for the BP bid and the BE bid, and analyze their properties as well as the properties of the resulting market outcomes.

Beforehand, we characterize the environment of our model. The SBP auction is a one-shot multi-unit procurement auction for inhomogeneous goods with bidders with single-unit supply. The inhomogeneity of the goods, which is caused by the merit-order, is crucial for the analysis because this distinguishes SBP auctions from the multi-unit auctions which are usually considered in the literature (Varian, 2006; Edelman et al., 2007; Müsgens and Ockenfels, 2011). For the same setting with homogeneous goods, the effects of the two different pricing rules are well known: If the lowest rejected bid sets the UP, bidders are incentivized to report their true costs in their bids (Krishna, 2002; Ausubel et al., 2014). As we will see, this property is no longer true in case of inhomogeneous goods. If the highest accepted bid sets the UP, there is a positive probability that a bidder sets the uniform price with her bid. Thus, bidders have an incentive to exaggerate their true costs in their bids, which declines with an increasing number of bidders. If PaB is applied, bidders always have an incentive to exaggerate their true costs in their bids because their bids determine their individual payments when awarded.

5.2.1.1 Positive market

We first analyze the positive market: a bidder's expected profit is stated, and the four combinations of pricing rules are discussed. Note that, for example, UP/PaB stands for UP for the BP bid and PaB for the BE bid.

Bidder's expected profit

Let p_{BP} and p_{BE} denote the BP price and BE price, function g the probability of winning the auction and function a the probability of being called for the delivery of BE.[5] The expected profit function of a bidder with variable costs c for a reserve period with length d is given by

$$E[\pi_{BP}] = g(\phi)\big(p_{BP} + a(\psi)(p_{BE} - c)\,d\big) + (1 - g(\phi))(p_W - c)\,d\,. \quad (5.1)$$

If a bidder is awarded in the SBP auction, she receives both the BP price and the BE price. However, the latter depends on the actual calling duration that is unknown before the auction. If a bidder is not awarded in the SBP auction, she will participate on the regular wholesale market and receive the margin of the wholesale market price and the variable costs.

PaB/UP for the BP bid and PaB for the BE bid

First, we analyze UP for the BP bid and PaB for the BE bid. That is, the uniform BP price is determined by the bidder with the highest BP bid among all awarded bidders, while the individual BE prices differ among the awarded bidders (depending on their BE bids). Proposition 5 establishes the existence of equilibrium bidding strategies.

[5] p_{BP}, p_{BE} depend on the respective bids in the case of PaB or on a uniform price in the case of UP.

Proposition 5. *In the positive SBP market with UP/PaB pricing, the bidding functions*

$$\begin{aligned} \phi(c) &= (p_W - c)\, d - \big(\psi(c) - c\big)\, d\, a_{max} \\ \psi(c) &= E[C|C \geq c] = c + \frac{\int_c^{c_1} 1 - F(u)\, du}{1 - F(c)} \end{aligned} \tag{5.2}$$

constitute the unique symmetric Bayesian Nash equilibrium in monotonic bidding functions.[6]

Proof. See Appendix C. □

The equilibrium BP bid comprises of two components: the foregone profits of trading at the wholesale market minus the expected profit of the BE bid. Hence, bidders do not report their true opportunity costs in their BP bids. The BP bid reflects a bidder's lost profit in case of being on the first rank of the merit-order. With

$$\phi'(c) = -\big((1 - a_{max}) + \psi'(c)\, a_{max}\big)\, d < 0\,,$$

the BP bid decreases with the variable costs. The intuition is that low variable costs are accompanied with high opportunity costs of sale on the wholesale market.

The equilibrium BE bid is based on a bidder's variable costs and a markup, which is due to PaB and corresponds to the markdown in sales auctions that is called "bid-shading" (Milgrom and Weber, 1982; Kremer and Nyborg, 2009; Ausubel et al., 2014). The amount of the markup depends on a bidder's beliefs about the competition level (Myerson, 1981;

[6] The variable u in the integral are the costs of an representative opponent with higher costs than c.

Kahn et al., 2001). The BE bid ψ is independent of her BP bid ϕ with

$$\psi'(c) = \frac{f(c)\int_c^{c_1} 1 - F(u)\,du}{\big(1-F(c)\big)^2} > 0\,.$$

That is, ψ is strictly increasing in c, i.e., the BE bid increases with c.

We turn to the analysis of PaB for both the BP bid and BE bid, which is the market design currently implemented Austria and Germany. Proposition 6 shows that under PaB/PaB pricing equilibrium bidding strategies exist and are unique.

Proposition 6. *In the positive SBP market with PaB/PaB pricing, the bidding functions*

$$\begin{aligned}
\phi(c) =& \frac{\int_{c_0}^{c}\big((p_W - c)\,d - (\psi(u) - u)\,d\,a_{max}\big)f_{(b)}(u)du}{F_{(b)}(c)} \\
=& (p_W - c)\,d - \big(\psi(c) - c\big)\,d\,a_{max} \\
&+ \frac{\int_{c_0}^{c}\Big(1 - a_{max} + a_{max}\frac{\int_u^{c_1} 1 - F_{(b)}(x)dx}{\big(1-F_{(b)}(u)\big)^2}f(u)\Big)dF_{(b)}(u)du}{F_{(b)}(c)} \\
\psi(c) =& E[C|C \geq c] = c + \frac{\int_c^{c_1} 1 - F(u)\,du}{1 - F(c)}
\end{aligned} \tag{5.3}$$

constitute the unique symmetric Bayesian Nash equilibrium in monotonic bidding functions.

Proof. See Appendix C. □

Bidders submit the same equilibrium BE bids as under UP/PaB pricing. The reason is that the BE bid is independent of the BP bid. However, the equilibrium BP bid under PaB/PaB pricing (5.3) differs from that under UP/PaB pricing (5.2) by the additional term in (5.3). Under PaB/PaB pricing, $\phi(c) > (p_W - c)\,d - \big(\psi(c) - c\big)\,d\,a_{max}$, i.e., bidders conduct bid-shading compared to the BP bid under UP/PaB. Furthermore, we have

$$\phi'(c) = \frac{f_{(b)}(c)}{F_{(b)}(c)}\big((p_W - c)\,d - (\psi(c) - c)\,d\,a_{max} - \phi(c)\big) < 0\,.$$

Thus, the BP bid decreases with the c.

If PaB is applied for the BE bids in the positive market, unique equilibria exist under both pricing rules for the BP bid. Proposition 7 summarizes the properties of the equilibrium bidding functions in the positive market in these two cases.

Proposition 7. *In the equilibrium of the positive SBP market with both PaB/PaB pricing and UP/PaB pricing the following hold.*

(a) ϕ *is decreasing in* c*.*

(b) ψ *is increasing in* c*.*

(c) *The auction outcome is efficient.*

(d) $\phi^{UP/PaB}$ *is independent of* n*.*

(e) $\phi^{PaB/PaB} > \phi^{UP/PaB}$ *and* $\phi^{PaB/PaB} \to \phi^{UP/PaB}$ *for* $n \to \infty$*.*

(f) $\psi(c) \in [c, p_W]$ *for all* $c \in [c_0, c_1]$*.*

Proof. See Appendix C. □

The equilibrium bidding functions for the BP bid (BE bid) decrease (increase) in the variable costs. This is consistent with the conditions for an efficient auction outcome (see Section 5.1.3). While the equilibrium BP bid under UP/PaB pricing is independent of the number of bidders, this is not the case for PaB/PaB pricing. Here, the markup depends on a bidder's beliefs about the competition level: the higher the expected competition level, i.e., number of competitors, the lower is the markup. Hence, the equilibrium BP bid under UP/PaB pricing serves as an upper bound for the equilibrium BP bid under PaB/PaB pricing. Finally, the equilibrium BE bid does not exceed the wholesale market price.

Proposition 8 summarizes the properties of bidders' expected profits.

Proposition 8. *In the equilibrium of the positive SBP market with both PaB/PaB pricing and UP/PaB pricing the following hold.*

(a) $E\left[\pi_{BP}^{PaB/PaB}(c)\right] = E\left[\pi_{BP}^{UP/PaB}(c)\right]$ *for all* $c \in [c_0, c_1]$.

(b) $E\left[\pi_{BP}(c)\right] > E\left[\pi_{W}(c)\right]$ *for all* $c \in (c_0, c_1]$.

(c) $E\left[\pi(c)\right]$ *is decreasing in* c.

(d) $E\left[\pi(c)\right]$ *is decreasing in* n *for all* $c \in (c_0, c_1]$.

Proof. See Appendix C. □

Equilibria in strictly increasing bidding functions for PaB/PaB and UP/PaB pricing yield revenue equivalence. This is directly implied by a straightforward adoption of the revenue equivalence theorem (Myerson, 1981). Since bidders' expected profits of the SBP auction are greater than the respective profits in the wholesale market, bidders are incentivized to participate in the SBP auction. The expected profits decrease in the variable costs. Moreover, the expected profits decrease with the competition level. Therefore, all desirable properties of a well-performing auction can be guaranteed in the equilibrium of the positive market.

PaB/UP for the BP bid and UP for the BE bid

If PaB is applied for the BP bid, the equilibrium BP bid of Proposition 6 still holds.

Proposition 9. *If there exists a symmetric equilibrium in strictly monotonic bidding functions of the positive SBP market with both PaB/UP* *pricing and UP/UP pricing, bidders underbid their variable costs, i.e.,*

$$\psi(c) < c \qquad \textit{for all } c \in (c_0, c_1)\,.$$

Proof. See Appendix C. □

If UP is applied for the BE bids, bidders underbid their variable costs in their BE bids. Hence, the argument that UP will incentivize bidders to reveal their true costs is not correct. The reason for this is that the tendered goods (i.e., ranks in the merit-order of BE bids) are not homogeneous, as already mentioned by Müsgens and Ockenfels (2011) and Ehrhart et al. (2016).[7] By underbidding, bidders can reach a lower rank in the merit-order of the BE bids without (necessarily) reducing the uniform BE price. Since the ranks in the merit-order differ in the expected calling probability, a lower rank is more valuable than a higher rank because of a longer time span of activation and, thus, higher profits (Ocker et al., 2016b). The incentive to underbid increases when the BEPP (i.e., the time period for the settlement of the uniform price) increases: the longer the BEPP, the higher is the expected maximum rank in the merit-order that must be called to meet the BE demand. Note that there does not exist an explicit expression for the equilibrium BE bid if UP is applied. Yet, we can prove that bidders underbid their variable costs in an equilibrium. The analytical reasoning is illustrated in Appendix C.

If UP is utilized for both BP bid and BE bid, Proposition 5 for the BP bid and Proposition 9 for the BE bid apply respectively.

[7]Similar results hold the generalized second-price auction for advertisements in search engines such as Google or Yahoo! (Varian, 2006; Edelman et al., 2007; Varian, 2009).

5.2.1.2 Negative market

In this section we analyze the negative market: a bidder's expected profit is presented, and the four combinations of pricing rules are discussed. As in the positive market, for example, UP/PaB stands for UP for the BP bid and PaB for the BE bid.

Bidder's expected profit

The BP price and BE price are denoted by p_{BP} and p_{BE}, the probability of winning the auction by the function g and the probability function of being called for BE by a. The expected profit of a bidder with variable costs c for a reserve period with length d is given by

$$\begin{aligned} E[\pi_{BP}] =& g(\phi)\big(p_{BP} + (p_W - c)\, d + a(\psi)(p_{BE} + c)\, d\big) \\ &+ (1 - g(\phi))(p_W - c)\ d. \end{aligned} \tag{5.4}$$

The payment of an awarded bidder consists of the BP price and BE price, as in the positive market. However, the calculation of the expected profit is more complex. Negative BP is demanded if the power system has an oversupply of energy. Then, bidders reduce the load level of their plants. This requires that their plant is already operating and the corresponding energy is sold at the wholesale market. If they are called for negative BE, they are still remunerated on the wholesale market because the oversupply covers their tendered capacities. That is, in addition to the BP price and BE price, they also receive the margin of the wholesale market and save their variable costs when reducing the load level of the power plant. If a bidder is not awarded in the auction, she participates at the regular wholesale market.

The BP bid

For all equilibria in the negative SBP market the following holds.

Proposition 10. *If there exist equilibria of the negative SBP market with UP/PaB pricing or PaB/PaB pricing, bidders submit no BP bids, i.e.,*

$$\phi(c) = 0 \qquad \textit{for all } c \in [c_0, c_1].$$

Proof. See Appendix C. □

In the equilibrium of the negative market, BP bids equal zero. The reason for this is that bidders sell all of their produced energy at the wholesale market with a profit. Hence, there are no foregone profits and, thus, no opportunity costs (Hirth and Ziegenhagen, 2015).

UP/PaB for the BP bid and PaB for the BE bid

Proposition 10 holds for the BP bid. The BE bids, however, are negative.

Proposition 11. *In the negative SBP market with both UP/PaB pricing or PaB/PaB pricing, the bidding functions*

$$\phi(c) = 0 \ \textit{ and } \ \psi(c) = \begin{cases} -\dfrac{\int_{c_0}^{c} u\, f(u) \left(\int_{c_0}^{u} \frac{f_{(b)}(x)}{1-F(x)}\, dx \right) du}{\int_{c_0}^{c} \left(F(c) - F(u) \right) \frac{f_{(b)}(u)}{1-F(u)}\, du} & c > c_0 \\ -c_0 & c = c_0 \end{cases}$$

constitute the unique symmetric Bayesian Nash equilibrium.

Proof. See Appendix C. □

Note that $\psi(c)$ is negative for all $c > 0$. Bidders with positive variable costs are willing to pay for being called. This reflects the structure of the profit function in the negative market (5.4): bidders in the negative market are remunerated with the wholesale market price and save their variable costs. Therefore, bidders submit negative BE bids (see Section 2.3.2).

If in the negative market PaB is applied for the BE bids, equilibria exist under both pricing rules for the BP bid. Proposition 12 summarizes the properties of the equilibrium bidding functions in the negative market in these two cases.

Proposition 12. *In the equilibrium of the negative SBP market with both PaB/PaB pricing and UP/PaB pricing the following hold.*

(a) $\psi(c) \leq 0$ *for all* $c \in [c_0, c_1]$.

(b) ψ *is decreasing in* c.

(c) *The auction outcome is efficient.*

Proof. See Appendix C. □

In the equilibrium of the negative market, the BE bids are (weakly) negative and decrease with bidders' variable costs. This implies that an efficient market outcome is guaranteed, conditionally to the implemented tie-breaking rule (see Section 2.2.3).

Proposition 13 compares the expected profits of the bidders.

Proposition 13. *In the equilibrium of the negative SBP market with both PaB/PaB pricing and UP/PaB pricing the following hold.*

(a) $E\left[\pi_{BP}^{PaB/PaB}(c)\right] = E\left[\pi_{BP}^{UP/PaB}(c)\right]$ *for all* $c \in [c_0, c_1]$.

(b) $E\left[\pi_{BP}(c)\right] > E\left[\pi_W(c)\right]$ *for all* $c \in (c_0, c_1]$.

(c) $E\left[\pi(c)\right]$ *is decreasing in* c.

(d) $E\left[\pi(c)\right]$ *is decreasing in* n *for all* $c \in (c_0, c_1]$.

Proof. See Appendix C. □

An equilibrium in strictly increasing bidding functions for PaB/PaB pricing and UP/PaB pricing obviously yields revenue equivalence. The bidders' expected profits in the SBP auction are greater than the respective profits in the wholesale market and their expected profits decrease in the variable costs and with the number of bidders. Concluding, all desirable properties of a well-performing auction can be guaranteed in the equilibrium of the negative market.

UP for the BP bid and BE bid

Proposition 10 holds for the BP bid and the following for the BE bid.

Proposition 14. *If there exists a symmetric equilibrium in strictly monotonic bidding functions of the negative SBP market with both PaB/UP pricing and UP/UP pricing, bidders underbid their variable costs, i.e.,*

$$\psi(c) < -c \qquad \text{for all } c \in (c_0, c_1).$$

Proof. See Appendix C. □

That is, UP does not induce bidders to report their variable costs in their BE bids, as in the positive market (see Proposition 9). Bidders underbid their negative variable costs in an equilibrium. The intuition is the same as in the positive market: by underbidding, bidders move up in the merit-order of the BE bids without (necessarily) influencing the uniform BE price. This results in a longer time span of activation and, thus, in higher expected profits. As in the positive market, there is no explicit expression for the equilibrium BE bid if UP is applied. Yet, by analogous reasoning as in Proposition 9, we can prove that bidders underbid their negative variable costs in an equilibrium.

5.2.1.3 Summary

We show that all investigated market designs (in the positive and negative market) have desirable properties: the expected auction outcomes are efficient (conditionally to the implemented tie-breaking rule), the equilibrium bids are competitive, and bidders' profits reflect their technologies. However, with UP, bidders do not report their true costs. They take their expected profits of the BE bid in their BP bids into account, and understate their variable costs in their BE bids. The latter finding seems to be new to literature since it is frequently postulated that UP induces bidders to state their true costs in their BE bids, which consequently simplifies the auctions (e.g., Müsgens et al., 2014; German Federal Ministry for Economic Affairs and Energy, 2015; Morch and Wolfgang, 2016; European Commission, 2017). We show that this is not the case. On the contrary, UP for the BE bid yields unusual and undesirable bidding incentives.

Our analysis illustrates two essential differences of the positive and negative SBP – even in the one-shot auction. Firstly, the optimal BP bids equal zero under all four pricing rule combinations in the negative market. This result raises the question whether the BP bid in the negative market is necessary and sensible in the first place. The fact that many (European) BP auctions rely exclusively on the BP bid for winner determination further emphasizes the importance of our findings (e.g., Section 2.2.2 and Ocker et al., 2016a). Secondly, all bidders submit negative BE bids in the equilibrium of the negative market. This finding reflects the fundamental contrast of the profit structure in the positive and negative market.

5.2.2 Introduction of voluntary balancing energy bids

The harmonized European SBP auction includes the introduction of voluntary BE bids. Bidders that were not awarded (or did not participate) in the regular auction are granted a second chance to be part of the merit-order of BE bids, i.e., they have the possibility to submit additional, voluntary BE bids without the power payment (European Commission, 2017).

5.2.2.1 Model extension

Let $\psi_2 \in \mathbb{R}^+ \cup \{\infty\}$ denote the voluntary BE bid of a bidder who is not awarded in the regular SBP auction with her BP bid ϕ, where $\psi_2 = \infty$ refers to not using this additional option. This modification is strategically equivalent to a market design in which each bidder submits a four-dimensional bid in the regular SBP auction: a power offer, a BP bid ϕ, a BE bid ψ and an additional voluntary BE bid ψ_2. The latter only becomes effective if the bidder is not awarded in the regular SBP auction.

5.2.2.2 Positive market

The introduction of voluntary BE bids in the positive market alters the calculus of a bidder, since the submission of an additional BE bid offers a further opportunity for profits. The adjusted version of the expected profit (5.1) is then given by

$$
\begin{aligned}
E[\pi_{BP}] = g(\phi)\big(p_{BP} + a(\psi)(p_{BE} - c)\, d\big) + \big(1 - g(\phi)\big)& \\
\big(g_2(\psi_2)\, a(\psi_2)(p_{BE,2} - c)\, d + (1 - g_2(\psi_2))\, (p_W - c)\, d\big)&\,,
\end{aligned}
$$

where g_2 denotes the probability of being awarded with the voluntary BE bid and $p_{BE,2}$ the BE price for the additional bid. A bidder receives the BP price p_{BP} and the BE price p_{BE} only if she is awarded in the regular SBP auction. Note that now the calling probability a also depends on possible additional BE bids ψ_2. If a bidder's voluntary BE bid is awarded, she obtains only the remuneration for delivered BE. Bidders that are still not awarded on the SBP market sell their energy on the wholesale market.

The following proposition states that – irrespective of the pricing rule – each equilibrium of the SBP market without voluntary BE bids also constitutes an equilibrium in the market with additional BE bids, i.e., bidders refrain from submitting an additional BE bid.

Proposition 15. *For any combination of pricing rules, let ϕ and ψ be the bidding functions in the symmetric Bayes-Nash equilibrium of the positive SBP auction without voluntary BE bids. Then, the bidding functions ϕ, ψ and $\psi_2 \equiv \infty$ constitute a symmetric Bayes-Nash equilibrium of the SBP auction with voluntary BE bids.*

Proof. See Appendix C. □

The intuition is that, since the resulting BE prices are below the wholesale market price, bidders would rather sell their energy on the wholesale market because they receive no additional power payment. Hence, the introduction of voluntary BE bids has no influence on the base game, and all equilibria and their properties carry over.

5.2.2.3 Negative market

The adjusted version of the expected profit (5.4) is given by

$$\begin{aligned} E[\pi_{BP}] &= g(\phi)\big(p_{BP} + (p_W - c)\, d + a(\psi)(p_{BE} + c)\, d\big) \\ &\quad + \big(1 - g(\phi)\big)\big((p_W - c)\, d + g_2(\psi_2)a(\psi_2)(p_{BE,2} + c)\, d\big) \,. \end{aligned}$$

Again, there is an additional possibility of being awarded with the voluntary BE bid ψ_2, where g_2 denotes the respective probability and $p_{BE,2}$ the respective BE price. In this case, the bidder only lacks the power payment. However, since equilibrium BP bids in the negative SBP market equal 0, the nonexistent strategic impact of voluntary BE bids is even more obvious than in the positive market. This is stated in Proposition 16.

Proposition 16. *For any combination of pricing rules, let ϕ and ψ be the bidding functions in the symmetric Bayes-Nash equilibrium of the negative SBP auction without voluntary BE bids. Then, the bidding functions ϕ, ψ and $\psi_2 \equiv \infty$ constitute a symmetric Bayes-Nash equilibrium of the SBP auction with voluntary BE bids.*

Proof. See Appendix C. □

As in the positive market, the intuition is that bidders would rather sell their energy on the wholesale market than submitting voluntary BE bids. That is, the introduction of voluntary BE bids has no impact on the base game, and all equilibria and their properties persist.

5.2.2.4 Summary

The introduction of voluntary BE bids has no impact on the base game in the positive and negative SBP market. Equilibria of the markets without additional BE bids remain equilibria with additional BE bids, since bidders do not use their voluntary BE bids.

5.3 German market data and theoretical findings

The model presented in Section 5.2 yields a benchmark for an empirical analysis of the German SBP market. Therefore, in this section, we contrast some of our theoretical findings with empirical evidence.

5.3.1 Descriptive price analysis

Beforehand, we present a descriptive price analysis of German SBP market results from 2013 to 2015 for the positive and negative market. In sections 5.3.2 and 5.3.3, we confront some of our theoretical findings with empirical market results, and discuss the price developments in more detail.

In Figure 5.1 (Figure 5.4), we depict the development of the BP prices from 2013 to 2015 in the positive (negative) market for the main period and the sub-period. Here, we refer to the mean weighted (normalized) BP bid for each week.[8] In figures 5.2 and 5.3 (figures 5.5 and 5.6), we depict

[8]Note that in contrast to figures 3.6 and 3.7, we normalize the BP bid to one hour of the reserve period, resulting in the unit Euro/MWh (60h for the main period, 108h for the sub-period). This is for consistency

the development of the BE prices (i.e., BE bids) on merit-order ranks 1, 500, and 1,000 from 2013 to 2015 in the positive (negative) SBP market for the main period and the sub-period.

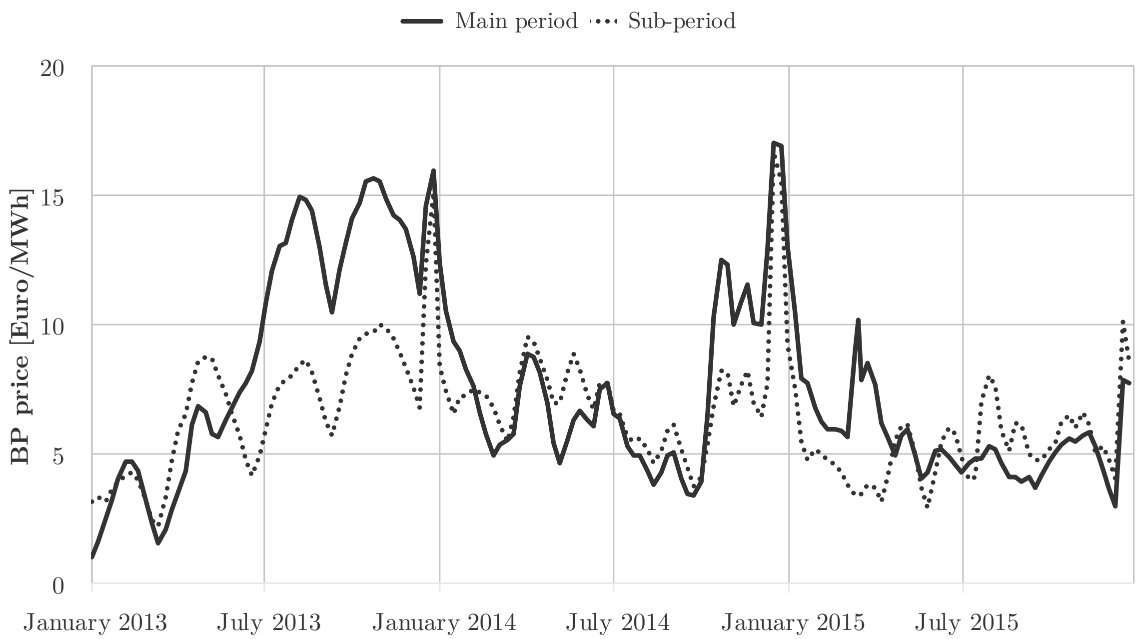

Figure 5.1: Development of the BP prices (mean weighted (normalized) BP bids) in the positive German SBP market (main period and sub-period) from January 2013 to December 2015 (regelleistung.net, 2018a).

Our theoretical analysis shows that the current German SBP market design has desirable theoretical properties. However, there is strong empirical evidence for market imperfections in the German SBP markets. Heim and Götz (2013) find evidence for high prices due to strategic supply reduction. Müsgens et al. (2014) argue that bidders guess the most expensive BP bid in the SBP market, instead of reporting their true capacity costs. Ocker and Ehrhart (2017a) suggest that bidders coordinate on high price levels by considering previous auction results (see Chapter 3). This indicates that bidders update their information sets with previous auction outcomes and adjust their bids accordingly. That is, a higher expected

reasons in this chapter because all other empirical data refer to the unit Euro/MWh.

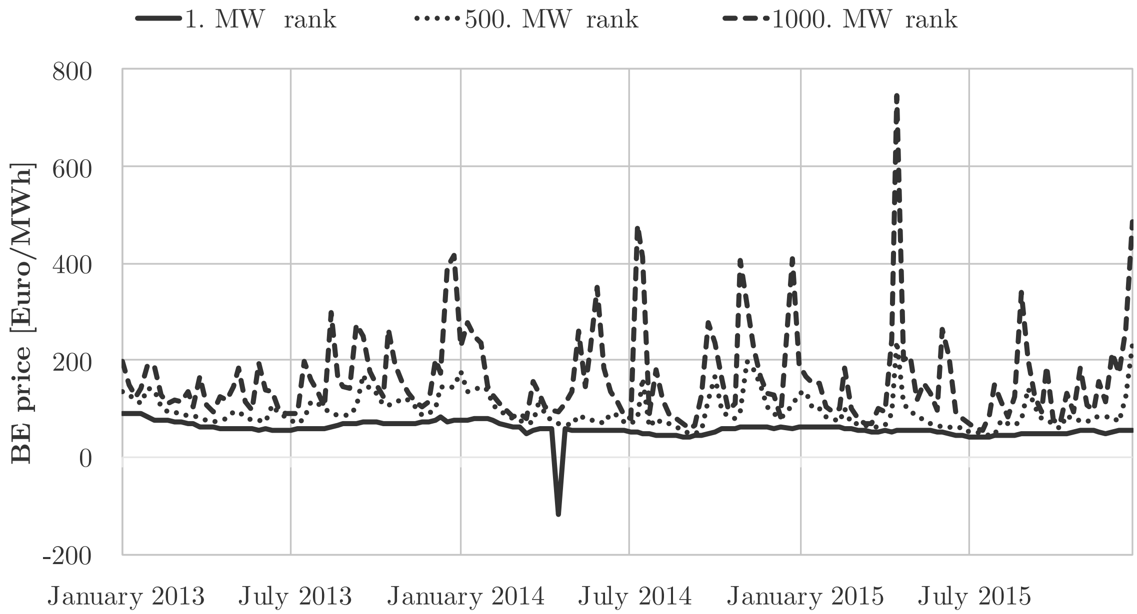

Figure 5.2: Development of the BE prices (i.e., BE bids) in the positive German SBP market (main period) on different merit-order ranks from January 2013 to December 2015 (regelleistung.net, 2018a).

price level leads to higher bids. The highest awarded BP bid serves as a focal point for coordination, which facilitates to establish higher price levels. This may lead to the strategy of "guessing the highest awarded bid" (Müsgens et al., 2014; Ocker and Ehrhart, 2017a). Furthermore, the consideration of the general market setting impacts the attractiveness of the SBP auctions: if, for example, low prices are observed in the wholesale market, the appeal of participating in SBP auctions rises.[9]

5.3.2 The positive market

A central finding of our work ist that BE prices are competitive, i.e., they are below the wholesale market price. We relate to this finding and verify whether it is reflected in empirical auction results. For this, Figure 5.7 depicts the BE price on merit-order rank 1 (i.e., lowest awarded BE bid)

[9]The same holds between the positive and negative SBP auctions.

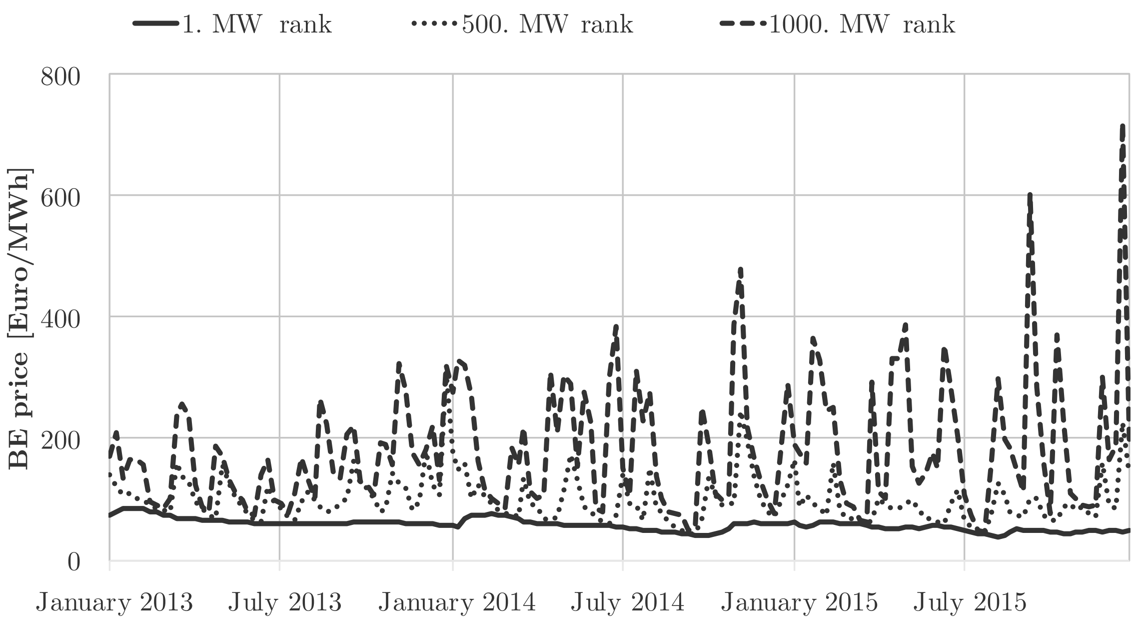

Figure 5.3: Development of the BE prices (i.e., BE bids) in the positive German SBP market (sub-period) on different merit-order ranks from January 2013 to December 2015 (regelleistung.net, 2018a).

in the German positive SBP market (main period and sub-period) for each auction from 2013 to 2015.[10] Note that these bids represent the prices on the first rank in the merit-order, i.e., the BE bids on subsequent ranks are (substantially) higher (see figures 5.2 and 5.3). Additionally, we depicted the wholesale market price, i.e., the Intraday Continuous auction price.[11]

The wholesale market price continuously falls below the BE bid on the first rank. This finding is supported by Ocker et al. (2018), who find that bidders subsidize the BP bid with (extremely) high BE bids, in order to increase the probability of winning. This facilitates the coordination on non-competitive prices (see Chapter 6).

Furthermore, we expect a negative correlation between bidders' BP bids and BE bids: The lower her variable costs, the lower is her BE bid, but

[10]Note that this figure includes the same curves as figures 5.2 and 5.3. For the sake of presentation, in particular regarding the granularity of the price-axis, we decided to add a figure that illustrates the price development of the first ranks in the merit-order and the wholesale market price.

[11]For further information refer to www.epexspot.com.

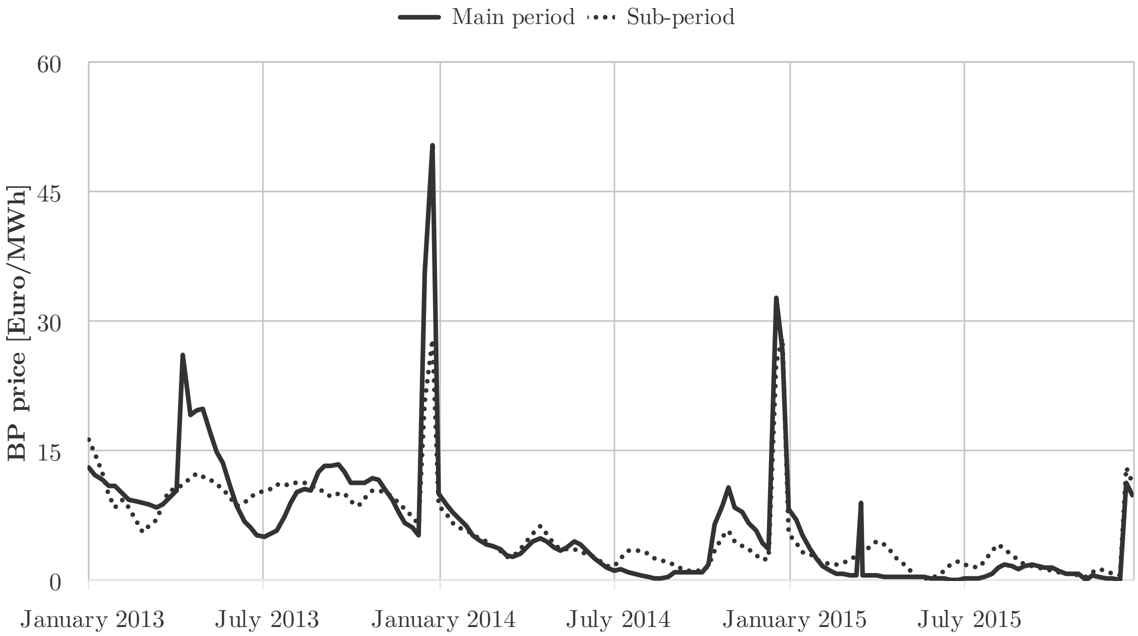

Figure 5.4: Development of the BP prices (mean weighted (normalized) BP bids) in the negative German SBP market (main period and sub-period) from January 2013 to December 2015 (regelleistung.net, 2018a).

the higher are her opportunity costs, and, thus her BP bid. For this, we illustrate the BE bids and BP bids in a scatter plot for an illustrative week, which is shown in figures 5.8 and 5.9.

The plots reveal that there is no clear relationship between BE bids and BP bids in the empirical data. This is a strong indication that there is no efficient market outcome in the German SBP auctions, since costs are not reflected in the bids. Therefore, an allocation that selects the right bidders to the wholesale market and to the SBP markets is impeded.

5.3.3 The negative market

Our model predicts efficient auction outcomes and competitive prices for the negative market as well. In the equilibrium, BP bids equal zero and each BE bid is strictly negative. Yet, again, the empirical data tells a different story. Although the BP bids seem – as predicted – to converge

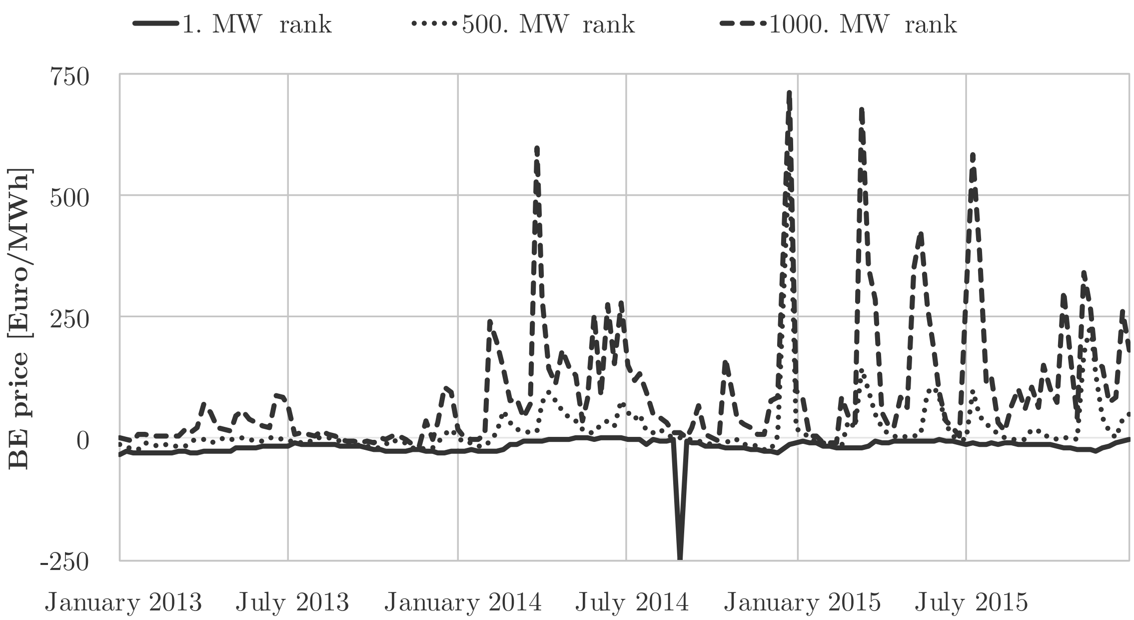

Figure 5.5: Development of the BE prices (i.e., BE bids) in the negative German SBP market (main period) on different merit-order ranks from January 2013 to December 2015 (regelleistung.net, 2018a).

to 0 over time (see Figure 5.4), our hypothesis for the BE bids does not hold. Referring to figures 5.5 and 5.6, the prices on merit-order rank 1 tend to be negative, however, the BE bids for higher ranks are clearly positive and extremely volatile. Table 5.1 presents the share of negative bids for different merit-order ranks. Evidently, the shares rapidly decline and BE bids for higher merit-order ranks are almost consistently positive.

	Merit-order rank							
	1	10	50	100	200	500	1,000	1,500
Main period	0.955	0.936	0.860	0.771	0.688	0.484	0.121	0.000
Sub-period	0.866	0.822	0.694	0.580	0.452	0.248	0.032	0.000

Table 5.1: Share of negative BE bids for different merit-order ranks in the negative German SBP market from January 2013 to December 2015 (regelleistung.net, 2018a).

Concluding, the market results of the negative market reveal substantial

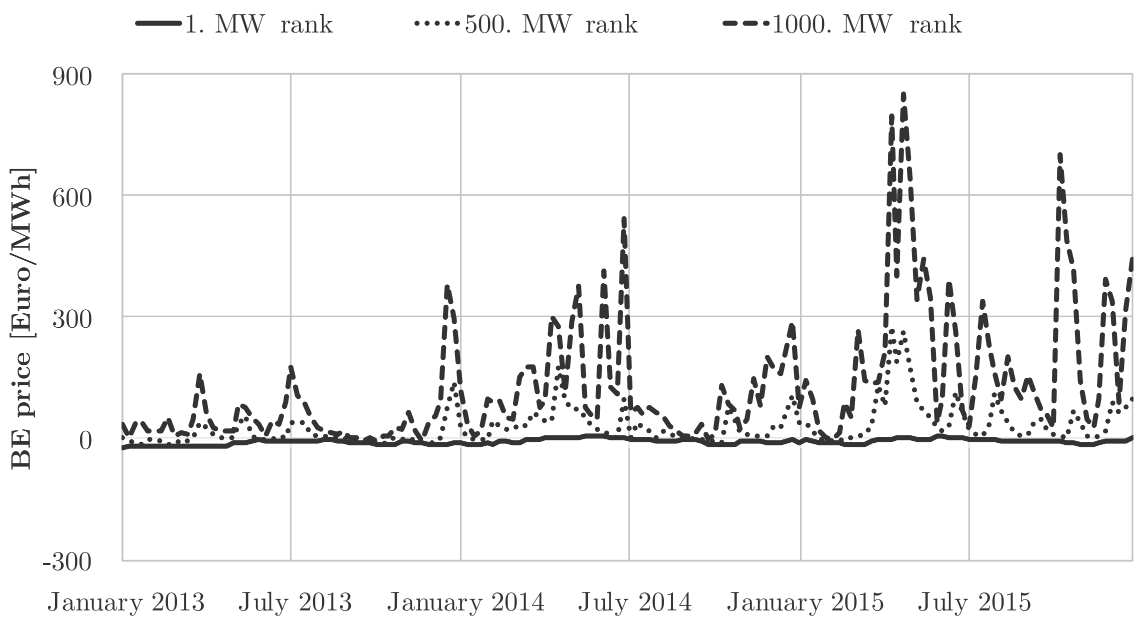

Figure 5.6: Development of the BE prices (i.e., BE bids) in the negative German SBP market (sub-period) on different merit-order ranks from January 2013 to December 2015 (regelleistung.net, 2018a).

discrepancies with respect to our theoretical findings. In particular, the BE bids are higher than predicted.

5.4 Repeated games

Empirical data from Germany's SBP markets show a huge and time-consistent discrepancy of the theoretical findings for the one-shot auction mechanism compared to empirical market results. In the following, we discuss a game-theoretical explanation for this disparity that is based on the interaction of the regular repetition of SBP auctions with the fact that the set of bidders remains constant over time.

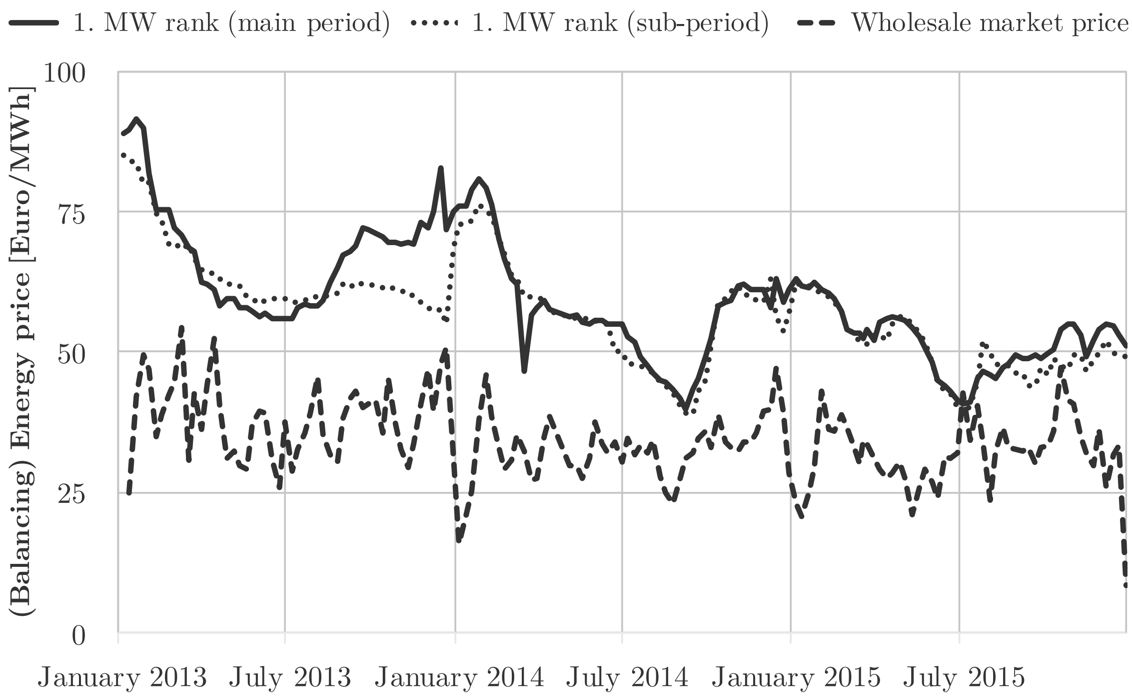

Figure 5.7: Development of BE prices (i.e., BE bids) in the positive German SBP market (main period and sub-period) on merit-order rank 1 and the German wholesale market price (Intraday Continuous price) from January 2013 to December 2015 (regelleistung.net, 2018a; EPEX Spot SE, 2016b).

5.4.1 Tacit collusion in repeated auctions

So far, we neglected one important feature of the SBP auction in our analysis: its frequent repetition. The auctions have been conducted weekly for many years. Hence, SBP markets should also be analyzed as a game in extensive form. Here, we consider the model of an infinitely repeated game with discounting as appropriate for the repeated SBP game in extensive form for the following reasons: Firstly, the set of bidders is relatively constant and has changed only little over time because prequalification requirements are high and very costly. Secondly, bidders are assumed to discount future profits and are uncertain when the game will terminate. We apply the existing results for this class of games to our setting.

The "folk theorem" states that there exists a large set of subgame perfect

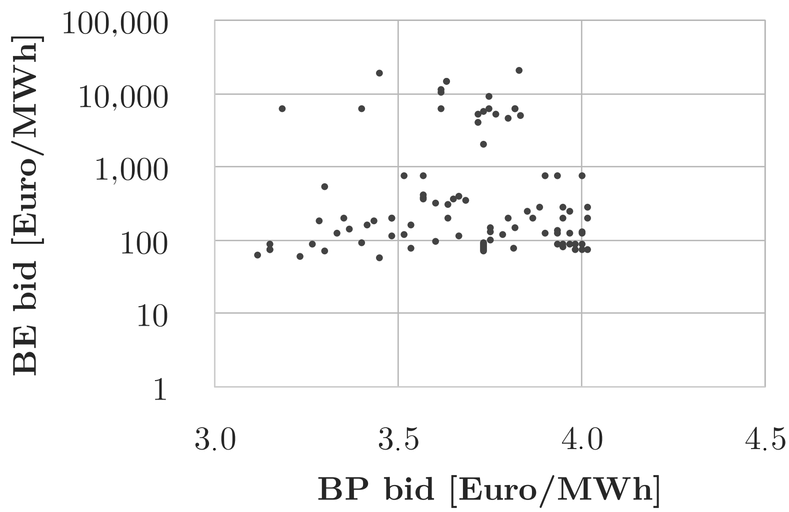

Figure 5.8: Distribution of BP bids and BE bids in the positive German SBP auction (main period) for an illustrative auction (logarithmic scale), i.e., calendar week 50 of 2015 (regelleistung.net, 2018a)

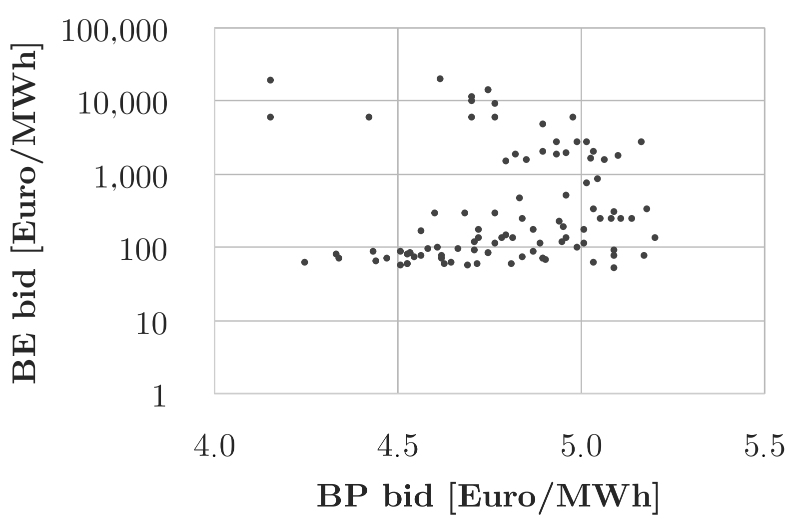

Figure 5.9: Distribution of BP bids and BE bids in the positive German SBP auction (subperiod) for an illustrative auction (logarithmic scale), i.e., calendar week 50 of 2015 (regelleistung.net, 2018a)

equilibria in infinitely repeated games. This set contains equilibria that lead to higher payoffs (i.e., profits) for the players (i.e., bidders) than the continuous repetition of the equilibrium of the base game (i.e., one-shot auction), which can be achieved also by a subgame perfect equilibrium in a repeated game (e.g., Fudenberg et al., 1994). Playing these equilibria in the repeated game is referred to as tacit or implicit collusion: Players tacitly coordinate on a solution, which is better for them than the equilibrium of the base game in form of higher prices, but cannot be reached by an equilibrium in the base game. These collusive solutions can be established by so-called trigger strategies, which punish players that deviate from the collusive strategy by, for example, playing the one-shot equilibrium in the subsequent rounds, which yields smaller payoffs for all players compared to the collusive solution (Friedman, 1971; Tirole, 1988; Vives, 1999).

There is a huge body of evidence for collusion in repeated auctions, both theoretically (e.g., Skrzypacz and Hopenhayn, 2004; Hortacsu and Puller, 2008) and empirically. Feinstein et al. (1985) and Porter and Zona (1993) analyze bid-rigging in procurement auctions for highway construction. Ehrhart (2001) shows that the fixed rate tender for refinancing operations invites bidders to continually raise their bids in repeated auctions. Macatangay (2002) reports tacit collusion in repeated multi-unit uniform price auctions for energy wholesale in England and Wales. Cramton and Schwartz (2000) and Bajari and Yeo (2009) find collusive bidding in multi-round FCC spectrum auctions. Porter and Zona (2004) examine collusive behavior in the school milk market in Ohio. Ishi (2009) conducts an empirical study of repeated procurement auctions in Japan to study the effect of exchanging favor. Lu et al. (2014) consider the effects of transparency on collusion in Dutch flower auctions. Ishii (2014) examines the "roundness level" of bids, which are defined as the number of zeros at the end of the bid, in public procurement auctions for construction works in Japan where bid-rigging is recorded. As mentioned before, Ocker and Ehrhart (2017a) present empirical evidence for collusion in the German BP auctions, i.e., bidders coordinate on non-competitive price levels (see Chapter 3).

5.4.2 Uniform pricing vs. pay-as-bid pricing

The European Commission (2017) suggests UP in the European SBP auction by arguing that it induces bidders to reveal their true costs in their bids and therefore impedes collusion.

We contradict this argumentation for two reasons: Firstly, according to our theoretical analysis of the one-shot auction in Section 5.2, bidders have an incentive to understate their true costs in their BE bids under UP in order to reach a better (i.e., lower) rank in the merit-order. Considering the one-shot SBP auction, we argue that neither PaB or UP induces bidders to report their true costs in their bids. If UP for the BE bids is applied, we advocate that the BEPP should be set to a short figure.[12]

Secondly, as pointed out in Section 5.4.1, both UP and PaB are prone to collusion in repeated auctions, theoretically and empirically. Collusive behavior is favored by the repetition of the auction, which is generally independent of the applied pricing rule. The cited works in Section 5.4.1 include both pricing mechanisms.

Concluding, neither theoretical nor empirical evidence supports the reasoning that a switch from PaB to UP is advantageous for the bidders or the auctioneer. The main reason is that a change of the pricing rule does not affect the source of the market imperfections: the regular repetition of the auction with (almost) the same set of bidders. We expect the bidders to stick to their (successfully) applied bidding strategies in order to maximize

[12] Only for a very short BEPP, bidders are incentivized to submit BE bids that equal their costs. If the BEPP is set to the lowest possible value, a bidder's expected payment is only a little above her BE bid. In this case, bidders may have an incentive to shade their bid as in the PaB auction.

profits: SBP bidders collude because they appreciate their higher profits achieved by tacit cooperation.

5.4.3 Voluntary balancing energy bids

The introduction of voluntary BE bids does not have an impact on the equilibrium outcome in the base game (see Section 5.2.2). However, the observation of extremely high BE bids in the German market illustrates the major drawback of the current design: it opens doors for tacit collusion in the repeated auction because it allows bidders to increase their probability of winning by submitting low BP bids (i.e., understating their capacity costs). In return, the uneconomical BP bids are compensated with extremely high BE bids (see Chapter 6).

Against this background, the introduction of voluntary BE bids needs to be re-evaluated. The result that bidders do not submit voluntary BE bids only holds in the equilibrium bidding strategy of the one-shot game (see Section 5.2.2). If bidders deviate by submitting low BP bids and high BE bids, the voluntary BE bids may serve as an appropriate measure. If the BE price – and therefore bidders' profits – is expected to be very high, bidders who are not awarded in the regular SBP auction have an incentive to submit voluntary BE bids and, thus, the initial merit-order is confronted with competition.[13]

5.5 Conclusion

This chapter provided a game-theoretical analysis of the current Austrian-German and the future European SBP auction. We examined the impact of different pricing rules and the introduction of voluntary BE bids. We

[13] The current Dutch SBP auction already applies voluntary BE bids. The study of Ocker (2017a) indicates that BE bids are in a competitive and comprehensible range.

showed that all investigated designs yield efficient outcomes and competitive prices in their one-shot versions. These desirable economic properties are not influenced by a switch of the pricing rule or the introduction of voluntary BE bids. Notably, UP does not induce bidders to truthfully report their costs in their bids – as aspired by the European Commission (2017). In fact, UP incentivizes bidders to underbid their true costs for both the BP bid and BE bid. We confronted our theoretical findings with empirical market data from Germany and found a large discrepancy. We argued that this is due to collusive behavior among the bidders. Moreover, we argued that a change of the pricing rule will not avoid collusive behavior because it does not consider the source of the market imperfection: the regular auction repetition and the relatively small and stable set of bidders.

Chapter 6

Bidding strategies in Austrian and German balancing power auctions

The previous chapters illustrated that empirical bidding behavior is not in line with theoretical results: there is evidence for collusive behavior among the SBP bidders. To analyze this collusive bidding, we present a decision-theoretical approach for the Austrian and German SBP auctions. Our approach allows the integration of future price expectations that, in line with the findings of chapters 3 and 5 and recent scientific work (Müsgens et al., 2014), build on previous auction outcomes. By comparing our findings with empirical auction data, we find accordance with theoretical predictions for bidders' market behavior.

The remainder of this chapter is structured as follows. Section 6.1 presents the bidder's decision-theoretic calculus. In Section 6.2 we provide a numerical case study of the bidder's calculus in different market scenarios. Section 6.3 confronts the theoretic predictions with empirical market data from Austria and Germany. The last section draws conclusions.

6.1 Decision-theoretical model

In the following, a bidder's decision-theoretical calculus for the SBP auctions is presented. First, we examine the different components of the bidder's calculus. Then, conditions for an optimal BP bid and BE bid are presented that allow the integration of the bidders' price expectations. Finally, the cost structures and stochastic influences are discussed.

6.1.1 The model

The bidder's calculus in this section applies to the positive and negative SBP market.[1] If a bidder's BP bid ϕ is awarded, his profit $\pi(\phi, \psi)$ consists of two elements, the profit $\pi_P(\phi)$ of the BP bid ϕ and the expected profit $E[\pi_E(\psi)]$ of the BE bid ψ:

$$\pi(\phi, \psi) = \begin{cases} \pi_P(\phi) + E[\pi_E(\psi)], & \text{if } \phi \text{ is awarded} \\ 0, & \text{else.} \end{cases} \tag{6.1}$$

The profit $\pi_P(\phi)$ of the BP bid is given by

$$\pi_P(\phi) = \phi\, q - l\, q = (\phi - l)\, q\,, \tag{6.2}$$

where l denotes the capacity costs per MW and q the power offer.

The expected profit $E[\pi_E(\psi)]$ of the BE bid is given by the calling costs k, the merit-order rank $r(\psi)$, the calling probability function $a(r(\psi))$ and the reserve period d:

$$E[\pi_E(\psi)] = \big(\psi\, q - k\, q\big)\, d\, a(r(\psi)) = (\psi - k)\, q\, d\, \big(a(r(\psi))\big)\,. \tag{6.3}$$

[1] For our approach to derive optimal bidding strategies we adjust the profit function of Bushnell and Oren (1995) to the Austrian-German SBP auction design.

A bidder is assumed to maximize her expected profit

$$E[\pi(\phi,\psi)] = g(\phi)\left(\pi_P(\phi) + E[\pi_E(\psi)]\right), \tag{6.4}$$

where the function g denotes the subjective winning probability in the auction. With (6.2) and (6.3), the expected profit can be written as

$$E[\pi(\phi,\psi)] = g(\phi)\, q\left((\phi - l) + (\psi - k)\, d\, a(r(\psi))\right). \tag{6.5}$$

6.1.2 Optimal balancing power and balancing energy bid

For maximizing the expected profit in (6.5), we compute the first-order conditions by differentiating the expected profit $E[\pi(\phi,\psi)]$ with respect to the two bid components ϕ and ψ.[2] The first-order condition for the optimal BP bid ϕ^* leads to the following condition:

$$\phi^* = l - (\psi^* - k)\, d\, a(r(\psi^*)) - \frac{g(\phi^*)}{g'(\phi^*)}. \tag{6.6}$$

With the function g' we denote the derivative of g, with $g' < 0$, i.e., the higher the BP bid, the lower is the winning probability. First note that the structure of the optimal BP bid is similar to the equilibrium bidding function in the game-theoretical model in Section 5.2. According to (6.6), the capacity costs are the basis for calculating the optimal BP bid. The term $(\psi^* - k)\, d\, a(r(\psi^*))$, which reflects the expected profit of the BE bid per MW, is subtracted from l. That is, the expected profit of the BE bid is taken into account for calculating the optimal BP bid. The higher the expected profit of the BE bid, the lower is the optimal BP bid. The term $g(\phi^*)/g'(\phi^*)$ is negative because the winning probability is positive and its derivative is negative. Thus, the term's absolute value is added to l. As discussed in Section 5.2, this markup is due to the PaB rule and

[2]For our assumptions on $g(\phi)$, $r(\psi)$, and $a(r(\psi))$ the second-order conditions are fulfilled.

corresponds to the markdown in sales auctions that is called bid-shading (Milgrom and Weber, 1982; Kremer and Nyborg, 2009; Ausubel et al., 2014). The amount of the markup depends on the bidder's beliefs about the competition level (Myerson, 1981; Kahn et al., 2001). The higher, ceteris paribus, the winning probability, the higher is the markup. Note that the optimal BP bid is independent of the power offer q.

The first-order condition for the optimal BE bid ψ^* yields:

$$\psi^* = k - \frac{a(r(\psi^*))}{a'(r(\psi^*))\, r'(\psi^*)}\,. \tag{6.7}$$

First note that the expression for the optimal BE bid is similar to the game-theoretical equilibrium bidding function from Section 5.2. The function r' denotes the derivative of r, and the function a' denotes the derivative of a. According to (6.7), the calling costs k form the basis for calculating ψ^*. Note that the fraction is always negative in the positive market: The derivative $r'(\psi^*)$ is positive (the higher the BE bid, the higher is the rank in the merit-order), while the derivative $a'(r(\psi^*))$ is negative (the higher the rank, the lower is the calling probability). In the negative market, the fraction is always positive: The derivative $r'(\psi^*)$ is negative (the higher the BE bid, the lower is the rank in the merit-order), while the derivative $a'(r(\psi^*))$ is also negative (the higher the position, the lower is the calling probability). The optimal BE bid is both independent of the power offer q and the optimal BP bid ϕ^*. Since the subtracted term in (6.7) is negative (positive) in the positive (negative) market, it expresses a markup (markdown).[3] This is again due to the PaB rule.

[3] In the positive market, for example, a bidder with $k = 50$ Euro/MWh always bids higher than her calling costs. In the negative market, the same bidder is willing to pay up to 50 Euro/MWh to the TSOs for being called, however, always bids lower than her calling costs.

6.1.3 Empirical identification of winning probability functions and calling probability functions

In the following, we consider the German positive market in the main period because this is the easiest case to compute (Müsgens et al., 2014).

To generate optimal BP bids and BE bids, a bidder's beliefs about the competition level and, thus, the BP price levels and BE price levels for the SBP auction have to be considered. These beliefs are described by the functions for the subjective winning probability g and calling probability a. What needs to be specified are the shapes and the intervals on which these functions are defined. The interval is later used to describe different market scenarios: For a low-price (high-price) level, the distributions for the expected BP bids and BE bids are defined on lower (higher) figures.

Supported by the findings of Chapter 3, we assume that bidders do not reveal their actual costs in their bids, but consider previous auctions results when deriving their beliefs about the BP price level in the next auction (modeled by the function g). For defining BP price levels, we consider the highest awarded BP bids ϕ_{max} from January 2012 until December 2013 with a total of 105 auctions. This is shown in Figure 6.1.

We consider it as suitable for our analysis to divide the total range of ϕ_{max} into three intervals.[4] Within the first weeks, ϕ_{max} moved in an interval of about [0, 320] Euro/MW. After that, there was a rise in prices leading to a maximum ϕ_{max} of about 720 Euro/MW. Hence, a second interval can be defined with boundaries of approximately [0, 720] Euro/MW. Ultimately, prices increased further, leading to boundaries for an interval of about [160, 1,100] Euro/MW.[5] Note that the demand for positive SBP was approximately on the same level during the considered time period

[4]The identification of price intervals serves only as input for our numerical example in the following section, illustrating the basic principle of bidding strategies. Hence, a more elaborate method for defining the price intervals (e.g., for both the Austrian and German SBP auctions) is not necessary.

[5]The outliers in week 8, 84 and 104 are neglected.

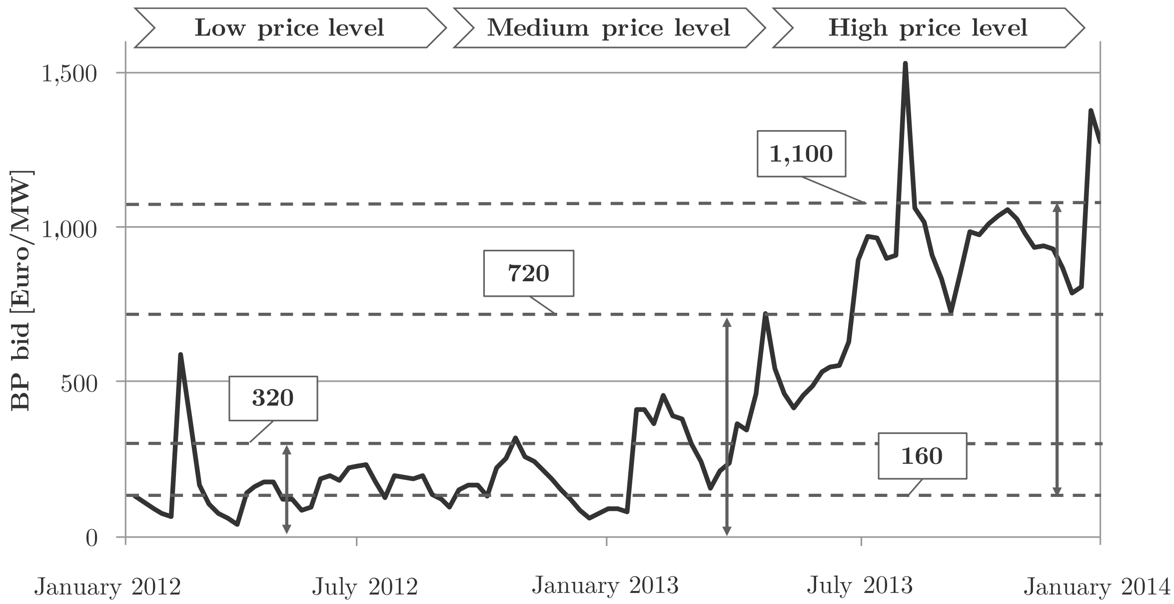

Figure 6.1: Development of the highest awarded BP bid ϕ_{max} in the positive SBP market (main period) from January 2012 to December 2013 (regelleistung.net, 2018a).

from January 2012 until December 2013 (see Figure 3.4). Therefore, we assume that bidders derive their subjective winning probability from the corresponding BP price level. For simplicity, we assume a linear shape of the winning probability, leading to the functions presented in the first part of Table 6.1.[6]

For the calling probability, an alternative approach for the identification of price levels is required. Since the calling probability depends on the rank in the merit-order of BE bids, which is determined by the figure of the BE bid, two different functions need to be simulated:

- $r(\psi)$ – rank function in the merit-order of BE bids, and
- $a(r(\psi))$ – calling probability function.

The function for the rank in the BE bid merit-order must consider the BE bid. In order to illustrate how different price levels can be modeled, BE bids for different ranks in the merit-order of the BE bids are taken

[6]Note that the winning probability below (above) the lower (upper) BP price level boundary is 1 (0).

BP price level	Interval	$g(\phi)$
Low price level	[0, 320]	$1 - \frac{1}{320} \cdot \phi$
Medium price level	[0, 720]	$1 - \frac{1}{720} \cdot \phi$
High price level	[160, 1,100]	$\frac{55}{47} - \frac{1}{940} \cdot \phi$
BE price level	**Interval**	$r(\psi)$
Low price level	[40, 250]	$-380 + \frac{1{,}990}{210} \cdot \psi$
Medium price level	[70, 1,120]	$-132 + \frac{1{,}990}{1{,}050} \cdot \psi$
High price level	[90, 6,000]	$-29 + \frac{1{,}990}{5{,}910} \cdot \psi$

Table 6.1: Three different BP price levels [Euro/MW] and BE price levels [Euro/MWh] for the positive German SBP market (main period).

into account. Again, we select the positive market in the main period between January 2012 and December 2013. Table 6.2 shows the mean BE bid $\mu(\psi)$, minimum BE bid Min(ψ), and maximum BE bid Max(ψ) for the merit-order ranks 1, 100, 500, 1,000 and 1,990.

MW rank	$\mu(\psi)$	Min(ψ)	Max(ψ)	$\sigma(\psi)$
1	73	43	94	11
100	80	59	118	13
500	105	68	200	26
1,000	161	83	415	61
1,990	1,116	254	6,001	1,341

Table 6.2: Characteristics of BE prices [Euro/MWh] in the positive German SBP market in the main period (regelleistung.net, 2018a).

The BE bids substantially deviate at each rank as illustrated by the figures of the standard deviation $\sigma(\psi)$. The standard deviation further increases with a higher rank. This could be a hint to a more hazardous bidding behavior: Since the calling probability decreases with a higher rank, bidding high BE bids seems to be a tempting approach for generating high profits when being called.

For simplicity, only the lowest rank $r = 1$ and the highest (for all BP demands recorded) rank $r = 1,990$ are considered for modeling BE price levels. Furthermore, we assume a linear shape of $r(\psi)$ and refer to the minimum, mean and maximum figures of the BE bids.[7] Hence, three different price levels for the BE bid can be computed.[8] This is presented in the second part of Table 6.1.

We model the calling probability function a as follows: Assuming that the demand for positive SBP is denoted by B^+, that a linear shape can be applied and that the calling probability for positive and negative SBP is the same (i.e., the maximum figure is 0.5), the function is given by:

$$a(r(\psi)) = \frac{1}{2}\left(1 - \frac{r(\psi) - 1}{B^+ - 1}\right). \tag{6.8}$$

Note that the lowest rank in the merit-order of the BE bids is 1, leading to a calling probability of 0.5. Hence, the rank in the merit-order and the demand need to be corrected by 1.

6.2 Application of bidder's decision-theoretical calculus

We compute optimal BP bids and BE bids for different market scenarios subject to empirical based beliefs.

6.2.1 Optimal bidding strategies

We calculate the optimal BP bids and BE bids for a bidder's fictive power plant. In order to carry out the calculation, we specify the market environment as well as certain characteristics of the plant. That is, the power offer q is set to 100 MW and the variable costs c to 20 Euro/MWh. For the

[7] We are aware that the actual calling probability function is not linear (see Chapter 4). However, for the approach taken in this chapter, we neglect a more complex functional relationship. A linear calling probability function results in higher profits of the BE bid.

[8] For the sake of simplicity, the values are rounded to the next decimal figure.

sake of simplicity, it is assumed that all 100 MW have the same rank as the first MW, which leads to a slight exaggeration of the calling probability. Furthermore, the wholesale market price p_W is set to 50 Euro/MWh. We consider the main period with a reserving period d of 60 hours, and set the demand B^+ to 1,990 MW. Since the variable costs of the power plant are lower than the wholesale price, the bidder' capacity costs c are opportunity costs of 1,800 Euro/MW.

To illustrate the effects that result from the variation of the BP and BE price levels, we compute optimal BP bids and BE bids for different market scenarios. With the help of the price levels from Section 6.1.3, we define nine different market scenarios. These and the corresponding optimal BP bids and BE bids are presented in Table 6.3.

BP price level	BE price level	ϕ^* [Euro/MW]	ψ^* [Euro/MWh]	$E[\pi(\phi,\psi)]$ [Euro]
Low	Low	115	135	$\approx$ 13k
	Medium	0	550	$\approx$ 600k
	High	0	3,010	$\approx$ 4,355k
Medium	Low	315	135	$\approx$ 22k
	Medium	0	550	$\approx$ 600k
	High	0	3,010	$\approx$ 4,355k
High	Low	505	135	$\approx$ 38k
	Medium	160	550	$\approx$ 700k
	High	160	3,010	$\approx$ 4,371k

Table 6.3: Different market scenarios in the German positive SBP market (main period) and optimal BP bids, BE bids and a bidder's corresponding expected profits.

6.2.2 Sample calculation and interpretation

We provide a brief sample calculation of the profit for the case of both a low BP and BE price level. Here, the optimal BP bid is 115 Euro/MW, which yields the following profit of the BP bid per MW, see (6.2):

$$\pi_P(\phi)/q = (115 - 1,800) \text{ Euro/MW} = -1,685 \text{ Euro/MW}.$$

The subjective winning probability is around 64.1%. The optimal BE bid is 135 Euro/MWh, which yields an expected merit-order rank of $r = 899$. At this rank, the subjective calling probability is around $a = 27.4\%$ of the reserve period $d = 60$ h, i.e., around 16.44 h. Thus, the expected profit of the BE bid per MW is given by, see (6.3):

$$E[\pi_E(\psi)] = (135 - 20) \text{ Euro/MWh} \cdot 16.44 \text{ h} \approx 1,891 \text{ Euro/MW}.$$

Adding up the profits of the BP bid per MW and the expected profits of the BE bids per MW yields combined profits of 206 Euro/MW. Consequently, the total expected profit results are given by, see (6.5):

$$E[\pi(\phi, \psi) = 64.1\% \cdot 206 \text{ Euro/MW} \cdot 100 \text{ MW} \approx 13k \text{ Euro}.$$

The expected profits for all scenarios are positive. The expected profit is rising (or at the same level) with a higher BE price level (BP price level) at a fixed BP price level (BE price level). The lowest (highest) expected profit is reached at a low (high) BP and low (high) BE price level.

The optimal BE bids are the same for each BE price level, independent of the BP price level. This reflects the reasoning in Section 6.1.2: The optimal BE bid is independent of the BP bid. The optimal BE bids are (far) higher than the variable costs. The reason is that the respective expected BE price levels are considered when calculating the BE bid.

On the contrary, the optimal BP bids differ with respect to the three BE price levels. Although the optimal BP bids are continuously lower than the opportunity costs, bidding the lower boundary of the BP price level is maximizing the expected profit if a medium or high BE price level is expected. Why is that? On the one hand, bidding the lower boundary of the expected BP bid price level yields a high probability of winning for the BP bid. Since the profits of the BE bid in the medium and high BE price level are extremely large, possible profits of the BP bid are neglected. This is in line with the results from Section 6.1.2: expected profits of the BE bid are considered for the calculation of the optimal BP bid. On the other hand, opportunity costs are small in this example.

6.3 Validation of theoretical results with empirical auction data

A central result of our approach is that the BP bid and BE bids are not independent of each other, i.e., expected profits of the BE bid are considered for the calculation of the optimal BP bid. This holds for both the positive and negative SBP market and is in line with chapters 3 and 5 and recent scientific work Müsgens et al. (2014). As Section 6.2 shows, this can lead to extreme optimal bidding, i.e., setting the BP bid to the lower boundary of the expected BP prices if expected BE prices are high.

To validate our theoretical findings, we use empirical SBP market data from Austria and Germany. In figures 6.2 and 6.3 (figures 6.4 and 6.5), the auction results for the German (Austrian) positive and negative SBP market are depicted for the time period from January 2014 to May 2016 (regelleistung.net, 2018a; Austrian Power Grid, 2018).[9] As in Chapter 5, the auction results for the BP bids are given in Euro/MWh.[10]

We find that our theoretical results are in line with Austrian and German empirical auction data. The range of the optimal BP bids and BE bids identified in the numerical example in Section 6.2 is reflected in the German market data.[11] Moreover, the inverse relationship of the two bid

[9]We chose this time period for our main empirical analysis because, beginning with July 2016, the Austrian and German SBP markets merged. For an analysis of the prices after the merger see the end of this section.

[10]Further, it enables to state the main period and sub-period in one curve.

[11]Recall that the average BP bids in Table 6.3 are given in Euro/MW, i.e., for a comparison, the identified

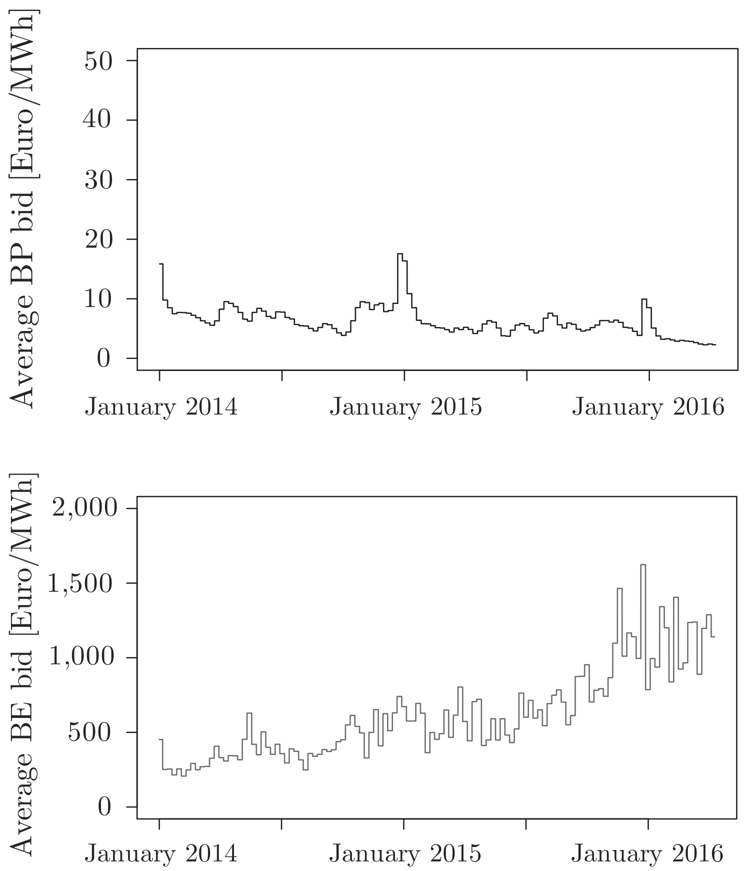

Figure 6.2: Empirical market data of the positive German SBP market (main and sub-period) in the time period from January 2014 to May 2016 (regelleistung.net, 2018a).

components is unambiguous: increasing BE prices are accompanied by decreasing BP prices.[12] Testing for Spearman's rank correlation confirms the hypothesized negative relationship as statistically significant in both German SBP markets.[13] The negative correlation of the BP bid and BE bid is also confirmed in the negative Austrian SBP market.[14]

Furthermore, even the identified extreme bidding behavior is reflected

optimal BP bids of the numerical example need to be divided by $d = 60$ h.

[12]Only the period around Christmas and New Year's Eve contradicts this trend. However, this can be traced back to an increased SBP demand and, thus, higher prices (see Chapter 3).

[13]Single-sided correlation test, $df = 19,895$: ρ = -0.42, p-value < 0.001 (positive SBP market); ρ = -0.37, p-value < 0.001 (negative SBP market).

[14]Single-sided correlation test, $df = 19,895$: ρ = 0.07, p-value > 0.5 (positive SBP market); ρ = -0.19, p-value < 0.001 (negative SBP market).

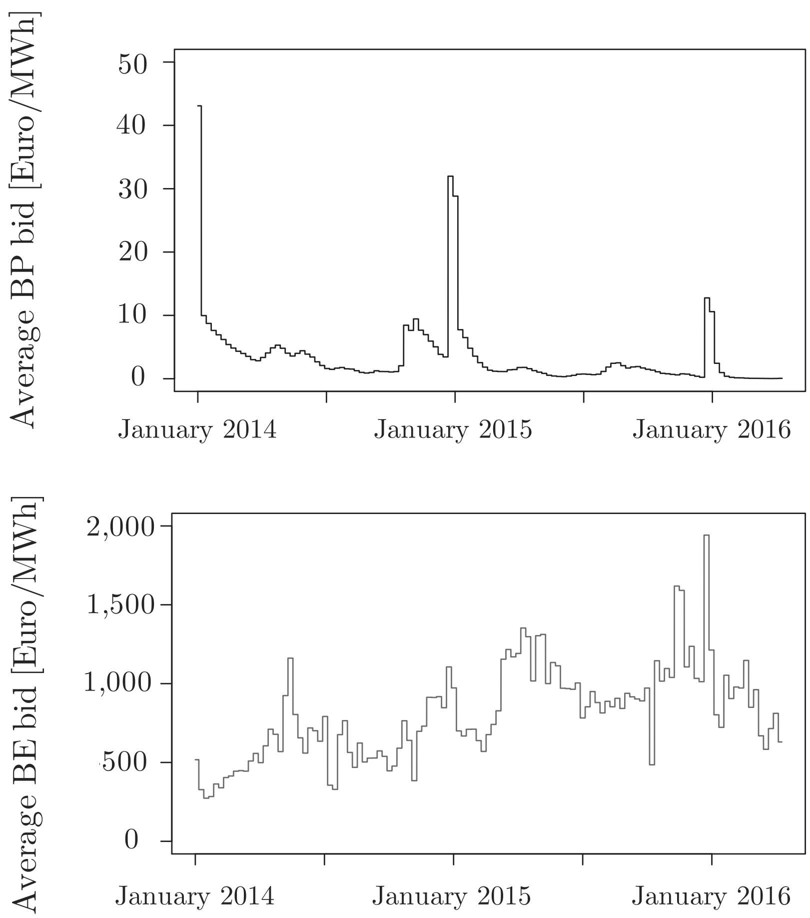

Figure 6.3: Empirical market data of the negative German SBP market (main and sub-period) in the time period from January 2014 to May 2016 (regelleistung.net, 2018a).

in the empirical market outcomes. In the considered period, 32% (19%) of the average BP bids in the negative (positive) Austrian SBP market, and 36% (0%) of the average BP bids in the negative (positive) German SBP are lower than 1 Euro/MWh (the lowest possible BP bid is 0). The higher share of average BP bids that are lower than 1 Euro/MWh in the two negative SBP markets can be traced back to the underlying cost structures: there are no opportunity costs that need to be reflected in the BP bids in the case of inframarginal bidders (see Section 2.3.2).

Since July 2016, the Austrian and German SBP markets merged, i.e., there exists a common procurement for the merit-order. According to the

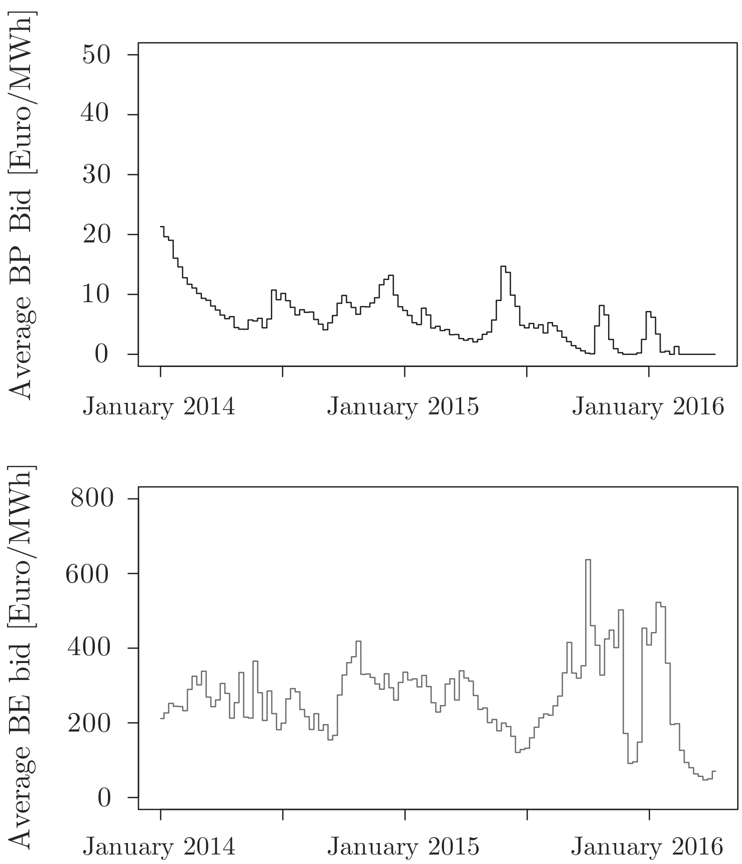

Figure 6.4: Empirical market data of the positive Austrian SBP market (main and sub-period) in the time period from January 2014 to May 2016 (Austrian Power Grid, 2018).

Austrian and German TSOs, the market merger serves as a trailblazer for the future harmonization of the European SBP markets, e.g., it lowers the BE costs because the cheapest SBP in both countries can be utilized (regelleistung.net, 2018a; Austrian Power Grid, 2018).

We also analyze market data after the cooperation and focus on the BE prices on high merit-order ranks in the positive market. Figure 6.6 depicts the BE bids on rank 1,900 in the German merit-order from January 2016 to June 2016 and in the common merit-order from July 2016 to August 2017. The development is clearly influenced by the common procurement of BE: there is a substantial decline in prices at the start of the cooperation. However, prices did not remain at this low level but increased again

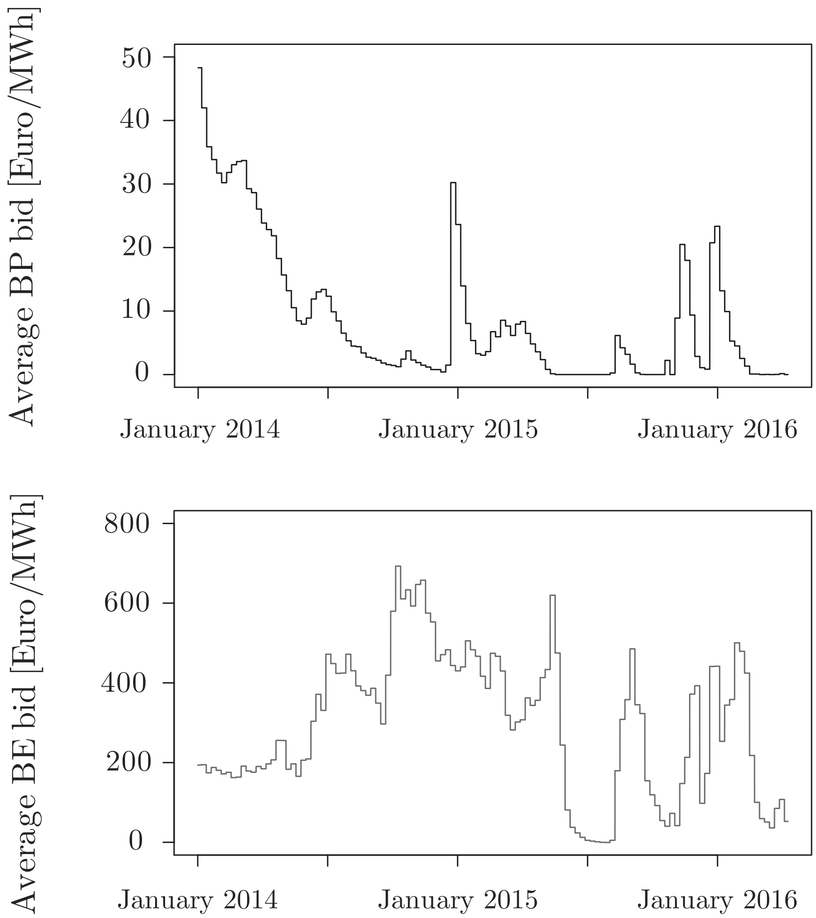

Figure 6.5: Empirical market data of the negative Austrian SBP market (main and sub-period) in the time period from January 2014 to May 2016 (Austrian Power Grid, 2018).

over time. A reason for this may be the limited grid transmission capacity between Austria and Germany: if these transmission capacities are exhausted, the common merit-order is split again, leading to two separated markets. In this case, the bidders face a reduced competition and, thus, are able to establish high BE price levels.

The German BP prices reacted as predicted on the development of the BE prices: At the beginning of the cooperation, the BP prices were stable at around five Euro/MWh, but seem to converge to zero since January 2017 (regelleistung.net, 2018a).

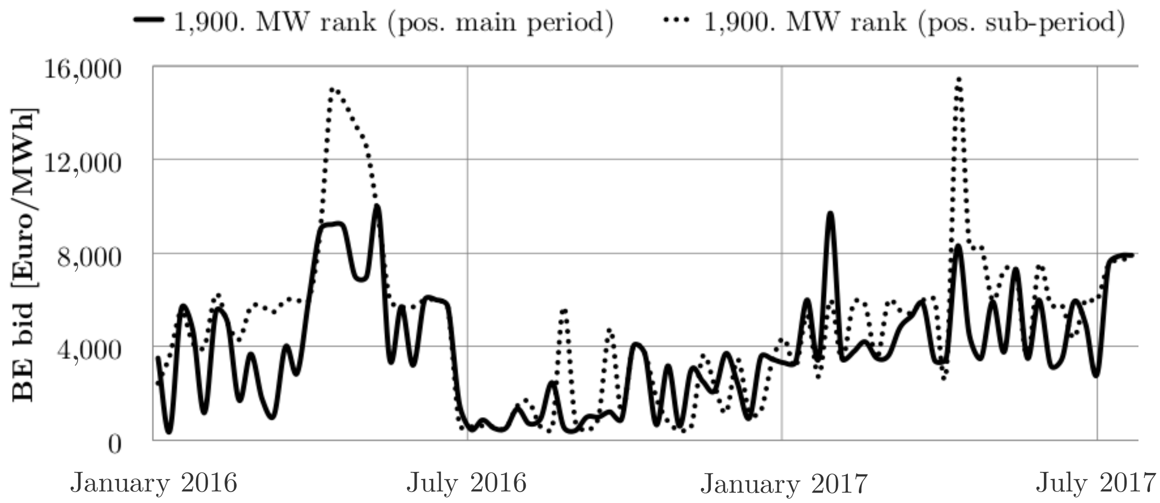

Figure 6.6: Merit-order rank 1,900 MW in the German merit-order from January 2016 to June 2016 and in the common merit-order from July 2016 to August 2017 for the positive Austrian-German SBP market (main period and sub-period) (regelleistung.net, 2018a).

6.4 Conclusion

This chapter presented an analysis of bidding strategies in the Austrian and German SBP markets. We developed a bidder's decision-theoretical calculus that lead to optimal BP bids and BE bids, allowing the integration of price expectations. A central result of our approach was that the two bids are not independent of each other. Our numerical example of the bidder's calculus illustrated this result: if high BE prices can be expected, bidders submit low BP bids. The reason for this is the applied scoring rule which consists only of the BP bid: Bidding a low BP bid increases the probability of being awarded. Hence, in this case, the BP bid is "subsidized": Bidders understate their true capacity costs. The low BP bid is in return compensated with an (extremely) high BE bid. In contrast, if the BE price level is low, bidders increase their BP bids conversely. We defined different market scenarios by analyzing the development of the market prices, and presented a case study of the bidder's calculus for nine scenarios. Finally, we validated our theoretical findings with empirical auction data from Austria and Germany. We found that the negative correlation of the BP bid and the BE bid is confirmed in the Austrian and German markets.

These findings are of relevance regarding the future European-wide harmonization of BP auctions, since these designs build mostly on the Austrian and German auction design (European Commission, 2017). Based on the findings of this chapter, we strongly encourage the European Commission to take into account empirically observed bidding strategies when designing a common auction. Our results point to coordinated bids based on previous auction outcomes. Therefore, we appreciate the introduction of voluntary BE bids. Voluntary BE bids were already implemented in Austria for wind power plants and in the Netherlands for all types of plants. The analysis of Dutch auction results indicates that these bids foster a competitive price level for BE bids (Ocker, 2017a). Therefore, we consider the implementation of voluntary BE bids as a first step to enhance competition and impede collusive behavior, which is facilitated by the regular repetition of the auctions (Belica et al., 2016) and the limited set of bidders (Knaut et al., 2017).

Chapter 7

Conclusions and outlook

The European-wide goal of increasing the share of final energy consumption from renewable sources to 27% by 2030 increases the supply volatility of the energy system considerably. To manage this volatility, ancillary services for the power system are indispensable. The most important short-term ancillary service is BP: it balances the energy demand and supply instantaneously and, thus, ensures a constant frequency over time in alternating current grids. In most liberalized energy markets worldwide, the BP procurement is organized with the help of auctions. This thesis analyzed BP auctions theoretically and empirically and focused on the current Austrian-German and the future European-wide SBP auction design.

7.1 Summary

The thesis considered two major theoretical research gaps on BP markets: Firstly, the interdependencies of the wholesale market and the BP market within an analytical model and, secondly, the appropriate representation of BP auctions within a game-theoretical model. Supplementary empirical analyses related to recent scientific work and a decision-theoretical model illustrated the bidding behavior in BP auctions.

An empirical study for 24 European countries that are members of the

Entso-E and procure BP with auctions was presented in this thesis. It illustrated the vast number of design options for BP procurement auctions. The latest possible short-term trading option on the wholesale market was stated. Furthermore, the currently implemented Austrian-German and the future European-wide BP market designs were discussed, and BP bidder characteristics (i.e., prequalification and cost structure) were illustrated.

It is found that there is no predominant BP market design in Europe but a large heterogeneity: 19 countries apply the three-quality pattern suggested by Entso-E, 23 countries apply asymmetric BP markets, the auction frequency ranges from daily to yearly procurement and both PaB and UP are applied. Remarkably, some of the Eastern European countries still rely on Russia for BP provision. In 21 countries there exist intraday trading options, however, the associated flexibility varies considerably: from five minutes to higher than three hours before energy delivery. In addition, it was illustrated that the future SBP auction design is based on the currently implemented design in Austria and Germany, but with two crucial changes. Firstly, UP will be utilized as pricing rule and, secondly, voluntary BE bids after the regular auction will be introduced.

The thesis provided answers to questions raised by Hirth and Ziegenhagen (2015) regarding the German paradox in the BP markets: In spite of the extreme increase in energy production by VRE, the BP demand has decreased. Quantitative analyses were conducted and plausible explanation for the paradox were presented. Furthermore, the price developments in the German BP markets were investigated by systematically examining the characteristics of the SBP market. Here, particularly the effects associated with the regular auction repetition were considered.

It is found that in spite of the increasing energy production from VRE, there was no need for a higher BP demand in Germany. The reason is twofold: Firstly, adaptations in the energy market design were undertaken and, secondly, grid control cooperations led to immense efficiency savings. With respect to the price developments in the German SBP market, the thesis presented evidence that bidders coordinated on a price level which is (far) above the competitive level. The high autocorrelation of consecutive BP bids supported this finding: instead of basing their bids on their costs exclusively, bidders adjust their bids to previous auction outcomes.

The interrelations of the energy wholesale market and the BP market were examined in this thesis. The analysis grounded on the market interdependencies that BP bidders cannot trade their entire capacities on the wholesale market, however, must run their plants at a minimal load. For this, an integrated market model was developed, which was based on conditions for an efficient allocation on the BP markets, stability among the markets and market clearing as well as energy balance. Our market setting related to the recently discussed harmonization of the European SBP market. The market model is the first which considered the interdependencies of the wholesale market and the BP market within an analytical approach.

It is found that there exists an equilibrium on all markets, which ensures efficiency under certain assumptions. The interplay between the markets induced a specific assignment of the energy producers to the different markets. Prices and costs in the markets as well as the distribution of surpluses were considered. The comparison with German market data revealed that the actual BP costs are significantly higher than in the equilibrium. Although the total costs gradually decreased over the last years, the gap between the predicted and observed BE costs increased.

This thesis also included a game-theoretical analysis of the current Austrian-German and the future European SBP auction design. It is the first game-theoretical model for a currently implemented BP auction design in Europe. The impact of the two pricing rules PaB and UP as well as the introduction of voluntary BE bids were examined. The theoretical findings were confronted with empirical market data from Germany and implications for the future European auctions were drawn.

It is found that all investigated designs yield efficient auction outcomes and competitive prices in their one-shot versions. These desirable economic properties were neither influenced by a switch from PaB to UP nor by the introduction of voluntary BE bids. Remarkably, UP does not induce bidders to truthfully report their costs in their bids, as aspired by the European Commission (2017) and argued by other scientific authors and regulatory authorities (e.g., Müsgens et al., 2014; German Federal Ministry for Economic Affairs and Energy, 2015; Morch and Wolfgang, 2016). In fact, UP incentivizes bidders to understate their true costs for both the BP bid and BE bid. The comparison of theoretical findings with German market data revealed a large discrepancy. A game-theoretically grounded explanation was offered, which is based on collusive behavior among the bidders. It was argued that a change of the pricing rule will not avoid collusion because it does not consider the source of the market imperfection: the regular auction repetition and the small and stable set of bidders.

This thesis also presented a decision-theoretical model for the analysis of bidding strategies in Austrian and German SBP auctions. The approach lead to optimal BP bids and BE bids. Different market scenarios were identified by analyzing historic market prices. A case study of the bidder's calculus in these market scenarios was presented. The findings of the case study were then confronted with empirical auction data.

It is found that the BP bid and the BE bid are not independent of each other: expected profits of the BE bid are considered for the calculation of the optimal BP bid. The numerical example of the bidder's calculus illustrated this result: If high BE bid prices can be expected, bidders submit low BP bids. Thus, bidders subsidize the BP bid with expected profits of the BE bid. The reason for this is the applied scoring rule, which consists only of the BP bid, i.e., bidding a low BP bid increases the probability of winning. In return, bidders submit extremely high BE bids for compensating the understated BP bids. Austrian and German auction data supported the negative correlation of the two bid components.

The following sections provide overarching conclusions and implications drawn from the results of this thesis, as well as a critical reflection of the applied methods and an outlook for further research.

7.2 Conclusions

The results of this thesis for the German BP market show that the increasing energy supply from VRE can be managed by implementing both national and international measures. For the latter, a further harmonization of European BP markets will be essential.

The goal of the European Commission (2017) of integrating the European SBP markets no later than 2021 is very ambitious. Yet, it seems to be the most promising action to solve the dilemma in BP auctions: the collusive behavior among bidders caused by the regular auction repetition and the limited set of bidders. That is, I welcome the prompt consolidation of European BP markets from an economical standpoint.

However, market consolidation is not a panacea as the common merit-order in the Austrian-German SBP market since July 2016 illustrates (see Chapter 6): the Austrian and German bidders adapted to the new market conditions and successfully re-established high BE prices. In particular, they learned that the limited grid transmission capacities between the two countries offered an opportunity for higher BE prices because the set of bidders is reduced in these cases. As a reaction, bidders adapted their bids in 2017, i.e., the share of Austrian BE bids at the end of the common merit-order significantly increased over time. That is, the Austrian bidders speculate on a separation of the two markets.

The activation of a BE bid of 77,777 Euro/MWh in the German TBP market on 17 October 2017 eventually requested an intervention of the regulatory authorities. Translated from the German, the Bundesnetzagentur (German regulator) argues: "The extremely high BE prices, which cannot be traced back to scarcity situations in the energy market, are favored by the scoring rule that only considers BP bids: Instead of awarding a bidder with an appropriate BP bid and BE bid, a bidder with a low BP bid and a clearly exaggerated BE bid is selected in this system. Against this background and the danger of recurrence, the scoring rule will be reevaluated, i.e., both bid components shall be considered for winner determination." (Bundesnetzagentur, 2018b). As a more short-term measure, the Austrian and German regulatory authorites introduced price caps on the SBP and TBP market at the beginning of 2018: the maximum BE bid is now 9,999 Euro/MWh (Energie-Chronik, 2018). The Austrian regulator further discusses to publish bidders who submit exaggerated BE bids on their website.

The findings of this thesis are of particular importance regarding the latest developments in the Austrian-German BP markets and, therefore, also for the future harmonized European BP markets. Firstly, the theoretical results of this thesis illustrate that the currently implemented auction design ensures an integrated efficiency on the energy wholesale market and the BP market under certain assumptions. An important condition for efficiency is the currently implemented scoring rule: it ensures that those plants with the highest variable costs are selected for BP provision. Thus, from a merely theoretical standpoint, I do not support the re-evaluation of the scoring rule. Against the background of the extremely high prices, however, I understand that the regulatory authorities must act rapidly. Therefore, secondly, the introduction of price caps may represent a short-term solution for impeding exaggerated BE bids. However, price caps may also serve as focal points and, thus, facilitate coordination among the bidders even more. Thirdly, as a more long-term solution for exaggerated BE prices, I welcome the introduction of voluntary BE bids because it enhances competition in the merit-order. As argued in Chapter 5, this does not hold for a switch of the pricing rule. I do not share the reasoning that a switch to UP will lead to truthful bidding and, thus, to a higher degree of efficiency in the BP markets. Instead, it sets undesirable incentives for bidders, i.e., underbidding their costs in their bids.

Furthermore, the future European BP market consolidation may be complicated because there is a large discrepancy in designs and degrees of VRE market integration (see Section 2.2.2). The BP market designs of France and Denmark elucidate two extreme examples. While both countries have substantially reduced their CO2-emissions in recent years (European Energy Agency, 2016) they achieved this with very divergent energy production mixes, market structures and liberalization levels.

On the one hand, in the French market, less than 6% of the electricity consumed is supplied from VRE, while about 77% of the electricity consumed is produced from nuclear power plants, the highest share in the world (Nuclear Energy Institute, 2016). Consequently, these power plants are obliged to provide BP to the grid. That is, there is no procurement of PBP and SBP within an open market (until 2016). Only TBP is organized with the help of a procurement auction. However, the French TBP auction has changed very little since 2003: the auction takes place once a year, allocating blocks of positive and negative TBP (Reseau de Transport d'Electricite, 2016). Since only two large power plant operators participate at the TBP market, the volumes are allocated flexibly to the power plants within each portfolio, which contradicts an open TBP market.

On the other hand, the Danish market is influenced by a high share of wind power plants, which lead to the opening of the BP market for VRE. Wind power generation corresponded to a share of about 42% of the Danish electricity consumption in 2014 (Ocker et al., 2016a). Since the wind parks are owned by various companies, BP procurement as in France would not be suitable: the relatively small and volatile electricity production of these wind plants cannot guarantee BP provision for an entire year. Therefore, Denmark changed their BP procurement towards VRE market integration in three steps. Firstly, Denmark installed a system to easily prequalify wind power plants for BP provision. Secondly, market participation was facilitated by conducting auctions on a daily basis. Thirdly, the reserve periods were reduced to a length of four hours (PBP) and one hour (SBP and TBP) (Energinet, 2016). Furthermore, the forecasts for wind energy generation are sufficiently precise to estimate wind production for the following day and, thus, allow a BP market participation. The Danish system was the first to integrate VRE into the BP system and now serves as a role model for future, flexible market structures (Borne et al., 2018). Notably, recent studies show that the integration of VRE into the energy system can even be accomplished without any BP backup from other sources of energy (MacDonald et al., 2016).

7.3 Critical reflection and outlook

The analyses conducted in this thesis offered a systematic empirical investigation of BP markets, and the developed theoretical models enhanced the understanding of the BP auction principles. However, this thesis sets only the starting point for further empirical and theoretical analyses.

Most of the German SBP bidders also participate in the PBP and TBP auctions. Therefore, further research should consider the price developments in these markets as well, e.g., with respect to collusive behavior. Furthermore, the interdependencies between the markets for different BP qualities should be analyzed more rigorously. In Austria and Germany, for example, the auction for PBP is conducted on Tuesday, while the SBP auction is conducted on Wednesday. The effects associated with this temporal order is an interesting field for further research and could be analyzed with econometric models.

This also holds for the implementation of voluntary BE bids. Here, the timing with the Intraday auction and the Day-ahead auction are of crucial importance because the option for short-term BP market participation may negatively impact the liquidity on those markets. The remuneration scheme should also be chosen carefully. Elsewise, there may exist options for bidders to misuse, for example, the BP bid payment: Bidders may submit low (but positive) BP bids in conjunction with BE bids that equal the price cap, and speculate for voluntary BE bids that replace their bids in the merit-order. Then, bidders could keep the BP bid payment and sell their energy in the Intraday auction again.

Although the presented integrated model is the first which considers the interdependencies of the energy wholesale market and the BP market within an analytical approach, some limitations remain. In particular, there are three assumptions that may reduce the external validity. Firstly, the assumption of a linear supply function does not entirely reflect real supply characteristics. Secondly, the model considers the same share of BP bidders across the entire supply function, which is a simplification of the actual market setting. Thirdly, our assumption of homogeneous must-run capacities across all types of power plants is an approximation to actual power plants' characteristics. Here, a differentiation for several classes of power plants may be adequate. In spite of these limitations, the integrated model can also be adapted to other European BP market designs. With respect to future research, I assess this application as most promising because it fosters the understanding of market outcomes considerably.

There are also disputable assumptions in the game-theoretical model and the decision-theoretical model. In the former, the analysis is restricted to bidders with variable costs lower than the wholesale market price. Although arguments for this assumption were presented, further research could consider an asymmetric model, i.e., integrating bidders with variable costs higher than the wholesale market price. In the decision-theoretical analysis, the functions for the winning probability and the calling probability are assumed to be linear. As the examination of empirical market data shows, this is not the case in actual BP markets. Therefore, the integration of non-linear functions may be considered for further modelling.

Future research could also examine BP market design options within a controlled economic laboratory experiment. Here, the bidding behavior (in repeated auctions) could be investigated in more detail, e.g., regarding alternative focal points in BP auctions.

A Appendix to Chapter 2

	Latest possible trading option	PBP market	SBP market	TBP market	Pricing rule	Scoring rule
Austria	30min	BP bid; SYM; WE; M.-O.; 1x168h; 1MW	BP&BE bid; ASYM; WE; M.-O.; Mo-Fr 8am-8pm, rest; 5MW	BP&BE bid; ASYM; DA; M.-O.; 6x4h; 5MW	PaB	lowest BP bids
Belgium	5min	TP; ASYM; MO; n/a.; base, peak, off-peak; 1MW	BP&BE bid; ASYM; MO; M.-O.; base, peak, off-peak; 5MW	BP&BE bid; ASYM; YE; n/a.; base, peak, off-peak; 5MW	PaB	SP
Czech Republic	Day-ahead market	BP bid; SYM; DA; n/a; 24x1h; n/a	BP bid; ASYM; DA; PAR; 24x1h; n/a	BP bid; SYM; DA; M.-O.; 24x1h; n/a	UP	lowest BP bids
Denmark	60min	BP bid; ASYM; DA; n/a; 6x4h; 0.3MW	BP bid; SYM; MO; PAR; 24x1h; 0.3MW	BP&BE bid; ASYM; DA; n/a; 24x1h; 10MW	PaB & UP	n/a
Estonia	60min	provided by Russian TSO	TP; n/a; n/a; M.-O.; 24x1h; 5MW	TP; ASYM; n/a; n/a; 24x1h; 5MW	PaB	n/a
Finland	60min	n/a; SYM; n/a; n/a; 24x1h; 1MW	BE bid; ASYM; n/a; PAR; 24x1h; 10MW	non-existent	UP	n/a
France	30min	compulsory, regulated prices	compulsory, regulated prices	TP; ASYM; YE; M.-O.; n/a; 10MW	PaB	n/a
Germany	30min	BP bid; SYM; WE; M.-O.; 1x168h; 1MW	BP&BE bid; ASYM; WE; M.-O.; Mo-Fr 8am-8pm, rest; 5MW	BP&BE bid; ASYM; DA; M.-O.; 6x4h; 5MW	PaB	lowest BP bids

Findings for 24 European energy markets (part 1/3) (Ocker et al., 2016a).

1MW	minimum power offer of 1 MW	24x1h	24 one-hour reserve periods
ASYM	asymmetric BP products	BE bid	balancing energy bid
BP bid	balancing power bid	lowest BP bids	scoring rule is lowest BP bids
MAN	manual BP activation	M.-O.	merit-order activation
PaB	pay-as-bid-pricing	PAR	parallel/pro-ratio activation
SP	stochastic programming	SYM	symmetric BP products
TP	total price (i.e., BP and BE bid)	UP	uniform pricing
YE/MO/WE/DA	yearly, monthly, weekly, daily BP procurement	n/a	parameter not available

	Latest possible trading option	PBP market	SBP market	TBP market	Pricing rule	Scoring rule
Hungary	120min	BP bid; ASYM; n/a; n/a; 24x1h; n/a	BP&BE bid; ASYM; n/a; M.-O.; 24x1h; n/a	BP&BE bid; ASYM; n/a; M.-O.; 24x1h; n/a	PaB	n/a
Iceland	Day-ahead market	TP; SYM; WE; M.-O.; 24x1h; 1MW	TP; SYM; WE; M.-O.; 24x1h; 1MW	TP; ASYM; WE; M.-O.; 24x1h; 1MW	UP	lowest TPs
Italy	250min	compulsory, regulated prices	BE bid; SYM; DA; PAR; 24x1h; 1MW	BE bid; SYM; DA; M.-O.; 24x1h; 1MW	PaB	n/a
Latvia	60min	provided by Russian TSO	MAN: n/a; ASYM; n/a; M.-O.; 24x1h; n/a	non-existent	n/a	n/a
Lithuania	60min	provided by Russian TSO	MAN: TP; n/a; DA; M.-O.; 24x1h; 5MW	TP; n/a; DA; M.-O.; 24x1h; 5MW	UP	lowest TPs
the Netherlands	5min	BP bid; SYM; WE; M.-O.; 1x168h; 1MW	BP&BE bid; ASYM; DA/YE; M.-O.; n/a; 4MW	BP&BE bid; ASYM; DA/YE; M.O.; n/a; 20MW	PaB & UP	lowest BP bids (PBP)
Norway	60min	BP bid; SYM; DA/WE; n/a; 24x1h; 1MW	BP&BE bid; ASYM; WE; PAR; n/a; 1MW	non-existent	UP	n/a
Poland	180min	BE bid; ASYM; n/a; n/a; 24x1h; n/a	BE bid; ASYM; n/a; n/a; 24x1h; n/a	BE bid; ASYM; n/a; M.-O.; 24x1h; n/a	UP	SP

Findings for 24 European energy markets (part 2/3) (Ocker et al., 2016a).

1MW	minimum power offer of 1 MW	24x1h	24 one-hour reserve periods
ASYM	asymmetric BP products	BE bid	balancing energy bid
BP bid	balancing power bid	lowest BP bids	scoring rule is lowest BP bids
MAN	manual BP activation	M.-O.	merit-order activation
PaB	pay-as-bid-pricing	PAR	parallel/pro-ratio activation
SP	stochastic programming	SYM	symmetric BP products
TP	total price (i.e., BP and BE bid)	UP	uniform pricing
YE/MO/WE/DA	yearly, monthly, weekly, daily BP procurement	n/a	parameter not available

	Latest possible trading option	PBP market	SBP market	TBP market	Pricing rule	Scoring rule
Portugal	195min	compulsory, no compensation	BP bid; ASYM; DA; PAR; 24x1h; n/a	BP&BE bid; ASYM; DA; M.-O.; 24x1h; n/a	UP	lowest BP bids
Romania	90min	compulsory, no compensation	TP; ASYM; DA; M.-O.; 24x1h; n/a	TP; ASYM; DA; M.-O.; 24x1h; n/a	UP	lowest TPs
Serbia	Day-ahead	non-existent	TP; ASYM; DA; PAR; 24x1h; n/a	TP; ASYM; DA; n/a; 24x1h; n/a	UP	lowest TPs
Slovenia	60min	compulsory, no compensation	BP&BE bid; n/a; YE; PAR; 24x1h; n/a	BP&BE bid; n/a; YE; M.-O.; 24x1h; n/a	PaB	n/a
Spain	195min	compulsory, no compensation	BP bid; ASYM; DA; PAR; 24x1h; n/a	BP&BE bid; ASYM; DA; M.-O.; 24x1h; n/a	UP	lowest BP bids
Sweden	60min	BP&BE bid; SYM; DA/WE; n/a; 24x1h; n/a	BP&BE bid; ASYM; WE; PAR; n/a; n/a	non-existent	PaB	n/a
Switzerland	60min	BP bid; SYM; WE; M.-O.; 1x168h; 1MW	BP bid; SYM; WE; PAR; n/a; 5MW	BP bid; ASYM; WE; M.-O.; 6x4h; 1MW	PaB	lowest BP bids
United Kingdom	75min	BP&BE bid; ASYM; MO; n/a; Mo-Fr, Sa, Su; 10MW	BP&BE bid; ASYM; MO; n/a; Mo-Fr, Sa, Su; 10MW	BP&BE bid; SYM; MO; n/a; Mo-Fr, Sa, Su; 50MW	PaB	n/a

Findings for 24 European energy markets (part 3/3) (Ocker et al., 2016a).

1MW	minimum power offer of 1 MW	24x1h	24 one-hour reserve periods
ASYM	asymmetric BP products	BE bid	balancing energy bid
BP bid	balancing power bid	lowest BP bids	scoring rule is lowest BP bids
MAN	manual BP activation	M.-O.	merit-order activation
PaB	pay-as-bid-pricing	PAR	parallel/pro-ratio activation
SP	stochastic programming	SYM	symmetric BP products
TP	total price (i.e., BP and BE bid)	UP	uniform pricing
YE/MO/WE/DA	yearly, monthly, weekly, daily BP procurement	n/a	parameter not available

B Appendix to Chapter 4

B.1 Proofs

B.1.1 Proof of Proposition 1

Proof. The existence of the equilibrium and 1., 2., and 3. follow by solving the equation system given by (M0), (M1), (M2), (S0), (S1), (S2), (S3), symmetric BP markets and $S(c) = \alpha\, c + \beta$. Alternatively, 3. follows directly from (M1). □

B.1.2 Proof of Proposition 2

Proof. 1., 2., and 3. follow directly by solving the equation system given by (M0), (M1), (M2), (S0), (S1), (S2), (S3), symmetric BP markets and $S(c) = \alpha\, c + \beta$. The restriction $p_W \leq m\, c_1^+ + (1-m)\, c_0^+$ is implied by $\pi_W(c) - \pi_{BP}(c) \leq 0$, which yields

$$p_W - c \leq \frac{m}{1-m}(c_1^+ - p_W) + a^+(r^+(c))\,\vartheta\,(c_1^+ - c)\,.$$

Now consider $\vartheta = 0$, and the condition $c \geq c_0^+$. This yields

$$p_W \leq m\, c_1^+ + (1-m)\, c_0^+\,,$$

which is a sufficient condition for the claim. □

B.1.3 Proof of Proposition 3

Proof. 1. The derivative of (4.6) is given by

$$\frac{\partial \pi^{+}_{BP}}{\partial c} = -\, m + (1-m)\,[\frac{\partial a^{+}(r^{+}(c))}{\partial c} + r^{+}(c)\,\frac{\partial r^{+}}{\partial c}\,\vartheta\,(c^{+}_{1} - c) \\ -\, a^{+}(r^{+}(c))\,\vartheta] < 0\,,$$

and is strictly decreasing in c, with $\frac{\partial a^{+}(r^{+}(c))}{\partial c} < 0$, $\frac{\partial r^{+}(c)}{\partial c} > 0$. Differentiation of (4.7) yields

$$\frac{\partial \pi^{-}_{BP}}{\partial c} = -\, 1 + (1-m)[\frac{\partial a^{-}(r^{-}(c))}{\partial c}\,\frac{\partial r^{-}(c)}{\partial c}\,\vartheta\,(c - c^{-}_{0}) \\ +\, a^{-}(r^{-}(c))\,\vartheta] < 0\,,$$

and is strictly decreasing in c, with $\frac{\partial a^{-}(r^{-}(c))}{\partial c} < 0$, $\frac{\partial r^{-}(c)}{\partial c} > 0$.

2. Equation (4.5) directly implies that $\pi_W \geq 0$ for all $c \in [c_0, p_W]$. In the positive market, reformulating (4.6) with $p^{+}_{BP} = \frac{m}{1-m}(c^{+}_{1} - p_W)$ immediately yields the result. For a stable market equilibrium, (M2) requires that $\pi^{-}_{BP}(c^{-}_{1}) = \pi^{+}_{BP}(c^{+}_{0})$, with $\pi^{+}_{BP}(c^{+}_{0}) \geq 0$. Since the profits of all BP bidders decrease in c, all profits in the negative BP market must be (weakly) greater than zero.

3. Consider the bidders with variable cost $c \in [c^{-}_{0}, c^{-}_{1}]$. The proposition requires $\pi_W(c) - \pi^{-}_{BP}(c) \leq 0$, which is immediately implied by straightforward computation. For the bidders with variable cost $c \in [c^{+}_{0}, c^{+}_{1}]$, see the proof of Proposition 2.

□

B.1.4 Proof of Proposition 4

Proof. The derivative of function T with respect to s_0 is given by

$$\frac{\partial T}{\partial s_0} = -S^{-1}_{nBP}\,(D - \frac{1+m}{1-m}\,\frac{B}{2} - s_0) + S^{-1}_{BP}(s_0) + \int\limits_0^{\frac{B}{1-m}} h(s)\, S'^{-1}_{BP}(s_0+s)\, ds$$
$$= -\frac{D - \frac{B}{2}\,\frac{1+m}{1-m} - s_0^* - \beta\,(1-\delta)}{\alpha\,(1-\delta)} + \frac{s_0^* - \delta\,\beta}{\delta\,\alpha} + \frac{B\,(1+m)}{2\,\alpha\,\delta\,(1-m)} \stackrel{!}{=} 0\,,$$

which yields

$$s_0^* = D\,\delta - \frac{B\,(1+m)}{2\,(1-m)}\,.$$

Reformulating shows that c_0^{-*} equals the equilibrium c_0^- in Proposition 2

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

$\square$

C Appendix to Chapter 5

C.1 Proofs

C.1.1 Proof of Proposition 5

Proof. Suppose that there exist strictly monotonic equilibrium bidding functions $\phi, \psi : [c_0, c_1] \to \mathbb{R}^+$, for the BP bid and the BE bid, respectively, and assume that the representative bidder with signal c submits the bids $\phi(v)$ and $\psi(w)$ instead. For her expected rent $E[\pi(c,v,w)]$ we have

$$E[\pi(c,v,w)] = \int_v^{c_1} (p_W - c) d f_{(b)}(c_b) dc_b + \int_{c_0}^{v} \phi(c_{(b)}) f_{(b)}(c_b) dc_b$$
$$+ \begin{cases} \int_{c_0}^{v} (\psi(w) - c) da_{max} (1 - \tilde{F}(w|C_{(b)} = c_b)) f_{(b)}(c_b) dc_b & v \leq w \\ \int_{c_0}^{w} (\psi(w) - c) da_{max} (1 - \tilde{F}(w|C_{(b)} = c_b)) f_{(b)}(c_b) dc_b + \\ \int_{w}^{v} (\psi(w) - c) da_{max} (1 - \tilde{F}(w|C_{(b)} = c_b)) f_{(b)}(c_b) dc_b & v > w\,, \end{cases}$$

where $1 - \tilde{F}(w|C_{(b)} = c_b) = \frac{1-F(w)}{1-F(c_b)}$. Thus, we have

$$E[\pi(c,v,w)] = (p_W - c) d (1 - F_{(b)}(v)) + \int_{c_0}^{v} \phi(c_{(b)}) f_{(b)}(c_b) dc_b$$
$$+ \begin{cases} (\psi(w) - c) da_{max} (1 - F(w)) \int_{c_0}^{v} \frac{f_{(b)}(c_b)}{1-F(c_b)} dc_b & v \leq w \\ (\psi(w) - c) da_{max} (1 - F(w)) \int_{c_0}^{w} \frac{f_{(b)}(c_b)}{1-F(c_b)} dc_b \\ +(F_b(v) - F_b(w))(\psi(w) - c) da_{max} & v > w\,. \end{cases}$$

For the derivative of $E[\pi(c,v,w)]$ with respect to v we have

$$\begin{cases} \Big(-(p_W - c)d + \phi(v) + (\psi(w) - c)da_{max}\frac{1-F(w)}{1-F(v)}\Big)f_{(b)}(v) & v \leq w \\ \big(-(p_W - c)d + \phi(v) + (\psi(w) - c)da_{max}\big)f_{(b)}(v) & v > w, \end{cases} \tag{1}$$

and for the derivative of $E[\pi(c,v,w)]$ with respect to w we have

$$\begin{cases} \big(\psi'(w)(1-F(w)) - (\psi(w)-c)f(w)\big)da_{max}\int_{c_0}^{v}\frac{f_{(b)}(c_b)}{1-F(c_b)}dc_b & v \leq w \\ \big(\psi'(w)(1-F(w)) - (\psi(w)-c)f(w)\big)da_{max}\int_{c_0}^{w}\frac{f_{(b)}(c_b)}{1-F(c_b)}dc_b & v > w\,. \end{cases} \tag{2}$$

Necessary conditions for a Bayesian equilibrium are

$$\frac{\partial E[\pi(c,v,w)]}{\partial v}\Big|_{v=w=c} = 0\,, \tag{3}$$

$$\frac{\partial E[\pi(c,v,w)]}{\partial w}\Big|_{v=w=c} = 0\,. \tag{4}$$

By (1) and (3) the equilibrium strategy for the BP bid is given by

$$\phi(c) = (p_W - c)d - (\psi(c) - c)da_{max}\,. \tag{5}$$

By (2) and (4) we get the differential equation

$$\psi'(c)(1-F(c)) - (\psi(c)-c)f(c)\big)da_{max}\int_{c_0}^{c}\frac{f_{(b)}(c_b)}{1-F(c_b)}dc_b = 0\,,$$

whose solution leads to the equilibrium strategy for the BE bid

$$\psi(c) = c + \frac{\int_c^{c_1} 1 - F(u)du}{1-F(c)}\,. \tag{6}$$

Firstly, the necessary condition in (6) is independent of ϕ and since

$$\psi'(c) = \frac{f(c)\int_c^{c_1} 1 - F(u)du}{(1-F(c))^2} > 0\,, \tag{7}$$

ψ is strictly increasing in c, secondly, we have

$$\phi'(c) = -\big((1 - a_{max}) + \psi'(c)a_{max}\big)d < 0\,,$$

and, thus, ϕ decreases in c. To verify the second-order condition, insertion of (6) and (7) into (2) yields

$$\frac{\partial E[\pi(c,v,w)]}{\partial w} = \begin{cases} (c-w)f(w)da_{max}\int_{c_0}^{v}\frac{f_{(b)}(c_b)}{1-F(c_b)}dc_b & v \leq w \\ (c-w)f(w)da_{max}\int_{c_0}^{w}\frac{f_{(b)}(c_b)}{1-F(c_b)}dc_b & v > w\,, \end{cases}$$

which is —independently of v— positive if $w < c$ and negative if $w > c$. That is, bidding in the second stage according to ψ as defined in (6) is optimal irrespective of the first stage.

Using this by setting $w = c$ in (1) and insertion of (5) and (6) gives

$$\begin{cases} \Big(-(p_W - c)d + \phi(v) + (\psi(c) - c)da_{max}\frac{1-F(c)}{1-F(v)}\Big)f_{(b)}(v) & v \leq c \\ \big(-(p_W - c)d + \phi(v) + (\psi(c) - c)da_{max}\big)f_{(b)}(v) & v > c \end{cases}$$

$$= \begin{cases} \Big((c-v) - \frac{\int_v^c 1-F(u)du}{1-F(v)}a_{max}\Big)df_{(b)}(v) & v \leq c \\ \Big(-(v-c) - \frac{\int_v^{c_1} 1-F(u)du}{1-F(v)}a_{max} + \frac{\int_c^{c_1} 1-F(u)du}{1-F(c)}a_{max}\Big)df_{(b)}(v) & v > c\,. \end{cases}$$

In the case $v < c$ it is

$$\frac{\int_v^c 1 - F(u)du}{1 - F(v)} \leq \frac{\int_v^c 1 - F(v)du}{1 - F(v)} = (c - v)\,,$$

which implies

$$\frac{\partial E[\pi(c,v,c)]}{\partial v} \geq (c - v)d(1 - a_{max})f_{(b)}(v) > 0\,.$$

Similarly, in the case $v > c$ it is

$$\begin{aligned}
&\frac{\int_c^{c_1} 1-F(u)du}{1-F(c)} - \frac{\int_v^{c_1} 1-F(u)du}{1-F(v)} \\
&= \frac{\int_c^{v} 1-F(u)du}{1-F(c)} + \frac{\int_v^{c_1} 1-F(u)du}{1-F(c)} - \frac{\int_v^{c_1} 1-F(u)du}{1-F(v)} \\
&\leq \frac{\int_c^{v} 1-F(u)du}{1-F(c)} \leq (v-c)\,,
\end{aligned}$$

which now implies

$$\frac{\partial E[\pi(c,v,c)]}{\partial v} \leq -(v-c)d(1-a_{max})f_{(b)}(v) < 0\,,$$

and thus, the second-order condition is satisfied.

□

C.1.2 Proof of Proposition 6

Proof. For the expected rent $E[\pi(c,v,w)]$ of a representative bidder bidding $\phi(v)$ and $\psi(w)$ we have

$$\begin{aligned}
E[\pi(c,v,w)] = (p_W - c)d(1-F_{(b)}(v)) + \phi(v)F_{(b)}(v) \\
+ \begin{cases} (\psi(w)-c)da_{max}(1-F(w)) \int_{c_0}^{v} \frac{f_{(b)}(c_b)}{1-F(c_b)} dc_b & v \leq w \\ (\psi(w)-c)da_{max}(1-F(w)) \int_{c_0}^{w} \frac{f_{(b)}(c_b)}{1-F(c_b)} dc_b & \\ +(F_b(v)-F_b(w))(\psi(w)-c)da_{max} & v > w\,, \end{cases}
\end{aligned}$$

which yields the derivative of $E[\pi(c,v,w)]$ with respect to v

$$\begin{aligned}
&\phi'(v)F_{(b)}(v) + \\
&\begin{cases} \big(-(p_W-c)d + \phi(v) + (\psi(w)-c)da_{max}\frac{1-F(w)}{1-F(v)}\big)f_{(b)}(v) & v \leq w \\ \big(-(p_W-c)d + \phi(v) + (\psi(w)-c)da_{max}\big)f_{(b)}(v) & v > w\,, \end{cases}
\end{aligned} \tag{8}$$

and the derivative of $E[\pi(c,v,w)]$ with respect to w

$$\begin{cases} \big(\psi'(w)(1-F(w)) - (\psi(w)-c)f(w)\big)da_{max}\int_{c_0}^{v} \frac{f_{(b)}(c_b)}{1-F(c_b)}dc_b & v \le w \\ \big(\psi'(w)(1-F(w)) - (\psi(w)-c)f(w)\big)da_{max}\int_{c_0}^{w} \frac{f_{(b)}(c_b)}{1-F(c_b)}dc_b & v > w\,. \end{cases} \tag{9}$$

Necessary conditions for a Bayesian equilibrium are

$$\frac{\partial E[\pi(c,v,w)]}{\partial v}\Big|_{v=w=c} = 0\,, \tag{10}$$

$$\frac{\partial E[\pi(c,v,w)]}{\partial w}\Big|_{v=w=c} = 0\,. \tag{11}$$

With (8) and (10) we get the differential equation

$$\phi'(v)F_{(b)}(v) + \big(-(p_W-c)d + \phi(c) + (\psi(c)-c)da_{max}\big)f_{(b)}(c) = 0\,,$$

whose solution yields the equilibrium strategy for the BP bid

$$\begin{aligned} \phi(c) =& \frac{\int_{c_0}^{c}\big((p_W-c)d - (\psi(u)-u)da_{max}\big)f_{(b)}(u)du}{F_{(b)}(c)} \\ =& (p_W-c)d - (\psi(c)-c)da_{max} \qquad (12) \\ &+ \frac{\int_{c_0}^{c}\Big(1-a_{max}+a_{max}\frac{\int_u^{c_1}1-F_{(b)}(x)dx}{\left(1-F_{(b)}(u)\right)^2}f(u)\Big)F_{(b)}(u)du}{F_{(b)}(c)}\,. \qquad (13) \end{aligned}$$

With (9) and (11) we get the differential equation

$$\big(\psi'(c)(1-F(c)) - (\psi(c)-c)f(c)\big)da_{max}\int_{c_0}^{c}\frac{f_{(b)}(c_b)}{1-F(c_b)}dc_b = 0\,,$$

whose solution yields the equilibrium strategy for the BE bid

$$\psi(c) = c + \frac{\int_c^{c_1}1-F(u)du}{1-F(c)}\,. \tag{14}$$

Because of

$$\psi'(c) = \frac{f(c)\int_c^{c_1} 1 - F(u)du}{(1-F(c))^2} > 0\,, \tag{15}$$

ψ is strictly increasing in c. Furthermore, it is

$$\phi'(c) = \frac{f_{(b)}(c)}{F_{(b)}(c)}\left((p_W - c)d - (\psi(c) - c)da_{max} - \phi(c)\right) < 0\,,$$

and thus, the BP bid decreases with c. To verify the second-order condition, insertion of (14) and (15) into (9) yields

$$\frac{\partial E[\pi(c,v,w)]}{\partial w} = \begin{cases} (c-w)f(w)da_{max}\int_{c_0}^{v}\frac{f_{(b)}(c_b)}{1-F(c_b)}dc_b & v \leq w \\ (c-w)f(w)da_{max}\int_{c_0}^{w}\frac{f_{(b)}(c_b)}{1-F(c_b)}dc_b & v > w\,, \end{cases}$$

which is —independently of v— positive if $w < c$ and negative if $w > c$. That is, bidding on the second stage according to ψ as defined in (6) is optimal irrespective of the first stage. Using this by setting $w = c$ in (8) and insertion of (13) and (14) yields the result.

□

C.1.3 Proof of Proposition 7

Proof. The proof of (a), (b), (d), (e) and (f) follows by straightforward computation. (c) follows from the monotonicity of bidding functions. □

C.1.4 Proof of Proposition 8

Proof. Follows by straightforward computation. □

C.1.5 Proof of Proposition 9

Proof. For the expected rent $E[\pi(c,v,w)]$ of a representative bidder bidding $\phi(v)$ and $\psi(w)$ we have

$$E[\pi(c,v,w)] = (p_W - c)d(1 - F_{(b)}(v)) + \phi(v)F_{(b)}(v) + \int_w^{c_1} (\phi(u) - c)da_{max}(1 - F(w)) \int_{c_0}^{v} \frac{f_{(b)}(c_b)}{1 - F(c_b)} f(u|C_b = c_b)dc_b du \,.$$

Derivation of the expected rent $E[\pi(c,v,w)]$ with respect to w yields

$$-(\psi(w) - c)da_{max}(1 - F(w))f(w) \int_{c_0}^{v} \frac{f_{(b)}(c_b)}{1 - F(c_b)} f(w|C_b = c_b)dc_b - \int_w^{c_1} (\psi(u) - c)da_{max} f(w) \int_{c_0}^{v} \frac{f_{(b)}(c_b)}{1 - F(c_b)} f(u|C_b = c_b)dc_b du \,.$$

If an equilibrium in strictly increasing bidding functions exists, this implies the necessary condition for the BE bidding function ψ

$$\frac{\partial E[\pi(c,v,w)]}{\partial w}\Big|_{v=w=c} = 0 \,,$$

which is

$$(\psi(c) - c)da_{max}(1 - F(c))f(c) \int_{c_0}^{c} \frac{f_{(b)}(c_b)}{1 - F(c_b)} f(c|C_b = c_b)dc_b = -\int_c^{c_1} (\psi(u) - c)da_{max} f(c) \int_{c_0}^{c} \frac{f_{(b)}(c_b)}{1 - F(c_b)} f(u|C_b = c_b)dc_b du \,.$$

This can be simplified to the condition

$$(\psi(c) - c)(1 - F(c)) \int_{c_0}^{c} \frac{f_{(b)}(c_b)}{1 - F(c_b)} f(c|C_b = c_b)dc_b = -\int_c^{c_1} (\psi(u) - c) \int_{c_0}^{c} \frac{f_{(b)}(c_b)}{1 - F(c_b)} f(u|C_b = c_b)dc_b du \,. \tag{16}$$

Now let $c \in (c_0, c_1)$ be arbitrary and suppose either $\psi(c) = c$ or $\psi(c) > c$.

This together with the assumption that ψ is strictly increasing, however, yields an immediate contradiction to (16) which implies the claim: In the former case, $\psi(c) = c$, the left-hand side is zero while the right-hand side is negative, and in the latter case, $\psi(c) > c$, the left-hand side is positive while the right-hand side remains negative. The proof for UP/UP pricing is analogous. □

C.1.6 Proof of Proposition 10

Proof. Proposition 10 can also be proved by straightforward analytical arguments. Here we give an intuitive proof. Suppose the contrary, i.e., there exists an equilibrium of the negative market in which at least one bidder submits a positive BP bid. In this case, at least one bidder with a positive BP bid is not successful in the SBP auction and sells her energy on the wholesale market. This bidder, however, can be better off by submitting a BP bid of zero and a BE bid higher than minus her variable costs. This contradicts the assumption of an equilibrium. □

C.1.7 Proof of Proposition 11

Proof. Analogous approach as in Proof of Proposition 6, with the equilibrium BP bid of zero (see Proof C.1.2). □

C.1.8 Proof of Proposition 12

Proof. The proof of (a) and (b) follows by straightforward computation, and (c) follows from the monotonicity of bidding functions. □

C.1.9 Proof of Proposition 13

Proof. Follows by straightforward computation. □

C.1.10 Proof of Proposition 14

Proof. Analogous approach as in Proof of Proposition 9 (see Proof C.1.5). □

C.1.11 Proof of Proposition 15

Proof. Recall that by Proposition 7 and Proposition 9 we have $\psi(c) < p_W$ for all c and let $j \in \{1, 2, \ldots, n\}$ be an arbitrary bidder. Note that if j submits an additional BE bid $p_W < \psi_2 \neq \infty$ she will never change the outcome of the auction. If she submits an additional BE bid $\psi_2 < p_W$, she runs the risk of being awarded with her voluntary BE bid. In this case, however, she would be better off by rather selling her energy on the wholesale market and, thus, by submitting the bid $\psi_2 = \infty$. Simultaneously, if no bidder submits a relevant additional BE bid, the bidding function ϕ and ψ maximize j's expected profit since they constitute a symmetric equilibrium of the auction without additional BE bids. □

C.1.12 Proof of Proposition 16

Proof. Proposition 10 yields that $\phi(c) = 0$ for all bidders in the equilibrium. This reduces the calculus of a bidder to the situation without voluntary BE bids, which immediately implies the claim. □

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