Auctions for Renewable Energy Support

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Abstract

Energy transition is on the cutting edge of policies. The expansion of renewable energy is a key factor to reach global and national climate targets. However, support from governments in form of monetary subsidies is still essential. For the allocation and determination of support levels, competitive bidding processes are globally becoming the instrument of choice. Auctions have proven to reduce the costs of support, increase efficiency, and control the expansion of renewable energy. Accompanied by a rapid increase of auctions for renewable energy support in the last few years, this thesis focuses on particular questions raised by practice. First, we provide a comprehensive theoretic framework for auctions in the renewable energy support context. Then, we discuss various design options with particular focus on three specific real-world auctions in Germany. The first example applies non-binding awards, the second discrimination and the third favoritism in the respective auction. All those design options are considered unconventional in theory and policy. We show that they address important market and framework conditions and hence offer great opportunities for successful auction implementations in the renewable energy support context. Our approach is based on game-theoretic and mathematic methods and partially complemented by laboratory experiments to test our theoretical hypotheses with regard to human behavior.

To my daughters Lena and Klara.

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List of Symbols

b	bid of a bidder
b^{HAB}	optimal bid in binding uniform price auction with HAB
b^{LRB}	optimal bid in binding uniform price auction with LRB
b^{PAB}	optimal bid in binding pay-as-bid auction
b^{ROS}	optimal bid in first-price auction with ROS
B	bonus for awarded high-cost bidders
$\hat{B}$	optimal bonus for awarded high-cost bidders (minimizing support costs)
$\beta(\cdot)$	symmetric bidding equilibrium of a bidder
$\beta^{HAB}(\cdot)$	symmetric bidding equilibrium in binding auction with UP-HAB
$\beta^{LRB}(\cdot)$	symmetric bidding equilibrium in binding auction with UP-LRB
$\beta^{PAB}(\cdot)$	symmetric bidding equilibrium in binding pay-as-bid auction
$\beta^{ROS}(\cdot)$	symmetric bidding equilibrium in first-price auction with ROS
$\beta^{ROS^{-1}}(\cdot)$	inverse symmetric bidding equilibrium in first-price auction with ROS
$\beta^{FA}(\cdot)$	symmetric bidding equilibrium in first-price auction
$\beta^{SA}(\cdot)$	symmetric bidding equilibrium in second-price auction
$\mathbf{c}$	bid vector in non-binding auction
$\mathbf{c^{HAB}}$	optimal bid vector in the non-binding uniform price auction with HAB
$\mathbf{c^{LRB}}$	optimal bid vector in the non-binding uniform price auction with LRB

$\mathbf{c}^{\mathbf{PAB}}$	optimal bid vector in the non-binding pay-as-bid auction
$C(\cdot)$	cumulated marginal costs
$\gamma^{\mathbf{HAB}}(\cdot)$	symmetric bidding equilibrium in non-binding auction with UP-HAB
$\gamma^{\mathbf{LRB}}(\cdot)$	symmetric bidding equilibrium in non-binding auction with UP-LRB
$\gamma^{\mathbf{PAB}}(\cdot)$	symmetric bidding equilibrium in non-binding pay-as-bid auction
D	total demand (auction volume)
$E[\cdot]$	expected value of a random variable
$\epsilon(\cdot)$	elasticity of supply
η	concavity parameter of the beta distribution
$f(\cdot)$	densitiy function of X
$F(\cdot)$	distribution function of X
$f_{(j:N)}(\cdot)$	density function of $X_{(j:N)}$
$F_{(j:N)}(\cdot)$	distribution function of $X_{(j:N)}$
$F^{ROS}(\cdot)$	distribution function of expected award price in first-price auction with ROS
$F^{SA}(\cdot)$	distribution function of expected award price in second-price auction
$g_K(\cdot)$	density function of K-th lowest competing leading bid
$G_K(\cdot)$	distribution function of the K-th lowest competing leading bid
H	index for high-cost bidders
$h_K(\cdot)$	density function of the K-th lowest competing binding bid
$H_K(\cdot)$	distribution function of the K-th lowest competing binding bid
i	index for a particular bidder
I	index for favored bidder
II	index for non-favored bidder
K	number of auctioned goods

L	index for low-cost bidders
λ	parameter for misestimated number of bidders
$\underline{\lambda}, \overline{\lambda}$	parameter for under- and overestimation of number of bidders, respectively
$MC(\cdot)$	marginal costs function
$\underline{MC}$, $\overline{MC}$	lower and upper bound for marginal costs, respectively
n	number of bidders per bidder class
N	number of bidders
p	award price
p^{ROS}	award price in first-price auction with ROS
p_s^{ROS}	award price in first-price auction with ROS and favoring the strong bidder
p_w^{ROS}	award price in first-price auction with ROS and favoring the weak bidder
p^{SA}	award price in second-price auction
p^*	market clearing price of free competition
$P(\cdot)$	probability of an event
π	profit of a bidder
q	volume shift from low-cost bidders to high-cost bidders induced by Q
Q	minimum quota for high-cost bidders
$\hat{Q}$	optimal minimum quota for high-cost bidders (minimizing support costs)
R	reservation price (maximum price) for the low-cost bidders
$\hat{R}$	optimal reservation price (minimizing support costs)
$\rho(\cdot)$	ratio of distribution and density function
s	index for strong bidder
$S(\cdot)$	supply function
t	index of a bid vector in non-binding auction with $t \in \{1, \ldots, T\}$

T	number of feasible bids
$TC(\cdot)$	total support costs
v	delivered volume per bidder
w	index for weak bidder
x	realisation of the random variable X
$\underline{x}, \overline{x}$	lower and upper bound for x
X	random variable of a bidder's signal
$X_{(j:N)}$	j-lowest order statistic with $j = 1, \ldots, N$
$z \geq 0$	withdrawal costs
ζ	convexity parameter of the beta distribution

Chapter 1

Introduction

"Climate change is one of the greatest challenges of our time" state the United Nations in their 2030 Goals for Sustainable Development (General Assembly of the United Nations, 2015). The General Assembly of the United Nations (2015) alert about diverse climate change impacts, which endanger "the survival of many societies, and of the biological support systems of the planet". Responding to this challenge, the parties of the United Nations Framework Convention on Climate Change (2015) set a milestone for global climate actions in the Paris Agreement. They aim to limit global warming to well below 2 degree Celsius above pre-industrial levels this century by reducing greenhouse gas emissions. For that, the transition from fossil fuels, the main emitter of greenhouse gases, to clean and sustainable energy sources becomes a key factor.

Renewable energy is collected from naturally replenished sources like wind, solar, wave or biomass (Lund, 2007). We focus on renewable energy provided for electricity generation, but renewable energy is also used for heating or cooling and in the transport sector. In 2015, renewable energy provided 23.7% of the global generation of electricity (REN21, 2017). Although energy transition is well underway in many countries, policies have to further promote the global expansion of renewable energy in order to fulfill the ambitious goal of the Paris Agreement.

In both global and national agreements, governments decide about their individual and legally binding contributions to a sustainable development. IRENA and CEM (2015) report that, as of 2015, 164 countries commit to individual expansion goals for renewable energies. Among those, some even aim to be a 100% renewable energy country by mid-century (REN21, 2017).

In 2000, the German Federal Parliament (2000) released the Renewable Energy Act (EEG) to foster the expansion of renewable energy in Germany. Until today many adaptations have been made, however, basically the EEG regulates the support for renewable energy and grants feed-in priority to electricity from renewable energy. Starting with 8.6% of electricity generated by renewable energy in 2002, they provide 38.2% in 2017 (Fraunhofer ISE, 2017). Furthermore, Germany sets a minimum target of 80% by 2050 (German Federal Parliament, 2017a).

1.1 Background

1.1.1 Renewable Energy Support

The sun shines, wind blows and water flows without consuming essential resources. Hence renewable energy sources are unlimited and available for free. However, due to not matured technologies and still high investment costs the generation of electricity from renewable energy is not yet competitive with conventional power plants. Therefore, governments support the expansion of renewable energy.

They grant feed-in priority to renewable energy and subsidize new installations (German Federal Parliament, 2000). In the past, support levels predefined by government have been widely used as support schemes. That is, project developers received a long-term contract including a predefined monetary amount depending on their electricity generation. While project developers benefit by reduced uncertainties, predefined support levels caused diverse problems for governments. Especially, the determination of appropriate support levels represents a fundamental problem. On the one hand, expansion stagnates, if support is insufficient. Overcompensation, on the other hand, may lead to an uncontrolled expansion and hence uncontrolled support costs.

A good example is the German photo voltaic (PV) installation boom starting in 2001. Expansion goals have been exceeded for years leading to excessive costs for government and consumers. Several adjustments of the EEG have been released to successively reduce predefined support levels from 50,6EURct per KWh in 2001 to below 20EURct per KWh in 2012 with further degressions to below 10EURct per kWh in 2014 (German Federal Parliament, 2000; Appunn, 2014; Wirth, 2018). Rapidly falling prices for PV collectors because of technological developments have been the main reason (Wirth, 2018). However, those multiple adjustments indicate that predefined support levels are not suitable to adequately reflect volatile installation costs for renewable energy. Further, due to long-term support contracts over 20 years, Germany still bears the consequences of overcompensation (Wirth, 2018). The introduction of a volume limit might have mitigated overfulfillment of expansion, however, would have raised the question of whom to grant support in case of oversupply.

Consequently, government needed to rethink the support scheme towards a controlled and sustainable renewable energy expansion by simultaneously reducing costs. In case of oversupply, competitive bidding mechanisms, i.e. auctions, enable competitive price determination and aim to efficiently allocate support to project developers.[1] Many countries have recently implemented or are planning to implement auctions for the allocation of support and determination of support levels for renewable energy. IRENA (2017) report that the number of countries worldwide that already implemented auctions for renewable energy support raised from 5 in 2005 to at least 67 in 2016. Many of these countries already achieved record low support costs through the introduction of auctions (del Río and Linares, 2014).

Finally, we enter a new era by introducing competition in the so far non competitive and non balanced sector of renewable energy support. Rule-based and competitive awarding designs, as auctions, are predestined to harmonize supply and demand in this challenging market. However, auctions traditionally are also accompanied by practical challenges, which is the point where this thesis steps in.

1.1.2 Laws and Guidelines for Auctions for Renewable Energy Support

The State Aid Guidelines from the European Commission (2014) determine that from 2017 onwards renewable energy support, with only very few exceptions, has to be determined through competitive bidding processes. Basically, the auctions shall be open to all generators producing electricity from renewable energy sources on a non-

[1] Alternatives to auctions are discussed in del Río et al. (2016) and Kitzing et al. (2016)

discriminatory basis. However, due to different stages of technological development for renewable energy technologies so far, technology specific tenders are allowed. In addition, member states are free in designing appropriate auctions within their countries.

In Germany the Renewable Energy Act 2017 (EEG 2017) specifies technology specific auctions for renewable energy support for electricity from solar, wind onshore, wind offshore and biomass (German Federal Parliament, 2017a). Projects with smaller nominal capacity are excluded and will still receive fixed support levels.[2] For all others, auctions are held on a regular basis, up to quarterly, throughout the year. The auction volume is aligned to the expansion targets, where a slight exaggeration is due to default risks. Additionally, prequalification criteria and penalties in case of non-realization after award have been introduced. Furthermore, from 2018 to 2020 technology neutral auctions for renewable energy support for electricity from solar and wind onshore are scheduled as a pilot. Besides the EEG 2017 further laws have been enacted. For instance, the detailed implementation of the technology neutral auctions, as suggested in the EEG 2017, is regulated in German Federal Parliament (2017b). The Offshore Wind Energy Act (WindSeeG) provides implementation rules for wind offshore auctions in Germany (German Federal Parliament, 2016b).

1.2 Objective

In general, this thesis aims to contribute important lessons learned from theory for auctions for renewable energy support to facilitate successful implementations in real-world. In particular, we consider three different auction designs as implemented in Germany.

[2] Solar and wind onshore projects with a nominal capacity greater than 750 MW can participate in the auction. For biomass, nominal capacity must exceed 150MW.

So far, a close link between auction theory and renewable energy has been missing and speculations or half-truths exist that discourage project developers and policy makers. This thesis analyses different auction formats and implementations under renewable energy relevant conditions and shows how sensitive auctions are. In auctions for renewable energy support an immense diversity (regarding auctioned goods, bidders and auctioneers) has to be combined - starting with different renewable energy sources, geographic conditions and technologies to political goals and frameworks as well as financing conditions. Though global guidelines, the concrete decision about auction design and implementation are surrendered to the countries. The large variety of design parameters pose a challenge to both policy makers and project developers. Governments need to design suitable auctions that adequately reflect their goals. Project developers, on the other side, now face an award uncertainty and have to deduce an optimal bidding strategy. So far, neither side is particularly experienced with auctions. Here this thesis steps in and sheds light on the promising opportunity of auctions for renewable energy support.

The basis of our work forms a comprehensive introduction into the principles of auction theoretic modeling in the context of renewable energy support, in Chapter 2. Motivated by three German examples, we investigate auctions with non-binding awards, discriminative auctions and favoritism in auctions.

In Germany's auctions for renewable energy support for electricity from solar, bidders have to provide a security within a certain time frame after being awarded. If they did not submit this security their award expired (German Federal Parliament, 2017a). As a consequence, awarded bidders may withdraw from their award and expansion targets may be missed. Previous research on non-binding awards in auctions barely[3] exists and hence became a matter of urgency in 2015 when the first pilot

[3] Cramton et al. (2015), Merlob et al. (2012), McMillan (1994) mention and analyze prominent examples of non-binding auctions that were, however, implemented with minor success.

auctions started. Besides our theoretical analysis, we also investigated the impacts of non-binding awards in laboratory experiments in Chapter 3.

Asymmetries among bidders in renewable energy auctions are diverse and inevitable. For instance, installation costs may differ significantly between renewable energy sources. Thus, discriminative measures as quotas, different maximum prices and boni are often discussed with regard to technology-neutral auctions. The European Commission (2014) presupposes non-discriminative auctions, however, several countries[4], e.g. Germany, insist on specific discriminations to address asymmetries in their technology-neutral auctions (German Federal Ministry for Economic Affairs and Energy, 2017; German Federal Parliament, 2017b). Beyond existing literature[5], this thesis contributes a general theoretic analysis of three different forms of discrimination in renewable energy auctions followed by a discussion of those regarding practical implementation, in Chapter 4.

In the early stage of Germany's wind offshore auctions, from 2017 to 2018, existing projects are auctioned. To accommodate the special position of the project owners in the auction a right of subrogation is granted to them (German Federal Parliament, 2016b). In more detail, the favored bidder has the option to win the auction by matching the winning bid after award. Chapter 5 presents a simplified model with specific asymmetries among bidders to analyze this favoritism in auctions with regards to its cost decreasing potential.

1.3 Approach

We combine auction theory and practice to identify factors for (un)successful auction implementations in the renewable energy context. Our research is based on abstracted

[4] For instance, also Denmark, California and Mexico implemented discriminatory elements in their technology-neutral auctions.

[5] Discriminatory instruments have been theoretically analyzed in a general context by, e.g., Varian (1989), Bulow and Roberts (1989), McAfee and McMillan (1989), Schmalensee (1981) and Myerson (1981).

models that allow us to analyze auctions in a structured way with game-theoretical and mathematical methods. Furthermore, we use laboratory experiments to analyze human behavior and decision-making, i.e. bidding, in such auctions.

Chapter 2 highlights the general suitability of auctions for renewable energy support substantiated by auction theoretical findings and statements from the renewable energy sector. Based on previous research, we provide basic principles of auction theory and establish a standard theoretical framework for renewable energy auctions. General theoretic advantages and disadvantages of potentially suitable auction formats are presented in this simplified framework. However, in the real world, market and framework conditions may deviate from what is suitable, may differ among countries, and may change over time. This is why, we then widen our simplifying assumptions successively and analyze the impacts.

In Chapter 3, we develop a model with non-binding awards and reallocation in multi-unit auctions. We deduce explicit, if applicable, and numerical solutions for optimal bidding strategies and symmetric Nash equilibria. In those, we compare auctions with non-binding awards to the respective binding auctions. Furthermore, we conduct laboratory experiments to test our theoretical hypotheses with regard to human bidding behavior. In both theory and experiments, we conclude that auctions with non-binding awards are not necessarily doomed to failure suggested by previous examples.

Chapter 4 introduces three discriminative measures - quota, different maximum prices and boni - into auctions for renewable energy support. Thereby, we assume that bidders are asymmetric regarding their individual costs, which is modeled by different elasticities of supply for each bidder group. Based on this assumption, we show that despite favoring weaker bidders, the support costs for governments are minimized and the three measures are theoretically equivalent, however, differ regarding their practical implementation.

In Chapter 5, we focus on favoritism of one particular bidder through a right of subrogation. This chapter is based on Haufe (2014) and extends the results to the context of auctions for renewable energy support. Haufe (2014) chooses beta distributions as exemplary costs distribution functions and models asymmetries among bidders by the concept of stochastic dominances, or more precisely by the reverse hazard-rate order. This theoretical analysis reveals cases of asymmetry where a first-price auction with right of subrogation outperforms a standard second-price auction in terms of higher profit for the auctioneer.

Each chapter is based on a separate paper with only minor adaptations for consistency and reader-friendly presentation. Table 1.1 provides an overview of the corresponding authors and titles as well as the current publication status and the journal of submission.

Ch.	Authors	Title	Status	Journal
2	Marie-Christin Haufe, Karl-Martin Ehrhart	Assessment of Auction Types Suitable for RES-E	Published 1/2016	AURES Project Report [6]
3	Marie-Christin Haufe, Karl-Martin Ehrhart, Matej Belica	Non-binding Award in Multi-unit Procurement Auctions	Working Paper	
4	Karl-Martin Ehrhart, Marie-Christin Haufe, Jan Kreiss	Discrimination in Auctions for Renewable Energy Support – Three Theoretically Equivalent but Practically Different Concepts	Submitted 4/18	Resource and Energy Economics
5	Marie-Christin Haufe	Last-Call Auctions with Asymmetric Bidders	Submitted 5/2018	International Journal of Industrial Organization

Table 1.1: Overview of publications authored during this work.

Chapter 2

Auction Theory meets Renewable Energy Support

Auctions are a promising approach for the support of electricity from renewable energy sources (RES-E). The aim of this chapter is to assess relevant auction formats for RES-E per se as well as under specific market and framework conditions from an auction theoretic perspective. Pros and cons of relevant auction formats are discussed under different assumptions regarding RES-E specific market and framework conditions.

In order to promote a deeper understanding of those auction formats per se, we start with a first overview of their fundamental characteristics and emphasize general differences between them. For that, we base our theoretical analysis on simplifying basic assumptions for the beginning and refer to those as benchmark case. As an important result from auction theory, under these particular assumptions, there are no crucial differences between certain auction formats due to which the auctioneer should prefer one over another. Nevertheless, we emphasize smaller differences that become decisive for real-world applications, identifying those auction formats that are not considered suitable for the RES-E context, and consequently skip these auction formats in the subsequent analysis.

In the next step, we neglect and extend the simplifying assumptions in order to investigate the remaining auction formats under market and framework conditions relevant for RES-E. We will find that auction formats differ widely in several situations, because they react differently to specific conditions. Hence, in some situations the negative characteristics of a particular format prevail, whereas under different conditions this format will be the most suitable compared to others. As a result, this section provides guidance about which chances and risks are involved in particular auction formats under certain RES-E specific market and framework conditions and consequently which is the most appropriate one in each case.

2.1 Why are Auctions Potentially Suitable for RES-E?

In the beginning the question arises why auctions are potentially suitable for RES-E at all. Indeed, several answers or good reasons exist for their implementation in that specific context. Note that the following reasons are not unique features of auctions and there might also exist further appropriate RES-E support mechanisms that fulfill certain context specific requirements presented in the following. First, an important factor is that project developers usually have more precise information on their expected costs and revenues than the government, i.e. in the RES-E context there exists a situation of information asymmetry (McAfee and McMillan, 1986; IRENA and CEM, 2015). Therefore, project developers should come up with a suggestion of a cost-covering support level as it is the case in auctions and not vice versa as for example in case of fixed feed-in tariffs predetermined by government. Hence a decentralization of information about costs and revenues can be exploited by introducing auction schemes. Another valid reason for auctions for RES-E is the option of controlling costs, expansion and the technology mix (IRENA and CEM, 2015).

That is, the auctioneer can either limit the annual auction budget for RES-E, where the number and total size of awarded projects is uncertain, or restrict the annual number or total size of awarded projects and thereby leave the budget needed uncertain (Latacz-Lohmann and Schilizzi, 2005). Further, the alternatives of conducting technology-neutral or technology-specific auctions enable the regulation of the technology mix in an appropriate manner (Kopp et al., 2013). Since auctions primarily are an allocation mechanism, the auctioneer aims to ensure allocative efficiency. Namely, if an auction allocates the good or multiple goods efficiently to the bidders, there exist no ex post incentives for resale (Ausubel et al., 1998). Therefore, we will focus on the identification of allocative efficient auctions in our following analysis. However, there might be certain market and framework conditions that rather compromise allocative efficient outcomes than others (see Subsection 2.7). Furthermore, well-designed auctions are a competitive market mechanism through which valuable information can be generated. On the one hand, the government collects signals about cost-covering support levels. On the other hand, even project developers can learn from the auction outcome, especially if the award prices are released. Because project developers face competition in an auction in form of award risks, a well-designed auction also generates incentives for innovation (Kopp et al., 2013).

2.2 Classification of Auctions Relevant for RES-E

An auction is a mechanism (institution) in which a good or several goods (here: the power (MW) or physical work (MWh) of renewable energies) are offered up for bidding. It is a market mechanism with several aims, whereby auction theory mainly focuses on competitive price determination and efficient allocation of one or multiple goods. Consequently, auctions for renewable energy support are applied in order to reduce costs of support and identify the "best" (with respect to predefined targets and criteria) suppliers for renewable energy. Since those suppliers will act as bidders (sellers), who offer the auctioned good to the auctioneer, we refer to these auctions as so-called procurement auctions. That is, the auctioneer will buy the good from those bidders offering the best bid, e.g. the lowest price. As the auctioned volume might be split up and delivered by several bidders, our analysis focuses on multi-unit auctions with homogeneous or heterogeneous goods. The homogeneous goods are certain equivalent subsets of the total power offered up for bidding, where the scaling may differ (1MW, 10MW, etc.). The heterogeneous goods are predetermined projects by the auctioneer that are offered for realization. The bidders (suppliers) will be awarded an amount of the power subsets or projects according to their bids, i.e. the best bids will win as long as the offered amount is less than or equal to the demanded amount. In addition, single-unit auctions may be implemented (see wind offshore auctions in Denmark), which represent a special case of multi-unit procurement auctions with only one single good. Here the same applies as above, the auctioneer can either predetermine the project auctioned and bidders compete for this sole project (intra-project competition) or the each bidder participates with his individual developed project (inter-project competition). The best bid(s) can either be determined based solely on the price (i.e. costs of support) or by multi-attributive criteria such as price, actor diversity, geographical and technological conditions, etc. For reasons of clarity, we will limit our analysis on the former kind of auctions, i.e. homogeneous or heterogeneous multi-unit procurement auctions with the bidding price as sole criterion. Note that each multi-criteria auction can be transformed into a single-criterion auction, if the criteria and evaluation approach are traceable and transparent to all bidders and hence the corresponding bid reflects all criteria (e.g. price-based weighting of all relevant criteria).

2.3 The Specifics of RES-E as an Auctioned Good

2.3.1 What is Auctioned?

The question of what is or should be auctioned strongly depends on the preferences regarding the auctioneer's aims. Is his fundamental aim to keep to a predetermined budget? Or is his primary aim to achieve the expansion goal? Hence, we start by attending to the determination of the auction volume, which can either be determined endogenously or exogenously. That is, the auctioneer has two options, where he can either restrict the monetary budget or limit the amount of supported RES-E, e.g. the awarded rating power in MW, the amount of supported MWhs or the number of projects. Latacz-Lohmann and Schilizzi (2005) conducted controlled laboratory experiments in order to compare budget-constrained and target-constrained auctions and find that there exist no crucial reasons to favor one approach over the other.

Endogenous Auction Volume The first option, that is to limit the budget, strongly focuses on controlling and reducing the support costs and even accepts the risk of not achieving predefined expansion goals. The bids demanding the lowest support levels will be awarded until the total budget is reached. Hence, if bidders submit relatively high bids the total budget is reached early and consequently the expansion goal is missed. However, note that an appropriate reservation price (i.e. maximum price) may reduce the risk of strategically high bids. Finally, this approach only makes sense for multiple and only individually developed projects, i.e. bidder specific projects. An application example of this option can be found in the Dutch SDE+ auction.

Exogenous Auction Volume The second option, to limit the supported amount, corresponds to the idea of achieving a predefined expansion target, where the support costs become a secondary goal. Although the government aims to increase the expansion of RES-E, they are interested in a controlled expansion, for example due to grid constraints or public acceptance issues. In this case, the lowest bids based on demanded support levels will be awarded until the expansion target (MW or MWh) is reached. However, this option leaves the support costs uncertain in favor of a fulfilled expansion goal. Note that the support costs, however, can be limited by setting an adequate reservation price (i.e. maximum price).

Based on the volume dependent approach, there exist several options for the goods auctioned in an RES-E auction. Consequently, the auctioneer has to determine beforehand whether a single good, multiple homogeneous goods or multiple heterogeneous goods are offered up for bidding. In the RES-E context, the former option occurs if only the support for one renewable energy project (or one bundle of projects) is awarded per auction. In this case, the project can either be predetermined by the auctioneer or individually developed by each participating bidder. If the support for more than one project should be determined per auction, on the one hand, the auctioneer can demand a certain amount of homogeneous power or energy units that is delivered by several individual projects of the bidders. On the other hand, he can auction the support of particular heterogeneous projects predetermined by himself, e.g. specific projects at different locations.

Depending on what the auctioneer demands and offers up for bidding, different auction formats will be considered relevant in our analysis, as presented in Table 2.1. Moreover, they fulfill specific requirements for suitability in real-world applications as presented in Section 2.6, where we undertake a detailed analysis of those auction formats.

2.3.2 Revealed or Hidden Auction Volume

In addition to the choice of auction volume itself (i.e. the monetary budget or the amount to be supported), the question arises if the auction volume should be revealed

	Single good	Multiple goods	
		Homogeneous	Heterogeneous
Static auctions	First-price auction, Second-price auction	Pay-as-bid auction, Uniform price auctions, Vickrey auction	Generalised Vickrey auction
Dynamic auctions	Dutch auction, English auction	Descending clock auction	Simultaneous multi-round descending auction

Table 2.1: Suitable multi-unit auction formats for RES-E auctions depending on the auctioned goods.

or hidden. A public auction volume represents a signal that is relevant for the bidders estimation of competition. In this regard, a hidden auction volume incorporates the same effects with regard to uncertainties of the estimated competition level for bidders as an unknown number of participants from a theoretical point of view. However, from a practical perspective, potential bidders are rather more suspicious of a hidden auction volume, which seems to be consciously undisclosed by the auctioneer potentially for some intransparent reason, than of an unknown number of participants, which in contrast can be taken rather as a given by the participants. For the following argumentation, we will limit the discussion on the question about revealed or hidden auction volumes. In general, a revealed auction volume provides certainty and represents transparency and reliability for potential bidders in real-world applications. A hidden auction volume in contrast induces high uncertainties for potential bidders and thus may lead to a reduced acceptance of the auction or even lower the participation. In theory, uncertainties generated by a hidden auction volume refer to the bidders estimation of competition, i.e. the competition they believe to face in the auction. The higher bidders estimate the competition level the more aggressive is their bidding behavior, i.e. the lower their submitted bids. Especially non-incentive compatible auction formats are sensitive to this effect, since the degree of costs exaggeration strongly depends on the bidders beliefs about competition. Under certain basic assumptions , both alternatives, i.e. revealed or hidden level of competition, generate the same expected auction outcome in first-price and second-price auctions (Harstad et al., 1990), whereas under modified assumptions of risk averse bidders the auctioneer benefits from a hidden number of bidders in terms of a higher expected auction revenue in the first-price auction (McAfee and McMillan, 1986). However, the unknown competition level because of a hidden auction volume may lead to misestimating in real-world applications. On the one hand, bidders may underestimate the competition level and submit less aggressive, i.e. higher, bids. Supposing all bidders behave according to this, a hidden auction volume increases the expected support costs. However, on the other hand, especially in case of low competition, general overestimating of the competition level might be indeed favorable for the auctioneer in terms of lower expected support costs. To conclude, a hidden auction volume should in practice only be implemented with caution. Misestimating of competition can always happen in both directions, leading to some bidders bidding more and others less aggressively under the assumption of higher or lower competition. Consequently, hidden auction volumes may induce allocative inefficiencies, especially in non-incentive compatible auction formats, which could have been reduced by revealing the monetary budget or amount of RES-E offered up for bidding. Finally, the main argument for a revealed auction volume is the clear and transparent signal provided by the auctioneer, which creates confidence and acceptance among potential bidders, especially in light of a repeated conduction of the auction. Note that for an incentive compatible auction mechanism the weakly dominant strategy to bid one's true costs is preserved for revealed and hidden auction volumes and hence no related inefficiencies may occur in both cases. Further, Damianov et al. (2010) observe in their experiments that the uniform-price auction outperforms the pay-as-bid auction in terms of higher auction revenues and allocative efficiency under uncertainties regarding the auction volume. Furthermore, Back and Zender (2001) find that an ex post reduction of the auctioned volume may eliminate collusive strategies for multi-project bidders in uniform-price auctions.

2.3.3 Valuations for RES-E as an Auctioned Good

In the following we define the valuations for RES-E as an auctioned good from the bidder's perspective as well as from the auctioneer's perspective. Bidders evaluate the good, i.e. the projects, in two dimensions: On the one hand, they expect a certain project specific energy generation [MWh] over a plant's lifetime which is for instance based on regional conditions and project size. On the other hand, they have certain individual costs to bear over the lifetime [], e.g. for project development, realization, operations and maintenance. Assuming that all costs have to be covered by the support of the project, the minimum required support level is defined by the Levelized Cost of Electricity (LCOE). Hence, from now on we refer to a bidder's valuation for a RES-E project as the expected average LCOE, i.e. the project specific cost-covering support level. Besides achieving the expansion goal and reducing the support costs, the auctioneer may have further aims as, for instance the promotion of domestic industry or a certain regional distribution of RES-E plants (IRENA and CEM, 2015). To analyse those further aims theoretically, they have to be reflected in the auctioneer's individual valuation, e.g. by a monetary quantification. Imagine that two auctions generate the same expected support costs and the same amount of RES-E awarded. If the auctioneer benefits more from the auction that scores better in terms of actor diversity or regional distribution he should consider further appropriate criteria for allocation. Hence, in order to transfer multiple goals of the auctioneer adequately in the auction, so-called multi-criteria auctions can be used. Multi-criteria auctions are auctions in which further (weighted) criteria beyond the bidding price, such as the institutional organization or project location, are relevant for the award decision (Che, 1993; Branco, 1997). For the implementation of a (multi-criteria) auction that takes the individual valuation of the auctioneer into account, the scoring and evaluation principles of the auctioneer have to be clear and transparently published to all participants (Bushnell and Oren, 1994; Bichler, 2000; De Smet, 2007). Furthermore, there exist specific design options for RES-E auctions as the implementation of contingents within an auction for certain bidder groups that may also serve those requirements, see Chapter 4.

2.3.4 Bid Specification

Based on the good specification and the valuations, the auctioneer defines what information bidders have to submit within their bids. We limit our analysis to the following bid specification: If the auctioned project(s) is (are) completely predetermined by the auctioneer, then bidders bid on their requested support level for the realization regarding the particular project. If bidders participate with their own individually developed projects, they submit bids representing all project specific data relevant for the evaluation of the auctioneer, e.g. size, power rating, region, business form, etc., and the corresponding support level requested. Finally, all (valid) submitted bids are transferred into the award process of the auction, where the auctioneer evaluates them according to the predefined criteria and correspondingly awards them until supply equals demand.

2.4 Criteria to Assess Different Auction Types Suitable for RES-E

In our subsequent analysis we will assess the relevant auction types with regard to

- Price determination
- Signal generation
- Expected auction revenue (RES-E support costs)
- Incentive compatibility
- Allocative efficiency
- Auctioneer's risks, e.g. risks of unfavorable strategic behavior (strategic reduction of competition, implicit collusion)
- Bidder's risks, e.g. award risk, award price risk, risk of the winner's curse.

Note that for an overall assessment of an auction, those criteria should not be considered separately but combined and weighted according to the auctioneer's goals.

Price Determination A well-designed auction is a mechanism that serves to generate competitive prices, in particular in markets where the market clearing price is unknown. We distinguish between different forms of price determination, i.e. either a common price for all winning bidders is generated or each bidder receives an individual price. However, all prices are determined through the submitted bids in the auction. Finally, one common price per RES-E auction might be favored from a political point of view, because a common price represents one clear price signal. We will go more into detail with the price determination issue in the further work of the project.

Signal Generation If information about the auction outcome, e.g. the award price(s) as the spectrum or average of bids and/or award prices and the awarded volume as well as the submitted volume, is revealed during or after the auction, the auction generates signals for the participating bidders as well as for potential bidders in future auction rounds. That is, project developers receive information from the auction outcome that helps them evaluating their individual risks and chances regarding a future participation in the auction as well as to re-evaluating their strategy in the past round. Provided that the auction is well-designed and generates competitive prices, potential project developers learn about their competitors support levels and can thus derive which costs and bids are competitive. Although dynamic auctions, for instance, may generate more information during the bidding process than static auctions, the ex post accessible information strongly depends on what the auctioneer reveals after conduction of the auction. In addition, there are auction formats that generate information that is more precise than others. For example, in some auction formats the submitted bids correspond to the expected costs of the particular bidders. We refer to this characteristic as *incentive compatibility*, see below. Incentive compatible mechanisms facilitate the acquisition of information.

Expected Auction Revenue (RES-E Costs) The reduction of support costs for renewable energy has become an important goal pursued by the introduction of auctions. Hence, the success of an auction will be evaluated based on the support costs generated through the auction, for instance, in comparison to alternative support level setting mechanisms such as administratively set feed-in tariffs, where further results as the expansion achievement etc. may be considered as well. The expected auction revenue may differ between auction formats, where not only the auction format itself but also the market and framework conditions in which those auction formats are conducted play a crucial role. Assuming the auctioneer is only focused on achieving the expansion goal, he aims to minimize his expected support costs by choosing the corresponding cheapest auction format based on the existing market and framework conditions. However, if the auctioneer pursues additional goals, e.g. actor diversity or regional distribution of RES-E plants, by conducting the auction, these goals have to be incorporated in his individual valuation, e.g. by a monetarily quantification. This may lead to the auctioneer benefiting more from an auction outcome that ensures actor diversity than from another that generates lower support costs.

Incentive Compatibility As the auctioneer aims to minimize the expected support costs through the choice of an appropriate auction format, a bidder maximizes his expected profit by optimizing his bidding strategy in the auction. The incentive compatibility is an important characteristic of bidding induced by certain auction formats and framework conditions. It means that bidders have an incentive to reveal their true costs in their bids. One reason for that is that bidders cannot influence their own support level through their bid in incentive compatible auction formats. They only determine whether they will be awarded or not by bidding. Usually, incentive compatible auctions induce weakly dominant bidding strategies. In non-incentive compatible auctions, bidders determine or at least partly impact their support level in case of being awarded. As a consequence, they usually have an incentive to exaggerate their true costs in their optimal bidding strategies. Hence, bidders submit higher bids in non-incentive compatible auctions than in incentive compatible formats. However, incentive compatible auction formats do not necessarily generate lower support costs. There are also situations in which it is exactly the opposite. Under specific conditions, certain incentive and non-incentive auction formats even generate the same expected support costs (see Section 2.5). This auction theoretical phenomenon is stated in the so called revenue equivalence theorem. The main advantages of incentive compatibility are that the optimal bid is easy to calculate for the bidders and that incentive compatible auctions result in allocative efficient outcomes, since the truthful (optimal) bid of a bidder is independent of his risk attitude and his beliefs about his competitors. It is a very straight-forward strategy to bid one's own expected costs in contrast to calculate an optimal bid exaggeration in non-incentive compatible auctions. Hence, it is often argued that incentive compatible auctions are easier to understand and to manage, especially for smaller or less experienced bidders (Harrison, 1989). Nevertheless, it is often observed that bidders do not honestly reveal their true costs in incentive compatible auctions in real-world applications. Especially, the practical risk of underbidding is higher in incentive compatible auctions than in non-incentive compatible auctions (Kagel and Levin, 1993; Cooper and Fang, 2008). Finally, the incentive compatibility only applies under very limited conditions that, however, may not adequately reflect the given reality. For instance, the uniform-price auction with lowest rejected bid is often mentioned as an incentive compatible auction mechanism (Myerson, 1981). Nevertheless, only single-project bidders, who further participate in only one single auction round, have incentives to reveal their true costs in that particular auction. Multi-project bidders would have incentives to exaggerate their costs at least for some of their projects (see Section 2.7.2). The same applies if bidders have the chance to participate in later auction rounds as well. Then incentives for bidders occur to exaggerate their individual costs in an earlier round, since they anticipate an additional winning probability through their participation in later rounds. From a theoretical point of view, it can be expected that the bids regarding one project of a particular bidder will decrease continuously over multiple rounds and converge towards the optimum bid in the corresponding one-time auction (Gale and Hausch, 1994).

Allocative Efficiency An auction serves not only as price determination but also as allocation mechanism of goods in case of excess supply. In theory, the question of an optimal allocation generally addresses the aim of Pareto efficiency and of maximizing welfare. An allocative efficient auction mechanism maximizes welfare by allocating the good to the participant with the highest valuation. Or in other words, the best bidder wins, i.e. the project developer with lowest support costs and/or highest scores in other relevant transparent criteria predetermined by the auctioneer and represented in the corresponding bid. Hence, the aim of allocative efficiency is important in terms of fairness, mitigating resale incentives (Ausubel et al., 1998). Allocative efficiency can be at risk due to incentives for unfavorable strategic bidding behavior, asymmetries regarding valuations and information between bidders, e.g. because of different risk attitudes or planning periods, and the participation of multi-project bidders in the auction. Since the actual or expected costs of project developers are (at least partly) private information, it is not possible to assess an auction outcome in real-world applications as allocative efficient. Consequently, note that though allocative efficiency is an ex post criterion, it cannot be proven ex post in real-world applications but only in theory. However, from an auction theoretical perspective auction formats can also be evaluated ex ante with regard to their expected allocative efficiency. That is, a theoretical efficiency investigation serves at least the purpose of identifying which auction format is expected to be suitable for generating allocative efficient outcomes in practice.

Auctioneer's Risks In the decision of conducting an auction for RES-E the auctioneer has to face and balance certain risks such as excessive prices, insufficient competition and unfavorable strategic bidding behavior. The latter refers particularly to strategic supply reduction and implicit collusion. Obviously those three categories of risk, the former two in particular, may interact. For instance, decreasing competition increases prices. However, their triggers are complex and in order to identify their original causes, the analysis benefits from a separate consideration. Although the auctioneer can choose the auction format generating the lowest expected support costs under given market and framework conditions, there exist further reasons beyond the auction format that lead to increasing bid prices, e.g. uncertainties regarding high penalties or a high willingness of bidders to take award risks in non-incentive compatible auctions. Furthermore, potential bidders may distrust an intransparent or too complex auction mechanism. Additional uncertainties which the bidders, such as sunk costs stemming from expenditures for prequalification in unsuccessful bids, may discourage bidders and hence lower the participation in the auction. Strategic supply reduction is a phenomenon that, on the one hand, can occur if at least one bidder is interested in realizing more than one project and consequently submits more than one bid in the same auction. These multi-project bidders consider before as well as during the auction, especially in dynamic auctions, whether it is better for them to bid on all units they are interested in or to withhold some bids in order to generate more profitable support levels for the remaining ones. If a bidder is able to increase his expected rent by waiving additional units, he will reduce his bids accordingly. This behavior is called strategic supply reduction and leads to a reduced competition in favor of higher support levels. On the other hand, the issue of strategic supply reduction is also relevant before the background of repeated auction rounds, since bidders may have incentives to reduce their supply in particular rounds and instead coordinate their total supply over multiple auction rounds. Finally, collusion is an unfavorable strategic bidding behavior that is eventually less tangible and benefits from a transparent bidder structure, meaning that bidders know each other quite well and/or the number of participating bidders is relatively low. Explicit collusion is commonly prohibited by law, but in real-world applications it can be observed that bidders succeed to circumvent the law by implicit collusion. A famous example of implicit collusion is the auction for telecommunication licenses in Germany in 2000, where bidders succeeded to communicate via number combinations in their bids (Klemperer, 2002). Appropriate auction designs, for instance static auctions instead of dynamic auctions or pay-as-bid instead of uniform-price auctions (see Section 2.6), minimize any incentives for bidders to coordinate as well as hinder the realization of implicit collusion strategies.

Bidder's Risks The first obvious difference between the more traditional renewable support schemes, such as feed-in tariffs with guaranteed support levels, and competitive auction mechanisms is the award risk. The necessary condition of sufficient competition for a successful auction implies that some bidders have to go away empty-handed. Consequently, whereas project developers often had a guarantee for support in earlier schemes, they now have to handle the risk of not being awarded in an auction mechanism. How the bidders evaluate/quantify this risk strongly depends on the investments for prequalification, since these costs are sunk and lost in case of not being successful in the auction. The higher the sunk costs, the more are bidders discouraged to bear the award risk and participate in the auction. Furthermore, there are auction mechanisms in which the award price is uncertain at the time of bid submission. That is the case if a bidder's bid has no influence on the corresponding award price in case of winning, which applies for instance in the uniform-price auction (with lowest rejected bid) and the Vickrey auction. The award risk as well as the award price risk increase uncertainties on bidders side and might discourage bidders to participate in the auction at all. Another prevalent phenomenon that may occur under specific assumptions is the risk of the winner's curse. If a bidder suffers from the winner's curse, he realizes after being awarded that his actual costs exceed the award price. This phenomenon applies to situations where the individual actual costs are unknown before the auction and bidders can only estimate them, whereas the support costs are either the same for all bidders or at least are interdependent among all bidders. From a theoretical perspective, a rational bidder will ex ante never suffer from the winner's curse as he anticipates this aspect adequately in his bidding behavior. However, the phenomenon may still occur from an ex post point of view. In general, there are auction mechanisms with higher and lower risks of the ex post winner's curse. For instance, dynamic auctions potentially mitigate this risk as they can facilitate the adequate anticipation of the winner's curse because bidders may obtain valuable information during the auction. This is true if the individual valuation of a particular bidder depends in fact on the signals of the competing bidders, e.g. in case of interdependent valuations, and he can actually observe those during the bidding procedure. A similar but different risk is the risk of underbidding, i.e. the risk that bidders bid below their costs. We distinguish between conscious underbidding for strategic reasons and unconscious underbidding that may occur if bidders had not calculated their costs appropriately. Whereas a rational bidder would never unconsciously underbid, conscious underbidding may occur in real-world applications due to securing long-term market power through crowding out.

Excursus: Irrational Bidding An auction theoretical analysis is always based on the assumption of rational bidders. A rational bidder maximizes his expected profit by submitting an optimal bid according to his available information at the time of bid submission. However, if auctions are implemented in real-world applications the assumption of rationality cannot be taken as a given and irrational bidding behavior may occur (Miller and Plott, 1985; Harrison, 1989; Manelli et al., 2006), i.e. submitting bids that are not expected to be profit maximizing according to the information available. There exist several reasons for irrational bidding in practice. First, the auction format can be misunderstood by the participants and it can be an overly high burden for bidders to develop an optimized bidding strategy (e.g. Uniform-price auctions, see Section 2.6). Besides, bidders may incorporate the available information incompletely and/or incorrectly in their bidding strategies. Finally, the insufficient anticipation of the winner's curse may provide another reason for underbidding in case of an interdependent value approach (see Section 2.5). In general, each auction format involves a different risk of irrational bidding behavior and hence auction formats have to be evaluated separately in that context. However, the auctioneer could reduce the general risks of irrational bidding by providing appropriate information and/or trainings for potential participating bidders, as the experiences of participating bidders regarding the implemented auction format plays a crucial role. That is, if bidders are rather experienced with auctions or particularly the specific auction format, the risks of irrational bidding behavior can be mitigated.

2.5 Theoretical Framework: Independent Private Value Model or Interdependent Value Model

In auction theory, two approaches are distinguished in order to model bidders valuations (costs and revenues, see Subsection 2.3.3) of the good (Krishna, 2009). Both approaches are relevant for the RES-E context depending on the specification of the auctioned good: On the one hand, all bidders can participate with their individually developed projects in the auction and only be awarded with their own project. On the other hand, one or several project(s) can be predetermined and offered up for bidding by the auctioneer, where multiple potential project developers compete for the award of those predetermined project(s). Whereas the so-called independent private value approach lends to model the former case, the interdependent value approach can serve to abstract the latter case. Consequently, we will look at two different value models here in order to distinguish between individually developed projects by bidders and predeveloped projects by government. This will form the basis for understanding the auction formats which are introduced in the next section.

2.5.1 The Independent Private Value Model (IPV)

The independent private value approach (IPV) is often used as a starting point because of its simplifying theoretical properties. This model assumes that each bidder exclusively knows his own costs and only has certain beliefs about the other bidder's costs, where the costs of all bidders are independently drawn from a known distribution. All that is common knowledge to all participants, meaning that all bidders and the auctioneer have the same information.

From a theoretical point of view, there exists a unique symmetric Nash-equilibrium in pure strategies in the IPV model under the assumption of symmetric, risk-neutral, single-project bidders for the following multi-unit auction formats

- Static auctions: pay-as-bid auction, uniform-price auctions and Vickrey auction
- Dynamic auctions: ascending and descending clock auction

Hence, let us have a first look at these auctions under those assumptions. In the corresponding equilibria, all multi-unit auction formats are expected to be allocative efficient as well as revenue equivalent (Engelbrecht-Wiggans, 1988). That is, although bidders submit different bids depending on the auction format, all auctions end with the same expected result (Maskin et al., 1989). In each auction, a bidder chooses the strategy that maximizes his expected rent (profit). The expected rent is computed from all possible rents, which can be achieved by the strategy, weighted by their corresponding possibilities of winning. In all auction formats bidders will submit bids equal to or greater than their costs in order to ensure a positive profit in case of winning. The uniform-price auction with lowest rejected bid, the Vickrey auction, and the descending clock auction are incentive compatible under above mentioned assumptions, which means, that bidders have an incentive to bid their true costs. One reason for that is that bidders cannot influence the award price through their bids in case their bids are awarded and consequently bid exactly their true costs. The pay-as-bid auction and the uniform-price auction with highest accepted bid as well as the ascending clock auction, in contrast, are not incentive compatible, since the bid determines the award price, i.e. the award price is equal to the bid in the pay-as-bid auction and is determined by the bid with positive probability in the uniform-price auction or the ascending clock auction. As a consequence, bidders exaggerate their true costs in order to balance the trade-off between increasing their rent in case of winning (higher bidding) and increasing their winning probability (lower bidding). Nevertheless, the higher bids in the non-incentive compatible auctions are balanced in the corresponding equilibria and all above mentioned auction formats result in the same efficient allocation as well as in the same expected award price (Engelbrecht-Wiggans, 1988). Because of the revenue equivalence, the IPV approach provides an appropriate starting point for further analyses and a profound understanding of the particular auction formats as well as for carving out differences between them.

Note that this result also applies for single-unit auctions, i.e. first-price auction and second-price auction. But whereas the second-price auction is incentive compatible, bidders have the incentive to exaggerate their true costs in the first-price auction (Myerson, 1981).

How the IPV Approach Applies to the RES-E Context We consider the option for RES-E auctions where each bidder participates with one or several individual projects that differ e.g. by their particular locations. Each project developer knows his individual project-related costs but not those of his competitors. The reason is that, on the one hand, individual cost structures per se are usually not public and, on the other hand, bidders often do not know who else participates in the auction. Nevertheless, project developers may have certain estimations about the competition level as well as their competitors costs, e.g. based on earlier experiences in the particular industrial sector or respective market analyses. That is, project developers have only certain beliefs about their competitors costs, but do not know them exactly. Further, the competitive costs are widely irrelevant for their own cost calculation as projects differ significantly, e.g. depending on the location. Another aspect is that project developers often have to face long development periods and thus uncertainties regarding their individual costs estimations may occur as well. That is, potential bidders have not only limited information on their competitors costs but sometimes even with regard to their own costs. However, since they can undertake assessments of their own particular situation as for example quantify the potential of wind or solar power for their individual project and know their planned power rating and construction type, bidders can estimate their individual costs quite well (Bofinger, 2013). Assuming the bidders know their individual costs exactly, uncertainties regarding the competitor's costs are mathematically modeled by random variables. In these models, the spread of the expected cost outcomes decreases as information about the competitors costs structures improves, i.e. the more precise the approximations of their competitors costs structures become. Note, for example, that bidders in technology-specific auctions may have quite similar costs structures, whereas in technology-neutral auctions costs can vary significantly between bidders. In case there are also uncertainties regarding the individual costs of a bidder, the IPV approach has to be extended correspondingly. Therefore, the individual costs can also be modeled by random variables that represent the expected individual costs including all relevant uncertainties. However, the success of an adequate mapping from real costs (competitive and/or individual) into a theoretical distribution is limited. Nevertheless, the abstraction of the real situation for RES-E described above into the IPV model involves only very small natural trade-offs and hence serves as a suitable theoretical approach.

2.5.2 The Interdependent Value Model (IV)

The interdependent value approach (IV) includes private value components as well as common value components. That means that the individual valuation of a bidder depends not only on his own signal but also on other (unknown) signals as for example those of his competitors or even further external signals. A pure common value approach, as an extreme case of the interdependent value approach, acts on the assumption that all bidders have the same valuation for the good. This applies if the individual valuations of all bidders are affected equally by the same signals, e.g. if the actual valuation of the good is represented by the sum or average of all signals. In contrast, the individual valuation of the good may also be primarily influenced by the bidder's individual signal, for example, which leads to different actual valuations among bidders. However, in all cases the exact valuation of the good is uncertain for all participants at the time of the auction. That is, although bidders have a private signal regarding the value of the good, they can only estimate the exact value based on their individual signal plus common information such as the distribution functions of the other relevant signals or the scope of the value distribution of the good. In general, the value estimation would be facilitated if bidders also received the other relevant signals, e.g. those of their competitors. That is, the more signals a bidder would receive the more accurate becomes his estimation about the value of the good. At this point, the question may arise why it is actually important for the bidder to make his valuation as accurate as possible at the time of the auction. The reason is that bidding without knowing one's actual valuation carries a general risk of under- and overbidding based on erroneous valuations. Especially underbidding may represent a serious risk for bidders in procurement auctions, since a non-cost award price may be the consequence. In auction theory, we refer to this phenomenon as the winner's curse. We suppose that the bidder submitting the lowest bid wins, who is in the extreme case of a common value model probably exactly the bidder who unfortunately underestimated the costs of the good the most. Hence, it is apparent that in an interdependent value model, bidders benefit from learning about other bidders signals, e.g. in dynamic auctions, in order to reduce their risk to suffer from winner's curse. In general, the higher the common value component in an interdependent value model, the higher is the risk of the winner's curse (Krishna, 2009).

How the IV Approach Applies to the RES-E Context? If one (or several) particular project(s) is (are) offered up for bidding to several potential project developers, there exist common value aspects, e.g. represented by the potential of wind or solar power in the region of the corresponding project(s). Before the auction, bidders may have different estimations about this potential and only in case of being awarded they will learn the actual potential of the project. Particularly, all bidders will realize the same potential over time if they have been awarded. Consequently, this is a common value dimension. In addition, there remain bidder specific private value aspects as for example operating and investment costs. Hence, if bidders compete for identical projects the, IV approach is suited as a theoretical model. The more project features such as power rating, equipment manufacturers and others are predetermined by the auctioneer, the higher the common value component.

2.6 Auction Formats Suitable for RES-E

As auction mechanisms are not a panacea, there are several requirements to fulfill in order to ensure the suitability in general and for RES-E in particular. First and foremost, a necessary condition is sufficient competition, i.e. supply must exceed demand in procurement auctions, in order to avoid excessive prices. Hence, the auctioneer needs to determine the auction volume (supply) in an appropriate manner, e.g. ensure excess of supply based on recent market analyses. A suitable auction design reflects adequately the predetermined policy goals as well as the bidder's calculus (Kopp et al., 2013). First, that means that each specific design element is implemented in the auction so as to trigger a specific behavior or situation that can be directly linked to the policy goal it was aimed at. The adequate reflection of bidders calculus by a corresponding bidding structure can for example be implemented with quantity price-bids, since for a bidder's calculation the power rating of the project [MW] and the related support level [per MWh] is decisive. Further, a suitable auction mechanism should minimize bidders risks as well as specific risks of the auctioneer. Note that these risks are likely to occur particularly under certain market and framework conditions (see Section 2.7). For multi-unit procurement auctions a broad variety of auction formats exists. For those, we distinguish between static and dynamic auctions as well as hybrid auction formats. Our analysis here will be limited to auctions in which the following three basic principles are met:

- Bids are binding
- The best bids (according to a pre-specified evaluation rule considering all relevant criteria) will win
- The winning bidders will at least receive their bid price

These principles are motivated by the aim of a transparent and fair auction mechanism that induces high acceptance among project developers and hence a high level of participation, especially against the background of repeated auctions. First, the option to crowd out other projects within the auction, e.g. the submission of relatively low bids that are withdrawn in case of award, should be avoided by binding bids and awards that are combined with withdrawal penalties. Second, an allocation which is subsequently considered fair should award the best bids according to relevant criteria, with the criteria having been revealed before the auction to the participating bidders. Finally, bidders have to face award price risks in some auction formats, i.e. they do not know their future award price as they have no influence on their price in case of winning. Hence, a bidder friendly auction should at least guarantee a minimum award price for each bidder based on his corresponding bid. Namely, in light of bidders already having to cope with award volume risk, it might lead to excessively high risk for investors if they also should face award price risk in an auction design that does not guarantee them at least receiving their bid level when being awarded.

Another reason for the third principle is, that auctions in which bidders may receive less than their bid set strong incentives for unfavorable bidding behavior. Although these basic principles seem very intuitive, there exist auction formats, not only in theory but also in practice, which do not meet all of them. For instance, the median price auction, which was implemented to auction durable medical equipment in the U.S.in 2009 and failed in many respects, does not meet the third criterion, as the following example illustrates (Cramton et al., 2015).

Example: Unfavorable Characteristic of the Median-price Auction We assume, that $K = 3$ goods are auctioned and $i = 1, , 5$ potential suppliers, where each supplier can only deliver one good, submit the following bids in monetary units: $b_1 = 10$; $b_2 = 12$; $b_3 = 13$; $b_4 = 15$; $b_5 = 16$. Then the auction allocates the 3 goods to Bidder 1, 2 and 3. The award price p is the median of the winning bids, i.e. $p = b_2 = 12$. Consequently, Bidder 3 gets less than his bid, $p = 12 < 13 = b_3$. This characteristic sets strong incentives for unfavorable bidding behavior as strategically high bids, for example, and hence should be avoided.

In the following we will focus on suitable auction mechanisms for RES-E that fulfill those three basic principles. If not mentioned separately, we will as a starting point base our analysis on the following simplifying assumptions: We investigate relevant auction formats under the standard assumptions of an independent private value (IPV) model with symmetric, risk-neutral single-project bidders. Further, we start by assuming that there are no prequalification or penalty measures. Hence, for now we limit our investigation to these basic assumptions without further restrictions in order to understand and emphasize essential characteristics of the relevant auction formats for RES-E as well as identify fundamental differences between them. Furthermore, we will discuss suitable auction systems under specific market conditions deviating from these basic assumptions in Section 2.7.

Finally, in the following relevant auction formats are analyzed and evaluated regarding their suitability for RES-E. Based on our simplifying assumptions, Table 2.1 divides the relevant auction formats in single- and multi-unit auctions. To avoid redundancy, the subsequent assessment in Subsection 2.6.1 covers single-unit auctions as a special case of multi-unit auctions for homogeneous goods with only one unit, where bidders participate with their individual projects. Furthermore, multi-unit auctions for heterogeneous goods are analyzed separately in Subsection 2.6.3. Note that single-unit auctions in which the auctioned project is predetermined by the auctioneer have to be analyzed under common value assumptions and are hence considered in Subsection 2.7.3 rather than in this section.

2.6.1 Multi-unit Auctions for Homogeneous Goods

Static auction formats

The most common static auction formats of multi-unit auctions for homogeneous goods are the pay-as-bid auction, both variants of the uniform-price auction and the Vickrey auction.

Pay-as-bid auction First note that the pay-as-bid auction corresponds to the first-price auction if only one good is auctioned. In a pay-as-bid auction, bidders determine their winning probability as well as their award price through their submitted bid. That is, they have an incentive to exaggerate their costs in order to benefit from a higher rent in case of winning, however, at the expense of a lower winning probability (Krishna, 2009). Note that a bidder realizes only a positive profit in case of winning, if his bid exceeds his costs. Hence in other words, the higher the bid the higher the profit in case of winning, but also the lower the probability to be successful at all. In balancing this trade-off a bidders risk attitude plays a decisive role, because the higher the risk aversion of a bidder, the smaller the exaggeration of his costs (Myerson, 1981). In laboratory experiments it is often observed that human beings rather behave in a risk-averse manner (Harrison, 1989). The main advantage of the pay-as-bid auction is that bidders have no uncertainties about their award price in case of winning, since they receive exactly their bid. Further, the pay-as-bid auction is relatively stable against unfavourable bidding behaviour even under specific market conditions as we will see in Section 2.7. However, the main disadvantage of the pay-as-bid auction is the risk of generating very different award prices among bidders as the following example illustrates.

Example: Different Award Prices in the Pay-as-bid Auction We assume that three homogeneous goods are offered up for bidding and four potential suppliers with single-unit supply submit the following bids: $b_1 = 7MU$, $b_2 = 9MU$, $b_3 = 14MU$, $b_4 = 15MU$. Consequently, the bids of Bidder 1, 2 and 3 are awarded and the highest awarded bid ($b_3 = 14$) is two times higher than the lowest awarded one ($b_1 = 7$).

Uniform-price Auctions The two variants of the uniform-price auction differ in regard to the pricing rules, which induce different incentives for bidders and hence affect the bidders individual bidding behavior in different ways. The uniform-price auction with lowest rejected bid (LRB) is incentive compatible (at least for single-project bidders as assumed here). In contrast, the bidders have incentives to exaggerate their true costs by bidding in the uniform-price auction with highest accepted bid (HAB) (Krishna, 2009). One reason (i.e. necessary condition) for the incentive compatibility in the former case is that bidders who only submit one bid never determine their award price in case of winning, whereas in the second variant a positive probability exists to determine the award price through the submitted bid. An obvious disadvantage of the uniform-price auction, especially in contrast to the pay-as-bid auction, is that bidders have to face uncertainties at the time of bid submission regarding their award price in case of winning, see example.

Example: Award Price Risk in the Uniform-price Auction We assume that three homogeneous goods are offered up for bidding and four potential suppliers with single-unit supply submit the following bids: $b_1 = 6MU$, $b_2 = 9MU$, $b_3 = 10MU$, $b_4 = 15MU$. Hence, the bids of Bidder 1, 2 and 3 are awarded at a price of $15MU$ if the uniform-price variant of the lowest rejected bid applies. If Bidder 4 submitted a bid of $b_4 = 11MU$, the award price of bidder 1, 2 and 3 would have been $11MU$.

Consequently, the awarded bidders have no influence on their price at all in case the award price solely depends on the lowest rejected bid. However, bidders know beforehand that the award price is at least equal to their bid or even higher. Based on this fact, another disadvantage of the uniform-price auction is the increased risk of irrational underbidding. This is obviously caused by mistaking the auction form by inexperienced bidders (Miller and Plott, 1985). Namely, in case of underbidding, bidders basically follow the idea of increasing their winning probability by an excessively low bid. At the same time they seem not to recognize that they only increase their winning probability compared to a cost-covering bid by the cases of being awarded with a not cost-covering support level. That is, they do not take into account that a bid below their (expected) costs might lead to a not cost-covering award price in case of winning. Finally, the main advantage of the uniform-price auction, in both variants, is the common award price, which from a political perspective may be favored in contrast to different award prices in an auction due to a clear and common price signal. The vulnerability of unfavorable strategic behavior strongly depends on further market conditions (see Section 2.7).

Note that if only one good is auctioned, the uniform-price auction with lowest rejected bid corresponds to the second-price auction and the uniform-price auction with highest accepted bid turns into a first-price auction.

Vickrey Auction The Vickrey auction for homogeneous goods exactly corresponds to the uniform-price auction with lowest rejected bid if all participating bidders are only interested in one unit and consequently submit only one single bid.

Excursus: Submitting Multiple Bids in Static Multi-unit Auctions If bidders are interested not only in one unit but in multiple ones, they will consequently submit multiple bids in the auction. This is a general option to be considered in the context of auction mechanisms for RES-E, since a project developer may plan several projects at the same time and hence also participate with multiple projects in an auction round.

We assume that four homogeneous goods are offered up for bidding and three potential suppliers participate in the auction, which is either conducted as a pay-as-bid, uniform-price or Vickrey auction. One supplier is interested in two units, we will refer to him as Bidder 1, and the two others, Bidder 2 and 3, are each interested in three units. They submit the following bids: Bidder 1 bids for the first unit $b_1^1 = 6MU$ and for the second unit $b_1^2 = 8MU$, Bidder 2 bids $b_2^1 = 12MU$, $b_2^2 = 12MU$ and $b_2^3 = 14MU$, Bidder 3 submits $b_3^1 = 7MU$, $b_3^2 = 9MU$ and $b_3^3 = 10MU$. Since the lowest bids are awarded in the pay-as-bid, uniform-price and Vickrey auction, both bids of Bidder 1 and the two lowest bids of Bidder 3 are awarded in every auction. Bidder 2 is not successful with any of his bids. Pay-as-bid auction: Each successful bid determines the corresponding award price, hence Bidder 1 is awarded two units at a price of $6 + 8 = 14MU$ and Bidder 3 receives two units at a price of

$7+9=16MU$. Uniform-price auction (highest accepted bid): If the highest accepted bid, here $b_3^2 = 9MU$, is price-determining, Bidder 1 and 3 receive each two units at a price of $2*9 = 18MU$. Uniform-price auction (lowest rejected bid): If the lowest rejected bid, here $b_3^3 = 10MU$, is price-determining, Bidder 1 and 3 receive each two units at a price of $2*10 = 20MU$. Vickrey auction: If Bidder 1 had not participated in the auction, all bids of Bidder 3 and the lowest bid of Bidder 2 would have been awarded. That is, instead Bidder 1 with his two bids, Bidder 3 would have been awarded with $b_3^3 = 10MU$ and bidder 2 with $b_2^1 = 12MU$. Consequently, the award price of Bidder 1s two units is $10 + 12 = 22MU$. If Bidder 3 had not participated in the auction, all bids of Bidder 1 and the two lowest bids of Bidder 2 would have been awarded. That is, instead Bidder 3 with his two lowest bids, Bidder 2 would have been awarded with $b_2^1 = 12MU$ and $b_2^2 = 12MU$. Consequently, the award price of Bidder 3s two units is $12 + 12 = 24MU$.

Please note that the different auction formats induce different incentives and, thus, the submitted bids will differ between auction formats. Hence, the examples above serve solely for illustration. Conclusions regarding a comparison of auction revenues or efficiency are not representative. Since under different auction formats different incentives regarding the bidding behavior occur and consequently the existence of multi-project bidders has to be considered carefully in auction format specific analyses, which will be done adequately in Subsection 2.7.2.

2.6.2 Dynamic Auction Formats

In contrast to the sealed-bid one-shot situation in static auction formats, in dynamic auctions bidders have the chance to observe the development of the auction price and other bidders bids and to adapt their bidding strategies during the auction process. Thus, dynamic auctions reveal more information than static ones, but are also more complex to implement as well as more vulnerable to implicit collusion (Cramton, 1998). However, since bidders can observe their competitor's bidding behavior and adapt their strategies accordingly, dynamic auctions reduce the risk of winner's curse in case of common value situations (McMillan, 1994).

Ascending Clock Auctions Clock auctions are quite established because of their fast realization. For instance, in the Netherlands, flowers are sold via clock auctions within seconds (Van Heck and Ribbers, 1997). In case of multi-unit procurement auctions the procedure is as follows: The clock starts with a support level that is low enough that no participant is willing to accept. Then the price is increased continuously within predefined fractions of time and bidders signalize successively their acceptance of the recent price. That is, bidders are awarded one after another by dropping out of the auction until the demanded amount of RES-E is reached. The award price will be determined by the last awarded bidder. Hence, this auction format is equivalent to the uniform-price auction with highest awarded bid. If only a single unit is auctioned the auction corresponds to the dynamic counterpart of the first-price auction, the Dutch auction.

Descending Clock Auctions The descending clock auction is incentive compatible for single-project bidders. Furthermore, from a theoretical perspective, the descending clock auction then corresponds to the static uniform-price auction with lowest rejected bid under simplifying basic assumptions. However, in the dynamic descending clock auction the participating bidders can observe exactly their competitors dropping out at the corresponding award prices, if this information is revealed in the auction. Consequently, even though the descending clock auction is strategically equivalent to the uniform-price auction with lowest rejected bid, the dynamic auction generates weigh more information during the auction procedure than its static counterpart. Note, that the descending clock auction can also be implemented with the highest accepted bid (last auction price) variant. Nevertheless, the auctioneer has to deliberate carefully on the implementation of descending clock auctions under certain market and framework conditions, see Section 2.7.

2.6.3 Multi-unit Auctions for Heterogeneous Goods

For the purpose of a comprehensive analysis of multi-unit auctions with heterogeneous goods we extend the aforementioned simplifying assumptions insofar as bidders can also be interested in multiple goods. The essential difference of heterogeneous goods, in contrast to homogeneous goods, is that they differ from each other. In case of single-project bidders these differences between heterogeneous goods are just disregarded in bidders valuations as they are only interested in one of the goods anyway. Hence a separate analysis for single-unit bidders is not necessary. Finally, in case of multi-project bidders for heterogeneous goods not only the number of units awarded might be relevant for bidders but also which unit or combination of units they will be awarded with. For example, a bidder who participates with two projects in the auction may be only interested in realizing both projects simultaneously due to economies of scale. Consequently, he focuses on the award of both projects at a certain price. Otherwise, he would not realize any of his projects or at least only at a significantly higher price. With the objective of an efficient auction outcome, the bidder should have the option to reflect his (complementary) valuations regarding the realization of his projects adequately in his bids. That is, in a well-designed auction, he should be allowed to submit a combinatorial bid for the realization of both projects as well as two exclusive bids for the separate realization of each project. In case of substitutive valuations (costs) the combinatorial bid is lower than the sum of the exclusive bids. In addition, substitutive valuations (costs) exist if the combinatorial bid is higher than the sum of the exclusive bids. This is the case, if a bidder favors a separate realization of his multiple projects over the simultaneous one, for example due to financial or capacity constraints. If the combinatorial bid equals the sum of exclusive bids, we refer to this as additive valuations. To integrate complementary, substitutive and additive valuations (costs) adequately in the auction mechanism specific auction formats are considered in the following. This includes the static generalized Vickrey auction and the dynamic simultaneous multi-round descending auction. In both auction formats bidders have the option to submit combinatorial as well as non-combinatorial bids according to their individual valuation.

Static Auction Formats

Generalized Vickrey Auction The generalized Vickrey auction is an extension of the Vickrey auction to heterogeneous goods. Here, bidders are allowed to submit exclusive bids for single units as well as bids for any combination of units. Finally, those bids are awarded that minimize the total award costs (RES-E support costs) of the auctioneer under the conditions that all units are allocated, each unit is only allocated to one bidder and each bidder is only successful with one of his bids. We refer to this allocation as the optimal allocation. The award price of a bidder is the difference of virtual award costs in case the particular bidder had not participated in the auction and the award costs of all other bidders in the optimal allocation. Or in other words, a successful bidder receives the opportunity costs of society of his participation in the auction. As a consequence, award prices may differ among winning bidders.

From a theoretical perspective, the main advantage of the generalized Vickrey auction is its incentive compatibility. This should especially be emphasized in the context of heterogeneous goods, because most appropriate combinatorial auction formats generate complex incentives for bidders and are not incentive compatible at all (Ausubel et al., 2006). As a consequence, the generalized Vickrey auction possesses the advantageous characteristic of generating allocative efficient outcomes. Nevertheless, although the generalized Vickrey auction has favourable theoretical properties such as incentive compatibility and allocative efficiency, it is rarely found in real-world applications (Ausubel et al., 2006). One potential reason is that the procedure is very elaborate from a bidder's perspective regarding the possible number of up to $2^K - 1$ bids, if K units are auctioned. Further, the determination of the optimal allocation is a NP-complete problem. Besides the argument of being too complex especially for unexperienced bidders, the auction format is very vulnerable to collusion and to multiple bidding identities by a single bidder. Furthermore, a risk of very high award prices arises, which is often mentioned as show stopper (Ausubel et al., 2006).

	Good $\{A\}$	Good $\{B\}$	Goods $\{A, B\}$
Bidder 1	10	10	15
Bidder 2	5	10	15
Bidder 3	10	5	15

Table 2.2: Exemplary bids in the generalized Vickrey auction.

Example: High Award Prices in the Generalized Vickrey Auction The above mentioned example illustrates the disadvantage of high award prices in the generalized Vickrey auction in the specified situation of two bidders with additive costs and another with complementary costs. In the following we compare the exemplary results, i.e. the total award costs of $20MU$ and the allocative efficiency in the generalized Vickrey auction, with potential results of a pure combinatorial option in the same situation. For reasons of simplicity, we assume that bidders also submit the same incentive compatible bids. In an auction mechanism, where solely combinatorial bids for {A, B} are allowed, the total award costs would be $15MU$. However, the allocation would not be efficient. That is, with this option lower support costs could have been generated, however, at the expense of an inefficient allocation. Consequently, the advantageous characteristic of allowing both combinatorial and exclusive bids in a generalized Vickrey auction may generate an allocative efficient outcome due to incentive compatibility, but may at the same time lead to high award prices. To conclude, the generalized Vickrey auction serves rather as a theoretical benchmark for multi-unit auctions for heterogeneous goods because of its advantageous theoretical properties than as a promising option for real-world applications, e.g. in the context of RES-E.

Dynamic Auction Formats

Simultaneous Multi-round Descending Auctions The simultaneous multi-round descending auction, which is considered relevant for the RES-E context in case of auctioning heterogeneous goods, is often called the multi-unit analogue to the well-known English auction. However, the strategic incentives for bidders generated by the simultaneous multi-round descending auction are much more complex than those in the English auction for a single good. Often, it is even not possible to make statements regarding an optimal bidding strategy since e.g. multiple bidding equilibria may exist. A simultaneous multi-round descending auction consists of multiple bidding rounds. In each bidding round, bidders can simultaneously submit bids for a number of auctioned units according to the activity rules. At the end of each bidding round, the standing best bids per unit are announced and bidders have the chance to underbid in the subsequent round. The particular auction for a unit ends if no more bids are submitted for this unit in the recent bidding round. Then the bidder who submitted the last best standing bid for this unit is awarded at the price of his bid. Since the simultaneous multi-round descending auction represents a dynamic mechanism it is in particular suitable if bidders have interdependent valuations for the heterogeneous goods. This is motivated by the fact that bidders with interdependent valuations may benefit from learning about their competitors costs signals during a dynamic auction process since this may reduce the risk of the winner's curse (see Section 2.5). However, even in the case of private valuations bidders may have incentives not to reveal their true costs in the auction but drop out already at higher prices which increases the award costs of the auctioneer. If bidders have complementary valuations for the goods, another disadvantage may occur. Because complementary valuations cannot be reflected adequately in the bidding in a simultaneous multi-round descending auction, bidders with complementary valuations often suffer from the so-called regret or exposure problem (Cramton, 2004; Goeree et al., 2006). Furthermore, the procedure of the simultaneous multi-round descending auction may lead to very long delays. Based on that, this auction format can be hardly suitable for RES-E, where continuous support and expansion represent essential goals. Another unfavorable practice in simultaneous multi-round descending auctions is strategic supply reduction, which leads to lower competition and hence should be avoided by the auctioneer (Cramton, 2004). Thereby, the German auction of telecommunication licenses in 1999 often serves as a famous example of strategic supply reduction in practice (Klemperer, 2002; Grimm et al., 2003). In the following example the basic principle of strategic supply reduction is illustrated. Assume that the support of two projects is auctioned and two Bidders 1 and 2 participate, where both can either realize one project or two projects. The example emphasizes the risk of strategic supply reduction in simultaneous multi-round descending auctions.

Example: Strategic supply reduction in simultaneous multi-round descending auctions

	Assumptions: The cost-covering support level of Bidder A is $10MU$ per project and that of Bidder B is $12MU$ per project. Both bidders are interested in realizing both projects. The starting price (reservation price) is $15MU$ per project.
Case I: No coordination / no strategic supply reduction	A and B both bid straightforward for both projects until their individual minimum support level is reached. That is, B bids $12MU$ for each of the both units and drops out afterwards. A would stay further in the auction since he would bid $10MU$ for each of the two units. Then both bids of bidder A are awarded and A receives a support of $12MU$ per project. The rent of A is $2 \cdot (12 - 10)MU = 4MU$. The rent of B is zero. The total award costs of the auctioneer are $2 \cdot 12MU = 24MU$. The auction outcome is allocative efficient.
Case II: Coordination / strategic supply reduction	A and B both bid straightforward for one project each until their individual minimum support level is reached. That is, B bids $12MU$ for one project and A bids $10MU$ for the other. Then one bid of each bidder, A and B, is awarded and both receive the starting price of $15MU$ per project. The rent of A is $5MU$ and the rent of B is $3MU$. The total award costs of the auctioneer are $2 \cdot 15MU = 30MU$. The auction outcome is not allocative efficient.

Conclusion	Both bidders increase their rent with strategic supply reduction to the disadvantage of the auctioneer, who suffers from higher award costs. Further, in case of strategic supply reduction, allocative inefficiency occurs.

The risk of strategic supply reduction can be reduced by an ambitious reservation price. For example, if the starting price (reservation price) was $13MU$, Bidder 1 would not have increased his rent by strategic supply reduction and hence not use this option. However, although an ambitious reservation price may reduce the risk of strategic supply reduction, it is an additional design element needed to maintain the success of the auction in the exemplary case. In addition, the determination of an appropriate reservation price is another challenge: A low reservation price may reduce the number of bidders and hence involves the risk of insufficient competition, whereas a high reservation price still sets incentives for strategic supply reduction. The risk of strategic reduction of competition or implicit collusion is aggravated by the situation of repeated auctions and a relatively low number of bidders or bidders who know each other very well (see Subsection 2.7.5). Hence, the suitability of simultaneous descending multi-round auctions for RES has to be treated with caution and based on an in-depth analysis of the corresponding national or international market.

2.6.4 Hybrid Auction Formats

Hybrid auctions consist of a combination of different auction mechanisms. Prevalently, static and dynamic auction formats are combined in a multi-stage auction process. For instance, in the first stage bidders participate in a dynamic auction and the winning bidders qualify for the second stage, i.e. the award stage, which is conducted as a static auction. The idea behind is to concentrate competition in the final phase via suspending weaker bidders already in an earlier stage. If there are high discrepancies among bidders strengths and uncertainties regarding the level of competition, a hybrid mechanism may increase transparency by structuring the allocation process in multiple stages. On the one hand, bidders in an advanced stage know that they belong to the stronger participants but also that strengths have increased among their competitors. The latter may lead to a more aggressive bidding behavior, i.e. decreased bids. However, note that a rational bidder takes the existence of multiple bidding stages already into account when bidding in an earlier stage, e.g. for example by relatively higher bids in the beginning. Consequently, a general conclusion regarding the expected support costs in a hybrid auction compared to a non-hybrid one cannot be drawn. On the other hand, implementing a dynamic auction, where bidders can observe their competitors bids, may reveal valuable information about competition. This information can especially be helpful for the bidding behavior in subsequent stages. This is why the conduction of a dynamic auction is particularly reasonable in earlier stages. In Brazil, a two-stage hybrid auction mechanism was implemented, in which a descending-clock auction was conducted in the first stage and a pay-as-bid auction in the second stage. Furthermore, hybrid formats are also planned or already implemented in further countries as the UK, Mexico or Morocco.

2.6.5 Summary: Evaluation of Suitable Auction Formats for RES-E and Conclusion

The first analysis based on simplifying assumptions presented in the beginning of Section 2.6 enables us to draw a first summary for auction formats suitable for RES-E. The following table provides a first assessment of relevant auction formats for RES-E according to the general auction theoretical criteria introduced and discussed in detail in Section 2.4. Tables 2.3 and 2.4 compare the auction formats individually discussed above for multi-unit auctions for homogeneous and heterogeneous goods with regard to those criteria. Thereby, we distinguish for the price determination whether a common award price for all successful bidders per auction is generated, which we evaluate as advantageous (+) or several individual award prices are determined, which is consequently evaluated as rather disadvantageous (-) the argumentation behind that can be found in Section 2.4. Regarding the signal generation, auction formats in which participating bidders may learn during the auction procedure about their competitors valuations are considered positive (+). However, please note here, that learning about competitive signals is only relevant in case of interdependent valuations. Further, the signal generation of an auction, especially not only for participating but also potential bidders and the public, strongly depends on what information the auctioneer reveals afterwards. This aspect we denote by (). As we stated in 2.5, all auction formats mentioned in Table 2.3 generate the same expected auction revenue (=) under our simplifying assumptions. Further, we evaluate in Table 2.3 and 2.4 if the listed auction formats are incentive compatible (+) or not (-) and if they end in an allocative efficient outcome (+) or not (-) from a theoretical perspective. Further, if there may exist specific risks for the auctioneer as well as for bidders we mention those explicitly. Since auctions are a competitive mechanism, the award risk for bidders is inevitable and consequently not mentioned here. In practice, the risk of irrational bidding may occur, which can have negative impacts on the auction outcome (see Section 2.4). If incentives for irrational bidding behavior are high, we mark this with (-). If they are rather low, we mark this with (+).

For a comparative conclusion of the auction formats for homogeneous goods, the criteria of expected auction revenue, allocative efficiency and auctioneer's risks can be neglected since all auction formats perform equally in this regard. According to Table 4 the dynamic ascending and descending clock auctions are slightly advantageous over their static counterparts, the uniform-price auctions (HAB and LRB), due to a stronger signal generation during the auction. However, as already mentioned, this is only relevant in case of interdependent valuations. Further, dynamic auctions are in their practical implementation usually more complex and expensive than static

	price determination (common)	signal generation	expected auction revenue	incentive compatibility	allocatice efficiency	auctioneer's risks	bidder's risks	risk for irrational bidding
Pay-as-bid auction	−	()	=	−	+	none	none	+
Uniform-price (HAB) auction	+	()	=	−	+	none	award price risk	−
Uniform-price (LRB) auction	+	()	=	+	+	none	award price risk	−
Vickrey auction	−	()	=	+	+	none	award price risk	−
Descending clock auction	+	+,()	=	+	+	none	award price risk	+

Table 2.3: Comparison of multi-unit auctions for homogeneous goods under simplifying assumptions.

ones. The pay-as-bid auction outperforms both variants of the uniform-price auction in terms of no award price risk and lower risk of irrational bidding behavior. However, the pay-as bid auction generates a different award price for each successful bidder, whereas the uniform-price auction defines a common one for all successful bidders. Consequently, under simplifying assumptions, a ranking of the three options for a practical implementation depends on the individual weighting of the above discussed aspects by the auctioneer. We will learn in the following Section 2.7 that under RES-E specific market and framework conditions, such ranking is subject to further ambiguity. Therefore, we will briefly discuss the clock auctions as the dynamic parts of the multi-unit auctions for homogeneous goods under specific market conditions in more detail below.

For the heterogeneous goods, we analyzed the generalized Vickrey auction as a static format and the simultaneous multi-round auction as a dynamic format. The latter format slightly outperforms the former in terms of signal generation in case of

	price determination (common)	signal generation	expected auction revenue	incentive compatibility	allocative efficiency	auctioneer's risks	bidder's risks	risk for irrational bidding
Generalized Vickrey auction	–	()	benchmark case	+	+	complexity, high prices, collusion	award price risk	–
Simultaneous multi-round auction	–	+,()	no statements	–	+	strategic supply reduction, long delays	award price risk	–

Table 2.4: Comparison of multi-unit auctions for heterogeneous goods.

interdependent valuations among bidders. Admittedly, both auctions generate different award prices for bidders in an auction round. Statements regarding the expected auction formats are not possible since there exists no unique equilibrium for bidding in the simultaneous multi-round auction. Due to the incentive compatibility the expected auction outcome of the generalized Vickrey auction is often used as benchmark case. However, the main disadvantage of both auction formats is that they involve high risks for the auctioneer, which are presented in detail in Subsection 2.7.4. This is why the practical implementation is very sensitive to given market conditions and requires besides a profound understanding of the market almost individually perfect conditions, which is usually not the case in reality. The hybrid auction formats in the combinations as described above represent a specific class of auction formats that can be split up in their individual combined parts, i.e. auction formats, for which the corresponding evaluation above applies as well. However, the specific characteristic of a hybrid mechanism to concentrate competition in the final phase via suspending weaker bidders in earlier stages may play a crucial role in some situations. Consequently, it may be worthwhile to keep hybrid formats in mind even though they are more complex and time-consuming to implement in real world applications.

2.6.6 Applicability to RES-E Support Instruments

Any auction format has to be embedded in a RES support scheme, which can make use of different instruments such as tariffs or premiums. Hence, in the following paragraphs potential interactions between chosen auction formats and support instruments will be discussed with regard to general impacts on strategic incentives for project developers in an auction, expected auction outcomes and the resulting achievement of policy goals. For that purpose, we distinguish for the subsequent analysis between support instruments with external dependence, i.e. support levels are partially derived from other market prices, e.g. spot market prices and support instruments without external dependence (Menanteau et al., 2003; Couture and Gagnon, 2010; Klein et al., 2008). RES-E projects are characterized by a high share of fixed costs for project development and implementation and usually have relatively low variable costs. This characteristic requires relatively high upfront investments of project developers and consequently induces the need to recover investment costs by an adequate remuneration over the project lifetime. However, the electricity rates on the electricity market are neither cost-covering for RES-E yet nor stable as electricity markets feature a high price volatility. Consequently, support instruments have been implemented by the government in the past to balance price differences to provide long-term financial security to project developers in order to increase the expansion of renewable energies.

Whereas support schemes solely based on instruments without external dependence (such as tariffs) are often criticized in terms of lacking competitive incentives, they represent high investment security for project developers thanks to the predictability of future cash flows that they provide (Mitchell et al., 2006; Couture and Gagnon, 2010). The predefined support levels are oriented at the specific generation costs and differ e.g. according to technologies or locations. As a consequence, they further attract especially smaller and rather risk-averse bidders and hence may increase expansion (Mitchell et al., 2006; Couture and Gagnon, 2010). For example, feed-in-tariffs (FITs) without external dependence were successfully implemented with regard to an increased deployment in Germany (Butler and Neuhoff, 2008). However, predetermined support levels in FITs may lead to an uncontrolled and inefficient expansion of RES-E technologies in a non-competitive context and hence in particular lead to excessive support costs (Butler and Neuhoff, 2008). If instruments without external dependence are combined with auctions, bidders demand their optimal cost-covering support level individually by bidding in the auction. Thereby, a rational bidder bases his optimal bid on the expected total costs and energy generation over project lifetime, as well as on his beliefs about competition. That is, electricity market specific conditions can be disregarded by bidding, which may facilitate the bid calculation for less experienced project developers. Furthermore, the allocation via auctions is expected to be allocative efficient from a theoretical point of view under simplifying assumptions. However, the suitability of combining instruments without external dependence and auctions with regard to policy goals is ambiguous. On the one hand, an individually demanded market-independent instrument ensures to cover individual investment costs and consequently may be advantageous for high participation and/or realization rates. On the other hand, incentives for bidders based on other relevant markets, as the spot market for example, are only limited. Although they will face competition in terms of outbidding their competitors, their bidding strategies can be developed completely isolated from external markets as the electricity market. This fact may hinder a smooth integration of RES-E into the electricity market which is planned by many policy makers for the long term. With instruments without external dependence, project developers may not have the chance to learn about electricity market specific fluctuations and how to develop an adequate strategy according to the market.

An instrument with external dependence (such as premiums) in which project developers receive support on top of the electricity market price, in contrast, already postulates the anticipation of electricity market specific uncertainties. Because the premium will only partly cover the individual costs, project developers are incentivized, for instance, to generate RES-E in time of high demand (Couture and Gagnon, 2010; Klein et al., 2008). However, instruments with external dependence increase several risks for bidders (Mitchell et al., 2006; Klein et al., 2008) and hence perform worse than those without external dependence in terms of providing investment security for project developers, which may lead to lower participation (Couture and Gagnon, 2010). Thus, if bidders in an auction submit bids for their individual cost-covering premium over project lifetime, they bear the risk of non-cost-covering total support levels in case of underestimating future revenues at the electricity market. These uncertainties regarding the total support level can be theoretically abstracted by common value aspects (see Section 2.5) since the uncertainties of future electricity prices apply to all project developers equally. This fact may affect the bidding behavior in the way that bidders (with interdependent valuations) may suffer from the risk of winner's curse due to non-sufficient anticipation of the particular situation (see Subsection 2.7.3). Since, as a consequence, awarded bidders may not finalize their projects due to not-cost covering support levels, the political expansion target may be at risk. However, bidders would learn to anticipate future market developments and related uncertainties adequately in their bids in order to exist in a competitive market over the long term. This would finally facilitate to integrate large shares of RES-E in the electricity market (Klein et al., 2008).

2.7 Chances and Risks of the Identified Auction Types in the Context of Specific Market Conditions

The suitability of the auction format depends on various framework and market conditions such as level of competition, participation of multi-project bidders, uncertainty of bidders regarding project costs and energy generation, predictability of project costs and energy generation by the auctioneer, transparency of bidders, asymmetric beliefs, repeated conduction of the auction and last but not least default risks. The impacts of those factors on the before identified auction types are discussed in the following.

The previous simplifying assumptions are now relaxed in order to model relevant aspects and settings for real-world applications in the RES-E context. We emphasize related chances and risks for each auction type and conclude with a suggestion for which auction format might be most suitable under given conditions. In each subsection only one assumption is neglected, all others are maintained as in the simplifying case. Note that in reality a mix of several conditions might be most applicable and hence the auctioneer needs to decide which corresponding chances and risks are most relevant to him in the particular situation. Finally, we conclude our results in a market and framework conditions specific evaluation.

2.7.1 Level of Competition

Sufficient competition is a necessary condition for the success of any auction. Klemperer (2002) mentions high participation as a key element of successful auctions. However, this condition is difficult to quantify and there exists no best practice of how to ensure high participation rates in an auction per se. It is obvious that the question of who and how many bidders will probably participate in the auction is crucial here. The answer strongly depends on the specific market situation and is very sensitive to auction related risks for the bidders. Basically, competition is increased by a higher number of bidders as well as by replacing weaker bidders by stronger ones.

Assuming low competition, Klemperer (2002) states that weaker bidders prefer the pay-as-bid auction over the uniform-price auction because they benefit from a positive probability to be awarded. Unfortunately, this fact is due to inefficiencies occurring under low competition in pay-as-bid auctions. In fact, all auction formats suitable for RES-E benefit from a higher level of competition in terms of reduced expected support levels and increased allocative efficiency. However, allocative efficiency is hardly traceable in real-world auctions and very sensitive to asymmetries regarding information and cost structures among bidders. Consequently, an auctioneer focusing on reduction of support costs as well as achieving allocative efficiency should always aim at finding appropriate measures beyond the auction format to ensure both results at the same time. For that reason, the auctioneer should aim at increasing participation in the auction by reducing bidders risks adequately, for instance, by a transparent and simple auction design with low participation barriers, which enjoys high acceptance among all potential bidders. Furthermore, appropriate measures to integrate asymmetric bidder groups, e.g. bidders with essential costs differences, might be helpful to increase participation, see e.g. establishment of boni and mali or contingents in auctions that are analyzed in detail in Section 4.

Number of Bidders Whereas the number of bidders has no impact on the optimal bidding behavior of a single-project bidder in a uniform-price auction with highest rejected bid and the descending clock auction, the optimal bidding strategy, in particular the degree of cost exaggeration, strongly depends on the number of bidders in a pay-as-bid auction and a uniform-price auction with highest accepted bid, supposed that the auction volume is constant. Since single-project bidders have a weakly dominant strategy to bid truthfully their costs in a one-time uniform-price auction with lowest rejected bid and descending clock auction, their bidding behavior is independent of the beliefs about their competitors, e.g. number and strengths. In a pay-as-bid auction bidders exaggerate their true costs less strongly if more bidders participate. That is, higher competition because of an increased number of bidders induces more aggressive bids. The same results occur for uniform-price auctions with highest accepted bid, where the impacts are even aggravated by the reduced probability of bids to be price-determining when more bidders participate. Nevertheless, from a theoretical point of view, expected revenue equivalence and allocative efficiency of all four auction formats apply independent from the number of bidders. Note that this result presuppose that the (expected) number of participating bidders is common knowledge in all auction formats.

Asymmetric Bidders As bidders strengths are modeled by distribution functions, symmetric and asymmetric bidders differ in the way that symmetric bidders draw their individual cost signals from the same distribution function, whereas asymmetric bidders draw them from different ones. If bidders are symmetric, all bidders have ex ante the same expected strength, where the particular signals may differ and are private information. Whereas we focused on symmetric bidders in our simplifying assumptions, we now investigate the consequences of asymmetric bidders, i.e. bidders that ex ante have different cost expectations. Consequently, for asymmetric bidders not only the private cost signals may differ but also the expected strengths, i.e. asymmetric bidders are ex ante distinguishable from each other by their expected strengths. In order to assess bidders strengths, we assume that different distribution functions can be ranked, for instance by concepts of stochastic dominance such as first-order stochastic dominance (Maskin and Riley, 2000). That is, a stronger bidders cost signal is more likely to fall below a certain value than that of a weaker bidder. Or in other words, a stronger bidder is expected to have lower costs than a weaker one.

Because of the existence of a weakly dominant strategy for single-project bidders in the uniform-price auction with lowest rejected bid and the descending clock auction, the incentive compatibility persists. Thus allocative efficiency is maintained in these auction formats under asymmetric bidders. However, in the pay-as-bid auction inefficiencies may occur due to asymmetries among bidders: weaker bidders submit more aggressive bids than stronger ones as they face higher competition.

Maskin and Riley (2000) show for the first-price and second-price auctions that expected revenue equivalence no longer holds by neglecting the assumption of symmetric bidders. However, neither the first-price nor the second-price auction is per se superior in generating lower expected support costs under asymmetric bidders. The auction format favored by the auctioneer in terms of minimization of support costs depends strongly on the specific form of asymmetry, i.e. for instance if the distributions are shifted or stretched. Since in real-world applications, e.g. the RES-E auctions, it might be difficult to capture and describe the form of asymmetry in an appropriate manner, the condition of asymmetric bidders should not be taken as crucial factor when searching for the most suitable auction format in a specific situation.

The bidding behavior in first-price and second-price auctions can be transferred to its multi-unit extension in case of single-project bidders. Hence, there exists no ranking of pay-as-bid and uniform-price auctions regarding expected support costs as well, if bidders are asymmetric.

2.7.2 Participation of Multi-project Bidders

Since project developers may plan and realize several projects simultaneously, they may also submit multiple bids in the same auction. To start with, we assume that each bidder has additive costs for multiple projects, i.e. the cost of simultaneously developing multiple projects equals the cost of developing each project separately. Hence, neither economies of scale nor additional costs due to simultaneous project developments exist. We assume that each bidder may apply with more than one project and submit multiple bids accordingly, i.e. for each project one bid is submitted.

The participation of multi-project bidders induces the risks of strategic supply reduction and allocative inefficiencies (Noussair, 1995; Ausubel et al., 2014a). If a bidder is interested in participating with multiple projects, ha may have the incentive withhold some projects in favor of a higher award price for the remaining ones. Multi-project bidders balance the trade-off between realizing more projects at lower support levels and realizing fewer projects in favor of higher support levels. Note that supply reduction can either be reached by submitting relatively high bids on additional projects or by not submitting any bids on additional projects at all in an extreme case. However, incentives for strategic supply reduction for multi-project bidders particularly occur in certain auction formats, especially in auctions where additional bids may influence the award price for another bid of the same bidder.

Hence, in a pay-as-bid auction, where a bid only impacts its own winning probability as well as its own award price in case of being successful, bidders cannot benefit from strategic supply reduction in case of binding bids. This is, because a bidder only increases his award price and simultaneously lowers his award probability in case of submitting strategically higher bids. As a result, the pay-as-bid auction even allocates the goods efficiently under the assumption of additive valuations of the multi-project bidders. Nevertheless, assuming that awards are not binding, i.e. bidders can withdraw their award without additional costs, incentives occur to exaggerate supply and submit multiple bids that differ slightly. This bid diversification serves as an optimization of cost exaggeration and hence as an optimized bidding strategy (Belica et al., 2015). Note that this situation is rather theoretical as in reality, project developers usually have to apply for the auction with concrete specified projects.

Whereas there exists a weakly dominant strategy to bid truthfully ones costs in case of single-unit supply in a one-time uniform-price auction, the situation is different if a bidder is interested in more than one unit and submits multiple bids: the additional bids, i.e. the higher ones, determine with a certain probability the award price of the previous bids, i.e. the lower ones. This fact induces incentives to bid relatively higher on additional bids in order to gain a higher award price in case the additional bids are price-determining (Engelbrecht-Wiggans and Kahn, 1998). Of course, this effect strongly depends on the probability of determining the award price with such additional bids, i.e. the fewer bidders participate or the lower the ratio of number of bidders to number of auctioned goods the higher is the chance to determine the price. Consequently, in both variants of the uniform-price auction the risk of unfavorable bidding strategies, i.e. supply reduction, exists if bidders are interested in more than one unit. This is illustrated in the following example.

Example: Incentives for Supply Reduction for Multi-project Bidders in the Uniform-price Auction with Lowest Rejected Bid We assume that three homogeneous goods are offered up for bidding to three potential Bidders 1, 2 and 3 in a uniform-price auction with lowest rejected bid. Bidder 1 is interested in two goods, Bidder 2 and 3 only have a single-unit supply. The following bids are submitted: $b_1^1 = 5MU$, $b_1^2 = 6MU$, $b_2 = 8MU$ and $b_3 = 10MU$. Hence, the bids of Bidder 1 and 2 are awarded and the award price is $10MU$. Alternative behavior of Bidder 1 (strategic supply reduction): Bidder 1 bids $b_1^1 = 5MU$ and $b_1^2 = 20MU$. Then all winning bidders receive one good at a price of $20MU$. Consequently, Bidder 1 increases his award price of the first good by refusing the second good.

Hence the favorable characteristic of incentive compatibility only applies for the specific case of single-project bidders and the first bid of multi-project bidders who only participate in one single auction. In all other cases there exist incentives for bidders to exaggerate their true costs in the bids. Consequently, even in a uniform-price auctions inefficiencies are likely to occur in case of multi-project bidders.

In a descending clock auction the risk of strategic supply reduction is even aggravated for multi-project bidders compared to the static counterpart, the uniform-price auction. Because multi-project bidders can observe the bidding procedure, they can optimize their decision of dropping out of the auction process early with one bid for the benefit of a higher award price of the other bids.

By relaxing the assumption on additive costs, i.e. supposing bidders have sub- or super-additive costs for multiple projects, the impacts discussed above remain the same, except when synergies (economies of scale) between multiple projects of a bidder become too strong. In that case, combinatorial auctions are considered more appropriate.

2.7.3 Uncertainties of Bidders' Valuations (IV Approach)

In this subsection we move away from the IPV model and consider the IV model, i.e. uncertain and interdependent values (costs). This model applies to the case that the auctioned projects are predetermined by the auctioneer (see Subsection 2.5.2). In this case, we assume that bidders are more uncertain about their actual costs for realizing the projects than in the case of individually developed projects, for which we consider the IPV approach appropriate. Therefore, bidders have to build beliefs about their uncertain costs based on the information provided by the auctioneer as well as their private costs signals. Here, the other bidders private costs signals may help a bidder in estimating his cost estimation more precisely. As mentioned in Subsection 2.5.2, these properties are captured by the interdependent value (IV) model. In this context, the main risk is that those bidders will win who have estimated the costs as being the lowest - the risk of the winner's curse. Misestimating of costs, however, can be reduced by the auctioneer as the level of uncertainties depends on the information that the auctioneer reveals. Thus, the auctioneer may reduce the risk of winner's curse by publishing valuable information about the project(s) before the auction. However, the information communicated should be transparent, traceable and reliable, otherwise potential bidders could be discouraged to participate in future auction rounds or they might base their expected valuation on inadequate information again leading to misestimations. In an IV framework, bidders benefit from auction formats that reveal information during the auction, so that they can learn from their competitors about the actual costs, which allows them to adapt their costs estimations and bidding strategies, respectively. This induces that dynamic auction formats as the descending clock auction or the reverse English auction in the single-unit case should be favored over their static counterparts. Nevertheless, the increased transaction costs of dynamic auctions have to be weighed against the advantages of information acquisition. Regarding the uniform-price auction and the pay-as-bid auction, so far no essential differences have been found with respect to the risk of the winner's curse.

2.7.4 Uncertainties of Auctioneer's Valuation

Since information asymmetries between auctioneer and bidders are characteristic for the RES-E context, it is a relevant issue to address the consequences of uncertainties regarding the auctioneer's valuation. Assuming that project developers participate with their individual planned and developed projects in the auction, they usually are the better informed party with respect to expected costs and revenues. Nevertheless, why is it crucial for the auctioneer to have precise information about expected support levels? Besides increased uncertainties in estimating future support costs, he will have difficulties to determine an adequate reservation price. If he sets a too ambitious (low) reservation price, he will risk missing his expansion goal. However, a too high reservation price may lead to excessive prices. Consequently, valuable and accurate information on expected support levels will help to balance this trade-off. The auctioneer benefits in all auction formats from an optimal reservation price in terms of reduced expected support costs. However, allocative inefficiencies may occur in case the lowest valuation (costs) of all bidders exceed the reservation price but not the auctioneer's valuation. As ex ante uncertainties in the auctioneer's valuation persist independent of the auction format, there is no auction format that is per se more suitable than another in order to reduce negative consequences in this particular situation. However, if there exist further incentives for unfavorable strategic bidding behavior because of specific market and framework conditions, an adequate reservation price gains in importance: For instance, in situations where the risk for strategic supply reduction is relatively high (due to participation of multi-project bidders in certain auction formats for example), an ambitious reservation price is a unique measure to avoid unfavorable strategic behavior.

2.7.5 Transparency of Bidders

If project developers know their competitors in the auction very well, stronger incentives occur to coordinate with each other in all auction formats. Especially in repeated auctions bidders might learn about their competitors. The risk of collusion increases especially with frequent auction rounds as here the coordination is easily continued and transferred to the next rounds. A high transparency of bidders is favored additionally by a relatively low number of project developers in the market. Whereas it might be difficult to eliminate the incentives for collusion per se, the auctioneer can at least hinder the continuing of collusive strategies. Consequently, if a high transparency of bidders exists the auctioneer should choose an auction format that is less vulnerable to collusion.

As a rule of thumb, static (sealed bid) auction formats are considered as more appropriate to avoid collusion than dynamic auction formats as the latter facilitate implicit collusion strategies during auction process. In contrast, the sealed-bid auction formats, i.e. both variants of the uniform-price auction and the pay-as-bid auction, rather prevent collusive bidding behavior since bidders cannot observe their competitors bids. Here, the risk for collusion is considered higher under uniform-pricing than under pay-as-bid. Klemperer (2002) emphasizes that there exist incentives for bidders to coordinate on particular shares of the auctioned volume in favor of a common high award price. Note that in uniform-price auctions, award and award price are (at least with a positive probability) decoupled by bidding, whereas in a pay-as-bid auction each awarded bidder receives his corresponding bid. Consequently, there exists a positive probability that a bidder's bid is awarded in a uniform-price auction with a relatively high award price even if the bid itself is relatively low.

2.7.6 Asymmetric Beliefs

We denote beliefs as a participant's expectation about competition or, in particular, his expectations about the (competitive) bidder's strengths. Each bidder has a concrete signal about his own strength but only beliefs about the other participants strengths. In the beginning, we acted on the simplifying assumption that all participants, i.e. auctioneer and bidders, have the same beliefs about each other before the auction. Relaxing this assumption yields the case that participants may have different information about each other. In particular, asymmetric beliefs imply that at least one participant has wrong beliefs about reality. The higher the number of misinformed participants and the more fallacious the misinformation, the greater is the effect of asymmetric beliefs regarding the auction outcome. However, asymmetric beliefs can be advantageous and disadvantageous as well as effectless for the auction outcome. This depends on the type of misinformation and the implemented auction format. The crucial question is if the prevailing misinformation leads to beliefs of higher or lower competition as compared to reality. For instance, let us assume that all bidders believe that their opponents are relatively strong, whereas all bidders in fact are rather weak. Then, competition is overestimated. If those bidders participate in a pay-as-bid auction, the auctioneer will benefit from lower support costs generated by the auction compared to the case where all bidders know that they are all weak in reality. In contrast, if all bidders act on the assumption of weaker competitors (misinformation), exactly the opposite applies: The auction generates higher support costs. The reason for that is that bidders exaggerate their costs in pay-as-bid auctions based on their beliefs about competition. Therefore the higher bidders expect the competition to be, the lower are their submitted bids in a pay-as-bid auction, independent if their beliefs are correct or based on misinformation. A similar result follows for the uniform-price auction with highest accepted bid, where the optimized bid also incorporates an exaggeration based on beliefs about competition as there exists a positive probability to be price determining in case of winning. In the uniform-price auction with lowest rejected bid, it is obvious that the weakly dominant bidding strategy remains unaffected even under asymmetric beliefs. Consequently, the pay-as-bid auction and the uniform-price auction with highest accepted bid generate lower (higher) expected support costs than the uniform-price auction with lowest rejected bid in case of overestimation (underestimation) of competition. In dynamic auctions bidders may recognize their asymmetric beliefs and adapt them according to their observations during the auction process, e.g. the incentive compatible descending clock auction reveals bidders actual cost estimations sequentially.

2.7.7 Repeated Conduction of the Auction

In order to ensure a continuous expansion of RES-E, several auction rounds have to be conducted during a year. One motivation behind this is that bidders should have the opportunity to participate in an auction round whenever their project status fulfills the prequalification criteria and hence avoid delays caused by the new system. However, repeated auctions have specific properties that induce specific risks which may be disadvantageous for the auctioneer. Since a bidder can take the repeated conduction into consideration by determining his optimized bidding strategy, he can incorporate the option to be awarded in a future round, if not being successful in the current round. To start with, we suppose that the volume of supply is a fixed amount for each year and all projects participate in the auction rounds until they are awarded. Then incentives for bidders occur to bid higher in earlier rounds than in later ones in all four auction formats (pay-as-bid, uniform-price (LRB and HAB), descending clock auction). The reason for this is that in the beginning the bidders face the additional chance to be successful in upcoming rounds. Note that even the weakly dominant strategies in the uniform-price auction with lowest rejected bid and the descending clock auction are not preserved in this case. If no new projects are added to the supply over time, these effects are, from a theoretical perspective, compensated over time and the expected total support costs equal those that would have been generated by a single auction with the same amount of supply and aggregated awards. In the RES-E context, however, it is more appropriate to assume that there accrue new projects to the amount of supply over time. Hence, if the expected level of competition is the same in each auction round, the optimal bid will be the same, i.e. the optimal bidding strategy will be constant over rounds, if the number of auction rounds is uncertain. Nevertheless, the argument that bidders may speculate of being awarded in a later round may persist from a psychological point of view and induce relatively higher bids in earlier rounds (McAfee and Vincent, 1993). In that context, expected costs of delays regarding project development and realization play a crucial role, because the lower the costs are the stronger is the incentive to wait for being awarded in later rounds. The experimental analysis from Abbink et al.

(2005) states that less experienced bidders submit more aggressive bids in a pay-as-bid auction. Consequently, the pay-as-bid auction is supposed to generate lower support costs than the uniform-price auctions in an early phase. However, as bidders will learn about the competition and adapt their bidding strategies respectively, these differences of expected support costs will converge over time. Moreover, it has to be taken into account that the repeated conduction of auctions increases the chance and, thus, the incentives for multi-project bidders to successfully implement strategic supply reduction at the expense of higher prices and, thus, higher support costs. The reason for this is that repeated conduction eases (implicit) collusion.

To conclude, there is no essential reason to favor a certain auction format over another against the background of repeated auctions. However, it might be reasonable to choose an auction format that is relatively stable against collusion, since the repetition may increase transparency between project developers and hence facilitate collusive strategies.

2.7.8 Default Risks

The adequate integration of default risks plays a crucial role for the design of a suitable auction mechanism for RES-E, if project developers participate in the auction before their projects are completely finalized. In that case, already awarded bidders may not succeed to realize their corresponding projects in time or even not at all. There can be several reasons for a default, such as insufficient support, missing approvals or force majeure (act of nature beyond control) that all refer to uncertainties for bidders at the time of bid submission. Hence, the auctioneer may benefit by reducing these uncertainties for the bidders project planning and realization phase, e.g. through variable support levels, appropriate prequalification measures or adequate penalties. First, through variable support levels (such as sliding feed-in premiums), specific uncertainties regarding actual costs and energy generation are transferred from the project developer to the auctioneer. Second, the auctioneer may demand specific prequalification requirements, where bidders have to ensure a predetermined project planning status involving the most important approvals for their project or other appropriate proofs of suitability. Penalties may encourage bidders to pursue their projects although their realization may not be profitable in itself. Unfortunately, all the aforementioned default risks persist in all auction formats suitable for RES-E. Hence, in order to accommodate these default risks, a standard auction format has to be complemented by further appropriate RES-specific design options in addition to the auction format, e.g. prequalification and penalty measures.

2.8 Conclusion

In the beginning of the chapter a general classification of relevant auction formats for RES-E was presented and a comprehensive introduction to their general characteristics was provided under simplifying assumptions. The main result of this first approach is that the considered auction formats perform equally well regarding expected auction revenue (i.e. support costs) and allocative efficiency in theory, even if the optimal bidding behavior differs in the particular auctions. However, since auctions for RES-E as real-world applications have to be evaluated before the background of specific market and framework conditions, we extended our analysis by relaxing those simplifying assumptions. As a result our analysis revealed a certain ambiguity of auction formats under changing market conditions. Hence, a profound market analysis is necessary before the implementation of auctions in order to find potential chances and risks with regard to relevant auction formats.

Chapter 3

Multi-unit Auctions with Non-binding Award and Reallocation – Theoretical and Experimental Analysis

There are real world auctions in which bidders are allowed to reject their award after the auction, typically in combination with a reallocation procedure. The main reason for non-binding awards is to increase competition by reducing bidders' risks after being awarded. We develop a theoretical model for non-binding awards in sealed-bid multi-unit auctions. We report that non-binding awards in combination with an appropriate reallocation mechanism do not have unfavorable effects in pay-as-bid and uniform price auctions, i.e., auction outcomes are efficient and revenue (payment) equivalence holds. Our experimental study supports our theoretical results. Moreover, we find that with an exhaustive reallocation procedure, the non-binding pay-as-bid and the non-binding uniform price auctions outperform their standard counterparts in terms of efficiency.

3.1 Introduction

Auctions with non-binding awards are characterized by the option for the bidders to withdraw awarded bids. To offer bidders this option may appear dubious at a first glance. However, as we illustrate in the following paragraphs, this option can be found in sales auctions and in procurement auctions. Here, the option to withdraw awarded bids has been either explicitly implemented or rather accidentally enabled by the auction rules.

The main argument for the explicit implementation of this option is to invite and not to deter bidders from participating in the auction. This, for example, applies when the bidders face uncertainties concerning the auctioned goods at the time of the auction, which can first be reduced or even dissolved after the award. Then, bidders may sometimes be better off by withdrawing their award in order to mitigate initially unforeseen costs. Particularly in procurement auctions, reducing those uncertainties may be possible before the auction but incurs costs. McAfee and McMillan (1987) interpret the costs of learning what the item is worth as entry costs. However, entry costs are sunk costs for the bidders and, thus, induce lower participation in the auction. An alternative is to let bidders gain information about uncertainties by being awarded in the auction and simultaneously offer the possibility to withdraw the award in case of an imminent loss. For instance, Ecofys, ZSW, ISI, and Takon (2015) focusing on renewable energy auctions, emphasize that bidders may have better opportunities to prepare and finance their project after the award than before the auction.

In combination with the option to withdraw awards, specific measures should be implemented concomitantly. The most prominent one is a reallocation procedure: after awarded bids have been withdrawn, the best losing bids move up and are awarded instead. In case of auctions with uniform pricing, the application of a reallocation procedure requires a recalculation of the award prices on the basis of the new allocation after the reallocation.

The option to withdraw awarded bids generates the inventive for the bidders to submit different bids for the same good in order to withdraw an awarded bid if another bid, which is better for the bidder, will be awarded instead. Internet-based auctions, for example, often facilitate multiple bidding through false instances as multiple email addresses or user accounts due to very low costs (Yokoo et al., 2004). Guo and Conitzer (2010) continue this line of research by studying online auctions in which bidders are allowed to withdraw their winning bids after the auction finished. The incentive to submit multiple bids is reinforced by a reallocation procedure because the withdrawal of an awarded bid may induce that another and better bid of the bidder will move up and will be awarded instead.

There are several prominent examples of auctions with non-binding awards. In the Australian license auction for satellite-television services in 1993, where two licenses were put up to sale, the bidders were allowed to submit as many bids as they wanted with zero withdrawal costs. McMillan (1994) joked that "what followed was high comedy", however, politicians called it "one of the world's great media license fiascoes". The winning bidders kept on withdrawing their award just to regain it with a lower bid after reallocation. This happened for 19 times, after which the licenses were allocated to the very same bidders but with a delay of one year and at approximately half of the initial award price.[1] In 2009, the Centers for Medicare and Medicaid Services (CMS) conducted auctions to replace administrative pricing of medical services allowing non-binding bids with minor success: the auction neither satisfied demand nor generated competitive prices. The New York Times reports that the chosen auction was "incredible in the inefficiency of its flawed design".[2] Cramton, Ellermeyer, and Katzman (2015) theoretically and Merlob, Plott, and Zhang (2012) experimentally

[1]For more details see McMillan (1994).
[2]For more details see Ayres and Cramton (2010).

point to the major problem in the design of the CMS auction: the combination of the median-price rule and the option to withdraw bids after the award price has been announced. More recently, numerous examples of non-binding auctions are found in the renewable energy (RE) sector. In these procurement auctions, project developers often face high planning uncertainties before their projects are awarded in the auction (e.g. Kreiss, Ehrhart, Haufe, and Soysal, 2017). That is, an awarded bidder may realize after the auction that the awarded support level is insufficient for getting further agreements for funds and for finishing the project. In order to reduce these award risks, winning bids will typically be non-binding. In fact, in many RE auctions the option to withdraw awards is explicitly implemented. Wigand, Foerster, Amazo, and Tiedemann (2016) report that in almost all countries bidders are basically allowed to withdraw their awards after the auction. Nevertheless, in most cases withdrawal costs occur in form of penalty payments depending on timing or reasons of withdrawal (e.g. German Federal Ministry for Economic Affairs and Energy, 2015). Only few countries, e.g. Denmark and Germany, implement supplemental reallocation procedures instead in order to preserve high realization rates and, thus, to reach the expansion target in case of withdrawals (Kitzing and Wendring, 2015; Tiedemann, 2015).

This paper provides a first theoretic and experimental analyses of auctions with non-binding awards. Our main focus are the incentives caused by this option and their impact on the auction outcome. In order to gain first insights that help to detect the basic principles and effects of non-binding awards in combination with a reallocation procedure, we set up an idealized model to isolate the strategic effects of the option to withdraw awarded bids as far as possible and to reduce complexity, particularly in the experiment. First, we consider simultaneous sealed-bid auctions for multiple homogeneous goods. Second, we allow bidders to submit multiple bids for one good without incurring costs. Third, we consider an exhaustive reallocation procedure, i.e., the number of reallocation rounds is not limited. Bidders may also withdraw awarded bids after a reallocation has taken place and every withdrawal again triggers a reallocation. Fourth, we abstract from uncertainty concerning the value of the auctioned goods. We discuss relaxations of these assumptions in Section 3.4.

Within an IPV framework, we theoretically analyze multi-item sealed-bid procurement auctions with single-unit supply bidders. We consider pay-as-bid (PAB) pricing and uniform pricing with lowest rejected bid (UP-LRB) and highest accepted bid (UP-HAB). In non-binding auctions with PAB or UP-HAB, if costs of rejection are neglected, bidders have an incentive to submit as many bids as feasible and the non-binding bids spread around the equilibrium bid in corresponding auction with binding awards. In a non-binding auction with PAB or UP-HAB, if costs of rejection are neglected, bidders have an incentive to submit as many bids as feasible and the non-binding bids spread As the binding UP-LRB auction, the non-binding UP-LRB auction is incentive compatible and bidders do not have an incentive to submit more than one bid. For the PAB auction we show that with symmetric and risk-neutral bidders, there exist pure strategy Bayesian Nash equilibria in monotone bidding functions. We analogously discuss the symmetric equilibrium strategy in non-binding UP-HAB auctions, that we also investigate in our experiment. We show that all considered binding and non-binding mechanisms are efficient and expected revenue (payment) equivalent.

We conduct an experiment to test the theoretical findings of auctions with binding awards and non-binding awards. We implement procurement auctions with PAB and UP-HAB because these two formats are mostly used in real-world applications. For renewable energy auctions, both price rules were recently implemented in the German pilot auctions for photo voltaic according to the German Federal Ministry for Economic Affairs and Energy (2015) in order to test their suitability in that context. Also, in France and the United Kingdom experience on uniform and pay-as bid auctions for renewable energy support were gained (Wigand et al., 2016; del Río and Linares, 2014). Moreover, these two price rules also become subject of controversial debate due to their ambiguous ranking regarding revenue (payment) and efficiency, e.g., California electricity auctions (Kahn et al., 2001) or U.S. Treasury auctions (Ausubel et al., 2014b).

The remainder of this paper is structured as follows: Section 3.2 provides the theoretical analysis of binding and non-binding auction with different price rules. The experiment is presented in Section 3.3: the experimental design in 3.3.1, the hypotheses in 3.3.2, and the results in 3.3.3. In Section 3.4 we discuss some extensions of our model. Section 3.5 concludes.

3.2 Theoretical Analysis

3.2.1 Model for Auctions with Non-binding Awards

Consider a sealed-bid multi-unit procurement auction in which $N \geq 2$ bidders compete for the supply of $K \geq 1$ indivisible units of a homogeneous good, $K < N$. Bidder have *single-unit supply* and *symmetric independent private costs*: bidder i can produce one unit of the good and has private production costs X_i, which is independently and identically distributed on the interval $[\underline{x}, \overline{x}]$ according to the increasing distribution function F with density f. Let $X_{(j:N)}$ denoted the j-lowest order statistic and $F_{(j:N)}$ and $f_{(j:N)}$ its distribution and density, $j = 1, \ldots, N$. That is, $X_{(1:N)} \leq X_{(2:N)} \leq \ldots \leq X_{(K:N)} \leq \ldots \leq X_{(N:N)}$.

In the *non-binding awards* setting, bidders have the option to withdraw awarded bids. Since this option may generate an incentive to submit multiple bids even for bidder with single-unit supply, we allow the bidders to submit up to $T \leq K$ bids, each offering one unit of the good at a certain price. That is, a bidder submits a bid vector $\boldsymbol{c} = (c_1, c_2, \ldots, c_T)$ with $c_1 \leq c_2 \leq \ldots \leq c_T$. We assume that the withdrawal of awarded bids is costless.[3]

We further assume that the option of withdrawing awarded bids is accompanied by an *exhaustive reallocation procedure*. If a bidder withdraws one of her awarded bids, a reallocation round starts. The best (i.e., lowest) non-awarded bid moves up and is awarded instead of the withdrawn bid and award prices are adjusted. If then again a bidder withdraws one of her awarded bids, a new reallocation round starts, and so on. The reallocation procedure is repeated until no bidder withdraws an awarded bid. After the bidders submit their bid vectors, the K lowest submitted bid components of all submitted bid vectors are initially awarded. If bidders submit multiple bids, it is possible that more than one bid of a bidder is awarded. In this case, the bidder has an incentive to withdraw her lower awarded bids. Since this is a weakly dominant strategy, we assume that the bidders withdraw all but the highest awarded bids in case of multiple awards in each reallocation round.

In each reallocation round, bidders have *individual successor foresight*: a bidder knows if one of her bid components is the best non-awarded bid and would move up in case of reallocation. In this case, if the bidder is already awarded with a bid, she will withdraw this because she knows that then her higher bid will move up and will become an awarded bid.

In those non-binding auctions, bidders compete against the first, i.e., the lowest components c_1 of each opponent's bid vector $\boldsymbol{c}$. Since c_1 will play a crucial role in our analysis we will refer to it as the *leading bid*. A bidder is only successful, i.e., is awarded, if her leading bid outbids the K lowest leading bids of the other bidders.

Lemma 1. *In a non-binding auction with individual successor foresight with N bidders, a bidder is awarded if and only if her leading bid is lower than the K-th lowest leading bid of the other $N-1$ bidders.*

[3]We discuss a relaxation of this assumption in Section 3.4 and consider the case that withdrawing an awarded bid is not costless.

For the proof see A.1. As a consequence, the *additional bids* $c_2, c_3, \ldots, c_T$ may only impact the award price but never the award. Considering a representative bidder, we denote the distribution and density function of the submitted K-th lowest leading bid of her $N-1$ opponents by G_K and g_K.

3.2.2 Pay-as-bid Pricing (PAB)

In auctions with PAB, the award prices are determined by the respective awarded bids.

Binding Awards under PAB

Each bidder submits one bid and is awarded if her bid is lower than the K-th lowest bid of the opponents. The expected profit of a bidder with costs x is $\mathrm{E}[\pi(x,b)] = (b-x)(1-H_K^{PAB}(b))$, where H_K^{PAB} and h_K^{PAB} denote the distribution and density function of the bidder's beliefs about her opponents' K-th lowest bid. The first-order condition of the maximization of $\mathrm{E}[\pi(x,b)]$ with respect to b leads to the implicit representation of the optimal bid

$$b^{PAB} = x + \frac{1 - H_K^{PAB}(b^{PAB})}{h_K^{PAB}(b^{PAB})} \,. \tag{3.1}$$

That is, bidders have an incentive to exaggerate their costs. Analogously to sales auction (Weber, 1983a), the monotone bidding strategy of the unique symmetric equilibrium is

$$\beta^{PAB}(x) = x + \frac{\int_x^{\overline{x}} 1 - F_{(K:N-1)}(s)ds}{1 - F_{(K:N-1)}(x)} \,. \tag{3.2}$$

Each bidder bids the expected K-th lowest signal of the other bidders conditional on having a lower signal. The auction outcome is efficient and the expected average price per good is $\mathrm{E}[X_{(K+1:N)}]$ and the auctioneer's expected payment is $K\mathrm{E}[X_{(K+1:N)}]$.

Non-binding Awards under PAB

In a PAB auction with non-binding awards, a bidder has an incentive to submit multiple bids because there exists a positive probability for an additional bid to be awarded – initially or by moving up after reallocation. In these cases, the withdrawal of all but the highest winning (or succeeding) bid will increase a bidder's profit. Thus, the submission of additional bids weakly increases a bidder's profit.

Proposition 1. *The optimal bid vector $\boldsymbol{c}^{PAB} = (c_1^{PAB}, \ldots, c_T^{PAB})$ of a bidder with signal $x \in [\underline{x}, \overline{x}]$ in the non-binding PAB auction satisfies the following conditions.*

(1) $x < c_1^{PAB} < c_2^{PAB} < \ldots < c_T^{PAB}$

(2)

$$c_t^{PAB} = \begin{cases} x + \frac{G_K^{PAB}(c_2^{PAB}) - G_K^{PAB}(c_1^{PAB})}{g_K^{PAB}(c_1^{PAB})} & t = 1 \\ c_{t-1}^{PAB} + \frac{G_K^{PAB}(c_{t+1}^{PAB}) - G_K^{PAB}(c_t^{PAB})}{g_K^{PAB}(c_t^{PAB})} & 2 \leq t \leq T-1 \\ c_{T-1}^{PAB} + \frac{1 - G_K^{PAB}(c_T^{PAB})}{g_K^{PAB}(c_T^{PAB})} & t = T\,, \end{cases}$$

where G_K^{PAB} and g_K^{PAB} denote the distribution and density function of the bidder's beliefs about the K-th lowest leading bid of the bidder's $N-1$ opponents.

The proof is presented in Appendix A.1. A bidder's optimal leading bid c_1^{PAB} is higher than her costs x. Every additional bid c_t^{PAB}, $t \in 2, 3, \ldots, T$ exceeds the preceding bid c_{t-1}^{PAB}, where the markups depend on the distribution G_K^{PAB}. Note that (3.1) corresponds to c_1^{PAB} for $T = 1$.

The following proposition states that equilibria in monotone bidding strategies exist, i.e., bidders with lower costs submit lower bids than bidders with higher costs.

Proposition 2. *In the non-binding PAB auction, there exists a symmetric bidding equilibrium in pure strategies $\boldsymbol{\gamma}^{PAB} = (\gamma_1^{PAB}, \gamma_2^{PAB}, \ldots, \gamma_T^{PAB}) : [\underline{x}, \overline{x}) \to \mathbb{R}^T$, where $x < \gamma_1^{PAB}(x) < \gamma_2^{PAB}(x) < \ldots < \gamma_T^{PAB}$ and each component γ_t^{PAB} with $t = 1, \ldots, T$ is increasing in x.*

The proof is presented in Appendix A.1. Because of the monotonicity of $\boldsymbol{\gamma}_1^{PAB}$, the outcome of the non-binding PAB auction is efficient and the same as of its binding counterpart.

Proposition 3. *In the symmetric equilibrium generated by $\boldsymbol{\gamma}^{PAB}$ of the non-binding PAB auction the following holds.*

(1) The auction outcome is efficient.

(2) The bidders' winning probabilities and expected profits and the auctioneer's expected average payment per good (equal to $E[X_{(K+1:N)}]$) are the same as in the binding PAB auction.

The proof is presented in Appendix A.1. Although both auctions result in the same allocation, the actual award prices for the auctioned K units may differ. In the binding PAB auction the award prices are determined by the K lowest bids, while in the non-binding auction award prices may also be determined by additional (i.e., non-leading) bids. Moreover, although bidders' winning probability and their expected profit do not differ between the two auctions, the awarded bidders' actual profits may be different. If a bidder only wins with her leading bid in the non-binding auction, her actual profit is lower than her profit in the binding auction. If a bidder also wins by withdrawing bids, her actual profit may be higher than in the binding auction. Thus, the non-binding PAB auction offers an optimization of bid-shading by diversifying bids.

Corollary 1. *Let $\beta^{PAB} : [\underline{x}, \overline{x}] \to \mathbb{R}$ be the equilibrium bidding strategy in a binding PAB auction and $\boldsymbol{\gamma}^{PAB} = (\gamma_1^{PAB}, \gamma_2^{PAB}, \ldots, \gamma_T^{PAB}) : [\underline{x}, \overline{x}] \to \mathbb{R}^T$ be the equilibrium bidding strategies in a non-binding PAB auction with exhaustive reallocation procedure. Then the non-binding bid components spread around the corresponding binding* *bid, i.e.,*

$$\gamma_1^{PAB}(x) < \beta^{PAB}(x) < \gamma_T^{PAB}(x) \text{ for all } x \in [\underline{x}, \overline{x}] \text{ and } T \geq 2.$$

The proof is presented in Appendix A.1. In the binding PAB auction, a bidder has only "one shot" $\beta^{PAB}(x)$ to balance the trade-off between the winning probability and her profit in case of winning. The non-binding auction allows multiple shots, which incentivizes bidders to diversify their K bids. That is, $\gamma_1^{PAB}(x) < \beta^{PAB}(x)$ increases the winning probability compared to $\beta^{PAB}(x)$ but lowers the profit in case of winning, while $\gamma_K^{PAB}(x) > \beta^{PAB}(x)$ generates a higher profit in case of winning, while reducing the chance of winning.

If the bidders are allowed to submit as many bids as they want, they will submit a continuous bidding function from x to any maximum bid. Then, the award price equals the market clearing price given by the $K+1$-lowest costs $x_{(K+1:N)}$.

Example 1: The symmetric equilibrium in the binding PAB auction (3.2) of our experimental setting with $K = 2$, $N = 3$ and uniformly distributed costs on $[100, 199]$ is given by

$$\beta^{PAB}(x) = x + \frac{x - \frac{1}{99^2}(\frac{1}{3}x^3 - 100x^2 + 10000x)}{1 - (\frac{x-100}{99})^2}.$$

We compute the two bidding functions $\gamma_1^{PAB}(x)$ and $\gamma_2^{PAB}(x)$ of the symmetric equilibrium in the non-binding PAB auction in the experiment with $T = 2$ numerically via the corresponding differential equation system (see A.4). Figure 3.1 shows that $\gamma_1^{PAB}(x)$ is below $\beta^{PAB}(x)$, $\gamma_2^{PAB}(x)$ is above $\beta^{PAB}(x)$, both functions converge towards $\beta^{PAB}(x)$ if x increases, and the three functions meet in $\bar{x} = 199$ with $\gamma_1^{PAB}(\bar{x}) = \gamma_2^{PAB}(\bar{x}) = \beta^{PAB}(\bar{x}) = \bar{x}$.

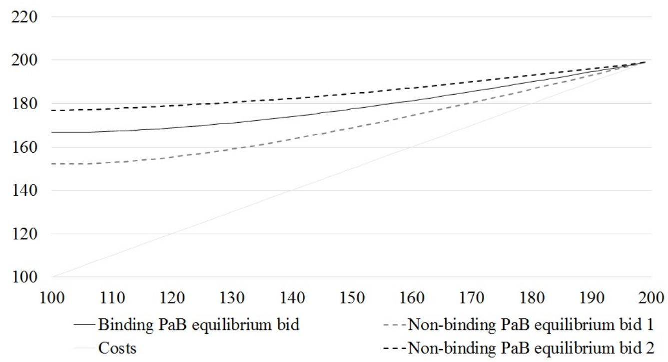


Figure 3.1: Symmetric equilibrium bidding functions in the binding and the non-binding PAB auction.

3.2.3 Uniform Pricing (UP)

We consider two variants of uniform pricing in procurement auctions: lowest rejected bid (UP-LRB) and highest accepted bid (UP-HAB). While UP-LRB is incentive compatible, UP-HAB induces bidders to exaggerate their costs. However, both versions lead to an efficient outcome and the same expected auction prices (e.g. Engelbrecht-Wiggans, 1988).

Binding awards under UP-LRB

Under UP-LRB, bidders have the (weakly) dominant strategy to reveal their costs: $b^{LRB}(x) = x$. Thus, the unique symmetric equilibrium is given by $\beta^{LRB}(x) = x$ (e.g. Smith et al., 1985). The auction outcome is efficient and expected average price per good and the auctioneer's expected payment are $\mathrm{E}[X_{(K+1:N)}]$ and $K\mathrm{E}[X_{(K+1:N)}]$.

Non-binding Awards under UP-LRB

In auctions with non-binding awards and UP-LRB, it is (weakly) dominant for a bidder to reveal her costs in the leading bid (i.e., first bid component), as with binding awards: $c_1^{LRB}(x) = x$. Additional bids are irrelevant for a bidder because they neither increase her winning probability nor the award price. If an additional bid determines the award price, the bidder will withdraw her awarded bid, which leads to same results without submitting additional bids. Thus, additional bids can be set arbitrarily or simply skipped.

Proposition 4. *In an auction with non-binding awards and UP-LRB there exists a class of equilibria with dominant leading bids $\gamma_1^{LRB}(x) = x$ and arbitrary additional bids.*

The outcome of these equilibria is efficient as in the uniform price auction with binding awards and UP-LRB. This equivalence also holds for the bidders' winning probabilities and their expected profits and the award price.

Binding awards under UP-HAB

In an auction with binding awards and UP-HAB, a bidder's optimal bid has to fulfill the following condition (see A.2):

$$b^{HAB}(x) = x + \frac{H_{K-1}^{HAB}(b^{HAB}(x)) - H_K^{HAB}(b^{HAB}(x))}{h_K^{HAB}(b^{HAB}(x))}\,, \tag{3.3}$$

where H_K^{HAB} and h_K^{HAB} denote the distribution and density function of the bidder's beliefs about her opponents' K-th lowest bid. Bidders exaggerate their costs with their bid, i.e., $b^{HAB}(x) > x$, which depends on the probability of being price-determining $H_{K-1}^{HAB}(b^{HAB}(x)) - H_K^{HAB}(b^{HAB}(x))$, i.e., $b^{HAB}(x)$ lies between the $(K-1)$th and K-th lowest opponents' bid (Hao, 1999). The symmetric equilibrium strategy of the UP-HAB auction with K goods and N bidders is the same as in the first price auction (i.e., PAB auction with one good) with $N - K + 1$ bidders.

Proposition 5. *The unique symmetric equilibrium in monotone bidding strategy of the binding UP-HAB auction with K goods and N bidders with $x \in [\underline{x}, \bar{x}]$ is given by*

$$\beta^{HAB}(x) = x + \frac{\int_x^{\bar{x}} 1 - F_{(1:N-K)}(s)ds}{1 - F_{(1:N-K)}(x)}\,. \tag{3.4}$$

The proof is presented in Appendix A.1. As a consequence, the auction outcome is efficient and revenue equivalence applies, i.e., the auctioneer expected payment per good is the same as under UP-LRB and PAB and, thus, equal to $\mathrm{E}[X_{(K+1:N)}]$. Because under UP-HAB the highest accepted bid determines the uniform price, whereas under PAB an awarded bid determines its award price, the UP-HAB equilibrium bids are smaller than the PAB equilibrium bids and higher than the UP-LRB equilibrium bids:

$$\begin{aligned}
&\beta^{PAB}(x) > \beta^{HAB}(x) > \beta^{LRB}(x) = x \quad \text{for} \quad x \in [\underline{x}, \bar{x})\,,\\
&\beta^{PAB}(\bar{x}) = \beta^{HAB}(\bar{x}) = \beta^{LRB}(\bar{x}) = \bar{x}\,.
\end{aligned}$$

Example 2: The symmetric equilibrium in the binding UP-HAB auction (3.4) of our experiment with $K = 2$, $N = 3$ and uniformly distributed costs on $[100, 199]$ is given by

$$\beta^{HAB}(x) = \frac{x + (N-2)\bar{x}}{N-1} = \frac{x + 199}{2}\,.$$

Non-binding awards under UP-HAB

Analogous to the non-binding PAB auction, a bidder has an incentive to submit as many different bids as feasible, which all exaggerate her costs. For illustration, we compare the case in which a bidder submits only one bid c_1 with the case in which the bidder also submits an additional bid $c_2 > c_1$. If c_1 is not awarded, neither c_2 is and the bidder's profit is zero in both cases. If c_1 is not awarded, either c_2 is not awarded or c_2 is also awarded (or will be awarded if c_1 is withdrawn). In the former case, bidder's profit is equal to the case of only submitting c_1. If in the latter case the bidder withdraws c_1, a higher bid (either an opponent's bid or c_2) moves up and determines the award price, which thus increases. Since this argumentation also holds for $T > 2$ bids, we can conclude that submitting additional bids is always worthwhile for a bidder. This argumentation leads to the following proposition.

Proposition 6. *If in the UP-HAB auction exists a symmetric equilibrium* $\boldsymbol{\gamma}^{HAB} = (\gamma_1^{HAB}, \gamma_2^{HAB}, \ldots, \gamma_T^{HAB}) : [\underline{x}, \overline{x}] \to \mathbb{R}^T$ *with* $\gamma_1^{HAB}(x)$ *is increasing in* x*, the following holds:*

(1) $x < \gamma_1^{HAB}(x) < \gamma_2^{HAB}(x) < \ldots < \gamma_T^{HAB}(x)$.

(2) The auction outcome is efficient.

(3) The bidders' winning probabilities and expected profits and the auctioneer's expected payment per good (equal to $E[X_{(K+1:N)}]$*) are the same as in the binding UP-HAB auction.*

(4) The non-binding bid components spread around the corresponding binding bid: $\gamma_1^{HAB}(x) < \beta^{HAB}(x) < \gamma_T^{HAB}(x)$ for all $x \in [\underline{x}, \overline{x}]$ and $T \geq 2$.

The proof is presented in Appendix A.1.

3.2.4 Summary of Theoretical Results

Also with the option to withdraw awarded bids in the non-binding auctions, the revenue equivalence theorem (RET) applies to the non-binding and binding auctions with PAB, UP-LRB, and UP-HAB. In the symmetric equilibrium of the binding and non-binding auctions, the outcome is efficient, the bidders' winning probability and their expect profit are equal, as well as the auctioneer expected (average) payment per good, which is equal to $\mathrm{E}[X_{(K+1:N)}]$.

However, their are differences with regard to the bidding behavior. Under UP-LRB, the option to withdraw awards has no effect: bidders have no incentives to submit additional bids in the non-binding auction, and both the binding and the non-binding auction are incentive compatible, i.e., to reveal the costs in the bid is a weakly dominant strategy. Non-binding awards affect bidding in the non-incentive compatible PAB and UP-HAB auctions, where the bidders submit as many bids as feasible, which spread around the corresponding binding bid, although revenue equivalence holds. This is the motivation and starting point for our experiment, in which we compare binding and non-binding auctions with PAB and UP-HAB.

3.3 Experimental Analysis

This section presents the experimental procedures, treatments, hypotheses and results.

3.3.1 Experimental Design

Our experiment is based on a procurement auction, in which the auctioneer demands two units of a homogeneous good. These can be produced by three subjects each with single-unit supply. Hence, the bids of two of three competing subjects are awarded. We implement two treatment variables *Award* and *Pricing*, each with two categories. (*Award*: binding awards and non-binding awards, *Pricing*: PAB and UP-HAB.) This results in four treatments: *Binding PAB, non-binding PAB, binding UP-HAB* and *non-binding UP-HAB.*

The binding treatments correspond to the standard auction mechanisms, i.e. each subject submits one bid and the two subjects with the lowest bids are awarded. In the non-binding treatments, subjects are allowed to submit up to two alternative bids for their supply of the single good, only one of which could finally be awarded. If in any initial allocation a subject profited from withdrawing her lower bid, an automated reallocation procedure would withdraw the lower bid and would replace it with the subject's higher bid.[4] Thus, still, the two subjects with the lowest bids are awarded, but their award prices not only depend on their lowest bids, but also on their higher bid.[5]

In the experiment, in each of the four treatments, the described procurement auction with three bidders is repeatedly played ten times (periods) under the respective treatment conditions within a matching group of six subjects (stranger setting). Each subject and, thus, each matching group participates only under one price rule, either under PAB pricing or UP-HAB, but under both award variations – binding awards and non-binding awards. That is, each matching group participates in two treatments, where it plays the repeated auction of both treatments twice. Binding and non-binding treatments alternated every 10 periods, e.g. periods 1-10 and 21-30 binding, periods 11-20 and 31-40 non-binding.[6]

In each of the 40 periods, each subject independently draws her private production costs and competes for the sale of one unit of a homogeneous good against two other subjects of their matching groups. In each period, every auction group of three bidders is randomly drawn out of a matching group of six subjects which remains constant over the 40 periods. For comparability, the private costs of all rounds were drawn from a uniform distribution over the set of integers $\{100, 101, \ldots, 199\}$ in advance. Each subject receives any particular costs signal only once, but the costs constellations, i.e., triples of production costs of the three bidders in one particular auction, are the same for each treatment and each matching group. We controlled for order effects within

[4]Withdrawing an awarded bid is only profitable if the second bid moves up and will be awarded instead.

[5]A similar experiment was conducted by Smith (1967), who also allows to bid for one or two of the auctioned units, however, bids are binding and each subject has resale opportunities for up to two units. Also, Smith, Cox, and Walker (1985) and Alsemgeest, Noussair, and Olson (1998)) conduct experiments with binding auctions, where all subjects are either interested in one unit or in two units predefined for each auction round.

[6]We controlled for order effects by permuting Binding (B) and Non-binding (N) awards within each treatment, i.e., BNBN, BNNB, NBBN, NBNB.

matching groups by using permutations of these pre-drawn costs constellations over the 40 periods.

In order to control for learning effects (e.g. Coppinger, Smith, and Titus (1980), Dyer, Kagel, and Levin (1989), Harstad (2000)), we implement *Experience* as a third treatment variable and classify subjects in periods 1-20 as *inexperienced* and in periods 21-40 as *experienced*. A summary of the experimental procedures is presented in Table 3.1.

Treatment	PAB		UP-HAB	
	Binding	Non-binding	Binding	Non-binding
# feasible bids per subject & period	1	2	1	2
# sessions	8		8	
# subjects	96		96	
# matching groups	16		16	
# periods	40		40	
with inexperienced subjects	20		20	
with experienced subjects	20		20	

Table 3.1: Experimental procedure overview: treatments, feasible bids, numbers of sessions, subjects, matching groups, and periods (periods with inexperienced and experienced subjects).

In the experiment we used the artificial currency unit ExCU with a conversion rate of 20 ExCU for 1 Euro. We set the minimum bid price at 50 ExCU and the maximum bid price at 250 ExCU. Before the experiment, the instructions were read aloud and subjects answered a set of multiple-choice comprehension questions. At the end of every session, subjects received their profits from 16 randomly drawn periods in cash. The sessions lasted about 75 minutes and the average total payment was 24.27 Euro per subject (minimum payment: 15.05 Euro, maximum payment: 35.55

Euro).[7][8] Any kind of communication during the experiment was not allowed. The experiment was conducted with z-Tree (Fischbacher, 2007).

3.3.2 Hypotheses

The hypotheses for our experimental analysis are derived from the theoretical results in Section 3.2. Our first hypothesis follows from Proposition 1 and 6 and Corollary 1.

Hypothesis 1. *In the non-binding PAB and UP-HAB auctions,*

(1) bidders submit two different bids,

(2) bidders spread their bids around the bid in the corresponding binding auction.

Our second hypothesis follows from the RET stated in Proposition 3 and 6.

Hypothesis 2. *In the four auctions (binding/non-binding PAB/UP-HAB),*

(1) the (average) auction prices per good are equal,

(2) bidders' profits are equal,

(3) the allocation is efficient.

3.3.3 Experimental Results

In this section we present and analyze the experimental results. When applying a statistical test, the level of significance is labeled with *, **, and *** for 5%, 1%, and 0,1%.

In line with Hypothesis 1 (1), in the non-binding auctions, subjects make consistently use of the option to submit two bids: 95.3% under PAB and 94.5% under

[7] Incl. 5 Euro show-up fee.

[8] In order to control for risk-aversion, subjects also participated in a pen-and-pencil Holt and Laury (2002) lottery-choice task after the experiment but before payment.

UP-HAB. Inexperienced subjects use this option in 95.0% and experienced subjects in 94.8%.

Result 1. *The option of two different bids in the non-binding auctions is used almost always. Under both PAB and UP-HAB, inexperienced and experienced subjects submit two different bids in the non-binding treatments in about 95% of all cases.*

In line with Hypothesis 1 (2), we observe in the non-binding auctions that, on average, subjects' lower bid is lower and their higher bid is higher than their corresponding bid in the binding auctions. This holds for every single induced value (see Figure 3.2). The degree of diversification is higher for subjects with low costs.[9]

Result 2. *In in the non-binding auctions with both PAB and UP-HAB, the subjects spread their bids around their corresponding bids in the binding treatments.*

The average auction prices in the four treatments are very homogeneous and range from 163.9 to 165.4 ExCU with small standard deviations of 1.9 to 3.3 ExCU (Table 3.2).[10]

The subjects' profits are more heterogeneous with higher profits in the UP-HAB treatments than in the PAB treatments (see Table 3.3).

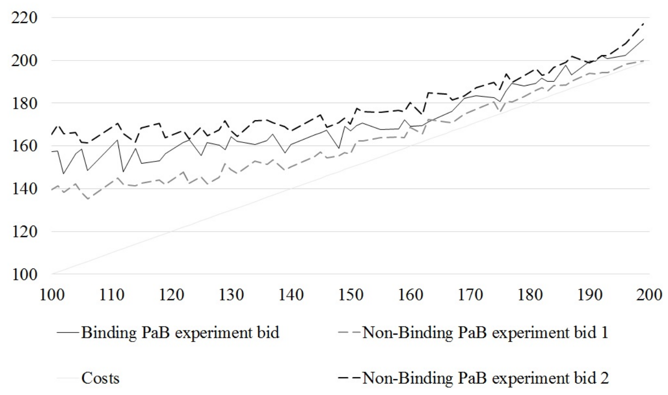
	PAB		UP-HAB	
	Binding	Non-binding	Binding	Non-binding
Mean	163.9	164.3	165.4	164.7
Median	162.8	163.7	165.0	164.8
Std. dev.	3.3	1.9	1.9	2.7

Table 3.2: Average auction prices [ExCU].

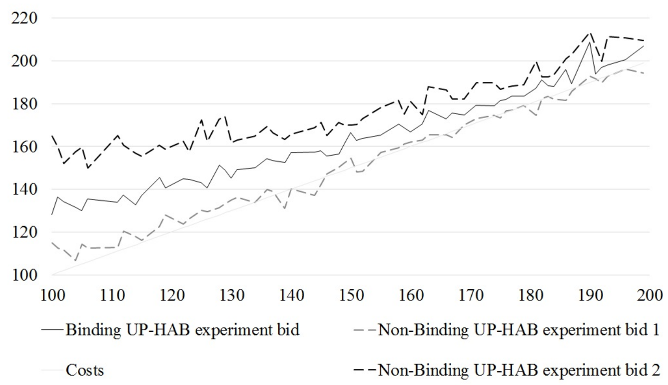
With respect to efficiency, we consider two commonly used measures. First, the efficiency rate, which is defined as the welfare surplus generated by the auction divided

[9]The Spearman's rank correlation coefficients are -0.889 for PAB and -0.837 for UP-HAB and the corresponding rank correlation tests yield p-values $< 0.001^{***}$.

[10]Details for auction prices on matching group level can be found in Table A.1.



(a) Binding and non-binding bids (PAB)



(b) Binding and non-binding bids (UP-HAB)

Figure 3.2: Bid diversification: average bids in the binding and non-binding auctions.

	PAB		UP-HAB	
	Binding	Non-binding	Binding	Non-binding
Mean	16.03	16.74	17.32	17.12
Median	15.53	16.52	17.38	17.44
Std. dev.	1.73	1.19	1.15	1.91

Table 3.3: Average bidders' profit [ExCU].

by the maximum achievable welfare surplus.[11] Second, the strict efficiency, which for

[11]Here, we (conservatively) assume that the auctioneer is able to produce both units of the good at the bidders' maximum cost, i.e., 199 ExCU.

any auction is either 1 if the auction outcome is efficient or 0 if not. That is, an auction is efficient in the strict sense, if and only if the two subjects with the lowest costs are awarded. The efficiency rate, on the other hand, also equals 1 if the auction outcome is efficient, but is positive for non-efficient allocations, and, thus, it also indicates the welfare loss. Table 3.4 reveals that all four treatments generate high efficiency rates of at least 97.5%.[12]

	PAB		UP-HAB	
	Binding	Non-binding	Binding	Non-binding
Mean	97.5%	98.6%	97.9%	98.8%
Median	97.9%	98.7%	98.0%	99.0%
Std. dev.	1.4%	0.5%	1.1%	0.8%

Table 3.4: Average efficiency rates.

	PAB		UP-HAB	
	Binding	Non-binding	Binding	Non-binding
Mean	76.3%	82.5%	79.8%	85.8%
Median	77.5%	82.5%	80.0%	83.8%
Std. dev.	7.2%	5.8%	6.2%	5.8%

Table 3.5: Average strict efficiency rates.

We get a similar picture for the strict efficiency (see Table 3.5). The share of efficient allocations ranges between 76.3% in the binding PAB treatment to 85.8% in the non-binding uniform treatment. However, the non-binding treatments show higher values and a lower variation for both efficiency measures.

For testing the Hypothesis 2, we first conduct a multivariate analysis of variance (MANOVA) in order to test whether the treatment variables Award and Pricing have an effect on the auction prices, bidders' profit, and efficiency.[13] As a control

[12]Details of auction prices on matching group level can be found in Table A.2.

[13]In the following statistical analysis we use the strict efficiency as the efficiency measure. All stated results, however, also hold if the strict efficiency is replaced by the efficiency rate.

variable we also include the subjects' dichotomous experience. As Table 3.6 shows, all treatment variables, Award, Pricing and Experience, have a significant effect on the dependent variables auction prices, bidders' profits and efficiency. However, we observe no interaction effects.

Variable	Pillai	approx. F	p-value
Award	0.131	4.416	0.002**
Pricing	0.118	3.919	0.005**
Experience	0.085	2.721	0.033*
Award:Pricing	0.055	1.724	0.149
Award:Experience	0.020	0.607	0.658
Pricing:Experience	0.048	1.473	0.215
Award:Pricing:Experience	0.014	0.426	0.790

Table 3.6: Multivariate analysis of variance. Fit: (Efficiency, Prices, Bidders' Profits) $\sim$ Award + Pricing + Experience + Award:Pricing + Award:Experience + Pricing:Experience + Award:Pricing:Experience. Number of observations $n = 128$, degrees of freedom $df = 117$.

We disentangle the effects found by the MANOVA by conducting a separate ANOVA for each dependent variable. The results of the three analyses are presented in Table 3.7.

None of the treatment variables show a significant effect on the auction prices, which supports Hypothesis 2 (1).

Result 3. *The auction prices in the four auctions are homogeneous and we observe no differences.*

However, we observe differences in the profits of the bidders with respect to the price rule, which contradicts Hypothesis 2 (2).

Result 4. *Bidders' profits are higher under UP-HAB than under PAB.*

	Auction Prices			Bidders' Profits			Efficiency		
Variable	Diff	F	p-value	Diff	F	p-value	Diff	F	p-value
Aw (NB-B)	-0.191	0.126	0.720	0.251	0.575	0.450	1.219	15.838	0.000***
Pr (UP-PAB)	0.987	3.444	0.067	0.837	6.383	0.013*	0.688	5.040	0.026*
Exp (E-I)	-0.419	0.602	0.435	-0.638	3.711	0.056	0.625	4.165	0.043*
Aw:Pr		0.933	0.336		1.869	0.174		0.010	0.919
Aw:Exp		0.144	0.705		0.004	0.951		1.760	0.187
Pr:Exp		0.133	0.716		0.149	0.700		1.499	0.223
Aw:Pr:Exp		0.471	0.494		0.416	0.520		0.260	0.611

Table 3.7: Analysis of variance. Fit: Prices/Bidders' Profits/Efficiency $\sim$ Award + Pricing + Experience + Award:Pricing + Award:Experience + Pricing:Experience + Award:Pricing:Experience.

This result can be attributed to the effect of the price rule on efficiency, which we now consider. The last column of Table 3.7 indicates that all three treatment variables have a significant effect on efficiency, which contradicts Hypothesis 2 (3).

First, we observe significantly more efficient auction allocations in the non-binding treatments. This suggests that the option to diversify bids in the non-binding auctions facilitates the calculation of optimal bid-shading, whereas the binding mechanism allows only one bid. The underlying intuition for the superiority of non-binding mechanisms is based on the diversification of bids: a bidder's lowest bid is nearer to her true costs than her bid in the corresponding binding auction. This leads to a more accurate mapping (regarding the monotonicity) of individual costs onto bids and, thus, better efficiency performance.

Second, UP-HAB leads to more efficient allocations than PAB.[14] The intuition is that a varying absolute value of bid shading in PAB auctions (due to e.g. risk

[14]This is in line with recent empirical studies and often referred to as one of the main advantages of a UP-HAB, see e.g. Vickrey (1961). Smith, Cox, and Walker (1985) observe that UP-HAB is more efficient than PAB in case of experienced subjects. For single-unit auctions the result holds independent from subjects' experience, see e.g. Cox, Roberson, and Smith (1982) and Coppinger, Smith, and Titus (1980).

aversion) may lead to inefficiencies. Since auction prices remain constant, subjects benefit from participating under UP-HAB with a higher efficiency (Result 4).

Third, we conclude that auctions with experienced subjects tend to generate more efficient outcomes, since the variance in bids of inexperienced subjects is higher due to their only sketchy understanding of the mechanism.[15]

Result 5. *The efficiency rate is higher*

- *in the non-binding auction than in the binding auctions,*
- *under UP-HAB than under PAB,*
- *for experienced subjects than for inexperienced subjects.*

Since the control variable experience is significant in the MANOVA, we further separate the data with respect to the subjects' experience and conduct two more analyses of variance (Table 3.8 and Table 3.9). For inexperienced subjects, the only significant effect is that of Award on efficiency: non-binding awards lead to significantly more efficient allocations than binding awards. For experienced subjects, both Pricing and Award have a significant effect on efficiency: UP-HAB and non-binding awards significantly increase the degree of efficiency.

3.3.4 Comparison of the Experimental and Theoretical Results

In this section, we compare the experimental observations with the corresponding theoretical results in Section 3.2. We conduct sign tests (two-tailed binomial tests)

[15] Similar results are presented by Cox, Smith, and Walker (1984), where subjects learned through repetition to adapt their bids towards the optimal bidding strategy in PAB auctions. Also, Coppinger, Smith, and Titus (1980) finds that learning results in more dominant strategy bids in second-price auctions. In contrast, Harstad (2000) states that even experienced subjects tend to overbid in second-price auctions. However, if subjects have bid in a dynamic English auction before, significant learning effects can be observed in form of bidding closer to the dominant strategy. Nevertheless, Smith, Cox, and Walker (1985) observe that submitted bids deviate stronger from optimal bidding in case of increasing experience in PAB and uniform price auctions, see also Smith (1967) and Miller and Plott (1985).

	Prices			Bidder's Profits			Efficiency		
Variable	Diff	F	p-value	Diff	F	p-value	Diff	F	p-value
Aw (NB-B)	-0.396	0.240	0.626	0.231	0.217	0.643	1.625	11.880	0.001**
Pr (UP-PAB)	1.184	2.143	0.148	0.709	2.047	0.158	0.313	0.439	0.510
Aw:Pr		1.215	0.275		1.809	0.184		0.070	0.791

Table 3.8: Analysis of variance for inexperienced subjects. Fit: Prices/Bidders' Profits/Efficiency $\sim$ Award + Pricing + Award:Pricing.

	Prices			Bidder's Profits			Efficiency		
Variable	Diff	F	p-value	Diff	F	p-value	Diff	F	p-value
Aw (NB-B)	0.013	0.000	0.985	0.272	0.382	0.539	0.813	4.319	0.042*
Pr (UP-PAB)	0.789	1.221	0.273	0.965	4.816	0.032*	1.063	7.385	0.009**
Aw:Pr		0.045	0.834		2.96	0.589		0.023	0.633

Table 3.9: Analysis of variance for experienced subjects. Fit: Prices/Bidders' Profits/Efficiency $\sim$ Award + Pricing + Award:Pricing.

with the null hypothesis that lower and higher observations than in the corresponding symmetric equilibrium are equally likely. The p-values are computed by the Z-statistics.

Each auction (Binding PAB, Non-Binding PAB, Binding UP-HAB, Non-Binding UP-HAB) is played in 16 blocks of ten rounds. Although we do not observe differences in the average auction prices between the four auctions (Result 3), the average price in each of the 16 blocks of each auction (Table A.1) is smaller than the expected (average) equilibrium price of 174.25 (determined by the expected value of the third order statistics).[16]

Result 6. *The (average) auction prices in each of the four auctions are smaller than the corresponding (average) equilibrium price.*

[16]Sign test for each treatment on the difference between the (average) equilibrium price and average auction price: 16 observations with no negative differences and 16 positive differences, p-value $< 0.001^{***}$.

The deviations of the observed bids from the equilibrium bids in the binding PAB and UP-HAB auctions (see Table 3.10) are in line with Result 6: subjects submit lower bids (i.e., they bid less aggressive) than theory predicted. However, Figure 3.3 reveals for both binding auctions PAB and UP-HAB that this does not apply for subjects with high costs, who on average submit higher bids than in the equilibrium.

Binding	PAB	UP-HAB
# Equilibrium	113	98
# Overbid	236	228
# Underbid	1571	1594
Z-statistics	28.562	31.979
p-value	<0.001***	<0.001***

Table 3.10: Binding auctions: number of bids equal, higher or lower than the corresponding equilibrium bid.

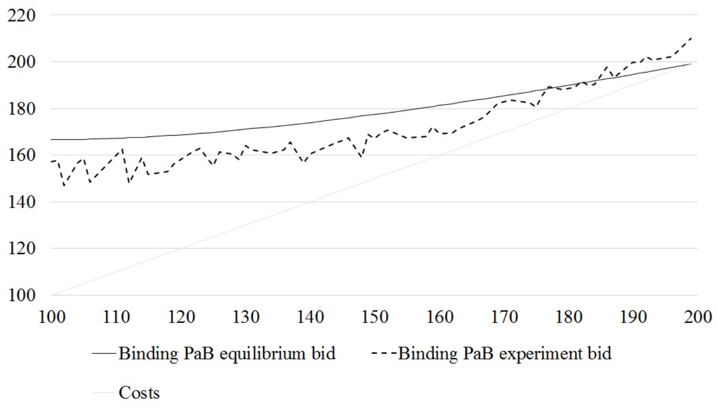
Result 7. *In the binding auctions with both PAB and UP-HAB, the subjects submit lower bids than in the symmetric equilibrium, except for high costs.*

The same applies to the non-binding PAB auctions (see Table 3.11 and Figure 3.4). For both the first and the second bid, the subjects submit lower values than theory predicts in the equilibrium, except for subjects with high costs.

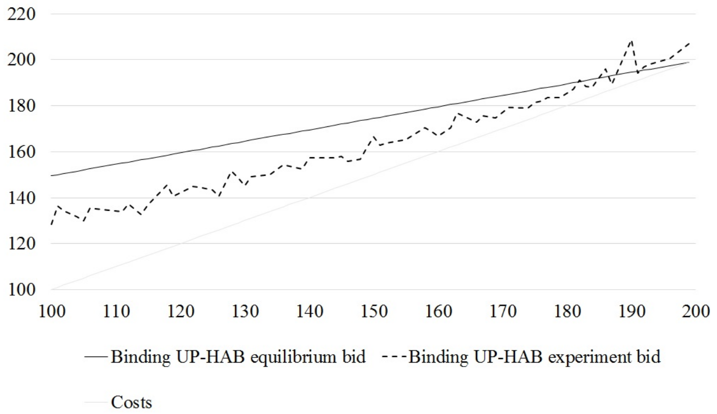
Non-binding PAB	Bid 1	Bid 2
# Equilibrium	211	39
# Overbid	435	201
# Underbid	1274	670
z-statistics	20.270	15.858
p-value	<0.001***	<0.001***

Table 3.11: Non-Binding PAB auctions: number of bids equal, higher or lower than the corresponding equilibrium bids.

Result 8. *In the non-binding PAB auctions, the subjects submit lower bids than in the symmetric equilibrium, except for high costs.*



(a) Binding PAB



(b) Binding UP-HAB

Figure 3.3: Binding auctions: average bids and corresponding equilibrium bids.

Figure 3.2 (b) together with Result 6 allow us to conclude that this also applies to the non-binding UP-HAB auction in the case that a symmetric equilibrium exists.

Our observation of less aggressive bidding behavior is in line with Harrison (1989), who also observes less aggressive bids in experimental binding PAB sales auctions. He argues that here risk aversion plays a crucial role. Subjects with high costs do not show this behavior in our experiment. They bid more aggressively and even submit higher bids than in the equilibrium. A plausible explanation for this phenomenon is

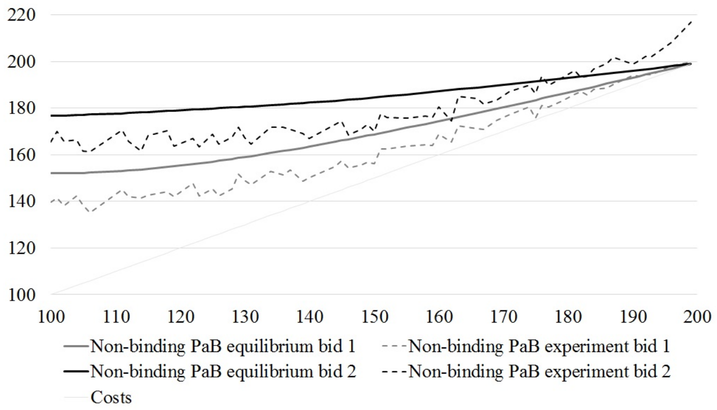


Figure 3.4: Non-binding PAB auctions: average first bids and second bids and corresponding equilibrium bids.

that the subjects add a minimum mark-up on their costs to ensure a minimum profit in case of winning, and this mark-up exceeds the equilibrium mark-up for high costs since this becomes very small (see Figure 3.3 and 3.4).

3.4 Extensions

Our model can be extended for further research. For a generalized and increasing number of bidders, we expect the results for PAB and UP-HAB to converge towards those for UP-LRB because costs exaggeration might converge to zero as competition increases. Next, the impact of positive costs of withdrawal $z > 0$ might be worthwhile to investigate. We anticipate that rational bidders only reject their award in case the difference between their actual award price and the award price after withdrawing exceeds the withdrawal costs z. As a consequence, increasing withdrawal costs inhibit withdrawals. Further analyses with multi-unit supply might be complex but also have far-reaching implications for real-world applications. Last but not least, penalties should be added to these analyses as they might become crucial for governments to ensure expansion goals.

3.5 Conclusion

We find both theoretical and experimental evidence that non-binding awards per se are not determinant for an auction to fail. Particularly, in case of a reallocation procedure, non-binding awards seem to have no unfavorable impact on the outcome of multi-unit auctions with single-unit supply, neither under PAB nor under UP.

As a main result, our theoretical analysis reveals that non-binding awards with exhaustive reallocation offer the bidders the chance to optimize their multiple bids for one good in the non-incentive compatible auctions with PAB and UP-HAB. First, it is a (weakly) dominant strategy to submit as many bids as feasible. In the experiment the subjects seize the opportunity to submit an additional bid in almost all cases. Second, according to our theoretical results, in a non-binding auction bidders spread their multiple bids around the corresponding bid of the binding auction, which we also observe in the experiment. By submitting lower and higher bids, bidders optimize the trade-off between increasing their winning probability (by a lower bid) and their individual profit in case of award (by a higher bid). However, we observe systematically lower bids in the binding and non-binding auctions than in the symmetric equilibria with risk-neutral bidders, except for bids for high costs with a low probability of winning. A plausible explanation is that subjects rather behave risk averse, but add a minimum mark-up on their costs in order to ensure a minimum profit in case of winning. Summarizing, the theory and the experiment yield the same form of bid diversification, but with systematically lower bids in the experiment. In theory, revenue equivalence holds among the considered auctions, which also applies to the experiment, however with a significant lower price level, which follows from the observation of experimental bids below the equilibrium.

We also observe deviations from the theory for bidder's profits and efficiency. While theory predicts equal profits in the PAB and UP-HAB auctions, we observe higher profits for experienced subjects in the UP-HAB auctions. This might be due to windfall profits under UP-HAB which arise in case the price determining bidder submits a very low bid in relation to the awarded ones. Finally, we observe in our experiment that non-binding awards increase efficiency. The reason is that lower bids in the bid diversification come closer to the bidder's costs signals and hence offer a more accurate mapping from costs onto bids, which increases the chances of efficient allocations. Further, the efficiency rate is higher under UP-HAB than under PAB and increased by experience. An intuitive explanation is that, first, UP-HAB bids are lower than PAB bids and hence closer to the bidders' costs, which again encourages efficient allocations, and, second, experience reduces irrational bidding and thereby leads to higher efficiency rates. We conclude that non-binding awards in combination with reallocation do not only offer bidders the chance to handle financing risks, but also increase efficiency.

Chapter 4

Discrimination in Auctions for Renewable Energy Support – Three Theoretically Equivalent but Practically Different Concepts

The design of auctions for renewable energy support becomes more complex by the integration of different types of bidder with asymmetric cost structures, e.g., multi-technology auctions or cross-border auctions with bidders from different countries. In order to privilege specific bidder groups and to control the allocation, discriminatory elements are often included into the auction design. We analyze the three most applied discriminatory instruments: a minimum quota or a bonus for a bidder class to be privileged or different maximum prices for different bidder classes. Typically, these instruments discriminate stronger bidders (with lower costs) in favor of weaker bidders (with higher costs). We show that all three instruments can reduce the support costs compared to free competition. Moreover, we prove that the three instruments are theoretically equivalent: every auction outcome that can be reached by one instrument can also be reached by the others including the outcome with minimal support costs. However, there are crucial differences concerning the practical application, particularly with respect to the robustness to misestimations of the cost structures. We show that the combination of the instruments helps to avoid costly errors.

4.1 Introduction

The European Commission proposes to conduct auctions that are open to multiple RE technologies (European Commission, 2014). This requirement is based on the assumption that multi-technology auctions increase efficiency and reduce support costs even further.[1] Multi-technology auctions have been implemented, e.g., in the United Kingdom (Department for Business, Energy & Industrial Strategy, 2017), Spain (Ministerio de Energia, Turismo y Agenda Digital, 2017a), the Netherlands (Minister van Economische Zaken, 2015) or Mexico (Centro Nacional de Control de Energia, 2017). Denmark and Germany conducted auctions for large photo voltaic installations that were open to bidders from both countries (Kitzing et al., 2016). Further, Germany conducts technology-neutral auctions for solar and wind onshore in a pilot phase from 2018 to 2020 (German Federal Parliament, 2017b).

The general differences between technology-neutral and technology-specific support is well discussed in the literature (Aghion et al., 2009; Azar and Sandén, 2011). According to Jägemann et al. (2013) and Jägemann (2014), technology-neutral support may reduce the overall expenses and CO_2 emissions of energy production. However, Gawel et al. (2017) and Lehmann and Söderholm (2017) state that the evaluation of technology-neutral and specific support is more complex. These considerations play a role when designing auctions for RES-E. With these auctions, national governments

[1] Concerns about windfall profits are sometimes cited as arguments against auctions with heterogeneous types of bidders, e.g., multi-technology auctions (Held et al., 2006).

typically pursue different targets, particularly with respect to the type of costs that are aimed to be minimized (del Río and Cerdá, 2014; Kreiss et al., 2017). There are arguments to address only support costs or only generation costs or also to include integration costs (Joskow, 2011; Ueckerdt et al., 2013).

Most commonly, the minimization of support costs is the stated primary goal and main reason for RE auctions, e.g., in the United Kingdom (Department of Energy and Climate Change, 2011), in Mexico (Centro Nacional de Control de Energia, 2017) and in California (Public Utilities Commission of the State of California, 2010) it is explicitly stated that the auctions should minimize the costs of RE support. The definition of auction goals in other countries and even the statement of the European Commission can be interpreted so that the support costs are (one of) the most important target (European Commission, 2014; Ministerio de Energia, Turismo y Agenda Digital, 2017b). That is, the minimization of support costs attracts particular attentions when designing auctions for RES-E.

Auctions for RES-E also include discriminatory design elements to privilege specific bidder groups and to control the allocation. The focus of this paper is to analyze different discriminatory instruments and their effects on the auction outcome, particularly on support costs. The considered instruments are minimum or maximum quotas, maximum prices (i.e., reservation prices), and boni or mali for different bidder classes. All these instruments have been implemented in auctions for RES-E: different maximum prices in the multi-technology auction in the Netherlands (Minister van Economische Zaken, 2015), a bonus depending on the location in the German auction for onshore wind (German Federal Parliament, 2016a) and quotas that depend on the availability in the Californian auctions (Public Utilities Commission of the State of California, 2010).

The implementation of discriminatory instruments is often not only intensified by the minimization of the support costs but also by other criteria, e.g., grid and system integration, mixture of different RE technologies, regional distribution of RE, or actor diversity (Kreiss et al., 2017). Also in the context of such criteria, it is important to understand the effects of the discriminatory instruments on the auction outcome and the support costs.

Discriminatory instruments have been theoretically analyzed in a general context by, e.g., Schmalensee (1981), Varian (1989), Myerson (1981), Bulow and Roberts (1989), and McAfee and McMillan (1989). This paper goes one step further with a detailed analysis of the three discriminatory instruments for the actual application of RE auctions.

We show that each instrument (quota, bonus, maximum price) can reduce the support costs, and we derive conditions (w.r.t. support cost minimization) for each instrument and prove that the instruments are theoretically equivalent: every auction outcome (including support costs) that can be implemented by a specific parameterization of one instrument can also be reached by the two other (correspondingly parameterized) instruments.

However, with respect to the application in practice, there are crucial differences between the instruments, which have to be taken into account when deciding on their implementation. This particularly refers to the robustness of the desired effects of discrimination and the risk and magnitude of undesired effects that may be caused by a wrong calibration, e.g., due to misestimation of the absolute and relative strength of the different bidder classes that are treated differently in the auction. This is also of particular interest in the above mentioned cases with additional or other targets than the minimization of support costs.

This paper transfers microeconomic theory to a dynamic environment of increasing importance. It helps to understand the effects that different discriminatory instruments have on bidding behavior and the auction outcome. Since auctions for RES-E become increasingly relevant and more and more auctions are opened for several technologies or participants from different countries, the relevance of this topic also increases.

In Section 4.2, we present our theoretic analysis of the discriminatory instruments quota, maximum price, and bonus in auctions for RES-E. An illustrating example is provided in Section 4.2.4. The results of our analyses are compared and discussed regarding the practical implementation in Section 4.3. We summarize in Section 4.4.

4.2 Model

Consider a procurement auction for RES-E with a fixed demand D for a specific good (e.g., capacity [MW] or energy [MWh per year]). The supply is given by single-project bidders each offering the same volume that sum up to the total supply. The bidders have independent and private project costs for producing an unit of the good. The ascending order of private project costs is given by the marginal cost function $MC(v)$ with $MC(0) > 0$ and $MC'(v) = \frac{\mathrm{d}MC(v)}{\mathrm{d}v} > 0$ for all $v \geq 0$. That is, if v is delivered by the projects with the lowest costs, $MC(v)$ are the highest marginal costs among these projects. The lowest total costs $C(v)$ for delivering v are given by the cumulated marginal costs, $C(v) = \int_0^v MC(z)dz$. In the context of RE, $MC(v)$ are the levelized costs of electricity (LCOE) at v, i.e., the net present value of the total life cycle costs per unit of generated electricity of the RE source which would be ranked in the ascending order at v (Short et al., 1995). Hence, $C(v)$ are the aggregated LCOE for delivering v of all RE sources with LCOE lower than or equal to $MC(v)$.

There are two disjoint classes of bidders (e.g., two different technologies): low-cost bidders (L) and high-cost bidders (H). The two bidder classes L and H are characterized by different marginal cost functions MC_L and MC_H with

$$MC_L(v) < MC_H(v) \quad \text{for all} \quad v \geq 0. \tag{4.1}$$

That is, the marginal costs and total costs for delivering any volume v are lower for the low-cost bidders than for the high-cost bidders. In the context of RE, this means that the high-cost bidders need higher support for delivering a certain volume v than the low-cost bidders. According to IRENA and CEM (2015), different RE sources in different countries and different years have significantly different cost structures. This means, costs to supply RE in a specific country and year are lower for one technology than for another. However, the overall costs might be minimized utilizing both technologies[2].

In the auction, the uniform price rule is applied and the uniform price is determined by the lowest rejected bid.[3] Bidders simultaneously submit their bids for the monetary support for their projects. In this auction, a bidder's optimal bidding strategy (weakly dominant strategy) is to bid the support that exactly covers his costs (Weber, 1983b). Therefore, the supply functions $S_L(p)$ and $S_H(p)$ of the low-cost and high-cost bidders are given by

$$S_L(p) = MC_L^{-1}(p) \;\text{ and }\; S_H(p) = MC_H^{-1}(p) \tag{4.2}$$

and increase in the price p. From (4.1) follows

$$S_L(p) > S_H(p) \;\text{ for all }\; p \geq MC_L(0)\,. \tag{4.3}$$

Thus, in free competition, the market clearing price p^* is determined by

$$S_L(p^*) + S_H(p^*) = D\,, \tag{4.4}$$

[2]Even though the marginal costs for every demand v are lower for one technology, there are demands y and $\tilde{y}$ with $\tilde{y} > y$ so that the marginal costs for the lower cost technology for demand $\tilde{y}$ are higher than for the higher cost technology and the lower demand y, i.e., $MC_H(y) < MC_L(\tilde{y})$

[3]Since the marginal cost functions and, thus, the supply functions are continuous, there is no difference between the price rule of the lowest rejected bid and the price rule of the highest accepted bid, which is more common in practice.

where the supply of the low-cost bidders exceeds the supply of the high-cost bidders: $S_L(p^*) > S_H(p^*) \geq 0$. The auctioneer's total costs amount to $TC(p^*) = p^* D$, i.e., the overall costs of all support payments to the awarded RE projects.

The elasticities of supply of the two bidder classes L and H are defined as

$$\varepsilon_i(p) = \frac{S_i'(p)}{S_i(p)} p \quad \text{with} \quad S_i'(p) = \frac{\mathrm{d}S_i(p)}{\mathrm{d}p}, \; i \in \{L, H\} \,. \tag{4.5}$$

Additional to (4.1), we state the following assumptions.

Assumption 1.

(i) The elasticities of supply $\varepsilon_L(p)$ and $\varepsilon_H(p)$ are non-increasing in p.

(ii) $S_H(p^*) > 0$ and $\varepsilon_L(p^*) < \varepsilon_H(p^*)$ at the market clearing price p^* of free competition.

Assumption (i) is a standard economic assumption and also supported by the RE literature (de Vries et al., 2007; Hoefnagels et al., 2011; Brown et al., 2016). Assumption (ii) is more context sensitive: the high-cost bidders at least gain a small share in a non-discriminatory auction.[4] Since this share is smaller than that of the low-cost bidders, it is reasonable to assume that the high-cost bidders' price elasticity of supply at p^* is higher than that of the low-cost bidders.

In the following, we analyze three discriminatory instruments. First, a quota guarantees the high-cost bidders a certain minimum supply volume. Second, a maximum (reservation) price for the low-cost bidders is set, which the low-cost bidders must not exceed with their bids. Third, the high-cost bidders receive a bonus in form of

[4] In case that the bidder classes are distinguished by their technology, there are examples of regions where one technology is much less costly than the other so that the high-cost bidders never have a chance to be awarded in a non-discriminatory auction. This, for example applies to North Dakota (Brown et al., 2016) or to Norway (Hoefnagels et al., 2011), where wind energy is much less costly than PV. However, there are many examples where wind and solar are both awarded in multi-technology auctions, e.g. Mexico (IRENA, 2017), or are awarded in separate auctions but at similar price levels, e.g. in Germany (German Federal Network Agency, 2017a,b).

an additional payment in case of award. All three forms of discrimination induce a (supply) volume shift from the low-cost to the high-cost bidders (by always covering the total auction volume D) involving a respective price change. Moreover, all three forms of discrimination necessarily involve different prices p_L and p_H for the awarded low-cost and the awarded high-cost bidders.

In our analyses, we consider the total support costs

$$TC(p_L, p_H) = p_L S_L(p_L) + p_H S_H(p_H) \tag{4.6}$$

which depend on the prices p_L and p_H and the corresponding supply volumes $S_L(p_L)$ and $S_H(p_H)$ with $S_L(p_L) + S_H(p_H) = D$.

4.2.1 Quota

Consider a minimum quota (minimum contingent) $Q < D$ for the high-cost bidders.[5] The quota guarantees that the high-cost bidder group will at least supply Q. Thus, the low-cost bidders' supply never exceeds $D - Q$. The quota only becomes effective if $Q > S_H(p^*)$, i.e., the high-cost bidders would not reach Q in free competition. If the quota is effective, each bidder class gets its own uniform award price p_L and p_H, which are given by

$$p_L = MC_L(D - Q) \;\text{ and }\; p_H = MC_H(Q)\,. \tag{4.7}$$

The volume shift

$$q = \max\{Q - S_H(p^*), 0\} \tag{4.8}$$

from the low-cost bidders to the high-cost bidders, induced by the quota Q, increases the award price for the high-cost bidders and decreases the award price for the low-

[5]Analogously, we could consider a maximum quota for the low-cost bidders.

cost bidders compared to free competition, $p_H < p^* < p_L$, if $q > 0$. The volume shift q and the price difference both effect the support costs. First, we investigate the effects by starting at $q = 0$, which corresponds to the situation of an ineffective quota.

Lemma 2. *Consider a procurement auction with uniform pricing, fixed demand D, two bidder classes L and H and a minimum quota Q for the high-cost bidders H. The support costs decrease when the quota becomes effective, i.e., $q = \max\{Q - S_H(p^*), 0\}$ becomes positive.*

Lemma 2, whose proof is presented in Appendix B.1, states that the auctioneer can reduce costs by limiting the low-cost bidders. Since the high-cost bidders' elasticity of supply exceeds that of the low-cost bidders at the free competition price p^*, the relative price change (savings) induced by a volume reduction for the low-cost bidder group is greater than the relative price change (costs increase) induced by a volume shift to the high-cost bidders. That is, the cost increase caused by the higher prices for the (few) high-cost bidders is smaller than the savings caused by the lower prices for the (many) low-cost bidders. Therefore, the auctioneer can reduce the support costs by implementing a quota that leads to $q > 0$.

Proposition 7. *There exists an unique quota $\hat{Q} > S_H(p^*)$ that minimizes the support costs. The optimal quota $\hat{Q}$ together with the award prices p_L and p_H are determined by $\hat{Q} = S_H(p_H)$, $S_L(p_L) + S_H(p_H) = D$ and*

$$p_H - p_L = \frac{S_L(p_L)}{S'_L(p_L)} - \frac{S_H(p_H)}{S'_H(p_H)}\,.$$

The proof is presented in Appendix B.1. The price difference $p_H - p_L > 0$ caused by the quota is also referred to in the literature. McAfee and McMillan (1989) show that this applies to international auction where domestic and foreign companies compete. Both results are based on the principle of monopolistic third degree price discrimination (Schmalensee, 1981; Varian, 1989). The monopolist discriminates different classes to absorb their different spending power. In auctions for RES-E, the auctioneer reduces the bidder rent by absorbing low-cost bidders' profits at the expense of an inefficient outcome. The total support decreases as long as the high-cost bidders' elasticity of supply is larger than that of the low-cost bidders.

4.2.2 Maximum Price

The next discriminatory instrument is a reservation price R in form of a maximum price for the low-cost bidders: low-cost bidders may not submit bids higher than R. The maximum price does not have an effect on bidding behavior and, thus, incentive compatibility holds: the bidders of both classes bid their true costs, except for the low-cost bidders with higher individual costs than R, who do not participate.

The maximum price is effective if $R < p^*$, i.e., the maximum price is lower than the uniform award price in free competition. Then, by (4.2) and (4.4), the low-cost-bidders receive a smaller volume $S_L(R) < S_L(p^*)$ and a lower price $R < p^*$ than in free competition, while by the high-cost bidders receive a higher volume and a higher price $p_H > p^*$. The maximum price induces a volume shift from the low-cost bidders to the high-cost bidders and a higher price for the high-cost bidders than for the low-cost bidders. These effects are equivalent to the effects of a volume shift (4.8) induced by a quota $Q > S_H(p^*)$, as derived in Section 4.2.1.

Corollary 2. *Consider a procurement auction with uniform pricing, fixed demand D, two bidder classes L and H and a maximum price R for the low-cost bidders L.*

(i) The support costs decrease when the maximum price R becomes effective, i.e., $R - p^*$ becomes negative.

(ii) There exists an unique maximum price $\hat{R} > 0$ that minimizes the support costs. The optimal maximum price $\hat{R}$ together with the award price p_H for the high-cost

bidders is determined by $S_L(\hat{R}) + S_H(p_H) = D$ *and*

$$p_H - \hat{R} = \frac{S_L(R)}{S'_L(\hat{R})} - \frac{S_H(p_H)}{S'_H(p_H)}\,.$$

4.2.3 Bonus

First, we consider a bonus in form of an additional monetary payment to the awarded high-cost bidders.[6] Let $B > 0$ denote the bonus that is added to the award price p for the awarded high-cost bidders.

Incentive compatibility holds in the sense that the low-cost bidders bid their true costs and the high-cost bidders reduce their bid by exactly the bonus B (Thiel, 1988). Thus, all bidders receive their costs if the award price equals their bid. However, the awarded low-cost bidders receive $p_L = p$, while the awarded high-cost bidders receive $p_H = p + b = p_L + b$.

The higher price p_H for the high-cost bidders leads to a corresponding supply increase for these bidders described by (4.2). Together with the analysis in Section 4.2.1, this directly implies the following. First, implementing a bonus $B > 0$ for the high-cost bidders is equivalent to a volume shift (4.8) from the low-cost bidders to the high-cost bidders that is induced by a quota $Q > S_H(p^*)$. Second, the bonus that fulfills the condition in Proposition 7, minimizes the support costs. We can state the following result.

Corollary 3. *Consider a procurement auction with uniform pricing, fixed demand* D*, two bidder classes* L *and* H *and a bonus* B *for the high-cost bidders* H*.*

(i) The support costs decrease when the bonus B *becomes positive.*

(ii) There exists an unique bonus $\hat{B} > 0$ *that minimizes the support costs. The optimal bonus* $\hat{B}$ *together with the award price* p *is determined by* $S_L(p)+S_H(p+$

[6] Analogously, we could consider a malus for the low-cost bidders in form of a deduction on the award price.

$B) = D$ *and*

$$\hat{B} = \frac{S_L(p)}{S'_L(p)} - \frac{S_H(p+B)}{S'_H(p+B)}.$$

The second bonus type is the so-called bid bonus, which reduces the high-cost bidders' bids by B. Incentive compatibility holds for both bidder classes, i.e., all bidders bid their true costs. The bid bonus is only relevant in competition and does not apply to the award price. It "strengthens" the high-cost bidders by increasing their chance of winning. The supply of the high-cost bidders $S_H(p_H)$ and their award price p_H are higher than in the free competition case, while the reverse holds for the low-cost bidders. Since the argumentation is the same as for the monetary bonus, Corollary 3 also applies to the bid bonus.

4.2.4 Example

The following example illustrates the principle of functionality of the three discriminatory instruments $\hat{Q}$, bonus $\hat{B}$ and maximum price $\hat{R}$. In our example, we assume that the marginal costs of the bidders in class $i \in \{L, H\}$ are uniformly distributed over the interval $[\underline{MC}_i, \overline{MC}_i]$ with $\underline{MC}_H > \underline{MC}_L > 0$, $\overline{MC}_H > \overline{MC}_L$, and $\overline{MC}_L > \underline{MC}_H$. We first assume $\overline{MC}_H - \underline{MC}_H = \overline{MC}_L - \underline{MC}_L$ and the same number of bidders in the two classes. This leads to linear marginal cost functions of the form

$$MC_i(v) = \frac{v}{m} + \underline{MC}_i \tag{4.9}$$

for $v \in [0, n(\overline{MC}_i - \underline{MC}_i)]$ with $n > 0$. The number of bidders is represented by n, i.e., the inverse of the gradient of the marginal cost function, which, by assumption, is the same in the two classes. Thus, the marginal cost functions are parallel shifts of each other. Translated to a practical application this means that there are as many low-cost bidders as high-cost bidders, however, there is a structural price difference $(\underline{MC}_H - \underline{MC}_L)$ between the two groups. Thus, the condition of lower costs for every quantity is fulfilled. By (4.2), the supply functions for $i \in \{L, H\}$ are

$$S_i(p) = \begin{cases} 0 & \text{for } p < \underline{MC}_i \\ n(p - \underline{MC}_i) & \text{for } p \geq \underline{MC}_i . \end{cases} \tag{4.10}$$

with

$$S_i'(p) = \frac{\mathrm{d}S_i(p)}{\mathrm{d}p} = m\,. \tag{4.11}$$

for $p > \underline{MC}_H$, which holds by Assumption 1 (ii). By (4.5), the elasticity of supply is

$$\varepsilon_i(p) = \frac{S_i'(p)}{S_i(p)} p = \frac{p}{p - \underline{MC}_i}\,, \tag{4.12}$$

which is non-increasing for all $p \geq 0$,

$$\frac{d\varepsilon_i(p)}{dp} = -\frac{\underline{MC}_i}{(p - \underline{MC}_i)^2} < 0 \;\text{ for all }\; p \neq \underline{MC}_i\,.$$

Since $\underline{MC}_H > \underline{MC}_L$, $\varepsilon_H(p) > \varepsilon_L(p)$ for all $p > \underline{MC}_H$. In free competition, the uniform award price p^* is determined by the market clearing condition (4.4) and (4.10):

$$p^* = \frac{D}{2m} + \frac{\underline{MC}_L + \underline{MC}_H}{2}\,.$$

This leads to

$$\begin{aligned} S_H(p^*) &= n(p^* - \underline{MC}_H) &= \frac{D}{2} - \frac{n}{2}(\underline{MC}_H - \underline{MC}_L)\,, \\ S_L(p^*) &= n(p^* - \underline{MC}_L) &= \frac{D}{2} + \frac{n}{2}(\underline{MC}_H - \underline{MC}_L)\,. \end{aligned}$$

That is, both bidder classes receive one half of the total demand plus/minus a spread that depends on the difference $(\underline{MC}_H - \underline{MC}_L)$ and the gradient n. Part (ii) of

Assumption 1 requires

$$\frac{D}{m} > \underline{MC}_H - \underline{MC}_L\,. \tag{4.13}$$

The total support costs are

$$\begin{aligned} TC(p^*) = \quad & TC_L(p^*) + TC_H(p^*) & = p^* S_L(p^*) + p^* S_H(p^*) = p^* n(2p^* - \underline{MC}_L - \underline{MC}_H) \\ = \quad & Dp^* & = \frac{D}{2}\left(\frac{D}{m} + \underline{MC}_L + \underline{MC}_H\right)\,. \end{aligned} \tag{4.14}$$

In Figure 4.1, the individual support costs $TC_L(p^*)$ and $TC_H(p^*)$ are visualized by the areas $p^*S_L(p^*)$ and $p^*S_H(p^*)$. Clearly, the low-cost bidders receive a larger payment as they supply more.

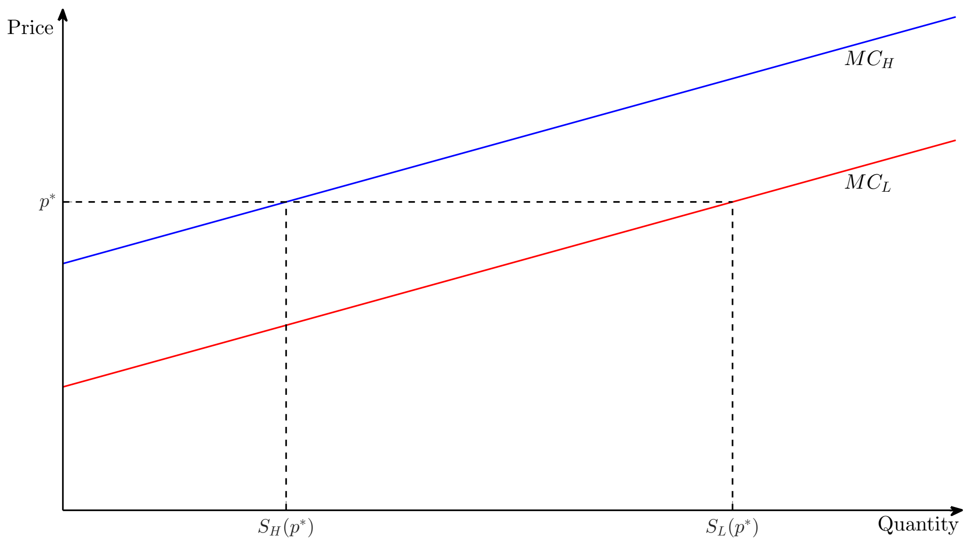


Figure 4.1: Illustration of the example with free competition.

We now consider the optimal quota $\hat{Q}$, bonus $\hat{B}$, and maximum price $\hat{R}$. According to Proposition 7 and Corollary 2 and 3, optimal values of discriminatory instruments are determined by the price difference

$$p_H - p_L = \frac{S_L(p_L)}{S'_L(p_L)} - \frac{S_H(p_H)}{S'_H(p_H)} = (p_L - \underline{MC}_L) - (p_H - \underline{MC}_H)\,,$$

which directly determines the optimal bonus $\hat{B}$:

$$p_H - p_L = \frac{\underline{MC}_H - \underline{MC}_L}{2} = \hat{B}\,. \tag{4.15}$$

Applying (4.4), the relationship between the free competition price p^* and the prices p_H and p_L under the optimal discriminatory instruments is given by

$$\begin{gathered} S_L(p^*) + S_H(p^*) = S_L(p_L) + S_H(p_H) = D\,, \\ \Rightarrow 2p^* = p_H + p_L\,. \end{gathered}$$

With (4.15), we get

$$\begin{aligned} p_H &= p^* + \tfrac{\underline{MC}_H - \underline{MC}_L}{4} &&= \frac{D}{2m} + \frac{3\underline{MC}_H + \underline{MC}_L}{4}\,, && (4.16) \\ p_L &= p^* - \tfrac{\underline{MC}_H - \underline{MC}_L}{4} &&= \frac{D}{2m} + \frac{3\underline{MC}_L + \underline{MC}_H}{4} = \hat{R}\,, && (4.17) \end{aligned}$$

which also determines the optimal maximum price $\hat{R}$.

The price increase for the high-cost bidders is equal to the price reduction for the low-cost bidders[7]. By (4.10), (4.16) and (4.17), the supply volumes and the optimal quota $\hat{Q}$ are

$$\begin{aligned} S_H(p_H) &= m\left(p^* - \tfrac{3\underline{MC}_H + \underline{MC}_L}{4}\right) &&= \frac{D}{2} - \frac{m}{4}(\underline{MC}_H - \underline{MC}_L) = \hat{Q}\,, && (4.18) \\ S_L(p_L) &= m\left(p^* - \tfrac{3\underline{MC}_L + \underline{MC}_H}{4}\right) &&= \frac{D}{2} + \frac{m}{4}(\underline{MC}_H - \underline{MC}_L) = D - \hat{Q}\,. && (4.19) \end{aligned}$$

[7]This equality is caused by the characteristics of the example because the marginal cost curves of both classes are parallel shifts of each other. This equality does not necessarily hold for other marginal cost curves.

With (4.18) and (4.19), the volume shift $q = \hat{Q} - S_H(p^*)$ from the low-cost bidders to the high-cost bidders is

$$q = m\left(p^* - \frac{3\underline{MC}_H + \underline{MC}_L}{4}\right) - n(p^* - \underline{MC}_H) = \frac{m}{4}(\underline{MC}_H - \underline{MC}_L)\,. \qquad (4.20)$$

Comparing the total support costs $TC(p_L, p_H)$ under the optimal quota $\hat{Q}$, bonus $\hat{B}$ and maximum price $\hat{R}$ with $TC(p^*)$ in free competition (4.14) yields

$$\begin{aligned} TC(p_L, p_H) &= p_H S_H(p_H) + p_L S_L(p_L) \\ &= \left(p^* + \frac{\underline{MC}_H - \underline{MC}_L}{4}\right) m \left(p^* - \frac{3\underline{MC}_H + \underline{MC}_L}{4}\right) + \\ &\left(p^* - \frac{\underline{MC}_H - \underline{MC}_L}{4}\right) m \left(p^* - \frac{3\underline{MC}_L + \underline{MC}_H}{4}\right) \\ &= TC(p^*) - \frac{m}{8}(\underline{MC}_H - \underline{MC}_L)^2 \; < \; TC(p^*)\,. \end{aligned}$$

The support costs $TC(p_L, p_H)$ are lower than $TC(p^*)$ by $\frac{m}{8}(\underline{MC}_H - \underline{MC}_L)^2$. In Figure 4.2, the individual support costs are visualized by the areas $p_H S_H(p_H)$ and $p_L S_L(p_L)$. Compared to Figure 4.1, the sum of the two areas, i.e., the total support costs, is smaller. Although the price increase for the high-cost bidders is equal to the price reduction for the low-cost bidders, the overall costs for the auctioneer decrease as the number of bidders for which the price increases is lower than the number of bidders for which the price decreases.

4.3 Assessment and Practical Application of the Instruments

We showed that the three instruments are theoretically equivalent in the sense that all outcomes (including the same support cost minimum) that can be achieved by one instrument can also be achieved by the others. However, there are differences

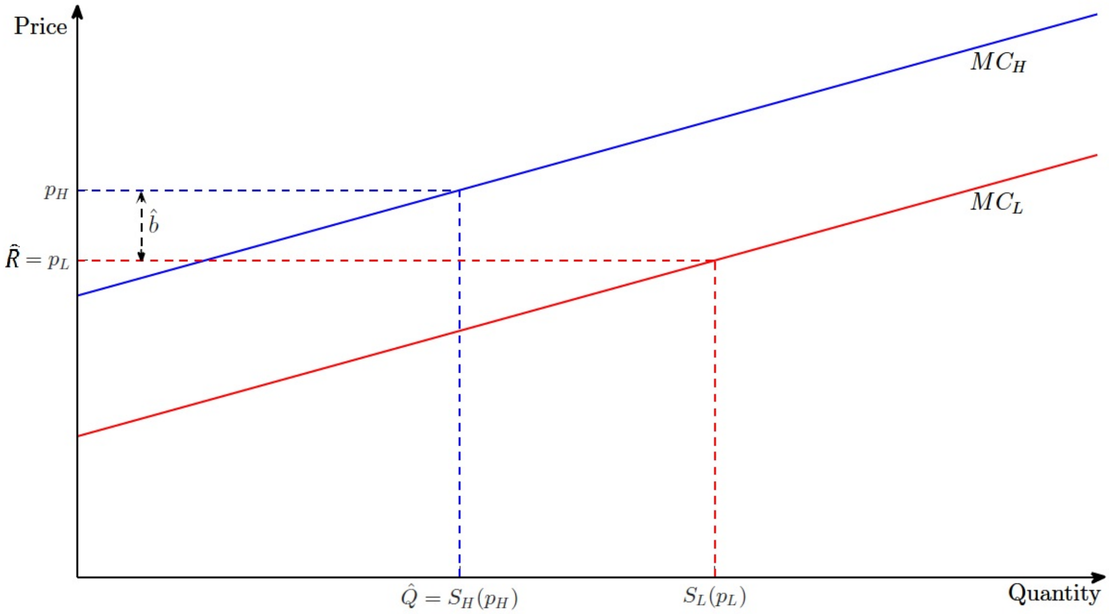


Figure 4.2: Illustration of the example with optimal discriminatory instruments $\hat{Q}$, $\hat{B}$ and $\hat{R}$.

concerning the practical implementations. In the following, we compare the three instruments with respect to their robustness to misestimations. In Section 4.3.3, we extend the example of Section 4.2.4 by including uncertainties regarding the marginal cost functions.

4.3.1 Robustness to Misestimations

As the exact number and strength of the bidders and thus their cost functions are usually unknown to the auctioneer, he has to calibrate the discriminatory instruments according to his beliefs and estimations. In the following, we analyze and compare the effects of misestimations, particularly on support costs, under the three different instruments.

Generally, a too low minimum quota for the high-cost bidders or a too high maximum price for the low-cost bidders may not have any effect, while a bonus is always effective.

For a more detailed analysis, we first consider the case that the auctioneer overestimates the costs of the high-cost bidders, i.e., the high-cost bidders are stronger than expected. Then, a quota does not have a negative effect because it is calibrated to high-cost bidders which are assumed to be weaker than they actually are. The same holds for the maximum price. In both cases, the calibration of the instrument is not optimal, but the costs are weakly lower than in free competition. A bonus, however, might over-privilege the high-cost bidders and, thus, increases the costs compared to free competition. This effect becomes stronger if the anticipated high-cost bidders are even stronger than the anticipated low-cost bidders. In this case, a quota or maximum price are ineffective, whereas a bonus discriminates in favor of the stronger bidders and, thus, increase the support costs.

Second, if the high-cost bidders' costs are underestimated, the negative effect of a bonus is lower than the negative effect of a quota or of a maximum price. The bonus might not be sufficient for enough high-cost bidders to be awarded. The quota and maximum price, however, will lead to an inappropriate share of awarded high-cost bidders.

As a matter of course, the arguments in the last two paragraphs analogously hold if the costs of the low-cost bidders are overestimated or underestimated. We also discuss these two cases in the example in Section 4.3.3. In this section, we also analyze the effects of a wrong estimation of the size of a bidder class, i.e., the number of bidders within a class. In this case, a bonus is more robust to misestimations than a quota or a maximum price, as long as the general cost difference between the two classes is estimated correctly. Under quota and maximum price, the negative effect of misestimations is stronger if the the number of high-cost bidders is overestimated than the other way round.

4.3.2 Combination of Discriminatory Instruments

The combination of discriminatory instruments can increase the robustness to misestimations. A good example is the combination of a bid bonus and a maximum quota: the high-cost bidders are privileged by a bid bonus, which, however, is only applied to a limited number of high cost bidders – those with the lowest bids. This number is determined by the maximum quota. Hence, the quota restricts the number of privileged bidders. In this way, the quota protects the auctioneer from excessive costs in case he overestimated the number or the strength of high-cost bidders.

This application reveals an important different between the monetary bonus and the bid bonus. As pointed out in Section 4.2.3, the two bonus types are to be considered equivalent if the bidders know that they will be privileged by the bonus. However, this is not the case here because the high-cost bidders do not know this when submitting their bid. Since a bid bonus has no impact on the optimal bid (i.e., bidding the true cost), whereas a monetary bonus induces bidders to reduce their bid by the bonus, the bid bonus is the right choice for this application.

The combination of a bid bonus and a quota increases the the robustness to misestimations compared to the two instruments alone as it combines their advantages and lessen their disadvantages. The effectiveness of the discriminatory instrument is guaranteed, while possible negative side-effects are limited. This also applies to other combinations. Thus, the advantages of discriminatory instruments in auctions with different bidder classes can be utilized without further information regarding the bidders' strength and number.

These considerations particularly apply to cases in which the implementation of discriminatory instruments is also guided by other targets than the minimization of support costs, such as grid and system integration, mixture of different RE technologies, regional distribution of RE, or actor diversity (Kreiss et al., 2017). Here, the considerations about the combination of instruments can help to keep costs low and to protect against "unpleasant surprises."

4.3.3 Illustrative Example of Consequences of Misestimations

In this section we illustrate the effects and implications of misestimations by means of the example of Section 4.2.4.

First, we examine the case in which the auctioneer does not correctly estimate the relation between the number of high-cost bidders and the number low-cost bidders. In line with our assumptions in Section 4.2.4, we model the relation between the number bidders by introducing parameter λ into the marginal cost function (4.9) of the high-cost bidders,

$$MC_H^{\lambda}(v) = \frac{\lambda}{n}v + \underline{MC}_H \tag{4.21}$$

for $v \in [0, \frac{n}{\lambda}(b_H - \underline{MC}_H)]$ with $MC_H(v) \in [\underline{MC}_H, b_H]$ and $\lambda > 0$. Since we consider only two classes, it is sufficient to only change the marginal cost function of one class. Thus, the low-cost bidders' marginal cost function (4.9) remains $MC_L(v) = \frac{v}{n} + \underline{MC}_L$ with $MC_L(v) \in [\underline{MC}_L, \overline{MC}_L]$ for $v \in [0, n(\overline{MC}_L - \underline{MC}_L)]$.

Let us assume that the auctioneer estimates $\lambda = 1$ as in the example in Section 4.2.4. Thus, an actual $\lambda \neq 1$ refers to a situation in which the auctioneer's estimate is wrong. For $\lambda > 1$ there are less and for $\lambda < 1$ there are more high-cost bidders than the auctioneer expects.[8] The actual supply function is

$$S_H^{\lambda}(p) = \begin{cases} 0 & \text{for } p < \underline{MC}_H\,, \\ \frac{n}{\lambda}(p - \underline{MC}_H) & \text{for } p \geq \underline{MC}_H\,. \end{cases} \tag{4.22}$$

[8] The combination of the parameters $\lambda, \underline{MC}_H, \underline{MC}_L, \overline{MC}_H, \overline{MC}_L$ is assumed to be such that the curves of the two classes do not intersect in the considered interval.

Note, by (4.12), the elasticity of supply $\varepsilon_i(p) = \frac{p}{p-\underline{MC}_i}$ does not depend on λ, which is due to the linear supply function.

In the the free competition case, the equilibrium price and the supply volumes are

$$
\begin{aligned}
p^\lambda &= \frac{D}{n}\frac{\lambda}{\lambda+1} + \frac{\lambda\underline{MC}_L + \underline{MC}_H}{\lambda+1}\,, \\
S_H^\lambda(p^\lambda) &= \frac{D}{\lambda+1} - \frac{n}{\lambda+1}(\underline{MC}_H - \underline{MC}_L)\,, \\
S_L(p^\lambda) &= \frac{D\lambda}{\lambda+1} + \frac{n}{\lambda+1}(\underline{MC}_H - \underline{MC}_L)\,,
\end{aligned}
\tag{4.23}
$$

which yields the total support costs

$$
K^\lambda(p^\lambda) = Dp^\lambda = \frac{\lambda}{\lambda+1}D\left(\frac{D}{n} + \underline{MC}_L + \frac{\underline{MC}_H}{\lambda}\right). \tag{4.24}
$$

That is, the price and the support costs decrease in λ.

Second, we consider the case that the auctioneer does not correctly estimate the general relation between the strength of the two classes, given by the difference between $\underline{MC}_H$ and $\underline{MC}_L$.

In the following, we investigate the effects of misestimations of λ and $\underline{MC}_H - \underline{MC}_L$ on the calibration of the discriminatory instruments and the support costs.

The optimal bonus is determined by the price difference $p_H^\lambda - p_L^\lambda$ in Corollary 3:

$$
\hat{B}^\lambda = p_H^\lambda - p_L^\lambda = \frac{S_L(p_L^\lambda)}{S'_L(p_L^\lambda)} - \frac{S_H^\lambda(p_H^\lambda)}{S'^\lambda_H(p_H^\lambda)} = \frac{\underline{MC}_H - \underline{MC}_L}{2}\,. \tag{4.25}
$$

Thus, the optimal bonus does not depend on λ and is equal to the optimal bonus in (4.15) for $\lambda = 1$. In the linear case, the bonus is robust to misestimations regarding the number of bidders and still leads to the support cost minimum. However, by (4.25), the optimal bonus $\hat{B}^\lambda$ depends on $\underline{MC}_H - \underline{MC}_L$ and, thus, is not robust with respect to misestimations of the general cost difference of the bidder classes.

Things are different for the optimal maximum price $\hat{R}^\lambda$ for the low-cost bidders. By (4.16), (4.17), and (4.22), the optimal award prices p_L^λ and p_H^λ for the two classes and $\hat{R}^\lambda$ are given by

$$\begin{aligned} p_H^\lambda &= \tfrac{D}{n}\tfrac{\lambda}{\lambda+1} + \tfrac{(2+\lambda)\underline{MC}_H+\lambda\underline{MC}_L}{2(\lambda+1)}\,, \\ p_L^\lambda &= \tfrac{D}{n}\tfrac{\lambda}{\lambda+1} + \tfrac{(2\lambda+1)\underline{MC}_L+\underline{MC}_H}{2(\lambda+1)} \quad = \hat{R}^\lambda\,. \end{aligned}$$

That is, $\hat{R}^\lambda$ depends on λ and, as shown in Appendix B.2, increases in λ.

The effect of misestimations regarding the number of bidders is the same for the optimal quota $\hat{Q}^\lambda$, which with (4.18), (4.19), and (4.22) is determined by

$$\begin{aligned} S_H^\lambda(p_H^\lambda) &= \tfrac{D}{\lambda+1} - \tfrac{n}{2(\lambda+1)}(\underline{MC}_H - \underline{MC}_L) &= \hat{Q}^\lambda\,, \\ S_L(p_L^\lambda) &= \tfrac{D\lambda}{\lambda+1} + \tfrac{n}{2(\lambda+1)}(\underline{MC}_H - \underline{MC}_L) &= D - \hat{Q}^\lambda\,. \end{aligned} \tag{4.26}$$

The optimal quota $\hat{Q}^\lambda$ depends on λ and, as shown in Appendix B.2, decreases in λ.

Hence, the implementation of the maximum price $\hat{R}$ yields the same result as the implementation of $\hat{Q}$. That is, a misestimation regarding λ has the same effect if either a quota or a maximum price is implemented.

Misestimations of the difference $\underline{MC}_H - \underline{MC}_L$ have the same effect for the optimal maximum price R^λ and the optimal quota Q^λ. The volume shift induced by both instruments

$$q^\lambda = \frac{n}{2(\lambda+1)}(\underline{MC}_H - \underline{MC}_L)\,,$$

which is given by the difference between (4.26) and (4.24) and which depends on λ and $\underline{MC}_H - \underline{MC}_L$. Hence, maximum price and quota are also not robust regarding misestimations of the general relation between the strength of the bidder classes.

If the auctioneer implements the quota $\hat{Q}$, which in this case is equivalent to the implementation of the maximum price $\hat{R}$, the support costs depend on the misestimation of λ. To see this, consider $TC^{\lambda}(Q)$, i.e., the support costs depending on a quota Q:

$$TC^{\lambda}(\hat{Q}) = (D - \hat{Q}) \cdot MC_L(D - \hat{Q}) + \hat{Q} \cdot MC_H^{\lambda}(\hat{Q}) \geq TC^{\lambda}(\hat{Q}^{\lambda}) \,. \tag{4.27}$$

The equality only holds for $\lambda = 1$. If $\lambda \neq 1$, the costs $TC^{\lambda}(\hat{Q})$ of the non-optimal quota $\hat{Q}$ are higher than the costs $TC^{\lambda}(\hat{Q}^{\lambda})$ of the optimal quota $\hat{Q}^{\lambda}$ and, as shown in Appendix B.2, the difference $TC^{\lambda}(\hat{Q}) - TC^{\lambda}(\hat{Q}^{\lambda})$ increases in $|\lambda - 1|$.

For $\lambda < 1$, $TC^{\lambda}(\hat{Q}^{\lambda}) \leq TC^{\lambda}(\hat{Q}) \leq TC^{\lambda}(0)$. That is, discrimination through $\hat{Q}$ or $\hat{R}$ still leads to lower costs than in the free competition case with $Q = 0$ although the auctioneer wrongly estimates the relation of the bidder classes (see Appendix B.2). This does not hold for $\lambda > 1$. In this case, $TC^{\lambda}(\hat{Q}) > TC^{\lambda}(0)$ is possible, i.e., the implementation of a non-optimal quota or maximum price leads to higher costs than in the free competition case without discrimination.

As shown before, the bonus $\hat{B}$ is (more) robust to wrong estimation of λ. In the linear model, the optimal bonus does not depend on λ but only on $\underline{MC}_H - \underline{MC}_L$. The key to design a discriminatory auction robust to misestimations of λ is to achieve the optimal cost difference (4.25) which is always fulfilled through the optimal bonus.

Figure 4.3 illustrates the effect of either the implementation of $\hat{Q}$ or $\hat{R}$ for different misestimations of λ. The optimal price difference $p_H - \hat{R}$ is only implemented if the relation of the number of high-cost bidders and low-cost bidders is estimated correctly. For $\underline{\lambda} < 1$ the price difference is lower than $p_H - \hat{R}$ and, thus, there is potential for further cost reductions. For $\overline{\lambda} > 1$ it is possible that the costs are even higher than in the free competition case.

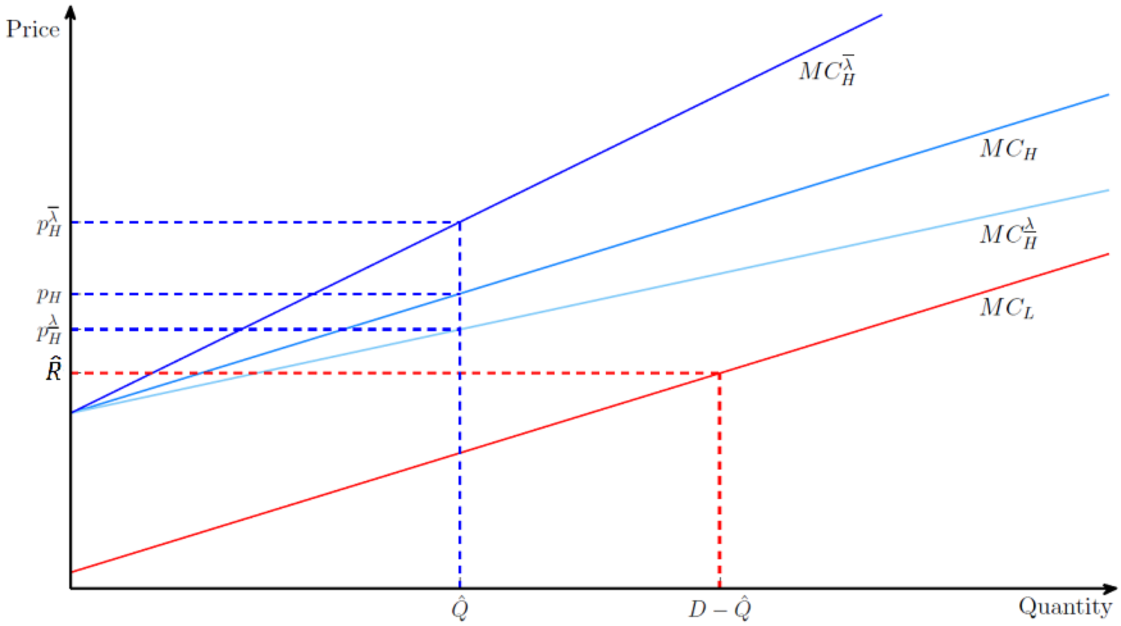


Figure 4.3: Illustration of the extended example.

4.4 Conclusion

It is a general trend in the expanded implementation of auctions for RES-E to open the auctions to either multiple technologies or to bidders from several countries. The corresponding buzzwords are "technology-neutral" and "cross-border" auctions. As a consequence, designing the auction becomes more complex and more stakeholders express their opinion and try to shift the design parameters in their favor. Obviously, the argumentation that more competition always reduces prices falls short. The most discussed topics regarding more open auction formats for RES-E are dynamic efficiency, integration costs and windfall profits.

We contribute to this discussion by transferring general microeconomic principles to the RE auction applications. We showed how three different discriminatory auction design elements – a quota, a bonus and a maximum price – can be implemented in auctions for RES-E and what their implications are. We proved for each instrument that the discrimination of the stronger bidders in favor of the weaker bidders reduces the overall support costs. Moreover, to formulate it the other way round, if the introduction of a discriminatory instrument does not reduce the support costs, then there is no sense in conducting a non-discriminatory, multi-technology auction because only the strong technology would be awarded.

Additionally, we proved that the support cost minimum can be achieved by each of the three instruments. However, the optimal implementation requires information regarding the cost distribution of the different bidder groups. Depending on the availability of this information the three instruments vary regarding their robustness.

If the auctioneer aims to minimize the support costs, the auction design should include discriminatory elements, which, however, is at the expense of efficiency. While effective discrimination reduces the support costs, the awarded bidders are not necessarily those with the lowest generation costs. This conflict between support cost minimization and efficiency highlights the importance for the auctioneer to be aware of his targets and their priority.

There is no panacea for designing the “right” auction for the promotion of RE sources. The design has to be adapted to the target and the current market and technological developments, possibly including discriminatory instruments.

Chapter 5

Favoritism through a Right of Subrogation

Since 2018, the German Federal Parliament (2016b) favors owners of existing projects in Germany's wind offshore auctions by a *right of subrogation* (ROS) to respect their special position in the auction. Thereby, the introduction of a ROS represents a completely new aspect in RES-E auctions. For a basic understanding, the model and results of Haufe (2014) are presented in the following, where sales auctions are investigated as usual in auction theory. Nevertheless, all results are easily transferable to procurement auctions.

First, the analysis in Section 5.3 provides basic theoretic results for first-price auctions with ROS, e.g., the bidding strategy as in Haufe (2014). Subsection 5.3.1 is based on Arozamena and Weinschelbaum (2009) and deduces that for specific value distributions of the favored bidder, the non-favored bidder's optimal bid is more aggressive in a first-price auction with ROS than without. Then, we follow Haufe (2014) by showing that a profit-maximizing auctioneer always (weakly) prefers to favor the weak bidder in Subsection 5.3.2. Based on that, Haufe (2014) highlights combinations of asymmetric bidders in which the auctioneer's expected revenue is increased by granting a ROS in comparison to a standard second-price auction. It is concluded that if the asymmetry between bidders is sufficiently high and the weak bidder is weak enough, the first-price auction with ROS can outperform a standard second-price auction, see Subsection 5.3.3. Section 5.4 concludes by summarizing the theoretical results in Subsection 5.4.1 and highlighting the relevance of the results for RES-E auctions in Subsection 5.4.2.

5.1 Introduction

In auctions different forms of favoritism can be established in order to accommodate the individual relationship between seller and buyer. In the following, we focus on favoritism through the assignment of a ROS as implemented in the German wind offshore auctions (German Federal Parliament, 2016b). In those, the support for wind offshore projects is auctioned to potential project developers. In the early stage, from 2017 to 2018, existing projects are already owned by particular project developers. To also integrate those projects in a competitive bidding process and respect their owners adequately a ROS is offered to them. Thereby, the project owners are excluded from competition, i.e., they do not participate in the competitive bidding process. But they have the chance to match the winning bid afterwards. In addition, this kind of favoritism is often used in industrial awarding for long-term business partners to grant them an exceptional position in the procurement process. A broad variety of practices of ROS can be found in Walker (1999).

The scientific literature already examines the ROS with respect to their impact on bidding behavior, expected auction revenue and efficiency in special cases. Bikhchandani et al. (2005) state that this form of favoritism will never be advantageous in terms of increased auction revenue and even may lead to inefficient outcomes in second-price auctions. All authors mentioned in the following examine first-price auctions with ROS. Though most of them consider the coalition of auctioneer and favored bidder, and hence only investigate the joint surplus of both. For example, Choi (2009) states for two symmetric bidders that the joint surplus of auctioneer and favored bidder can be increased by the assignment of a ROS, however, only at the expense of the third party's payoff. Burguet and Perry (2007) find that the auctioneer may benefit in a procurement auction with two asymmetric bidders from granting a ROS combined with certain forms of bribery. In contrast to those, we aim to find constellations in which the auctioneer's expected revenue increases independently of potential compensation payments by the favored bidder. In other words, we analyze the auctioneer's revenue without considering side payments. This approach is also adopted by Brisset et al. (2012), who show that heterogeneous risk attitudes of the bidders may be the crucial factor for an increased auction revenue. Furthermore, Lee (2008) demonstrates that a certain degree of asymmetry among bidders' strengths yields a higher expected profit for the auctioneer in a first-price auction with assigning a ROS than without. Related to his work we address the question under which assumptions regarding two asymmetric bidders the auctioneer can benefit from favoring one of the bidders in first-price auctions compared to incentive compatible second-price auctions. For that, we assume different forms of asymmetries between the participating bidders. Beyond the work of Lee (2008), who defines the asymmetry by uniform distributions on staggered intervals, we model the bidders' value distributions on a common interval by linear, strictly convex and strictly concave beta distributions. According to the work of Arozamena and Weinschelbaum (2009) the curvature of the favored bidder's value distribution may play a decisive role with respect to the aggressiveness of the non-favored bidder's bidding behavior. Furthermore, we find an increase in the expected auction revenue in case of asymmetric bidders – depending on the non-favored bidder's value distribution. [1]

[1]We act on the assumption of a two-bidder case, i.e., one favored and one non-favored bidder.

5.2 Model

We examine first-price auctions, in which the auctioneer favors one of the bidders by awarding a *Right of Subrogation*. In a sales auction, the ROS offers the favored bidder the option to buy the good at the best price submitted by the competing bidders. After the auctioneer has chosen a favored bidder and proclaimed her decision to all participants, a sealed-bid first-price auction is conducted. Hence the highest submitted bid determines the award price the winner has to pay. However, the highest bidder will win the auction only if the favored bidder does not exercise her ROS. In case the favored bidder exercises her ROS and so accepts the highest bid, she will win the auction and acquire the good at the award price. Thus, the award price is always the highest submitted bid in a first-price auction with ROS, the winner, however, can either be the favored bidder or the highest non-favored bidder, if the favored bidder declines to exercise the ROS. Further, it is to emphasize that the favored bidder is only allowed to match, if her initial bid was lower than the winning bid or she even did not submit any initial bid at all.[2] We limit our work on the following mechanism: The favored bidder does not submit any initial bid, but only decides at the second stage whether to match the winning bid or not. This basic auction mechanism is deduced from the work of Lee (2008).

As already discussed by Güth and Van Damme (1986), a first-price auction with ROS and two bidders can be interpreted as an auction, where the situation of the non-favored bidder corresponds to that in a first-price auction and the favored bidder's situation to that in a second-price auction. The non-favored bidder determines the award price she has to pay in case of winning through her submitted bid and the favored bidder decides whether to match her opponent's bid.[3]

[2] A first-price auction with ROS can be considered as a two-stage mechanism, where at the first stage a first-price auction is conducted and at the second stage the favored bidder has the option to match the winning bid.

[3] In particular, supposing two symmetric bidders, whose valuations are uniformly distributed on $[0, 1]$, the equilibrium bidding function of the non-favored bidder in a first-price auction with ROS is

Our analysis focuses on a two-bidder case for first-price auctions with ROS. Accordingly, one non-favored bidder (I) and one favored bidder (II) compete against each other. We suppose an independent private value model, i.e., both bidders assign values to the good represented by realizations of X_i, which are private information and independent of each other. We restrict our analysis to risk-neutral bidders and cases in which distributions of both bidders F_i are either linear, strictly concave or strictly convex beta distributions with support on $[0, 1]$ and publicly known. We assume that the auctioneer does not assign any value to the good. The number of bidders (here $N = 2$) as well as the fact that bidders are risk-neutral is common knowledge. In the course of the work this model is preserved as far as either symmetric or asymmetric bidders are supposed. For the asymmetric case, we distinguish between one strong and one weak bidder, i.e,. $i = \{s, w\}$. The bidders' valuations will be drawn independently from the same interval $[0, 1]$ of the beta distribution, where the weak bidder's distribution F_w on $[0, 1]$ is stochastically dominated by the strong bidder's distribution F_s on $[0, 1]$ according to the reverse hazard-rate order. Further it holds that F_s first-order stochastically dominates F_w, i.e., $F_s(x) \leq F_w(x)$ for all $x \in [0, 1]$, and therefore $E[X_w] \leq E[X_s]$. That is, the expected valuation of the strong bidder is higher than the weak bidder's expected valuation for the good.

5.3 Analysis

The non-favored bidder's bid always determines the price in the two bidder case, because the favored bidder does not submit any initial bid and only matches the non-favored bidder's bid if applicable. In the following, we refer to the non-favored and price-determining bidder's bid as $b^{ROS} = p$ and to the favored bidder's value distribution as $F_{II}(\cdot)$. First, we deduce the equilibrium bidding strategy of the non-

exactly the same as in a first-price auction. Further, the situation of the favored bidder corresponds exactly to that in a second-price auction as well.

favored bidder β^{ROS}. Then, we demonstrate how the information about the favored bidder's strength, i.e., $F_{II}(\cdot)$, affects this strategy.

Proposition 8. *The non-favored bidder's equilibrium bidding strategy $\beta^{ROS} : x_I \mapsto b^{ROS}$ in a first-price auction with ROS is given by*

$$\beta^{ROS}(x_I) = x_I - \frac{F_{II}(\beta^{ROS}(x_I))}{f_{II}(\beta^{ROS}(x_I))}, \tag{5.1}$$

where x_I is the non-favored bidder's valuation and the favored bidder's value distribution and density functions are given by F_{II} and f_{II}.

The proof is presented in Appendix C.1. Consequently, the non-favored bidder always shades her bid in equilibrium. By maximizing the expected rent, she finds herself in a trade-off situation: On the one hand a higher bid increases her winning probability. On the other hand, a higher bid reduces her profit in case of winning, because she determines the payment through this bid. Thus the equilibrium bidding strategy balances these opposite effects to maximize the bidder's expected rent.

The non-favored bidder's equilibrium bidding behavior is in the further analysis easier to handle by utilizing the explicit inverse equilibrium bidding function $\beta^{ROS^{-1}} : p \mapsto x_I$ instead of the implicit equilibrium bidding function presented above. Therefore we demonstrate below that the equilibrium bidding function is strictly monotone and therefore bijective and invertible for strictly concave, convex and linear beta value distribution functions.

Lemma 3. *If $\beta^{ROS}(x_I)$ is bijective, the inverse equilibrium bidding strategy of the non-favored and price-determining bidder I in a first-price auction with ROS is given by*

$$\beta^{ROS^{-1}}(p) = p + \frac{F_{II}(p)}{f_{II}(p)},$$

where $p \in [0,1]$ is the award price and F_{II} the favored bidder II's value distribution with corresponding density f_{II}.

Lemma 4. *Let the favored bidder's value distribution F_{II} be a linear, strictly concave or strictly convex beta distribution. Then the equilibrium bidding strategy of the non-favored bidder in a first-price auction with ROS, $\beta^{ROS}(x_I)$, is strictly monotone and hence bijective.*

The respective proofs are presented in Appendix C.1. The inverse equilibrium bidding strategy depends on the favored bidder's value distribution F_{II} and density function f_{II}, which are common knowledge. That is, the price-determining bid $\beta^{ROS}(x_I)$ is influenced by the strength of the competing favored bidder. The stronger the favored bidder the more aggressive is the non-favored bidder's submitted bid, i.e., a stronger opponent will lead the non-favored bidder to offer a higher price.

The fact that the non-favored bidder offers a higher price if the strength of her opponent increases is intuitive: a stronger opponent will lower the winning probability and the non-favored bidder attends to compensate this effect by bidding more aggressively.

Next, the expected auction revenue in a first-price auction with ROS is deduced. On the one hand the non-favored bidder's equilibrium bid depends on her individual valuation and on the other hand it is influenced by the strength of the competing favored bidder. Consequently, the expected auction revenue, determined by the non-favored bidder's bid, is affected by both bidders' strengths.

Proposition 9. *The distribution function of the expected payment in a first-price auction with ROS is given by*

$$F^{ROS}(p) = F_I(\beta^{ROS^{-1}}(p)),$$

where $\beta^{ROS^{-1}}(p) = p + \frac{F_{II}(p)}{f_{II}(p)}$ *is the inverse equilibrium bidding strategy of the non-favored bidder* I *and* $p \in [0, 1]$.

Proposition 10. *The expected auction revenue in a first-price auction with ROS is*

$$E[p^{ROS}] = \int_0^\infty 1 - F^{ROS}(p)dp = \int_0^\infty 1 - F_I(\beta^{ROS^{-1}}(p))dp. \tag{5.2}$$

The respective proofs are presented in Appendix C.1. Notice that Proposition 10 only applies if the favored bidder was selectively elected and not if one of the bidders is favored by chance. For the latter see Haufe (2014).

5.3.1 Impact of the ROS on Bidding Behavior

According to Bagnoli and Bergstrom (2005) linear, strictly concave or strictly convex beta distributions are log concave. Arozamena and Weinschelbaum (2009) find that for log concave value distributions symmetric bidders may bid more, less or equally aggressive in a first-price auction with ROS than without depending on the ratio $\rho(x) = \frac{F(x)}{f(x)}$: If $\rho(x)$ is strictly concave (convex) in x, symmetric bidders bid more (less) aggressively, whereas the bidding behavior remains unaltered in case $\rho(x)$ is linear in x. As we consider an asymmetric two-bidder case, the strength of the favored bidder is crucial for the bidding strategy of the non-favored and price-determining bidder. Hence, only the favored bidder's value distribution and density function are relevant for determining $\rho(x)$.

Proposition 11. *In case the favored bidder's value distribution is a linear or strictly convex beta distribution the bidding behavior is unchanged in a first-price auction with and without ROS.*

Proposition 12. *In case the favored bidder's value distribution is a strictly concave beta distribution the bidding behavior is more aggressive in a first-price auction with ROS than without.*

The proofs are presented in Appendix C.1. Surprisingly, the introduction of favoritism has no unfavorable effects on bidding behavior in the considered cases. Neither concave nor linear or convex opponents yield lower bids.

5.3.2 Favoring the Right Bidder

In the following, we demonstrate that in case of asymmetric bidders the expected auction revenue in a first-price auction with ROS may exceed that in a second-price auction. Especially, the form of asymmetry between bidders is a crucial factor for the auctioneer to decide whether to conduct a first-price auction with ROS or a second-price auction.[4] For that purpose, two asymmetric bidders are considered, one strong bidder s and one weak bidder w.

Recall that conducting a first-price auction with ROS with asymmetric bidders means for the auctioneer to decide which bidder is granted the ROS. In the following we focus for the defined asymmetric bidder constellations on the question, whether a selective assignment is advantageous for the auctioneer or not. For that purpose, we demonstrate that if the auctioneer knows who of the participating bidders in the first-price auction with ROS is the strong and who the weak one, it might be meaningful to favor the correct bidder in order to gain a higher expected profit. That is, we consider the different expected payments in case of favoring the strong and the weak bidder. We suppose two asymmetric bidders characterized either by a convex-convex, linear-convex or concave-linear combination of value distributions.

[4] In the symmetric case, the auctioneer does not benefit from granting a ROS to any bidder for the considered combinations of beta distributions.

For the convex-convex and linear-convex combination the bidding behavior of the non-favored bidder remains unchanged since in both cases the price-determining bidder faces an opponent whose value distribution and density function lead to linear ratios $\rho(x)$ or $\tilde{\rho}(x)$, see Proposition 12. Hence, it can be shown that for a linear-convex and convex-convex combination the expected auction revenue in the first-price auction with ROS is the same independent of favoring the weak or the strong bidder.

Proposition 13. *Let $F_s(x) = x^{\zeta}$ and $F_w(x) = x$ be the bidders' value distributions, $\zeta > 1$. The auctioneer's expected profit if the weak bidder is favored $E[p_w^{ROS}]$ equals the expected profit with granting the ROS to the strong bidder $E[p_s^{ROS}]$ for all $\zeta > 1$.*

The proof is presented in Appendix C.1. Thus, in the case of a weak bidder with a linear distribution and a strong bidder with a convex distribution the auctioneer's expected profit remains the same whether she favors the weak or the strong bidder, although the weak bidder submits a relatively more aggressive bid $\beta_w^{ROS}(x)$ for $\zeta > 1$ than the strong bidder with $\beta_s^{ROS}(x)$. The expected payment if the weak bidder determines the price, i.e, the strong bidder is favored, never exceeds the expected payment if the weak bidder is favored. The reason is that the weak bidder's expected valuation $E[X_w]$ is lower than the strong bidder's one $E[X_s]$, however her more aggressive bidding behavior is outweighed by her weakness compared to the strong bidder, which results in equal expected profits, i.e., $E[p_w^{ROS}] = E[\beta_w^{ROS}(X_s)] = E[\beta_s^{ROS}(X_s)] = E[p_s^{ROS}]$.

Proposition 14. *Let $F_s(x) = x^{\zeta_s}$ and $F_w(x) = x^{\zeta_w}$ be the bidders' value distributions, where $1 < \zeta_w < \zeta_s$. Then the auctioneer's expected profit if the weak bidder is favored $E[p_w^{ROS}]$ equals the expected profit if she grants the ROS to the strong bidder $E[p_s^{ROS}]$, $\forall \zeta_w, \zeta_s > 1$.*

The proof is presented in Appendix C.1. Notice that for $\zeta_s, \zeta_w \to \infty$ both bidders' bids will approach their true valuations. Further, the weak bidder's bidding strategy is more aggressive than the strong bidder's one, which is obvious, because the weak bidder faces a strong competitor, whereas the strong bidder competes against a weak one. However, the expected auction revenue by favoring the strong bidder never exceeds the expected auction revenue by favoring the weak bidder. The reason is that the more aggressive bidding behavior of the non-favored weak bidder is compensated by her lower expected valuation.

For the concave-linear combination the expected payment by favoring the weak bidder $E[p_w^{ROS}]$ and the expected payment by favoring the strong bidder $E[p_s^{ROS}]$ differ and do not correspond to each other as in the linear-convex or convex-convex combination. We find that under these assumptions favoring the weak bidder always generates a higher or equal expected revenue for the auctioneer compared to favoring the strong bidder.

Proposition 15. *Let $F_s(x) = x$ and $F_w(x) = 1 - (1-x)^\eta$ be the bidders' value distributions, $\eta > 1$. Then the expected payment in a first-price auction with ROS is higher or equal if the auctioneer grants the ROS to the weak instead of the strong bidder.*

The proof is presented in Appendix C.1. To conclude, favoring the weak bidder yields in all three considered cases an equal or higher expected revenue for the auctioneer compared to favoring the strong bidder.

5.3.3 Conditions for A-priori Superiority of First-price Auctions with ROS

Based on Proposition 13, 14 and 15, we presuppose that always the weak bidder is favored. In Appendix C.2, it is shown that the auction revenue in a second-price auction always exceeds that in a first-price auction with ROS for the linear-convex and the convex-convex combination.

Hence, we consider the concave-linear combination. As we learned from Proposition 12, bidding behavior may be more aggressive, at least if the weak bidder is favored in this combination. For the sake of completeness, we also assume that the strong bidder is favored in the first-price auction with ROS and find that the second-price auction still outperforms the first-price auction with ROS in terms of expected auction revenue, see Appendix 17. Nevertheless, this result may change if the weak bidder is favored in the first-price auction with ROS.

Proposition 16. *Let $F_s(x) = x$ and $F_w(x) = 1 - (1-x)^\eta$ be the bidders' value distributions, $\eta > 1$. Then the expected payment in the first-price auction with ROS, where the weak bidder is favored, exceeds that in the second-price auction if $\eta \gtrsim 2.745$.*

The proof is presented in Appendix C.1. Thus, a selective assignment of the ROS to the weak bidder yields a higher expected profit for the auctioneer if a certain degree of asymmetry is given among the participating bidders. The intuition behind is that the weaker the weak bidder is the more aggressive are the bids of the strong and price-determining bidder. Further, we assume the auctioneer only knows that the two participating bidders are unequally strong, but she is not informed about which bidder is the weak and which the strong one. Then, a randomly granted ROS also leads to a higher expected auction revenue than the expected auction revenue, in the concave-linear combination. For the selective favoritism of the weak bidder it holds that there exists a degree of asymmetry such that a higher expected auction revenue can be gained, which is also possible for a randomly assigned ROS. However, favoring one of the ex ante asymmetric bidders by chance will require a higher degree of asymmetry in order to gain a higher expected auction revenue in the first-price auction with ROS than in the second-price auction. Finally, we state that a weak bidder with strictly concave beta distributed valuations entails advantageous properties for the expected auction revenue in a first-price auction with ROS compared to weak bidders with linear or convex beta distributions.

5.4 Conclusion

5.4.1 Summary of Theoretical Results

In the concave-linear combination it makes a difference whether the weak or the strong bidder is favored, in contrast to the other combinations. In this case we show that the auctioneer is always better off in regard to her expected profit by favoring the weak bidder. Further, besides a sufficient degree of asymmetry, the weak bidder's concave value distribution is essential for the higher expected auction revenue in a first-price auction with ROS. In this case, if the ROS is appointed to the weaker bidder, the first-price auction with ROS generates higher expected auction revenues than a standard second-price auction. Even if the ROS is randomly granted to one of the two asymmetric bidders, the auction revenue in a first-price auction with ROS will exceed the revenue in a second-price auction as soon as the asymmetry is sufficiently large.

5.4.2 Applicability to Auctions for RES-E

Granting a ROS represents a clear and simple measure to favor owners of existing projects without foregoing competitive determination of support levels. As main disadvantage, it implies the risk of inefficiency. Namely in case the opponents have lower costs than the project owner but overbid the latter for increasing their profit in case of winning. Nevertheless, the implementation of a ROS is promising, which the following conclusions emphasize: In the considered combinations, bidding behavior is either unchanged or more aggressive, which is both not disadvantageous, first. Second, favoring the weak bidder is always the right choice. Applied to the wind-offshore auctions in Germany, it might be difficult to ensure that the project owner is the weak bidder. However, granting the ROS by chance leads similar results. Third and finally, governments can benefit from lower support costs induced by more aggressive bidding due to a ROS in the auctions. Summarizing, the implementation of a ROS is a potentially suitable measure in cases where one particular bidder deserves a favored position in the auction.

Chapter 6

Conclusion

Auctions can be a suitable instrument for the allocation and determination of renewable energy support (RES-E). However, there exists no one-size-fits-all auction design for RES-E. The appropriate choice of auction design crucially depends on the market framework, the political and economic targets, as well as the expected economic and technological development particularly of the renewable energy and electricity markets. That is, while general suitable as competitive and efficient mechanism, auctions are sensitive to existing market and framework conditions. Consequently, theoretical findings have to be applied carefully to prevent false conclusions.

6.1 Summary

From an auction theoretic perspective, this work first provided a basic framework for auctions for RES-E, then highlighted general chances and risks for their conduction, and finally analyzed real-world implementations.

Chapter 2 sensitized to general chances and risks of auctions for RES-E and revealed the ambiguity of auctions under different conditions with simple examples. This established a broad basis for auction implementations in the RES-E context and complemented with first lessons-learned from theory.

Then we focused on particular questions from practice and especially had a look at unconventional auction implementations as adopted in the German EEG (German Federal Parliament, 2017a).

Chapter 3 dealt with non-binding awards that offer bidders the option to withdraw after the auction due to financing risks. We learned from theory and laboratory experiments that non-binding awards in combination with reallocation yield equivalent auction outcomes compared to their binding counterparts. Surprisingly, we even observed an efficiency increase in non-incentive compatible auctions with non-binding award in the experiment. Hence non-binding auctions with reallocation represent a promising approach to address costs uncertainties in auctions for RES-E. Last but not least, the German solar auctions may finally overcome the prominent negative examples of non-binding auctions[1].

With regard to open auctions, discriminative measures were studied in Chapter 4. Due to persistent asymmetries among bidders, discrimination is inevitable to further control the technology mix or regional distribution of the expansion. Our analysis demonstrates that support costs can be minimized despite discrimination. In particular, the considered discriminatory measures, i.e., quota, bonus and different maximum prices, yield the same support cost minimum in their optimum. However, discrimination always is at the expense of efficiency. Further, optimal calibrating in practice is limited. We find that the robustness with regard to misestimations strongly depends on the available information regarding the cost distribution and size of the bidder groups.

Motivated by the German wind offshore auctions, Chapter 5 highlighted that the auctioneer can benefit from favoring a bidder by a right of subrogation in terms of higher profit. First, we learned that favoring the weak bidder is always revenue superior because then the strong bidder determines the price. Dependent on the

[1]See Cramton et al. (2015), Merlob et al. (2012) and McMillan (1994).

curvature of the opponent bidder's signal distribution, the non-favored bidder bids more aggressively, which increases the auctioneer's profit. Consequently, if the strong bidder's costs distribution function is a strictly concave beta distribution, the support costs can be reduced by favoring the weak one through a right of subrogation in case of sufficient asymmetry.

6.2 Scientific Outlook

Auctions for RES-E are still in their infancy. Their worldwide implementations increase not only in numbers and auction volumes but also in significance. As a consequence, many new scientific issues will appear in the future. Recent auction implementations already provide a broad variety of cases worth investigating. In the course of this thesis, our focus was limited to very special auction designs as implemented in Germany. Analogously, global implementations provide further research objects.

Moreover, regarding non-binding auctions only little research exists in general and from practice only negative examples have been reported. Due to our advantageous results for the implementation of non-binding awards, they should be further examined. Typically, the withdrawal of awards is associated with costs for both the bidder and the auctioneer. Thus, further research should be spent to analyze withdrawal costs, especially the optimization of penalty payments the bidders have to pay in case of withdrawal.

Discrimination might develop to the main question regarding auctions for RES-E as technology neutral auctions are the future. Not only different renewable but all energy sources are planed to be combined in one competitive energy system. In this, differences may persist not only regarding electricity generation costs but also with regard to availability of particular energy sources and regional need of electricity, to name just a few. An adequate integration is only possible with regulative instruments that will be discriminative, inevitably. Laboratory experiments may provide crucial insights into human behavior in case of favoritism and discrimination in auctions for RES-E.

Besides theoretical analyses of proposed auction formats, evaluations of conducted auctions in particular countries will become crucial. To date, lessons learned can be drawn only limitedly due to the early stage of auctions for RES-E. Because of long realization phases after the auction, general success and failure of auctions for RES-E will be unearthed only in the coming years, and finally allow broader conclusions.

6.3 Policy Implications

It seems that governments have realized the general potential of auctions for RES-E, currently become familiar with particular design options and already draw valuable conclusions from first experiences over the past few years. As a result, the success of auctions for RES-E is outstanding: First and foremost, many countries already benefit from the cost decreasing potential of competitive bidding (REN21, 2016). In Germany, for example, support levels for photo voltaic felt to such an extent (4,33 EURct per kWh) that they even beat support levels for wind-onshore (4,73 EURct per kWh) in February 2018 (German Federal Ministry for Economic Affairs and Energy, 2018a,b). This demonstrated that competivity between technologies can be achieved, which was considered impossible for many years. Another important remark is that bidders seem to highly accept auctions for RES-E despite being confronted with award risks. Oversupply, i.e., competition through an exceeding amount of supply compared to the tender volume, could be observed in many countries. In Germany's photo voltaic auctions the auction volume was exceeded by a factor of two to three for several times (German Federal Network Agency, 2016, 2018a). Although high competition and decreasing support levels may put project developers under pressure, high project realization rates can be achieved, for example in Germany (German Federal Network Agency, 2018b). Thus auctions for RES-E have already proven their potential to yield satisfactory results in many aspects. This development is based on several properties and advantages of auctions compared to other options for RES-E. Auctions create competition and hereby reduce the costs of RES and increase allocative efficiency. The auction results generate information about scarcity and prices, which is valuable for project developers and the auctioneer. The competitive auction environment also creates innovation incentives, which will lead to further support cost reductions. Moreover, auctions allow the policy maker to control the RE expansion in order to reach the respective targets. These are the main reasons why the European Commission requires that its member states conduct auctions for RES from 2017 on (European Commission, 2014). Although auctions become or already are mandatory in many countries throughout the world (REN21, 2016), national governments can usually select the particular auction design to a great extent. In conclusion, for the implementation of auctions for RES we recommend a theoretically and empirically proved auction design with a low level of complexity for the bidders, which facilitates a simple and straightforward determination of an appropriate bidding strategy. The auction should also minimize the incentives for strategic supply reduction and implicit collusion. Moreover, the auctions should be implemented in a long-term oriented framework with regular repetitions and should also be accompanied by appropriate measures (e.g., prequalification and penalties) in order to ensure sufficient and serious competition and reduce bidders' valuation uncertainty.

Appendix A

Appendix to Chapter 3

A.1 Proofs

Proof of Lemma 1

Proof. In the initial award allocation, an awarded bidder faces one of two constellations. First, only her leading bid is awarded and her second bid component would not move up if she withdraws. In this case, she will not withdraw her award. Second, the bidder is initially awarded with several bids or one of her bid components would not move up if she withdraws an awarded bid. Now, she will withdraw all winning bids but one as she is only interested in one of the K units. In this case, initially non-awarded bids move up but the bidder retains her award. Assuming an exhaustive reallocation procedure, this leads to a new allocation in which each bidder (either initially awarded or not) again faces the above mentioned constellations. However, the awarded bidder keeps her award, potentially with a higher price. Iteration of this procedure yields to an allocation in which none of the bidders has an incentive to withdraw her bid. This is the case if the bid that would move up is a leading bid of a non-awarded bidder. However, since awarded bidders always keep their award and always withdraw excessive awarded bids this implies the claim. □

Proof of Proposition 1

Proof. (1) Obviously, optimal bids have to exceed the bidder's cost, i.e., $c_t > x$ for $t = 1, 2, \ldots$, and have to be different. Without loss of generality, we can set $c_1^{PAB} < c_2^{PAB} < \ldots < c_T^{PAB}$.

(2) By Lemma 1, $1 - G_K^{PAB}(c_t^{PAB})$ is the award probability of a bid c_t^{PAB}, $t = 1, \ldots, T$, taking into account an exhaustive replacement procedure, i.e., $1 - G_K^{PAB}(c_t^{PAB})$ is the probability that c_t^{PAB} outbids the K lowest leading bids of the competing bidders. The situation where only the leading bid c_1^{PAB} of a bidder is awarded occurs with probability $G_K^{PAB}(c_2^{PAB}) - G_K^{PAB}(c_1^{PAB})$, i.e., c_1^{PAB} is lower than the K lowest competing leading bids and c_2^{PAB} is not. If the two lowest bids c_1^{PAB} and c_2^{PAB} are awarded, the bidder will withdraw the lower one c_1^{PAB} and pay $z \geq 0$. This occurs if c_2^{PAB} is lower than the K lowest competing leading bids and c_3^{PAB} is unsuccessful, i.e., with probability $G_K^{PAB}(c_3^{PAB}) - G_K^{PAB}(c_2^{PAB})$. Continuing for all L bids yields the bidder's expected profit $\mathrm{E}[\pi(x, \boldsymbol{c}^{PAB}, z)]$, which is given by

$$
\begin{aligned}
\mathrm{E}[\pi(x, \boldsymbol{c}^{PAB}, z)] =& (c_1^{PAB} - x)[G_K^{PAB}(c_2^{PAB}) - G_K^{PAB}(c_1^{PAB})] + \\
& (c_2^{PAB} - x - z)[G_K^{PAB}(c_3^{PAB}) - G_K^{PAB}(c_2^{PAB})] + \ldots + \\
& [c_T^{PAB} - x - (T-1)z](1 - G_K^{PAB}(c_T^{PAB})) \\
=& \sum_{t=1}^{T-1} (c_t^{PAB} - x - (t-1)z)[G_K^{PAB}(c_{t+1}^{PAB}) - G_K^{PAB}(c_t^{PAB})] + \\
& [c_T^{PAB} - x - (T-1)z](1 - G_K^{PAB}(c_T^{PAB}))
\end{aligned}
$$

where $\boldsymbol{c}^{PAB} = (c_1^{PAB}, c_2^{PAB}, \ldots, c_T^{PAB})$. Supposing that the bidder aims to maximize her expected profit through her submitted bids $c_1^{PAB}, c_2^{PAB}, \ldots, c_T^{PAB}$, we obtain the following first order conditions

$$\frac{\partial}{\partial c_1^{PAB}} \mathrm{E}[\pi(x, \boldsymbol{c}^{PAB}, z)] = \left(G_K^{PAB}(c_2^{PAB}) - G_K^{PAB}(c_1^{PAB})\right) - (c_1^{PAB} - x) g_K^{PAB}(c_1^{PAB}) \stackrel{!}{=} 0$$

$$\frac{\partial}{\partial c_2^{PAB}} \mathrm{E}[\pi(x, \boldsymbol{c}^{PAB}, z)] = \left(G_K^{PAB}(c_3^{PAB}) - G_K^{PAB}(c_2^{PAB})\right) - (c_2^{PAB} - c_1^{PAB} - z) g_K^{PAB}(c_2^{PAB}) \stackrel{!}{=} 0$$

$$\ldots$$

$$\frac{\partial}{\partial c_T^{PAB}} \mathrm{E}[\pi(x, \boldsymbol{c}^{PAB}, z)] = (1 - G_K^{PAB}(c_T^{PAB})) - (c_T^{PAB} - c_{T-1}^{PAB} - z) g_K^{PAB}(c_T^{PAB}) \stackrel{!}{=} 0$$

Solving these equations for $c_1^{PAB}, c_2^{PAB}, \ldots, c_T^{PAB}$ and verifying the second order-conditions provides the optimal bidding strategies. □

Proof of Proposition 2

Proof. Because of $c_1^{PAB} = \gamma_1^{PAB}(x)$ and $c_t^{PAB} = \gamma_t^{PAB}(c_{t-1}^{PAB})$ for $t = 2, \ldots, T$, a bidders optimization calculus is supermodular in $(x, c_1^{PAB}, c_2^{PAB}, \ldots, c_{T-1}^{PAB})$ and, therefore, fulfills the single crossing property. Thus, the first component of the equilibrium strategy $\gamma_t^{PAB}(x)$ exists (Ath; McAdams, 2003, 2006). Since $\gamma_T^{PAB}(c_{T-1}^{PAB}) = \gamma_T^{PAB}(\gamma_{T-1}^{PAB}(c_{T-2}))$ is monotone in $c_{T-2}^{PAB} = \gamma_{T-2}^{PAB}(c_{T-3}) = \gamma_{T-2}^{PAB}(\gamma_{T-3}(c_{T-4}))$ and so on, $\gamma_1^{PAB}(x)$ is monotone in x. □

Proof of Proposition 3

Proof. Because of the monotonicity of $\boldsymbol{\gamma}_1^{PAB}$, the K bidders with the lowest costs are awarded. That is, the allocation of the K units is efficient and corresponds to that in a binding PAB auction. Therefore, the expected bidder profits, winning probabilities and the auctioneer's expected payment equal those of the binding mechanism (e.g. Engelbrecht-Wiggans, 1988). □

Proof of Corollary 1

Proof. From Proposition 1 follows that bidders diversify their optimal bids in the non-binding mechanism. In addition, revenue (payment) equivalence of both mechanisms follows from Proposition 3. For analyzing the expected auction outcome of the non-binding PAB auction, we consider two cases: First, only leading bids are finally awarded and, thus, are price determining. Second, in the complementary case, in which at least one higher bid than leading bid is awarded, the auctioneer's payment is higher than in the first case. Since RET applies and the allocation is the same and efficient, the claim follows. □

Proof of Proposition 5

Proof. With the assumption of a symmetric monotone equilibrium strategy β^{HAB}, condition (3.3) leads to the differential equation

$$(\beta^{HAB}(x) - x)f_{(K:N-1)}(x) - (F_{(K-1:N-1)}(x) - F_{(K:N-1)}(x))\frac{d\beta^{HAB}(x)}{dx} = 0\,,$$

which with

$$f_{(K:N-1)}(x) = \frac{(N-1)!}{(K-1)!(N-K-1)!}F(x)^{K-1}(1-F(x))^{N-K-1} \tag{A.1}$$

$$F_{(K:N-1)}(x) = \sum_{j=K}^{N-1} \frac{(N-1)!}{j!(N-j-1)!}jF(x)^{j}(1-F(x))^{N-j-1} \tag{A.2}$$

$$\Rightarrow F_{(K-1:N-1)}(x) - F_{(K:N-1)}(x) = \frac{(N-1)!}{(K-1)!(N-K)!}F(x)^{K-1}(1-F(x))^{N-K}$$

(e.g. Ahsanullah et al., 2013) yields

$$\left(\left(\beta^{HAB}(x)-x\right)(N-K)f(x)-(1-F(x))\frac{d\beta^{HAB}(x)}{dx}\right)M(x,N,K)=0\,, \quad \text{(A.3)}$$
$$M(x,N,K)=\frac{(N-1)!}{(K-1)!(N-K)!}F(x)^{K-1}(1-F(x))^{N-K-1}\,.$$

By (3.1) the symmetric monotone equilibrium strategy of a first price auction (i.e., PAB auction with one good) with $N-K+1$ bidders is given by

$$\beta^{FA}(x)=x+\frac{\int_x^{\overline{x}}1-F_{(1:N-K)}(s)ds}{1-F_{(1:N-K)}(x)}\,, \quad \text{(A.4)}$$

which is derived from the differential equation

$$(\beta^{FA}(x)-x)f_{(1:N-K)}(x)-(1-F_{(1:N-K)}(x))\frac{d\beta^{FA}(x)}{dx}=0\,,$$

which with (A.1) and (A.2) yields

$$\left(\left(\beta^{FA}(x)-x\right)(N-K)f(x)-(1-F(x))\frac{d\beta^{FA}(x)}{dx}\right)(1-F(x))^{N-K-1}=0\,.$$

That is, $\beta^{FA}(x)$ fulfills (A.3) and, thus, $\beta^{HAB}\equiv\beta^{FA}$. □

Proof of Proposition 6

Proof. Given that in the non-binding UP-HAB auction there exists a symmetric equilibrium $\boldsymbol{\gamma}^{HAB}=(\gamma_1^{HAB},\gamma_2^{HAB},\ldots,\gamma_T^{HAB}):[\underline{x},\overline{x}]\to\mathbb{R}^T$ with $\gamma_1^{HAB}(x)$ is increasing in x.

First, $x<\gamma_1^{HAB}(x)<\gamma_2^{HAB}(x)<\ldots<\gamma_T^{HAB}(x)$ follows from the considerations above Proposition 6.

Second, according to Engelbrecht-Wiggans (1988) the RET applies, which can be transferred to the non-binding UP-HAB procurement auction: the auction outcome is efficient, the bidders' winning probabilities and expected profits and the auctioneer's expected payment per good (equal to $E[X_{(K+1:N)}]$) are the same as in the binding UP-HAB auction.

Third, from expected payment equivalence with the binding UP-HAB auction follows that the non-binding bid components have to spread around the corresponding binding bid, i.e., $\gamma_1^{HAB}(x) < \beta^{HAB}(x) < \gamma_T^{HAB}(x)$ for all $x \in [\underline{x}, \overline{x}]$ and $T \geq 2$. $\square$

A.2 Derivation of the Optimal Bid b^{HAB} in the Binding UP-HAB Auction

Proof. Given a bidder's costs x and her beliefs about the opponents' K-th lowest bid, which are described by the distribution and density function H_K^{HAB} and h_K^{HAB}. Two cases of winning with bid b are relevant: First, b is lower than the highest accepted bid, i.e., the price is determined by the opponents' $(K-1)$th lowest bid. Second, b is the highest accepted bid and determines the award price. Then, b lies between the opponents' $(K-1)$th and Kth lowest bid. The probability of this case is $H_{K-1}^{HAB}(b) - H_K^{HAB}(b)$. Thus, the bidder's expected profit is given by

$$\mathrm{E}[\pi(x,b)] = \int_b^\infty (y-x)h_{K-1}^{HAB}(y)dy + (b-x)(H_{K-1}^{HAB}(b) - H_K^{HAB}(b))\,,$$

whose maximization with respect to b yields the first-order condition

$$\frac{\partial}{\partial b}\mathrm{E}[\pi(x,b)] = (x-b)h_{K-1}^{HAB}(b) + H_{K-1}^{HAB}(b) - H_K^{HAB}(b) + (b-x)(h_{K-1}^{HAB}(b) - h_K^{HAB}(b)) \stackrel{!}{=} 0\,. \tag{A.5}$$

By rearranging (A.5) we get (3.3). $\square$

A.3 Additional Tables

	PAB			UP-HAB	
Matching group	Binding	Non-binding	Matching group	Binding	Non-binding
G01	161.5	163.6	G17	169.2	163.9
G02	174.0	163.2	G18	168.4	163.9
G03	161.7	166.6	G19	167.7	164.7
G04	162.8	163.9	G20	165.8	162.0
G05	161.1	164.7	G21	162.9	166.0
G06	167.1	168.6	G22	165.0	166.6
G07	163.4	165.6	G23	164.3	167.3
G08	164.8	163.0	G24	162.6	164.6
G09	168.6	162.1	G25	165.1	167.7
G10	162.8	164.7	G26	168.2	156.4
G11	161.8	163.5	G27	163.0	164.0
G12	163.9	167.3	G28	165.6	164.0
G13	160.4	162.9	G29	165.9	164.9
G14	164.4	164.2	G30	164.1	166.8
G15	162.2	162.2	G31	164.8	168.0
G16	162.3	162.1	G32	164.5	164.9
Mean	163.9	164.3		165.4	164.7
Median	162.8	163.7		165.0	164.8
Std. dev.	3.3	1.9		1.9	2.7

Table A.1: Average auction prices [ExCU] of all blocks of ten rounds.

	PAB			UP-HAB	
Matching group	Binding	Non-binding	Matching group	Binding	Non-binding
G01	98.9%	98.0%	G17	95.1%	97.8%
G02	93.4%	97.6%	G18	96.7%	99.7%
G03	97.5%	99.3%	G19	98.0%	98.7%
G04	97.9%	98.7%	G20	99.4%	96.8%
G05	98.0%	98.8%	G21	97.6%	98.8%
G06	96.7%	97.8%	G22	97.7%	98.8%
G07	96.4%	98.8%	G23	97.1%	98.6%
G08	97.0%	97.8%	G24	98.9%	99.6%
G09	95.9%	98.8%	G25	98.9%	98.7%
G10	99.1%	98.8%	G26	97.0%	97.6%
G11	97.1%	98.7%	G27	98.0%	99.3%
G12	98.7%	98.5%	G28	98.5%	99.6%
G13	98.4%	99.1%	G29	97.8%	99.3%
G14	98.7%	99.1%	G30	98.3%	99.4%
G15	97.9%	98.8%	G31	99.2%	99.1%
G16	98.6%	98.7%	G32	99.0%	99.5%
Mean	97.5%	98.6%		97.9%	98.8%
Median	97.9%	98.7%		98.0%	99.0%
Std. dev.	1.4%	0.5%		1.1%	0.8%

Table A.2: Average efficiency rates of all blocks of ten rounds.

A.4 Numerical Analysis

Let $\gamma_1^{PAB}(x)$ and $\gamma_2^{PAB}(x)$ denote the symmetric equilibrium in the non-binding PaB auction with $T = 2$. Further, G_2^{PAB} and g_2^{PAB} denote the distribution and density function of the bidder's beliefs about the lower leading bid of the two competing bidders, $N = 3$. Then, the differential equation system to be solved is

$$
\begin{aligned}
\gamma_1^{PAB}(x) = &\quad x + \tfrac{G_2^{PAB}(\gamma_2^{PAB-1}(\gamma_1^{PAB}(x))) - G_2^{PAB}(x)}{g_2^{PAB}(x)} \cdot \gamma_1^{PAB'}(x) \\
\gamma_2^{PAB}(x) = &\quad \gamma_1^{P}(x) + \tfrac{1 - G_2^{PAB}(\gamma_2^{PAB-1}(\gamma_1^{PAB}(x))) \cdot \gamma_2^{PAB'}(\gamma_2^{PAB-1}(\gamma_1^{PAB}(x)))}{g_2^{PAB}(\gamma_2^{PAB-1}(\gamma_1^{PAB}(x))) \cdot \gamma_1^{P}(x)'} \cdot \tfrac{\gamma_2^{PAB'}(\gamma_2^{PAB-1}(\gamma_1^{PAB}(x))}{\gamma_1^{PAB'}(x)}
\end{aligned}
$$

As numerical solution method the following source code was compiled with Wolfram Mathematica.

Clear ["Global'*"] ;

$n = 24$; (* number of iterations *)

(* initialization *)

SetPrecision[

$h = \text{Round}[(199 - 100)/(n + 1), 0.01]$; (* increment *)

values = Array$[x, n+1, 0]$; $x[n] = 199$;

Array$[y, n+1, 0]$; $y[n] = 199$;

bids1 = Array$[b1, n+1, 0]$; $b1[n] = 199$;

bids2 = Array$[b2, n+1, 0]$; $b2[n] = 199$;

nearestX = n ;

estimatedB2 = 199 ;

(* initial values for x and y *)

$y[n-1] = 199 - (h/2)$;

$x[n-1] = 199 - h$;

(* density and distribution function of values and of second order statistics with 3 bidders *)

$f[x\_] = 1/(199 - 100)$;

$F[x\_] = (x - 100)/(199 - 100)$;

$g[x\_] = 2 \cdot F[x] \cdot f[x]$;

$G[x\_] = F[x]^2$;

(*iteration*)

For[$i = n - 1$, $i > -1$, $i - -$,

(* reinitialization *)

If[$i < n - 1$,

estimatedB2 $= 2 \cdot b2[i + 1] - b2[i + 2]$;

$j =$ nearestX ;

While[$b1[j] >$ estimatedB2 && $j > i$,

nearestX $= j$;

$j - -$;

];

estimatedY = Round[x[nearestX] $-$ ($b1$[nearestX] $-$ estimatedB2)/(($b1$[nearestX] $-$ $b1$[nearestX $- 1$])$/h$)$, 10^{-50000}$];

Print[N[estimatedY]];

$y[i] =$ estimatedY ;

$x[i] = x[i + 1] - h$;

] ;

(* iteration step *)

$b1[i] = \mathrm{Round}[(g[x[i]] \cdot (x[i + 1] - x[i]) \cdot x[i] + (G[y[i]] - G[x[i]]) \cdot b1[i + 1])/(g[x[i]] \cdot (x[i + 1] - x[i]) + (G[y[i]] - G[x[i]])), 10^{-50000}]$;

$b2[i] = \mathrm{Round}[(g[y[i]] \cdot b1[i] \cdot (y[i + 1] - y[i]) + (1 - G[y[i]]) \cdot b2[i + 1])/(g[y[i]] \cdot (y[i + 1] - y[i]) + (1 - G[y[i]])), 10^{-50000}]$;

] ;

```
, MachinePrecision] ; ;

(* Print b1, b2 and x *)
N[DownValues[b1]]
N[DownValues[b2]]
N[DownValues[x]]
biddingData1=Transpose[values,bids1]; biddingData2=Transpose[values,bids2] ;
biddingFunction1=Interpolation[biddingData1];
biddingFunction2=Interpolation[biddingData2];
```

Please find the plotted numerical solutions for the bidding functions of $\gamma_1^{PAB}(x)$ and $\gamma_2^{PAB}(x)$ in Figure 3.1.

A.5 Experiment Instructions

Welcome to the Experiment

You are participating in an economic experiment. Please read the following instructions carefully. The instructions state everything you need to know about your participation in the experiment.

Please note:

- From this moment on, during the whole experiment, you are **not allowed to communicate** with other participants. Turn off your mobile phones. If you have any questions, please silently raise your hand.
- **All decisions are anonymous**. That means none of the other participants will learn about the identity of any other decision maker.
- **In this experiment, you can earn money**. The exact amount depends on your decisions as well as on the decisions of the other participants. The total amount of money you will have earned during the experiment will be paid out in **cash** at the end. The **payment will be individual and anonymous** that means no one learns about the payments of the other participants. This experiment uses the currency "Geldeinheiten" (GE). **20 GE corresponds to one Euro**, or 1 GE corresponds to 0.05 Euro.
- **For arriving on time to the experiment, you will receive an additional 10 Euro**.

The Experiment

The experiment consists of **40 rounds**. In each round, you will be grouped with two other randomly selected participants in a **group of three**. It will not be revealed with whom you were grouped and new groups will be randomly formed every round. In each round, you have exactly **one decision** to make.

EXPERIMENTAL PROCEDURE

The experiment with its 40 rounds is divided into **four sections** each consisting of 10 rounds: section 1 consists of rounds 1 - 10, section 2 consists of rounds 11 - 20, section 3 consists of rounds 21 - 30 and section 4 consists of rounds 31 - 40.

The sections differ only in the used **procurement procedure**. In all rounds in section 1 and section 3 (i.e. rounds 1 - 10 and 21 - 30) **procurement procedure 1** will be used. In all rounds in section 2 and section 4 (i.e. in rounds 11 - 20 and 31 - 40) **procurement procedure 2** will be used. The experiment informs you when a new section begins.

DECISIONS

In all 40 rounds, you represent a **company which produces one unit of a certain good** with the intention to sell. All participants (i.e. their companies) produce one unit of the same good and compete for selling their good only by setting a bid offer, respectively. At the beginning of each round, you will be informed of **your individual production costs of the good**. The costs are determined randomly and change every round.

In each of the 40 rounds, you can produce one unit of the good and sell it. Your decision consists of **submitting a bid offer for selling the unit**. **In each group, the three participants compete for selling two units of the good**. Therefore, in every round offers of only **two participants** per group are accepted. These two participants then produce the good and sell it at the **sales price** which **depends on the procurement procedure in use**.

If your offer is accepted, your **profit equals the sales price less your production costs**. If your offer is not accepted, you won't receive any payment, and no costs incur, as you do not produce the good, and hence, your profit equals zero.

THE STRUCTURE OF A ROUND

Each of the 40 rounds consists of the following four phases

(1) Random group formation

In each round, you are grouped with two other **randomly** selected participants in a **group of three**. The identities of the two members in your group will remain unknown to you. You will be reassigned to a new group every round and its composition changes every time.

(2) Individual production costs

At the beginning of every round, you will be informed of your **individual production costs** of the good. Your costs are determined **randomly** to be a **whole number between 100 GE and 199 GE**. Each of the numbers is **equally likely** to be chosen. The production costs for every participant can differ and you will be only told about your production costs and will not have any information about the production costs of any other participant.

(3) Decision

You make the **decision on the offer** for one unit of the good you produce. This decision is made by all participants **simultaneously** and **unaware** of the others decisions. Depending on the procurement procedure (1 or 2) your offer consists of **one bid offer (in procurement procedure 1)** or of **either one or two bid offers (in procurement procedure 2)**.

(4) Result

At the end of every round, you will be **informed about your result in this round**. This information consists of whether or not your offer has been accepted and if yes at which sales price you can sell your unit of the good and what your resulting profit in this round is.

The **phases (1)** and **(2)**, "Random group formation" and "Individual production costs" are **the same in all 40 rounds**. The **phases (3)** and **(4) differ** depending on **which procurement procedure** is being used: **procurement procedure** 1 or **procurement procedure 2**.

PROCUREMENT PROCEDURE 1

(3) <u>Decision</u> (Procurement Procedure 1)

Your offer for the sales of one unit of the good consists of **one bid offer**. A bid offer is a **whole number** (i.e. a number without decimal places) between **50 GE and 250 GE**. Enter your decision in the corresponding field "bid offer".

(4) <u>Result</u> (Procurement Procedure 1)

The **two best offers** in each **group of three**, i.e. the two offers with the **lowest bid offers**, are accepted.

The two participants whose offers are accepted sell their units of the good at the same sales price. The sales price equals the higher bid offer of the two accepted ones:

Sales price = Higher bid offer of the two accepted ones

If your offer is accepted, youll receive a payment in the amount of the sales price, and individual production costs incur. Your profit is thereby

Profit = Sales price - Production cost

If your offer is not accepted you wont receive any payment, and no production costs incur, and your profit equals zero.

At the end of every round, you will be informed of whether or not your offer has been accepted. If your offer has been accepted the sales price and profit will be displayed on the screen.

PROCUREMENT PROCEDURE 2

(3) <u>Decision</u> (Procurement Procedure 2)

Example 1: Suppose participants A, B and C with their production costs as written below respectively submit the following bid offers for one unit of the good:

Participant	Production costs [GE]	bid offer [GE]
A	110	120
B	150	130
C	190	210

Result: The two offers with the lowest bid offers are accepted. In this example, the offers made by A with a bid offer of 120 GE and B with a bid offer of 130 GE are accepted.

The two accepted bid offers are 120 GE and 130 GE. As the sales price for one unit of the good equals the higher bid offer both participant A and participant B sell their units of the good for 130 GE (B's bid offer). For both participants, individual production costs are incurred. Therefore, the profit made by A equals 130 - 110 = 20 GE and the profit made by B equals 130 - 150 = -20 GE, i.e. he incurs a loss.

The offer of participant C is not accepted, and therefore, no costs are incurred, and his profit equals zero.

Your offer for the sales of one unit of the good consists **either** of **one bid offer** or **two alternative bid offers**. A bid offer is a **whole number** (i.e. a number without decimal places) between **50 GE and 250 GE**.

- If you want to submit only **one bid offer**, enter your offer in the corresponding field "bid offer 1" and leave the field "bid offer 2" empty.
- If you want to submit **two alternative bid offers**, enter your offers in the fields "bid offer 1" and "bid offer 2" whereby your bid offer 2 has to be higher than your bid offer 1.

(4) Result (Procurement Procedure 2)

The **two best offers** in each **group of three**, i.e. the two offer with the **lowest bid offers 1**, are **accepted**.

The two participants whose offers are accepted sell their units of the good at the same sales price. The sales price equals the highest of all bid offers 1 and 2 of the two accepted offer, which are smaller than (or equals) the highest bid offer 1 in your group of three (i.e. the bid offer 1 of the participant whose offer has been rejected).

$$\textbf{sales price} = \textbf{Highest bid offer of the two accepted offers which is smaller than (or equals) the bid offer 1 of the rejected offer}$$

Therefore, your sales price is at least as high as your bid offer 1, if your offer is accepted.

If your offer is accepted, youll receive a payment in the amount of the sales price, and individual production costs incur. Your profit is thereby

$$\textbf{Profit} = \textbf{Sales price - Production cost}$$

If your offer is not accepted you wont receive any payment, and no production costs are incurred, and your profit equals zero.

At the end of every round, you will be informed of whether or not your offer has been accepted. If your offer has been accepted the sales price and profit will be displayed on the screen.

Example 2: Suppose participants A, B and C with their production costs as written below respectively submit the following bid offers for one unit of the good:

Participant	Production costs [GE]	bid offer 1 [GE]	bid offer 2 [GE]
A	110	120	170
B	150	160	210
C	190	200	

The participants A and B have obviously submitted two alternative bid offers and participant C only one.

Result: The two offers with the lowest bid offers 1 are accepted. In this example, the offers made by A with a bid offer 1 of 120 GE and B with a bid offer 1 of 160 GE are accepted.

The bid offer 1 of participant C whose offer has been rejected equals 200 GE. The accepted bid offers made by A and B are 120, 160, 170 and 210 GE. The highest of these four bid offers which is smaller than 200 GE is 170 GE (bid offer 2 by A). This offer defines the sales price, i.e. the sales price for one unit of the good equals 170 GE.

Therefore, both participant A and participant B sell their units of the good for 170 GE. Both participants incur costs in the amount of their individual production costs. Thus, the profit made by A equals 170 - 110 = 60 GE and the profit made by B equals 170 - 150 = 20 GE.

The offer of participant C is not accepted, and therefore, no costs are incurred, and his profit equals zero.

NOTE

In cases of equal bid offers the accepted offer(s) is (are) randomly chosen.

YOUR PAYMENT

For the payment at the end of the experiment, **in each of the four stages, four out of the ten rounds are randomly chosen**, all rounds having the same probability. The profits in the chosen rounds will be converted in Euro (20 GE corresponds to 1 Euro) and added to your show-up fee (10 Euros). **Therefore, in total, you will receive your 10 Euros show-up fee plus your profit in 16 randomly chosen rounds, where 20 GE corresponds to 1 Euro.**

The results in the remaining rounds are irrelevant for your payment.

FURTHER INFORMATION

Please give your decisions serious consideration as they will determine the amount of payment you will receive at the end of the experiment. Before the experiment starts, you have to answer a series of question to make sure that you have understood the experimental procedure and your tasks. Both, questions and possible answers, will be displayed on your screen.

If you have any questions during the experiment itself, remain quietly seated and raise your hand to indicate an issue. Please wait until the experimenter has approached you and ask your question as quietly as possible. However, your questions should only relate to the instructions and not to possible strategies!

Furthermore, please note that the experiment will only continue if all participants have made their decisions.

On the last page of the instructions, you may take notes during the experiment.

END OF EXPERIMENT

After you have finished the experiment, we would like you to complete a questionnaire.

Please remain seated after finishing the questionnaire until your seat number is called out. Bring the instructions and your seat number to the front. Only then you will receive your payment for participating in the experiment.

Thank you for your participation and good luck!

OVERVIEW OF THE MOST IMPORTANT INFORMATION

__General__

Rounds	40 rounds (rounds 1 - 10: procurement procedure 1, rounds 11 - 20: procurement procedure 2, rounds 21 - 30: procurement procedure 1, rounds 31 - 40: procurement procedure 2)
Groups	groups of three (randomly formed every round)
Production Costs	random whole number between 100 and 199 (individual, and for every participant in each round randomly determined)
Geldeinheiten (GE)	20 GE corresponds to 1 Euro, i.e. 1 GE corresponds to 0.05 Euro
Your Payment	10 Euros show-up fee plus your profit in 16 randomly chosen rounds

__Procurement Procedure 1__

Bid Offer	one bid offer
Accepted Offers	2 out of 3 offers with the lowest bid offers
Sales Price	If your offer is accepted: **Sales price = Bid offer**
Profit	If your offer is accepted: **Profit = Sales price - Production cost**

__Procurement Procedure 2__

Bid Offer	one or two bid offer(s) (bid offer 1 ¡ bid offer 2)
Accepted Offers	2 out of 3 offers with the lowest bid offers 1
Sales Price	If your offer is accepted: **sales price = Highest bid offer of the two accepted offers which is smaller than (or equals) the bid offer 1 of the rejected offer**
Profit	If your offer is accepted: **Profit = Sales price - Production cost**

Appendix B

Appendix to Chapter 4

B.1 Proofs

Proof of Lemma 2

Proof. Let $\Delta(q)$ denote the change in the support costs induced by q compared to free competition, which by (4.6) and (4.7) is

$$\Delta(q) = MC_L(S_L(p^*) - q) \cdot (S_L(p^*) - q) + MC_H(S_H(p^*) + q) \cdot (S_H(p^*) + q) - TC(p^*) \,.$$

Differentiating $\Delta(q)$ with respect to q, denoted by $\Delta'(q)$, yields

$$\begin{aligned}\Delta'(q) \quad &= \quad -MC'_L(S_L(p^*) - q)(S_L(p^*) - q) - MC_L(S_L(p^*) - q) \\ &\quad\quad +MC'_H(S_H(p^*) + q)(S_H(p^*) + q) + MC_H(S_H(p^*) + q) \,.\end{aligned}$$

Starting with an ineffective quota, $q = 0$, to prove that the costs decrease when the quota becomes effective, we have to show that

$$\Delta'(0) = -MC_L(S_L(p^*)) - S_L(p^*)MC'_L(S_L(p^*)) + MC_H(S_H(p^*)) + S_H(p^*)MC'_H(S_H(p^*)) < 0 \,,$$

i.e., the support cost change is negative and thus the costs decrease.

By $MC_L(S_L(p^*)) = MC_H(S_H(p^*)) = p^*$, we obtain

$$\Delta'(0) = S_H(p^*)MC'_H(S_H(p^*)) - S_L(p^*)MC'_L(S_L(p^*)) < 0\,. \tag{B.1}$$

With $MC'_i(S_i(p)) = \frac{1}{S'_i(p)}$ for $i \in \{L, H\}$, (B.1) becomes

$$\frac{S_L(p^*)}{S'_L(p^*)} > \frac{S_H(p^*)}{S'_H(p^*)} \iff \frac{S'_L(p^*)}{S_L(p^*)}p^* < \frac{S'_H(p^*)}{S_H(p^*)}p^*$$

By (4.5), this condition is fulfilled if

$$\varepsilon_L(p^*) < \varepsilon_H(p^*)\,,$$

which is given by Assumption 1 (ii). □

Proof of Proposition 7

Proof. Consider the support costs

$$TC(p_L, p_H) = p_L S_L(p_L) + p_H S_H(p_H) \;\text{ with }\; S_L(p_L) + S_H(p_H) = D\,. \tag{B.2}$$

The minimization of the Lagrange function of (B.2) with regard to p_L and p_H yields the first order conditions

$$\begin{aligned}
\frac{\partial TC(p_L, p_H)}{\partial p_L} &= S_L(p_L) + p_L S'_L(p_L) + \lambda S'_L(p_L) = 0 \\
\frac{\partial TC(p_L, p_H)}{\partial p_H} &= S_H(p_H) + p_H S'_H(p_H) + \lambda S'_H(p_H) = 0
\end{aligned}$$

which lead to the condition

$$p_H - p_L = \frac{S_L(p_L)}{S_L'(p_L)} - \frac{S_H(p_H)}{S_H'(p_H)}. \tag{B.3}$$

For $Q \leq S_H(p^*)$, $p_H = p_L = p^*$ and, thus, the left-hand side of (B.3) is zero. $Q > S_H(p^*)$ implies $p_H > p^* > p_L$. With an increasing Q, p_H increases and p_L decreases and, thus, the left-hand side of (B.3) increases. (4.5) and Assumption 1 (ii)imply that the right-hand side of (B.3) is positive at p^* which demonstrates that the optimality condition (B.3) does not hold for an ineffective quota, e.g., $Q \leq S_H(p^*$. By Assumption 1 (i), $\varepsilon_H(p_H)$ does not increase and $\varepsilon_L(p_L)$ does not decrease if p_H increases and p_L decreases. Thus, with (4.5), the right-hand side of (B.3) decreases. Since the left-hand side of (B.3) increases with an increasing quota Q and the right-hand side of (B.3) decreases, there exist a unique $\hat{Q}$ that fulfills (B.3). Together with Lemma 2, that an increasing quota Q above $S_H(p^*)$ reduces the support costs, $\hat{Q}$ is the unique cost minimum. □

B.2 Additional Calculations for the Extended Example in Section 4.3.3

To show that the equilibrium price p^λ increases if there are less high-cost bidders than expected, i.e., $\lambda > 1$, we calculate

$$p^\lambda - p^* = \frac{\lambda - 1}{(\lambda + 1)2}\left(\frac{D}{n} + \underline{MC}_L + \underline{MC}_H\right)$$

where $(\frac{D}{n} + \underline{MC}_L + \underline{MC}_H) > 0$ due to (4.13) and $\frac{\lambda-1}{(\lambda+1)2}$ is greater than zero for $\lambda > 1$ and negative for $\lambda < 1$. Therefore, the equilibrium price increases for an increasing λ.

As a direct result, also the support costs $TC^\lambda(p^\lambda)$ are greater than $TC(p^*)$ if there are less high-costs bidders and vice versa with more high-cost bidders.

To prove that the implementation of a quota $\hat{Q}$ in a case where $\lambda \neq 0$ is not optimal, we have to show that the difference $\hat{Q}^\lambda - \hat{Q} \neq 0$:

$$\hat{Q}^\lambda - \hat{Q} = \frac{1-\lambda}{\lambda+1}\frac{n}{2}\left(\frac{D}{n} - \frac{1}{2}(\underline{MC}_H - \underline{MC}_L)\right)$$

where again $(\frac{D}{n} - \frac{1}{2}(\underline{MC}_H - \underline{MC}_L)) > 0$ due to (4.13) and

$$\frac{1-\lambda}{\lambda+1}\begin{cases} > 0 & \text{if } \lambda < 1 \\ = 0 & \text{if } \lambda = 1 \\ < 0 & \text{if } \lambda > 1 \end{cases}$$

so that only for $\lambda = 1$ both quotas are identically. Moreover, for $\lambda > 1$ the optimal quota is lower than before and for $\lambda < 1$ it is the other way round.

Finally we calculate for $\lambda \neq 0$ and the optimal discriminatory auction the support costs

$$TC^\lambda(\hat{Q}^\lambda) = \frac{D^2(\lambda^2+1)}{n(\lambda+1)^2} + \frac{D}{\lambda+1}(\lambda\underline{MC}_L + \underline{MC}_H) - \frac{n}{4(\lambda+1)}(\underline{MC}_H - \underline{MC}_L)^2$$

and compare them to the costs given $\lambda \neq 0$ and a discriminatory auction with quota $\hat{Q}$

$$TC^\lambda(\hat{Q}) = \frac{D^2(\lambda+1)}{4m} + \frac{D}{4}\left((3-\lambda)\underline{MC}_H + (1+\lambda)\underline{MC}_L\right) - \frac{n}{16}(\underline{MC}_H - \underline{MC}_L)^2(3-\lambda)$$

which results in the difference

$$TC^\lambda(\hat{Q}^\lambda) - TC^\lambda(\hat{Q}) = \frac{D^2(\lambda-1)(\lambda^2+3)}{4n(\lambda+1)^2} - \frac{D}{4(\lambda+1)}(\underline{MC}_H - \underline{MC}_L)(\lambda-1)^2 + \frac{n}{16(\lambda+1)}(\underline{MC}_H - \underline{MC}_L)^2(\lambda-1)^2$$

which is negative for all $\lambda > 0$ and only equals zero for $\lambda = 1$. The difference $TC^\lambda(\hat{Q}) - TC^\lambda(\hat{Q}^\lambda)$ increases in $|\lambda - 1|$.

Appendix C

Appendix to Chapter 5

C.1 Proofs

Proof of Proposition 8

Proof. The expected profit of the non-favored bidder is the difference between her valuation x_I and her bid $b^{ROS} = \beta^{ROS}(x_I)$ in case of winning. The non-favored bidder wins, if b^{ROS} exceeds the favored bidder's valuation and consequently she declines to match , that is, with a probability of $F_{II}(\beta^{ROS}(x))$. If the opposite holds, the favored bidder will match and consequently the non-favored bidder's profit is zero. Let $F_{II}(\cdot)$ be the distribution function of the favored bidder's valuation. It follows

$$E[\pi_I] = (x_I - \beta^{ROS}(x_I))F_{II}(\beta^{ROS}(x_I)).$$

The non-favored bidder aims to maximize her expected profit through her submitted bid $\beta^{ROS}(x_I)$. With the first-order condition follows

$$\frac{\partial}{\partial \beta^{ROS}(x_I)} E[\pi_I] = x_I f_{II}(\beta^{ROS}(x_I)) - F_{II}(\beta^{ROS}(x_I)) - \beta^{ROS}(x_I) f_{II}(\beta^{ROS}(x_I)) \stackrel{!}{=} 0,$$
$$\Leftrightarrow \beta^{ROS}(x_I) = x_I - \frac{F_{II}(\beta^{ROS}(x_I))}{f_{II}(\beta^{ROS}(x_I))}.$$

□

Proof of Lemma 3

Proof. The inverse equilibrium bidding strategy follows immediately from Proposition 8, where p corresponds to the non-favored bidder's bid $\beta^{ROS}(x_I)$ and further $x_I = \beta^{ROS^{-1}}(p)$. □

Proof of Lemma 4

Proof. The monotony of $\beta^{ROS}(x_I)$ is implied by the monotony of $\beta^{ROS^{-1}}(p)$, i.e., by $\frac{\partial}{\partial p}\beta^{ROS^{-1}}(p) > 0 \ \forall p \in [0,1]$. First a linear beta distribution $F_{II}(p) = p$ is supposed for the favored bidder's value distribution. Then differentiating $\beta^{ROS^{-1}}(p) = 2p$ with respect to p ensues

$$\frac{\partial}{\partial p}\beta^{ROS^{-1}}(p) = 2 > 0 \ \ \forall p \in [0,1].$$

Assuming F_{II} is a strictly convex beta distribution, for the derivative of $\beta^{ROS^{-1}}(p) = \frac{\zeta}{\zeta+1}p$ with respect to p follows for $\zeta > 1$

$$\frac{\partial}{\partial p}\beta^{ROS^{-1}}(p) = \frac{\zeta}{\zeta+1} > 0 \ \ \forall p \in [0,1].$$

Finally, if F_{II} is a strictly concave beta distribution after differentiating $\beta^{ROS^{-1}}(p) = p + \frac{1-(1-p)^\eta}{\eta(1-p)^{\eta-1}}$ it holds for $\eta > 1$

$$\frac{\partial}{\partial p}\beta^{ROS^{-1}}(p) = 1 + \frac{1}{\eta}\left(1 - \frac{1-\eta}{(1-p)^\eta}\right) > 0 \ \forall p \in [0,1].$$

□

Proof of Proposition 9

Proof. The distribution function $F^{ROS}(p)$ is the probability that the expected auction revenue is lower than or equal to p. That is, the probability that the price-determining bid $b_I = \beta^{ROS}(x_I)$, where x_I is the non-favored bidder's valuation, is lower than or equal to p. Therefore the distribution function $F^{ROS}(p)$ corresponds to the probability $P(b_I \leq p) = P(x_I \leq \beta^{ROS^{-1}}(p)) = F_I(\beta^{ROS^{-1}}(p))$. □

Proof of Proposition 10

Proof. Let the distribution of the expected payment in the first-price auction with ROS be given by $F^{ROS}(p)$. Then for any $p \in [0,1]$ Proposition 9 yields the assertion.

□

Proof of Proposition 11

Proof. Let $F(x) = x$ and $\tilde{F}(x) = x^\zeta$ be the favored bidders' value distributions, where $\zeta > 1$. Then both value distributions are logconcave, see Bagnoli and Bergstrom (2005), and it follows

$$\rho(x) = \frac{F(x)}{f(x)} = \frac{x}{1} = x \ ,$$
$$\tilde{\rho}(x) = \frac{\tilde{F}(x)}{\tilde{f}(x)} = \frac{x^\zeta}{\zeta x^{\zeta-1}} = \frac{x}{\zeta}.$$

Consequently, $\rho(x)$ and $\tilde{\rho}(x)$ are linear in x and with Arozamena and Weinschelbaum (2009) we can follow that the bidding behavior is unchanged if the favored bidder's value distribution is either a strictly convex or linear beta distribution. □

Proof of Proposition 12

Proof. Let $\hat{F}(x) = 1 - (1-x)^{\eta}$ be the favored bidders' value distribution, where $\eta > 1$. According to Bagnoli and Bergstrom (2005) $\hat{F}(x)$ is logconcave and further,

$$\hat{\rho}(x) = \frac{\hat{F}(x)}{\hat{f}(x)} = \frac{1-(1-x)^{\eta}}{\eta(1-x)^{\eta-1}}$$

is strictly concave. With Arozamena and Weinschelbaum (2009), we conclude that the non-favored bidder's bid is more aggressive in a first-price auction with ROS than without. □

Proof of Proposition 13

Proof. First we describe the expected payments $E[p_w^{ROS}]$ and $E[p_s^{ROS}]$ in dependence of ζ and then we prove that Proposition 13 applies for all $\zeta > 1$. In order to calculate $E[p_w^{ROS}]$, we need the strong bidder's inverse bidding strategy, because she is the price-determining bidder in this case,

$$\beta_s^{ROS^{-1}}(p) = p + \frac{F_w(p)}{f_w(p)} = 2p.$$

And for the bidding strategy $\beta_s^{ROS}(x)$ follows

$$\beta_s^{ROS}(x) = \frac{1}{2}x, \text{ particularly } \beta_s^{ROS}(1) = \frac{1}{2}.$$

So the auctioneer's expected rent if she favors the weak bidder, is

$$E[p_w^{ROS}] = \int_0^{\beta_s^{ROS}(1)} 1 - F_s(\beta_s^{ROS^{-1}}(p))dp = \int_0^{\frac{1}{2}} 1 - (2p)^\zeta dp = \frac{1}{2} - \frac{1}{2(\zeta+1)} = \frac{1}{2}\frac{\zeta}{\zeta+1}. \tag{C.1}$$

Under the same assumptions and granting a ROS to the strong bidder follows for the auction revenue

$$\begin{aligned} E[p_s^{ROS}] &= \int_0^{\beta_w^{ROS}(1)} 1 - F_w(\beta_w^{ROS^{-1}}(p))dp = \int_0^{\frac{\zeta}{\zeta+1}} 1 - \frac{\zeta+1}{\zeta}pdp \\ &= \frac{\zeta}{\zeta+1} - \frac{1}{2}\frac{\zeta+1}{\zeta}\frac{\zeta^2}{(\zeta+1)^2} = \frac{1}{2}\frac{\zeta}{\zeta+1}, \end{aligned} \tag{C.2}$$

where the inverse equilibrium bidding strategy of the weak bidder, who determines the price, is

$$\beta_w^{ROS^{-1}}(p) = p + \frac{F_s(p)}{f_s(p)} = p + \frac{p^\zeta}{\zeta p^{\zeta-1}} = \frac{\zeta+1}{\zeta}p.$$

And for the equilibrium bidding strategy $\beta_w^{ROS}(x)$ holds

$$\beta_w^{ROS}(x) = \frac{\zeta}{\zeta+1}x, \text{ particularly } \beta_2(1) = \frac{\zeta}{\zeta+1}.$$

Comparing (C.1) and (C.2) provides the desired result. □

Proof of Proposition 14

Proof. If the weak bidder is favored the strong bidder will determine the price, where the strong bidder's inverse equilibrium bidding strategy in the convex-convex case is

$$\beta_s^{ROS^{-1}}(p) = p + \frac{F_w(p)}{f_w(p)} = p + \frac{p^{\zeta_w}}{\zeta_w p^{\zeta_w-1}} = \frac{\zeta_w+1}{\zeta_w}p.$$

This implies the strong bidder's bidding function

$$\beta_s^{ROS}(x) = \frac{\zeta_w}{\zeta_w + 1}x, \text{ particularly } \beta_s^{ROS}(1) = \frac{\zeta_w}{\zeta_w + 1}.$$

So the expected payment in a first-price auction with ROS, where the weak bidder is granted a ROS, is

$$\begin{aligned} E[p_w^{ROS}] &= \int_0^{\beta_s^{ROS}(1)} 1 - F_s(\beta_s^{ROS^{-1}}(p))dp = \int_0^{\frac{\zeta_w}{\zeta_w+1}} 1 - \left(\frac{\zeta_w + 1}{\zeta_w}p\right)^{\zeta_s} dp \\ &= \frac{\zeta_w}{\zeta_w + 1} - \left(\frac{\zeta_w + 1}{\zeta_w}\right)^{\zeta_s} \left(\frac{\zeta_w}{\zeta_w + 1}\right)^{\zeta_s+1} \frac{1}{\zeta_s + 1} = \frac{\zeta_w}{\zeta_w + 1}\frac{\zeta_s}{\zeta_s + 1}. \end{aligned}$$

Favoring the strong bidder leads to the same inverse equilibrium bidding strategy for the weak bidder, where ζ_w is replaced by ζ_s and it holds $\beta_w^{ROS}(1) = \frac{\zeta_s}{\zeta_s+1}$. Therefore the auction revenue if the strong bidder is favored amounts to

$$E[p_s^{ROS}] = \int_0^{\beta_w^{ROS}(1)} 1 - F_w(\beta_w^{ROS^{-1}}(p))dp = \frac{\zeta_s}{\zeta_s + 1}\frac{\zeta_w}{\zeta_w + 1}.$$

Both expected payments $E[p_w^{ROS}]$ and $E[p_s^{ROS}]$ are symmetric in their arguments ζ_s and ζ_w and therefore correspond to each other for all $\zeta_w, \zeta_s > 1$. □

Proof of Proposition 15

Proof. First we calculate the expected payment dependent of η in case of favoring the weak bidder. So the inverse equilibrium bidding function of the strong and price-determining bidder is

$$\beta_s^{ROS^{-1}}(p) = p + \frac{F_w(p)}{f_w(p)} = p + \frac{1 - (1-p)^\eta}{\eta(1-p)^{\eta-1}} = p + \frac{1}{\eta(1-p)^{\eta-1}} - \frac{1-p}{\eta}.$$

In order to calculate the expected auction revenue, the highest possible bid $\beta_s(1)$ is needed, which follows with

$$\begin{aligned}
& p + \frac{1}{\eta(1-p)^{\eta-1}} - \frac{1-p}{\eta} = 1 \\
& \Leftrightarrow (\eta+1)p + \frac{1}{(1-p)^{\eta-1}} = \eta + 1 \\
& \Leftrightarrow \frac{1}{(1-p)^{\eta}} = \eta + 1 \\
& \Leftrightarrow 1 - \sqrt[\eta]{\frac{1}{\eta+1}} = p \qquad \Rightarrow \beta_s^{ROS}(1) = 1 - \sqrt[\eta]{\frac{1}{\eta+1}}.
\end{aligned}$$

Then the expected payment in the first-price auction with ROS with favoring the weak bidder is

$$\begin{aligned}
E[p_w^{ROS}] &= \int_0^{\beta_s^{ROS}(1)} 1 - F_s(\beta_s^{ROS^{-1}}(p))dp = \int_0^{1-\sqrt[\eta]{\frac{1}{\eta+1}}} (1 - p - \frac{1}{\eta(1-p)^{\eta-1}} + \frac{1-p}{\eta})dp \\
&= \frac{1}{2}(1+\frac{1}{\eta}) - \frac{1}{\eta(2-\eta)} + (\eta+1)^{-\frac{2}{\eta}} \left(-\frac{1}{2} - \frac{1}{2\eta} + \frac{\eta+1}{\eta(2-\eta)} \right). \qquad \text{(C.3)}
\end{aligned}$$

In order to determine the expected auction revenue with favoring the strong bidder the following inverse equilibrium bidding function of the weak and price-determining bidder is used

$$\beta_w^{ROS^{-1}}(p) = p + \frac{F_s(p)}{f_s(p)} = 2p.$$

Hence the weak bidder's equilibrium bidding function as well as her highest possible bid yields

$$\beta_w^{ROS}(x) = \frac{1}{2}x, \text{ particularly } \beta_w^{ROS}(1) = \frac{1}{2}.$$

So the auctioneer's expected profit is

$$\begin{aligned}E[p_s^{ROS}] &= \int_0^{\beta_w^{ROS}(1)} 1 - F_w(\beta_w^{ROS^{-1}}(p))dp = \int_0^{\frac{1}{2}} 1 - (1 - (1-2p)^\eta)dp \\ &= \int_0^{\frac{1}{2}} (1-2p)^\eta dp = 0 + \frac{1}{2}\frac{1}{\eta+1} \\ &= \frac{1}{2(\eta+1)}.\end{aligned}$$

We demand $E[p_w^{ROS}] - E[p_s^{ROS}] \geq 0$ and it follows

$$E[p_w^{ROS}] - E[p_s^{ROS}] \geq 0 \;\Leftrightarrow\; -\eta^3 - \eta^2 + \eta\left((\eta+1)^{\frac{2\eta-2}{\eta}} - 1\right)\begin{cases}\geq 0, & \eta \leq 2\\ < 0, & \eta > 2\end{cases}$$

For the polynom $-\eta^3 - \eta^2 + \eta\left((\eta+1)^{\frac{2\eta-2}{\eta}} - 1\right)$ with roots at $\eta = 0, 1, 2$ applies

$$-\eta^3 - \eta^2 + \eta\left((\eta+1)^{\frac{2\eta-2}{\eta}} - 1\right)\begin{cases}\geq 0, & \eta \leq 0 \text{ or } 1 \leq \eta \leq 2\\ < 0, & 0 < \eta < 1 \text{ or } \eta > 2\end{cases}$$

Because of assuming that $F_w(x)$ is strictly convex only $\eta \geq 1$ is regarded and we gain

$$E[p_w^{ROS}] - E[p_s^{ROS}] \geq 0, \quad \text{for all } \eta \geq 1.$$

□

Additonal Proposition 17

Proposition 17. *Let $F_s(x) = x$ and $F_w(x) = 1 - (1-x)^\eta$ be the bidders' value distributions, $\eta > 1$. Then the expected payment in a first-price auction with ROS with favoring the strong bidder $E[p_s^{ROS}]$ is always lower than that in a second-price* *auction* $E[p^{SA}]$*, i.e.,*

$$E[p_s^{ROS}] < E[p^{SA}].$$

The proof is presented in Appendix C.1. Next, Proposition 16 will demonstrate that granting a ROS to the weak bidder generates a higher expected auction revenue in a first-price auction with ROS than in a second-price auction if the parameter η of the weak bidder's concave value distribution exceeds a certain value.

Proof. We suppose that in the second-price auction the bidders follow their weakly dominant bidding strategy and bid their true valuations, it holds $\beta^{SA}(1) = 1$ and the expected payment is

$$\begin{aligned} E[p^{SA}] &= \int_0^{\beta^{SA}(1)} 1 - F^{SA}(p)dp = \int_0^1 1 - (1 - (1-p)^{\eta+1})dp = \int_0^1 (1-p)^{\eta+1}dp \\ &= \frac{1}{\eta+2}. \end{aligned} \tag{C.4}$$

If the strong bidder is favored the weak bidder determines the payment through her bid. Therefore the equilibrium bidding strategy of the weak non-favored bidder is required as well as its inverse function

$$\beta_w^{ROS^{-1}}(p) = p + \frac{F_s(p)}{f_s(p)} = 2p \Leftrightarrow \beta_w^{ROS}(x) = \frac{1}{2}x.$$

With $\beta_w^{ROS}(1) = \frac{1}{2}$ for the expected payment in a first-price auction with ROS, where the strong bidder is favored, ensues

$$
\begin{aligned}
E[p_s^{ROS}] &= \int_0^{\beta_w^{ROS}(1)} 1 - F^{ROS}(p)dp = \int_0^{\frac{1}{2}} 1 - F_w(\beta_w^{ROS^{-1}}(p))dp \\
&= \int_0^{\frac{1}{2}} \left(1 - (1 - (1-2p)^{\eta})\right) dp = \int_0^{\frac{1}{2}} (1-2p)^{\eta} dp \\
&= \frac{1}{2\eta + 2}. \qquad \text{(C.5)}
\end{aligned}
$$

Comparing (C.5) and (C.4) leads to

$$
E[p_s^{ROS}] = \frac{1}{2\eta+2} < \frac{1}{\eta+2} = E[p^{SA}] \Leftrightarrow \eta + 2 < 2\eta + 2 \Leftrightarrow \eta > 0,
$$

which holds for all $\eta \geq 1$. □

Proof of Proposition 16

Proof. Assuming that the ex ante weak bidder is favored by the ROS, the expected payment in the first-price auction with ROS exceeds that in the second-price auction, see (C.4), if

$$
\begin{aligned}
& E[p^{SA}] < E[p_w^{ROS}] \\
& \Leftrightarrow -\eta^4 + \eta^3 - 2\eta^2 + (\eta+1)^{1-\frac{2}{\eta}} \left(\eta^3 + 2\eta^2\right) \begin{cases} > 0, & \text{if } \eta < 2 \\ \leq 0, & \text{if } \eta \geq 2 \end{cases} \\
& \Leftrightarrow \eta \gtrsim 2.745.
\end{aligned}
$$

□

C.2 Additional Propositions

Proposition 18. *Let $F_s(x) = x^\zeta$ and $F_w(x) = x$ be the bidders' value distributions, $\zeta > 1$. Then the expected payment in the second-price auction exceeds that in first-price auction with ROS for all $\zeta > 1$, i.e,*

$$E[p^{ROS}] < E[p^{SA}]$$

Proof. In the second-price auction the bidders follow a weakly dominant bidding strategy, which signifies to bid their true valuations. This property implies that $\beta^{SA}(1) = 1$ for all bidders. The auction revenue in the second-price auction amounts to

$$\begin{aligned} E[p^{SA}] &= \int_0^{\beta^{SA}(1)} 1 - F^{SA}(p)dp = \int_0^1 1 - F_s(p) - F_w(p) + F_s(p)F_w(p)dp \\ &= \int_0^1 (1 - p^\zeta - p + p^{\zeta+1})dp = \frac{1}{2} - \frac{1}{\zeta+1} + \frac{1}{\zeta+2}. \end{aligned}$$

Comparing the expected payments in the second-price and first-price auction with ROS, which follows from Proposition 13, provides

$$\begin{aligned} E[p^{ROS}] = \frac{1}{2}\frac{\zeta}{\zeta+1} \quad &< \quad \frac{1}{2} - \frac{1}{\zeta+1} + \frac{1}{\zeta+2} = E[p^{SA}] \\ \Leftrightarrow \quad & 0 < \zeta. \end{aligned}$$

□

With an increasing $\zeta > 1$ the expected auction revenue will raise in both auction forms and converge to $\frac{1}{2}$. The reason for the higher expected payment is that one of the bidders, in this case the strong bidder, becomes stronger since ζ increases and therefore this strong and price-determining bidder is expected to submit a higher bid. In a second-price auction the expected payment will also raise, if one of the potentially price-determining bidders becomes stronger. The fact that the expected auction revenues will never exceed $\frac{1}{2}$ in this linear-convex combination is obvious: Since we suppose that the weak bidder is favored in the first-price auction with ROS the strong bidder determines the payment in dependence of the weak bidder's strength, particularly it is $\beta_s^{ROS}(x_s) = \frac{1}{2}x_s$. Consequently, the price-determining bid converges to $\frac{1}{2}$ because the strong bidder's expected valuation $E[X_s]$ converges to 1 for $\zeta \to \infty$. In the second-price auction the second-highest bid or valuation will determine the price. If ζ increases the strong bidder's expected valuation converges to 1 and the weak bidder's expected valuation is $\frac{1}{2}$, which then will determine the expected payment.

Proposition 19. *Let $F_s(x) = x^{\zeta_s}$ and $F_w(x) = x^{\zeta_w}$ be the bidders' value distributions, $1 < \zeta_w < \zeta_s$. Then the expected payment in the second-price auction exceeds that in the first-price auction with ROS, i.e.,*

$$E[p^{ROS}] < E[p^{SA}].$$

Proof. The weakly dominant bidding strategy in a second-price auction is to bid one's true valuation, therefore it follows $\beta^{SA}(1) = 1$ and the expected payment in the second-price auction is

$$\begin{aligned} E[p^{SA}] &= \int_0^{\beta^{SA}(1)} 1 - F^{SA}(p)dp = \int_0^1 (1 - p^{\zeta_s} - p^{\zeta_w} + p^{\zeta_s+\zeta_w})dp \\ &= 1 - \frac{1}{\zeta_s + 1} - \frac{1}{\zeta_w + 1} + \frac{1}{\zeta_s + \zeta_w + 1}. \end{aligned}$$

So it follows

$$
\begin{aligned}
E[p^{ROS}] = \frac{\zeta_w}{\zeta_w + 1}\frac{\zeta_s}{\zeta_s + 1} \quad &< \quad 1 - \frac{1}{\zeta_s + 1} - \frac{1}{\zeta_w + 1} + \frac{1}{\zeta_s + \zeta_w + 1} = E[p^{SA}] \\
&\Leftrightarrow \zeta_s + \zeta_w + 1 < (\zeta_s + 1)(\zeta_w + 1) \\
&\Leftrightarrow 0 < \zeta_s \zeta_w .
\end{aligned}
$$

which is true for all $\zeta_w, \zeta_s > 1$. □

Finally, we state that for an increasing ζ_s as well as for an increasing ζ_w the expected payment in both auction forms is augmented, where the expected payments converge to 1 for $\zeta_s, \zeta_w \to \infty$. This is immediately obvious, because both bidders become stronger, i.e., their expected valuations, $E[X_s]$ and $E[X_w]$, converge to 1 for $\zeta_s, \zeta_w \to \infty$. Notice that for $\zeta_s = 1$ or $\zeta_w = 1$ the linear-convex combination is obtained as a special case.

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Karlsruhe, den 18.05.2018

Marie-Christin Haufe

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Abs. 2: Straflosigkeit tritt ein, wenn der Täter die falsche Angabe rechtzeitig berichtigt. Die Vorschriften des §158 Abs. 2 und 3 gelten entsprechend.

Karlsruhe, den 18.05.2018

Marie-Christin Haufe