Designing Auctions for Renewable Energy Support

Zur Erlangung des akademischen Grades eines
Doktors der Wirtschaftswissenschaften

(Dr. rer. pol.)

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

genehmigte

DISSERTATION

von

M.Sc. Ann-Katrin Fleck

Tag der mündlichen Prüfung: 21.03.2023
Referent: Prof. Dr. Karl-Martin Ehrhart
Korreferent: Prof. Dr. Wolf Fichtner

Karlsruhe, 2023

Danksagung

Eine Dissertation entsteht im ständigen Austausch und durch fortwährende Unterstützung vieler Personen im Umfeld des Autors. Bei diesen möchte ich mich hiermit bedanken.

Der größte Dank gebührt meinem Doktorvater Prof. Dr. Karl-Martin Ehrhart. Bereits während meines Studiums konnte ich in der Forschungsgruppe als studentische Hilfskraft Einblicke in die Welt der Auktionen gewinnen. Seiner Betreuung während meiner Masterarbeit und Dissertation verdanke ich viele wertvolle Diskussionen, neue Denkanstöße, und auch persönliches Wachstum durch meinen Aufgabenbereich. Ich blicke sehr gerne auf diese Zeit zurück.

Ebenso bedanken möchte ich mich bei meinem Korreferenten Prof. Dr. Wolf Fichtner, meinem Prüfer Prof. Dr. Christof Weinhardt, sowie dem Vorsitzenden der Prüfungskommission, Prof. Dr. Marc Wouters. Vielen Dank für Ihre Zeit und Ihr Interesse, sich mit meiner Arbeit auseinander zu setzen und diese zu bewerten. Ein herzlicher Dank gilt ebenfalls Prof. Dr. Stefan Seifert, der mich in meiner Arbeit durch neuen Input und viel organisatorischen Aufwand stets unterstützte.

Im Laufe der Jahre durfte ich viele schöne Stunden mit meinen Kollegen der Forschungsgruppe Strategische Entscheidungen verbringen. Gemeinsam haben wir uns über viele fachliche Probleme hinweggeholfen, aber auch privat sehr schöne Stunden verbracht. Danke daher an Dr. Marie-Christin Haufe, Dr. Fabian Ocker, Dr. Jan Kreiss und Runxi

Wang. Zudem möchte ich mich bei Andreas Schildknecht, Benedikt Renner, Jasper Weber und Philipp Büchner bedanken, die mich immer wieder insbesondere bei der Durchführung der Experimente unterstützt haben.

Ein weiterer Dank gilt meinen Koautoren und Koautorinnen. Dies sind insbesondere Dr. Marion Ott (ZEW Mannheim) und Dr. Vasilios Anatolitis (Fraunhofer ISI), denen ich eine jahrelange spannende Zusammenarbeit verdanke. Ebenso möchte ich meinen Kolleginnen und Kollegen aus den AURES und AURES II Projekten danken. Durch sie durfte ich meinen Horizont der Auktionen zur Förderung erneuerbarer Energien erweitern und andere Blickwinkel kennen lernen.

Ein letzter Dank gilt meiner Familie und meinen Freunden, auf deren Unterstützung ich mich immer verlassen kann. Insbesondere danke ich meinem Mann Tobias, der mir stets mit Rat und Tat zur Seite stand, und mir allein durch sein geduldiges Zuhören bei so manchem Problem helfen konnte.

Karlsruhe, im April 2023

Abstract

To ensure a sustainable and reliable electricity supply, expansion of plants from renewable sources is inevitable. At the moment, development and operation of these plants exclusively based on revenues from electricity markets is impossible. Thus, the European Union (EU) and many other countries worldwide implement additional financial support measures. The height and recipients of financial support are often determined via competitive mechanisms, i.e., auctions. Auctions for renewable energy support thus contribute majorly to energy transition, and their thorough design is of utmost importance.

This thesis analyses and evaluates different design options for auctions for renewable energy support both auction-theoretically and experimentally. This thesis contributes to a successful design of auctions, and aims at preventing premature decisions regarding unfavourable auction designs.

In some auctions for renewable energy support, the demand supposed to be awarded is not, or barely, met. In these cases, there is no or only minimal competition, and prices are almost at the level of the predetermined ceiling price. As these results are not in line with the goals of low prices and a high competition level, different suggestions to fix the situation have been made. The most prominent one, which has been implemented in various scenarios, is the so-called *endogenous rationing*, where only a certain portion of submitted bids is actually awarded. This

thesis shows, that rational bidders are not expected to participate in an auction with endogenous rationing. The experimental analysis supplements this finding: participation rates, i.e., supply in auctions as well as awarded projects, decreases in repeated auctions despite an equal number of potential projects. Both auctioneer's surplus as well as social welfare are lower in auctions with than auctions without endogenous rationing.

To optimise auctions for renewable energy support, methods of mechanism design are used. For this, the designated goals of the auctioneer are of utmost importance. Only with low levels of competition an auction is able to maximise auctioneer's surplus, social welfare, and expansion goals all at once. If competition levels are higher, the goals need to be prioritised. Suitable measure to fulfil those goals are ceiling price, as well as an adequate reimbursement of project preparation costs to bidders. Both measures are dependent on cost and competition structure.

Especially in times of low competition, a possible solution can be to open auctions across countries. In cross-border auctions, projects from different countries can compete and be awarded. In this thesis, different design options are auction-theoretically analysed and evaluated regarding efficiency and expected revenues. Joint auctions conducted by different countries together, as well as mutually opened auctions, which are conducted sequentially, are optimal regarding evaluation criteria. Further, sequential auctions seem to be appropriate regarding feasibility as well, as they can take different market characteristics of the participating countries into account. Thus, this auction format is recommended for use.

Theoretical analyses of project with different cost structures, e.g., project from different countries or of different technologies, are then supplemented with experimental studies. On the one hand, we analyse multi-technology auctions, where projects of different cost structures can compete against each other. On the other hand, we compare technology-specific auctions, where only projects with similar structures can compete. To ensure a better transferability of the real-world scenario, both single-project bidders, as well as multi-project bidders, are analysed. Multi-technology auctions lead to lower prices, a higher social welfare, as well as higher auctioneer's surplus, as technology-specific auctions. Further, a higher level of efficiency can be observed. While comparing different pricing rules, it can be seen that discriminatory pricing is to be preferred in comparison to uniform pricing for all considered criteria. Furthermore, uniform pricing has a higher risk of irrational bidding, and thus, in the worst case, undesired bankruptcies of bidders.

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

Kurzfassung

Zur Sicherung einer nachhaltigen und zuverlässigen Stromversorgung ist der Ausbau von Anlagen zur Stromgewinnung aus erneuerbaren Quellen unerlässlich. Zurzeit ist die Erschließung und der Betrieb dieser Anlagen ausschließlich basierend auf Einnahmen aus den Strommärkten noch nicht möglich. Daher sind in der Europäischen Union (EU) und in vielen anderen Ländern weltweit zusätzliche monetäre Förderungen implementiert. Die Bestimmung der Höhe der Förderung sowie deren Empfänger werden dabei oft über wettbewerbliche Mechanismen, d.h. Auktionen, geregelt. Da Auktionen zur Förderung erneuerbarer Energien somit einen wichtigen Beitrag zur Energiewende beitragen, ist die sorgfältige Gestaltung der Auktionen von äußerster Wichtigkeit.

Die vorliegende Doktorarbeit analysiert und bewertet daher verschiedene Gestaltungsmöglichkeiten für Auktionen zur Förderung erneuerbarer Energien sowohl auktionstheoretisch, als auch experimentell. Diese Arbeit soll einen wichtigen Beitrag zur erfolgreichen Ausgestaltung der Auktionen zur Verfügung zu stellen und vorschnelle Entscheidungen ungünstiger Auktionsdesigns verhindern.

In einigen Auktionen zur Förderung erneuerbarer Energien wird die zu bezuschlagende Nachfrage nicht oder nur kaum durch das Angebot gedeckt. In diesem Fall herrscht wenig oder kaum Wettbewerbsdruck, die entstehenden Preise sind nahe dem festgelegten Höchstpreis. Da diese Ergebnisse konträr zu den Zielen geringer Preise und eines hohen Wettbe-

werbsniveaus sind, wurden in der Vergangenheit verschiedene Vorschläge zur Behebung der Situation laut. Der wohl bekannteste und an verschiedenen Stellen implementierte Lösungsvorschlag ist die sogenannte *endogene Rationierung*, bei der nur ein Teil der eingereichten Gebote bezuschlagt wird. Diese Arbeit zeigt, dass bei dem Einsatz dieser Maßnahme bei rationalen Bietern keine Teilnahme erwartet werden kann. Auch bei der experimentellen Untersuchung finden sich ähnliche Ergebnisse: die Teilnahme, d.h. das Angebot in den Auktionen (und somit auch die Anzahl bezuschlagter Projekte) sinkt in mehrmals durchgeführten Auktionen trotz gleicher Anzahl potentiell zur Verfügung stehender Projekte. Sowohl die Rente des Auktionators als auch die soziale Wohlfahrt sind niedriger als in Auktionen ohne endogene Rationierung.

Zur Optimierung der Auktionen zur Förderung erneuerbarer Energien werden weiterhin Methoden des Mechanismus Designs verwendet. Hierbei ist vor allem die genaue Zielsetzung des Auktionators von Wichtigkeit. Nur unter niedrigem Wettbewerbsniveau kann eine Auktion mit geeignetem Höchstpreis die Ziele der Maximierung der Rente des Auktionators, der sozialen Wohlfahrt, und des Ausbaus alle gleichzeitig erfüllen. Bei genügendem Wettbewerb müssen diese allerdings priorisiert werden. Geeignete Maßnahmen zur Erfüllung der verschiedenen Ziele sind hierbei vor allem der Höchstpreis sowie eine damit verbundene angepasste Rückerstattung von Kosten an die Bieter. Beide Maßnahmen sind jeweils abhängig von der Kosten- und Wettbewerbsstruktur.

Insbesondere in Zeiten geringeren Wettbewerbs kann eine mögliche Lösung die Öffnung der Auktionen auch über Ländergrenzen hinweg sein. In den grenzüberschreitenden Auktionen können Projekte aus verschiedenen Ländern teilnehmen und bezuschlagt werden. Verschiedene Ausgestaltungsmöglichkeiten werden in dieser Arbeit auktionstheoretisch analysiert und bezüglich Effizienz und erwarteten Auktionserlösen miteinander verglichen. Hierbei erweisen sich die gemeinsam von allen Ländern durchgeführte Auktion und die sequentiell durchgeführten, für jeweils alle geöffneten Auktionen als optimal bezüglich der Evaluationskriterien. Sequentielle Auktionen scheinen auch in Bezug auf Durchführbarkeit bei verschiedenen Marktcharakteristiken der unterschiedlichen Länder gut geeignet zu sein, weshalb diese Form der grenzüberschreitenden Auktionen grundsätzlich empfohlen wird.

Die theoretischen Analysen von Anlagen mit verschiedenen Kostenstrukturen, wie z.B. bei Anlagen aus verschiedenen Ländern oder verschiedener zugrundeliegender Technologien, werden anschließend durch experimentelle Untersuchungen ergänzt. Verglichen werden einerseits technologieübergreifende Auktionen, in denen Projekte aller Kostenstrukturen teilnehmen können, und technologiespezifische Auktionen, in denen ausschließlich Projekte gleicher Strukturen miteinander konkurrieren. Zur besseren Darstellung der realen Situation werden sowohl Einprojektbieter, als auch Mehrprojektbieter betrachtet. Hierbei führen technologieübergreifende Auktionen zu niedrigeren Preisen, einer höheren sozialen Wohlfahrt sowie einer höheren Rente des Auktionators als technologiespezifische Auktionen. Zudem ist ein höheres Effizienzniveau zu erwarten. Beim Vergleich der am häufigsten verwendeten Preisbestimmungsverfahren zeigt sich außerdem, dass das Gebotspreisverfahren dem Einheitspreisverfahren in allen betrachteten Kriterien überlegen ist. Unter dem Einheitspreisverfahren ist weiterhin die Gefahr des irrationalen Bietens, und somit im schlimmsten Fall ungewollte Insolvenz, bedeutend höher.

Diese Doktorarbeit basiert auf drei Papieren, welche am Institut für Volkswirtschaftslehre (ECON) in der Forschungsgruppe Strategische Entscheidungen unter der Betreuung von Prof. Dr. Karl-Martin Ehrhart am Karlsruher Institut für Technologie (KIT) erarbeitet wurden. Die Arbeit ist in englischer Sprache verfasst.

Contents

List of figures

List of tables

List of abbreviations

CfD	Contract-for-Difference
DP	discriminatory pricing
EAV	endogenous auction volume
ECP	endogenous ceiling price
ER	endogenous rationing
EU	European Union
FiT	feed-in-tariff
GVA	Generalized Vickrey Auction
HAB	highest accepted bid
IC	incentive compatibility
IQR	interquartile range
IR	individual rationality
kW	Kilowatt
kWh	Kilowatt hour
LRB	lowest rejected bid
MW	Megawatt

MWh	Megawatt hour
PV	photovoltaic
RE	renewable energy
RED	Renewable Energy Directive
RES	renewable energy sources
UK	United Kingdom
UP	uniform pricing
VCG	Vickrey-Clarke-Groves

List of functions and variables

α	scaling parameter out of the interval $(0, 1]$
β	mixed equilibrium strategy
β_t	equilibrium bidding strategy
β_j	parameters in the linear mixed-effects model
$\beta(x_i, r)$	equilibrium bidding strategy of a company with private costs x_i and ceiling price r
$\beta^{DP}(x, r)$	symmetric equilibrium bidding strategy in the DP auction
$\beta^{UP}(x, r)$	symmetric equilibrium bidding strategy in the UP auction
δ	percentage of auction volume that is awarded
ϵ	vector of residual errors in the linear mixed-effects model
$\kappa(m)$	number of winning bids in an auction
$\bar{\mu}$	upper limit of range of number of bids in an auction
$\underline{\mu}$	lower limit of range of number of bids in an auction
$\pi(x_i)$	expected profit from the auction of bidder with private costs x_i
$\Pi(x_i)$	expected overall profit from the auction of bidder with private costs x_i and participation costs
Π^0	auctioneer's surplus

Π_t^0	auctioneer's surplus in auction t
$\varrho(b)$	endogenous ceiling price
Φ	ratio of number of bidders n_{t_1} and n_{t_2} in different auction types t_1 and t_2
$\mathbf{b}$	vector of bids
b_i	bid of bidder i
b_{ij}	bid of bidder i for good j
b_t	bid in auction t
c	participation costs equal for all bidders
c_{Sim}^0	auctioneer's total costs in simultaneous auctions
c_{Seq}^0	auctioneer's total costs in sequential auctions
c_t^0	auctioneer's costs in auction t
C_t^0	random variable of auctioneer's costs in auction t
C_{Seq}^0	random variable of auctioneer's total costs in sequential auctions
$C_{Seq,t}^0$	random variable of auctioneer's costs in sequential auction t
d	additive constant
D_{eff}^{bin}	degree of efficiency in the binary approach
D_{eff}^{rel}	degree of efficiency in the relative approach
D_{eff}^{rge}	degree of efficiency in the range approach
f	density function of private costs
f_t	density function of private costs from bidders of type t
f_{k_t}	density function of the k_t-th lowest private cost signal from bidders of type t

$f_{(k,n)}$	density function of the k-th lowest n private cost signals
$f_{(k,i,j)}$	density function of the k-th lowest private cost signal where i costs are from bidders of type t_1 and j costs are from bidders of type t_2
F	distribution function of private costs
F_t	distribution function of private costs from bidders of type t
$F_{(k,n)}$	distribution function of the k-th lowest of n private cost signals
$F(\hat{x})$	a bidder's ex-ante participation probability
g	parameter for the random effect in the linear mixed-effects model
$g(x)$	$f_{(k,n-1)}(x)$
$G(x)$	$F_{(k,n-1)}(x)$
H	joint distribution of individual cost distributions
H_{-i}	joint distribution of individual cost distributions without bidder i's distribution
j	elements from the set $\mathbb{N}^0$
k	number of goods auctioned
k_t	number of goods auctioned in auction t
m	number of risk-neutral companies participating in an auction
m_t	number of risk-neutral companies participating in auction t
n	number of risk-neutral companies potentially participating in an auction

n_t	number of risk-neutral companies potentially participating in auction t
N	set of all risk-neutral bidders
N_t	set of risk-neutral companies of type t
N_{awd}	set of awarded projects
N_{awd}^j	set of awarded projects in auction round j
N_{eff}	set of bidders with the lowest private costs
p	payment a bidder receives
p_i	payment bidder i receives
p_t	payment a bidder receives in auction t
P_t	random variable of payment a bidder receives in auction t
q	participation probability in an auction
q_t	participation probability in auction t
q_i^p	participation probability of bidder i
q_i^g	award probability of bidder i conditional on i's participation
Q_i	expected award probability of bidder i conditional on i's participation
r	ceiling price
r_t	ceiling price in auction t
r_s^{Oj}	optimal ceiling price for objective Oj and reimbursement s
s	reimbursement for companies
S	social welfare
t	capital letters representing different types of auctions and bidders

$\bar{t}$	upper limit of private cost interval t
$\underline{t}$	lower limit of private cost interval t
v	auctioneer's value of the good
W	test statistic of the Wilcoxon test
x_i	private realisation costs of company i
$x_{(k,n)}$	k-th lowest private cost signal out of n signals
$\hat{x}$	cutoff costs
$\hat{x}^{Oj}$	optimal cutoff type for objective Oj
$\bar{x}$	upper limit of private cost interval
$\underline{x}$	lower limit of private cost interval
$\mathbf{x}$	vector of private costs of all bidders
$\mathbf{x}_{-i}$	vector of private costs of all bidders except bidder i
$X_{(k,n)}$	random variable of k-th lowest private cost signal out of n signals
y	vector of dependent variables in the linear mixed-effects model

Chapter 1

Introduction

Primary energy consumption has been rising steadily over the last years (BP p.l.c, 2020). The only exception to this trend is in 2020, as Covid 19 and resulting lockdown measures had negative impacts on energy demand (Adam et al., 2020).[1] Although the amount of renewable energy (RE) consumption has been rising as well, it is still only about 5% of the total primary consumption (BP p.l.c, 2020). Especially with the newest political turbulences effecting amongst others the European energy market, establishing energy from renewable energy sources (RES) is more important than ever.[2]

To achieve a long-term high percentage of RE in the energy mix, it is inevitable to support its expansion. Since conventional energy sources are still producing with lower costs due to economics of scale and already existing plants (Widmann, 2022), this support must also be in terms of additional payments for RE plants on top of market energy prices. Determining these payments administratively is complicated. For one, an administrative decision has to be thoroughly planned and has to stand up against criticism. This is especially challenging when determining a price, which should fit every need of every market participant, while not

---

[1] The effects of the European energy crisis in 2022 might be another exception, though the magnitude of energy savings cannot be foreseen to this date.

[2] This thesis concentrates on the use of RES for electricity generation.

granting too much money. Furthermore, the responsible administrators are usually governmental agencies, which are not immediate experts in energy generation and its costs. This is where auctions have their greatest advantage: in case of information asymmetry, the party that has more information can influence the price by bidding. In this case, producers of energy out of renewable sources are far more knowledgeable about energy production costs per Megawatt hour (MWh).

Still, designing adequate auctions is not an easy task. Especially when considering a large number of different project developers with various characteristics, such as project site and scale effects, choosing an auction design can be difficult. This thesis analyses how to properly design auctions for RE support and shows pitfalls to avoid.

1.1 Political background

Over the last decades, countries worldwide have been setting goals to counteract the effects of climate change. In 2009, the European Union (EU) decided in the Renewable Energy Directive (RED) to set the goal of consuming at least 20% energy from renewable sources out of the total energy consumption in 2020 (European Parliament, 2009), which most European countries actually achieved (Broom, 2022). However, the goals of the RED have since been amended to ensure the achievement of the Paris Agreement, i.e., limiting global warming to 1.5 degrees Celcius (United Nations, 2019). While the different EU member states set various targets themselves (Fleck et al., 2023), the REDII set an overall goal of a RES share of at least 32% by 2030 in 2018 (European Parliament, 2018), followed by a proposal of increasing the goal to a 40% share in 2021 (European Parliament et al., 2021). This share might be even further increased (European Commission, 2022).

With these ambitious goals, a framework for RE expansion needs to be implemented. Energy from RES still needs financial support to compete with already established energy sources (Held et al., 2019). Before 2017, support payments and its recipients were determined administratively, e.g., by a feed-in-tariff (FiT)[3]. For this, the auctioneer had to decide on support payments (BMU,2000), while in auctions bidders can actively include their cost calculations in their bids, leading to a much clearer picture of the actual need for support. Thus, the European Commission has decided to restrict the determination of the recipients and the height of the financial support to competitive mechanisms in the State Aid Guidelines (European Commission, 2014). Since 2017, EU member states are thus obligated to determine support payments via auctions (European Commission, 2014).[4] By 2022, 19 EU member states as well as the United Kingdom (UK) had existing auction frameworks in place (AURES II, 2022). While in the long term, a transition to a no-subsidy world where all technologies compete against each other is desired, in the short term countries can conduct auctions specifically designed for only one technology to assist in establishing this technology (European Commission, 2014). So far, approximately 70% of all conducted auctions in the EU are technology-specific, where only projects of the same technology, e.g., photovoltaic (PV) or onshore wind, can participate (AURES II, 2022).

1.2 Implemented auction designs

The choice of an auction design is not an easy task and depends heavily on the defined targets the countries aim to achieve (Fleck et al., 2023).

---

[3] A detailed explanation of remuneration schemes can be found in 1.2.

[4] Exceptions can be granted under certain circumstances, e.g., for non-established sources with no competition.

Therefore, it is not surprising that different countries implement different auction designs to determine projects receiving support. In the past years, various design elements have shown to be suitable for auctions for RE support (Río et al., 2015). Most auctions for RE support are procurement auctions, where bidders receive a payment and deliver energy, if they are awarded. Only offshore wind projects, which are highly profitable, do not need support anymore. Thus, bidders pay for the chance to generate energy offshore (Reuters, 2021). This thesis will concentrate on procurement auctions, where bidders receive support.

In most RE auctions in the EU, the auctioned good is either installed capacity, electricity, or budget (AURES II, 2022), with capacity being the most prominent choice. In this case, bidders submit a bid pair consisting of the proposed capacity in Megawatt (MW) or Kilowatt (kW), and the price in MWh or Kilowatt hour (kWh). When the price is the only award criterion, bidders are awarded until the proclaimed auction volume is reached, beginning with the bidder with the lowest price (Río et al., 2015). When other award criteria, e.g., local content requirements, are also considered, a scoring rule needs to be implemented (Asker et al., 2010), where the optimal award allocation for the auctioneer is chosen based on the auctioneer's values for the different criteria.

Price bids are usually limited by a ceiling, and, less commonly, a floor price (AURES II, 2022). Thus, an auctioneer can protect themself against too high prices, as well as the bidders against too low prices. While the determination of awards is directly linked to a bidder's own bid, the level of support need not be equal to the price bid. First, the level of support depends on the remuneration scheme. With a FiT, bidders receive a predetermined payment, which is a payment independent of the market price, either on top of the market price[5] or as a stand-

---

[5] This is also called a fixed feed-in-premium.

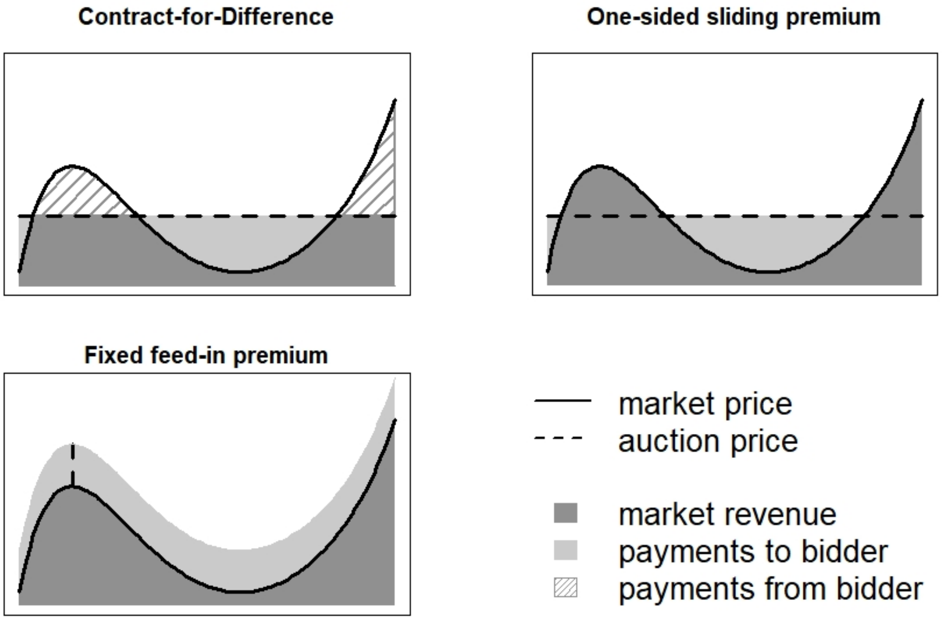

Figure 1.1: Different remuneration types

alone payment. A sliding premium is a support payment depending on the market price. In the one-sided sliding premium, awarded bidders always receive at least the price determined in the auction, either because the market price is higher than the auction price, or through the support payment in the height of the difference between market price and auction price. In the Contract-for-Difference (CfD), or two-sided sliding premium, awarded bidders receive exactly the auction price, as either they receive a payment, or have to make a payment, to account for the difference between market price and auction price. While in a CfD the market price risk is relatively low, a fixed feed-in premium cannot remove a bidder's market price risk (Kitzing et al., 2013). An overview of the most common remuneration schemes can be found in Figure 1.1.

The auction price in Figure 1.1 can be determined in different ways. The most commonly applied schemes are discriminatory pricing (DP), also called pay-as-bid, as well as uniform pricing (UP). In a DP procurement auction, bidders receive different prices based on their bid, i.e., in the easiest case, each receives a payment in height of their bid. In a UP auction, all awarded bidders receive the same payment. This payment is often determined by the lowest rejected bid (LRB) or the highest accepted bid (HAB).

Independently of the award procedure and price determination, bidders often need to fulfil certain prequalification criteria in order to participate. This includes material prequalification measures, e.g., environmental, or building permits, as well as financial prequalifications, e.g., bid bonds (Río et al., 2015). These measures aim to reduce non-realisation probabilities of awarded projects (Kreiss et al., 2017). Often, financial prequalifications are held back as penalties in case of breach of contract. In order not to risk inefficient auction outcomes, and still achieve high realisation rates, careful adjustment of the measures, i.e., higher financial and reasonable material prequalifications, is necessary (Kreiss et al., 2017).

To favour certain actors, e.g., energy communities, special rules can be applied, such as the implementation of a bonus system in terms of payment, or lower prequalification criteria (Amazo et al., 2020). It should also be kept in mind, that auctions for RE support are typically conducted not only once, but multiple times per year (AURES II, 2022). Bidders not successful in one auction thus can often participate again, though this might induce further costs, e.g., for renewals of permits.

1.3 Objectives

Auction design has a major influence on the auction outcome, not only in behalf of prices, but also in awards per se. With the impending difficulties of the energy transition, it is of vital importance to design an auction for RE support in a way which provides assistance to establish a long-term reliable market.

While auctions have been theoretically analysed over the last decades (e.g., Vickrey, 1961; Krishna, 2009), the implementation of auctions in the complex market of RE support still has room for improvement. A minor change in the auction design can affect auction outcomes and long-term objectives in various ways (Fleck et al., 2023), the most obvious one being auction prices. Even when conducting a well applied and long approved design, external variables, such as competition, can impact the outcome dramatically (Anatolitis et al., 2022).

The political decisions on auction design can be influenced by many different aspects, e.g., stakeholders from energy producers and tax payers in general. In this context, it is especially important to provide a thorough and unbiased analysis of the questions at hand. This thesis provides a link between auction theory on the one hand, and practical implementation of auctions in the RES sector on the other hand. By scientifically and objectively analysing the framework conditions, and then giving recommendations for real-world application, this thesis helps policy makers to design auctions carefully and foresighted. Thus, it gives important insights into fulfilling expansion goals and a valuable contribution to the ongoing path to a sustainable future.

1.4 Approach

This thesis sheds light on the difficulties of designing auctions for RE support. The topics addressed in this thesis stem from practical questions and problems policy makers face when conducting RE auctions. To allow a holistic understanding, a variety of methods is applied. In a first step, the situation is displayed in an abstract mathematical model, and then analysed auction-theoretically to derive game-theoretic equilibria. Following the pure theoretic approach, laboratory experiments complement the findings to transfer results into a more practical setting. Lastly, the results from both methods are compared and evaluated to derive a combined conclusion and give recommendations for real-world applications.

One major problem not only in auctions for RE support, but in auctions in general, is the dependence on competition. An auction is foremost an allocation mechanism, and not suited to guarantee low prices when not enough interested parties are present. Unfortunately, in some auctions for RE support, low competition has been a crucial factor, especially in the onshore wind auctions in Germany since 2018 (Bundesnetzagentur, 2022). A proposed solution has been the implementation of measures to endogenously reduce the auction volume. Chapter 2 critically analyses this proposal auction-theoretically and advises strongly against such measures. Further, the mechanism design approach is used to determine the optimal settings for an auction depending on the goals of the auctioneer.

To supplement the findings of Chapter 2, Chapter 3 presents a laboratory experiment, which was conducted to test whether the theoretical results can be replicated in a real-world setting. With the methods of experimental economics, this chapter examines how participants behave in a setting with low competition, both in the case where all of the a-priori disclosed auction volume is awarded, and when the awarded auction volume is reduced based on (the lack of) competition. For the evaluation of results, auction prices, auctioneer's surplus, as well as social welfare are considered.

A topic which is of increasing importance, especially with regards to optimise natural resource potential and competition, is the introduction of cross-border auctions (Kerres et al., 2021). Cross-border auctions could even be made mandatory in the future (European Parliament et al., 2021). To this date, Germany and Denmark conducted a successful cross-border cooperation in 2016, while other countries have announced interest in a future conduction but have been hesitant so far (Resch et al., 2021). To provide assistance in designing cross-border auctions, Chapter 4 auction-theoretically analyses different options for policy makers and compares expected results of different types of cross-border auctions.

Related to the topic of cross-border auctions, another decision policy makers have to face is the choice of technologies eligible for award. As explained in Section 1.1, in the future all technologies should compete against each other in one auction, or, even later, in a post-subsidy market. This is not the case in a majority of currently conducted auctions for RE support (AURES II, 2022). Thus, Chapter 5 experimentally analyses multi-technology auctions compared to auctions with only one technology to determine strengths or possible drawbacks of the different auction schemes.

Chapter 6 concludes the results of the previous chapters and gives an outlook on possible future research.

Chapters 2 through 5 are based on three papers that have been published, are under review, or are to be submitted to journals. The papers have been adapted slightly to account for readability and consistency. Ehrhart et al., 2022 has been split into the theoretic analysis, and the experimental one, to allow for more detailed results. Table 1.1 gives an overview of the different papers including authors and methods used.

Table 1.1: Overview of the papers prepared for this thesis

Ch.	**Authors**	**Title**	**Methods**	**Reference**
2	Karl-Martin Ehrhart, Ann-Katrin Fleck, Marion Ott	A Small Volume Reduction that Melts Down the Market: Auctions with Endogenous Rationing	Auction-theory, mechanism design	Ehrhart et al., 2022
3	Karl-Martin Ehrhart, Ann-Katrin Fleck, Marion Ott	A Small Volume Reduction that Melts Down the Market: Auctions with Endogenous Rationing	Auction-theory, experimental analysis	Ehrhart et al., 2022
4	Karl-Martin Ehrhart, Ann-Katrin Fleck, Vasilios Anatolitis, Jenny Winkler	Auction-theoretic aspects of cross-border auctions	Auction-theory	Ehrhart et al., 2019a
5	Ann-Katrin Fleck	Analysing Multi-Technology Auctions - Experimental Evidence	Auction-theory, experimental analysis	Fleck, 2022

Chapter 2

Auction-theoretic analysis of auctions with endogenous rationing

2.1 Introduction

Carbon-free electricity is key to achieving the ambitious climate goals.[1] The fast expansion of carbon-free generation and building of new renewable power plants is supported by public policies, which include tax credits, renewable portfolio standards, commitments to procure carbon-free electricity, and auctions (tenders).

Auctions for RE support are a growing field of application of multi-unit auctions, with yearly total award prices yielding a twelve-figure dollar amount.[2,3] The motivation for the use of auctions is to select the companies that have the lowest costs for providing the renewable energy and to determine the lowest necessary support payments, i.e., to ensure

---

[1] For example, the US aims to cut greenhouse gas emissions by 50–52% by 2030 as compared to 2005 levels. The EU aims to cut greenhouse gas emissions by at least 55% by 2030 as compared to 1990 levels, to at least double the share of renewable electricity production as compared to 2020 levels to reach a level of about 65%, and to become climate neutral by 2050 (European Commission, 2020).

[2] For example, the State Aid Guidelines of the European Commission (2014) and European Commission (2022) make auctions obligatory for all new support schemes for which member states wish to obtain state aid approval.

[3] Worldwide, an estimated total capacity of 111 gigawatt of renewable energy was auctioned in 2017–2018 (IRENA, 2019). For estimating the monetary value, we set a price of USD 50 per MWh, a duration of support of 20 years, and 2000 full load hours per year (mix of different renewable energy sources). This gives a monetary value of USD 222 billion in 2017–2018.

efficiency and proportionality of public support payments.

However, the idea of ensuring proportionality through auctions has been challenged by undersubscribed tenders with payments equal or close to the ceiling price, that is, the highest accepted support set by the auctioneer.[4] To address this challenge, auctions with *endogenous rationing (ER)* have been applied, in which the original auction volume may be reduced based on the total volume of the bids in order to assure that there is at least one losing bidder.[5] The question arises, how strongly this approach to ensure proportionality of support interferes with the other objectives of the auctioneer.

This chapter addresses this question by analysing auctions with ER theoretically and comparing them with standard auctions (i.e., auctions without rationing) and with optimal mechanisms with respect to the objectives welfare maximisation, surplus maximisation, and achieving the volume goals.[6]

We analyse multi-unit procurement (reverse) auctions with single-unit bidders and costly participation, which applies, e.g., to RE auctions.

---

[4] For examples, see auctions in Germany (BNetzA, 2022), Brazil and France (Robert et al., 2019), and Italy (Enerdata, 2021).

[5] For example, the auction may stipulate that only a pre-announced share (e.g., 80 %) of the original auction volume will be allotted to bidders if the total bid volume does not exceed the original auction volume. This kind of rationing (with an *endogenous auction volume*) is used for example in Germany (BReg, 2019), France (Ministre de l'Europe, 2018), Ukraine (Legislation of Ukraine, 2019), and Switzerland (Bundesamt für Energie, 2019). Similar measures are applied in Brazil (IRENA, 2015), Greece (Papachristou et al., 2017), Kazakhstan (Abylkairova, 2018), and Mexico (Jiménez, 2016). For another concept of ER, the *endogenous ceiling price*, see A.2.

[6] These objectives are mentioned in guidelines and directives. For example, the European Commission (2014) and Deutscher Bundestag (2017) stipulate, without prioritisation, the minimisation of the support payments and the minimisation of the overall costs to achieve the renewables expansion targets Kreiss et al. (2020). The minimisation of the support payments is stipulated, e.g., in the Netherlands and the United Kingdom, and proposed for developing countries. The minimisation of the overall costs to achieve the expansion target is stated, e.g., in California (US) and Mexico (Kreiss et al., 2020; IRENA, 2013). minimising the overall (social) costs, which is related to maximising the social welfare, is another goal in national laws (e.g., Umweltbundesamt, 2016; Deutscher Bundestag, 2017; Kazakh Government, 2009). The maximisation of the consumer surplus or low prices for the customers are also postulated (e.g., Umweltbundesamt, 2016; IRENA, 2013; Hochberg et al., 2018; Kreiss et al., 2020). The goal to achieve the targeted expansion of renewable energy, which implies allotting the volume put out to tender in the renewable energy auctions, is stated, e.g., in Germany, Kazakhstan, Brazil, Mexico, and proposed for developing countries (Deutscher Bundestag, 2017; Kazakh Government, 2009; Hochberg et al., 2018; IRENA, 2013).

Typically, in these auctions a total capacity is put out to tender and company's bid comprises the capacity of its project and a price. Based on the award price, support is provided for the energy produced by the realised project in some time period , e.g., the first 20 years. Participation costs in form of bid-preparation costs may be substantial and mainly arise because bidders have to meet physical requirements, e.g., submitting a (partial) approval for building a plant on a specific site, before the auction (AURES, 2016b; AURES, 2017).[7] For onshore wind projects, the costs of the physical requirements are between two and ten percent of the invested amount (Wallasch et al., 2015; Quentin, 2015; AURES, 2016a). As a consequence, only companies whose expected profit from the auction covers their participation costs will participate in the auction.

ER interferes with this necessity to cover the participation costs, not only by reducing the participation incentives per se but also by spurring a downward spiral on participation. By ensuring that there will always be at least one losing bidder, ER removes any participation incentive for the weakest bidder, causing any bidder that expects to be the weakest participant to stay out. As a result, there may be no participation incentive for any company. The main result of this chapter reveals this strong negative effect of ER on participation.

Based on this result, optimal mechanisms for multiple auctioneer's objectives are used to judge whether ER supports any of these and to identify alternate approaches for improvements in all objective functions.

The optimal mechanisms for the objectives surplus maximisation, wel-

---

[7] Bid-preparation costs are common in procurement auctions also in other settings. The auctioneer often requests a certain kind of project preparation as a requirement for participation to ensure the offers' quality or seriousness. To fulfil these requirements, bidders have to undertake costly measures and invest in their project before knowing whether it can be realised. Typically, the required measures are also necessary for realising a project. Examples for such measures are the development of a prototype in the industry sector or the collection of construction permits in the building sector.

fare maximisation and achieving volume goals can each be implemented by auctions that reimburse all bidders or all losing bidders for their full participation costs in combination with an appropriately adjusted ceiling price. Even if one questions the feasibility of reimbursement, the two objectives of welfare maximisation and surplus maximisation can also be achieved with designs in which all bidders, all losing bidders, or all winning bidders are partially reimbursed or not reimbursed at all. In general, the optimal mechanisms for the objectives differ; only in the case of a small number of bidders can they coincide.

Nevertheless, measures exist that contribute to all three objectives and to the aim to ensure proportionality through auctions (i.e., that bids and not the ceiling price determine the payments). Lowering the participation costs (unlike increasing the number of bidders) increases the auctioneer's surplus, social welfare, the allotted support volume, and competition by boosting participation. These effects of lowering participation costs on multiple objectives not only apply to the respective optimal mechanisms for the objectives but to any standard auction with a ceiling price below the auctioneer's valuation. Current discussions about renewable energy auctions suggest that lower participation costs can be achieved by reducing permitting and zoning challenges in particular for wind farm projects.

In accordance with the results of this paper, the European Commission recently added a rule to its State Aid Guidelines which stipulates that auctions with ER may not be used to establish proportionality of support: "the Commission considers that the proportionality of the aid is ensured if the following criteria are fulfilled: [...] (d) ex post adjustments to the bidding process outcome (such as subsequent negotiations on bid results or rationing) are avoided as they may undermine the efficiency of the process's outcome." (Paragraph 49 European Commission, 2022).[8]

Related literature

To the best of our knowledge, this is the first study to analyse auctions with ER. The topic is related to the literature on auctions with variable volume, in which the auction volume or the rule to determine the auction volume is not fixed before the auction. This is a common practice in treasury auctions (Nyborg et al., 2002). The idea is to avoid low-price equilibria in these forward auctions when UP is used. Since bidders in treasury auctions have multi-unit demand and are allowed to submit non-increasing demand functions, they have an incentive to coordinate on low-price equilibria by strategically reducing their demand. Back et al. (2001), Damianov (2005), McAdams (2007), and Damianov et al. (2010) show that the seller can reduce or even eliminate low-price equilibria if he has the right to adjust the volume after collecting bids, for example by choosing the optimal volume given the submitted bids. LiCalzi et al. (2005) find that the seller can restrict incentives for low bids if he commits to an increasing volume schedule before observing the bids.

There are crucial differences between treasury auctions and the auctions analysed in this chapter as well as between a variable auction volume and ER. The variable volume permits that all bids are successful, whereas the motivation for ER is to assure that there is at least one losing bid. Treasury auctions are offered frequently, some even on a daily basis. Bidders repeatedly demand multiple units of the good and their participation costs are insignificant. RE auctions and other pro-

---

[8] In the context of the revision of the State Aid Guidelines, the authors presented and discussed the findings of this chapter with the European Commission's competition department.

curement auctions are offered much less frequently and there is often only one or very few chances for a bidder to win.[9] Bidders' participation costs are crucial and projects are awarded that will be realised exactly once. Moreover, since most bidders participate with only one project, we analyse a setting with single-unit supply bidders, in which the collusive equilibria that are addressed by the variable volume approaches do not exist.[10]

Our theoretical analysis of standard auctions and optimal mechanisms with costly participation is an extension of existing work on single-unit auctions to our setting with an arbitrary number of goods, including cases with no competition, and an objective not yet considered in the literature, which is necessary to answer our research question on ER.[11] For the single-unit setting, Stegemann (1996) shows payoff equivalence of the symmetric equilibria of the first- and second-price auction, which extends to our multi-unit setting and all standard auctions. He, as well as Tan et al. (2006), Celik et al. (2009), and Lu (2009a) unlike us also analyse asymmetric equilibria and asymmetric mechanisms. Samuelson (1985) determines the socially optimal and the auctioneer's surplus-maximising ceiling price, which have later been shown to implement the optimal mechanisms. Further implementations of surplus- or revenue-maximising mechanisms have been identified by Lu (2009a) and Menezes et al. (2000) and of welfare-maximising mechanisms by Lu (2009b), including a second-price auction with an optimally chosen ceiling price,

---

[9] RE auctions usually take place at most a few times a year and re-participation entails further costs due to, e.g., rescheduling of the project or renewal of permissions.

[10] In RE auctions, the proportion of bidders offering only one project is usually high, often exceeding 90% (BNetzA, 2022). One reason for this is that a legally independent project company is usually established for each project (Rödl, 2015).

[11] Our approach is related to models with common participation costs where bidders know their private costs when deciding on participation. Further studies with this basic model, e.g., studying heterogeneous bidders and uniqueness of equilibria, are by Campbell (1998), Cao et al. (2010), Miralles (2008), and Cao et al. (2013). Models with common participation costs where bidders learn their private costs only after deciding on participation and models with private participation costs have also been analysed (e.g., R. P. McAfee et al., 1987; Li et al., 2009; Cao et al., 2018).

in which all participating bidders are reimbursed for their participation costs. We extend these findings to the multi-unit setting and show that auctions in which bidders receive reimbursement for any share of their participation costs can be used to implement welfare-optimal auctions (as Lu (2009a) has shown for surplus-optimal single-unit auctions). Moreover, we find that the auctioneer has further options for implementing the optimal mechanism as he can choose designs with only winning bidders or only losing bidders receiving full or partial reimbursement for their participation costs. However, for the objective to maximise the allotted volume, the optimal mechanism can be implemented only by an auction with either all bidders or all losing bidders receiving full reimbursement for their participation costs.

The chapter proceeds as follows. Section 2.2 presents the theoretical analyses of standard auctions and auctions with ER. Section 2.3 compares ER with optimal auctions for three objectives and discusses a policy measure suggested by their design. Section 2.4 concludes. All proofs except Proposition 1, which is proved in the main text, are in A.1.

2.2 Theoretical analysis

Consider a multi-unit procurement auction for k units of a good, $k \geq 1$. The set of potential bidders contains n risk-neutral companies each with single-unit supply, $n \geq 1$. We consider both $n \leq k$ and $n > k$ because ER has been suggested in particular for auctions with low or even no competition. Companies are symmetric and have independent private costs for supplying the good. The companies' private costs $x_1, x_2, \ldots, x_n$ are independently drawn from the distribution F with density f and full support on $[\underline{x}, \bar{x}]$, $0 \leq \underline{x} < \bar{x}$. Let $\mathbf{x} = (x_1, x_2, \ldots, x_n)$ and $\mathbf{x}_{-i} = (x_1, x_2, \ldots, x_{i-1}, x_{i+1}, \ldots, x_n)$. Furthermore, $F_{(k,n)}$ denotes the distribution function of the k-th lowest of n independent signals and $X_{(k,n)}$ denotes the associated random variable. Thus, $F_{(k,n-1)}(x) = \sum_{i=k}^{n-1} \binom{n-1}{i} F(x)^i (1-F(x))^{n-1-i}$ if $n > k$, and we define $F_{(k,n-1)}(x) = 0$ if $n \leq k$.

Our model of a multi-unit procurement auction follows the approach of Samuelson (1985) for a single-unit procurement auction. Companies simultaneously decide on their participation in the auction and on their bidding strategy in case of participation. Only participating companies can bid and win in the auction. We consider only pure strategies. The number of companies that participate in the auction is denoted by m, $m \leq n$.

To participate in the auction, each company has to incur participation costs $c > 0$, e.g., to meet qualification requirements set by the auctioneer. These are sunk costs for the companies when the auction starts and they are not paid to the auctioneer. A company knows c and their private costs x_i when deciding about their participation.[12] Conditional on participating in the auction, company i expects a profit $\pi(x_i)$ from the auction. Their profit from the auction is $p - x_i$ if the company wins a good at the payment p and is zero, otherwise. Company i aims to maximise their overall payoff $\Pi(x_i)$, where $\Pi(x_i) = \pi(x_i) - c$ if they participate in the auction and $\Pi(x_i) = 0$ if they do not participate.

2.2.1 Standard auction

We define and analyse standard auctions as a basic auction model that serves as a benchmark for our analysis of auctions with ER.

---

[12] This approach where companies know x_i when deciding on participation captures the renewables setting and other procurement settings with mature projects or (modifications of) standard products better than a model in which companies have no information about x_i and their expected position relative to their opponents as analysed by, e.g., R. P. McAfee et al. (1987), Tan (1992), and Levin et al. (1994).

2.2.1.1 Definition

Standard auctions are characterized by the following properties:

(P1) The n companies simultaneously decide whether or not to participate in the auction and commit to a bid if they participate. Thus, when bidding, the companies know n but do not know m, the number of participating bidders.[13]

(P2) Bids may not exceed a ceiling price $r \in \mathbb{R}_+$, $r > \underline{x} + c$, set by the auctioneer.[14]

We point out the following two properties of standard auctions because they do not apply to auctions with ER:

(P3) The k lowest bids win if $m \geq k$ (ties at the k-th lowest bid are broken randomly); all other companies obtain nothing. If $m < k$, all m bids win.

(P4) The ceiling price r is the maximum payment from the auction, and for each company there exists a bid such that the company's payment with this bid is r if $m \leq k$.

The basic model permits multiple payment rules which in particular include DP, where all winning bidders receive their bids, and UP, where the lowest rejected bid determines the payment to all winning bidders. For these two payment rules, Lemma 3 shows that monotone symmetric equilibria exist. The property required for our analysis, which auctions with either of these two payment rules satisfy by Lemma 3, is the following:

---

[13] Menezes et al. (2000) prove revenue equivalence of first- and second-price auction with known (i.e., revealed participation) and unknown number of bidders in the single-unit sales auction with participation costs.

[14] If $r < \underline{x} + c$, no company will participate in the auction.

(P5) The participating companies have an equilibrium bidding strategy $\beta(x_i, r)$ that is strictly increasing in x_i if $n > k$ and weakly increasing in x_i if $n \leq k$.

We call an auction with properties P1–P5 a standard auction. In particular, standard auctions have exogenous demand k and no ER. As we will prove below, the class of standard auctions includes auctions with DP and UP. If auctions have multiple equilibria, we will focus on equilibria with P5.

P3 and P5 imply that the goods are supplied by the companies with the lowest costs, i.e., the allocation is efficient conditional on the participating companies. However, according to P1 and P3, it is possible that not all k goods are supplied, even if the costs of k or more companies are below r. This is because the participation costs c prevent all companies with costs x_i above *cutoff costs* $\hat{x}$ from participating in the auction.[15]

2.2.1.2 Analysis

The company with the cutoff costs $\hat{x}$ of equilibrium participation is denoted by $\hat{i}$. Company $\hat{i}$ submits the highest bid, which wins only if a maximum of $k-1$ other companies bid. Therefore, $\hat{i}$ adjusts her bid to this case and bids to ensure the payment r in the event that she wins. For example, in the DP auction, $\hat{i}$'s optimal bid is $\beta(\hat{x}, r) = r$. If $\hat{x} < \bar{x}$, company $\hat{i}$ is indifferent between participating and not participating, and the cutoff costs $\hat{x}$ are uniquely determined by $\Pi(\hat{x}, r, c, n) = 0$, where

$$\begin{aligned}\Pi(\hat{x}, r, c, n) &= (r - \hat{x})\left(1 - F_{(k,n-1)}(\hat{x})\right) - c \\ &= (r - \hat{x})\textstyle\sum_{i=0}^{\min\{k,n\}-1}\binom{n-1}{i}F(\hat{x})^i\left(1 - F(\hat{x})\right)^{n-1-i} - c\,. \quad (2.1)\end{aligned}$$

---

[15] A cutoff level $\hat{x}$ that separates participating companies with costs $x_i \leq \hat{x}$ from non-participating companies with $x_i > \hat{x}$ exists because P5 implies $\pi(x_i) > \pi(x_j)$ for $x_i < x_j$ in equilibrium. If this did not hold, company i could profitably deviate by bidding like the higher-cost company j.

The cutoff costs $\hat{x}$ determine a company's ex-ante participation probability $F(\hat{x})$. The following lemma collects properties of $F(\hat{x})$.

Lemma 1. *For a company's ex-ante participation probability $F(\hat{x})$ the following hold:*

- $\frac{dF(\hat{x})}{dr} > 0$ *and* $\frac{dF(\hat{x})}{dc} < 0$ *if* $n > k$ *or* $r < \bar{x} + c$.
  $F(\hat{x})$ *increases in* k *if* $n > k$. $F(\hat{x})$ *decreases in* n *if* $n \geq k$.
- $F(\hat{x}) \begin{cases} < 1 & \text{if } n > k \text{ or } r < \bar{x} + c\,, \\ = 1 & \text{otherwise.} \end{cases}$

The intuition behind Lemma 1 is as follows. Increasing the ceiling price r or (if $n > k$) the number of goods k increases the marginal bidder's expected profit from the auction via an increased profit in case of winning or an increased winning probability. This results in higher cutoff costs $\hat{x}$, which implies a higher expected number of participants. Participation costs c have to be absorbed by the expected profits from the auction. Therefore, a higher c lowers the cutoff level. A growth of the pool of companies reduces the marginal bidder's expected profits from the auction if $n \geq k$. Thus, $\hat{x}$ decreases in n.[16]

Under mild conditions ($n > k$ or $r < \bar{x} + c$) we have $\hat{x} < \bar{x}$, that is, high-cost companies do not participate. If $n > k$, there is no ceiling price that can induce full participation because type $\bar{x}$'s profit from the auction is zero if all companies participate. If $n \leq k$, each bid wins but high-cost companies forgo the auction if the ceiling price r does not cover their total costs $x_i + c$.

The cutoff type $\hat{x}$ is the same in all standard auctions and is the worst-off type among the participants. Payoff equivalence holds for all

---

[16] Li et al. (2009) find empirical evidence of this "entry effect": a negative relationship between the number of potential bidders n and the participation probability.

standard auctions.[17]

Lemma 2. *Standard auctions are payoff equivalent.*

That is, a company with costs x has the same expected profit in all standard auctions and the auctioneer has the same expected surplus.

Lemma 3. *The symmetric equilibrium bidding strategy in the DP auction is given by, for all $x \in [\underline{x}, \hat{x}]$:*

$$\beta^{DP}(x, r) = \begin{cases} x + \dfrac{(1 - F_{(k,n-1)}(\hat{x}))(r - \hat{x}) + \int_x^{\hat{x}} 1 - F_{(k,n-1)}(y) dy}{1 - F_{(k,n-1)}(x)} & \textit{if } n > k \\ r & \textit{if } n \leq k \,. \end{cases}$$

The symmetric equilibrium bidding strategy in the UP auction is given by, for all $x \in [\underline{x}, \hat{x}]$ and $n \gtreqless k$:

$$\beta^{UP}(x, r) = x \,.$$

If there is no competition, $n \leq k$, the equilibrium payment of standard auctions equals r, either because all bidders bid r in anticipation of the low number of bids or because the payment rule determines a uniform payment of r.

2.2.2 Auction with endogenous rationing

Instruments of ER have been suggested as a means to avoid high payments in cases of low competition and to assure proportionality of support. The prevalent variant of ER is the *endogenous auction volume*, that is, the adaption of the auction volume to the supply volume (number of

---

[17] See Stegemann (1996, Theorem 4) and Menezes et al. (2000) for payoff equivalence between symmetric equilibria of single-unit first- and second-price auctions with participation costs.

bids).[18] An applied example is the 80 %-rule. If m bids are submitted, the number of winning bids is $\min\{\lceil 0.8\,m \rceil, k\}$. With for example a tendered volume of $k = 9$, there will be nine winning bids if $m > 10$, eight winning bids if $m \in \{9, 10\}$, $m - 1$ winning bids if $m \in \{5, 6, 7, 8\}$, and m winning bids if $m \leq 4$. With this rule, rationing occurs if m is less than or equal to ten and larger than four.

For the comparison with standard auctions, we use the same ceiling price r, number of goods k, number of companies n, and payment rule. ER auctions are defined as follows.

Definition 1. *An ER auction is an auction in which, if m bids are submitted, the number of winning bids $\kappa(m)$ is determined according to a commonly known function*

$$\kappa(m) \begin{cases} = k & \text{if } m > \bar{\mu}\,, \\ < \min\{k, m\} & \text{if } \underline{\mu} < m \leq \bar{\mu}\,, \\ = m & \text{if } m \leq \underline{\mu}\,. \end{cases}$$

The integer parameters $\underline{\mu}$ and $\bar{\mu}$ with $0 \leq \underline{\mu} < k \leq \bar{\mu}$ mark the limits of the range of the number of bids m in which the original auction volume $\min\{k, m\}$ *is reduced by at least one unit. The $\kappa(m)$ winning bids are the lowest bids and payments are determined as in the related standard auction.*

In the above example of the 80%-rule, we have $\underline{\mu} = 4$ and $\bar{\mu} = 10$. Payments in the ER auction are determined as in the related standard auction. For example, in an UP auction, the $\kappa(m)$ winning bidders are

---

[18] Another variant is the *endogenous ceiling price*, which is analysed in A.2 with the same main finding. In auctions with endogenous ceiling price, decreasing a bid price can even reduce the auction volume, whereas with endogenous volume, the auction volume depends on the bid volume but not on the bid price. However, some rules for endogenous ceiling price adjustment, like quantile rules, can be translated into endogenous volume rules.

paid the $(\kappa(m)+1)$-th lowest bid, and in a DP auction, winning bidders are paid their bid.

ER auctions meet P1 (participation and bidding) and P2 (bids are limited by the ceiling price r). They violate P3 ($\min\{m,k\}$ lowest bids win): albeit the lowest bids win, less than m bids win if $m \leq k$ and less than k bids may win even though more bids have been submitted. ER auctions are designed to prevent an auction price r when $n \leq k$ and thus also violate P4. ER auctions assign goods differently than standard auctions and give a different payment to the worst-off type. Therefore, payoff equivalence to the standard auctions fails (e.g., Krishna, 2009, Section 3.2.2).

ER auctions share some basic properties of standard auctions, e.g., a bidder's probability of winning increases if she reduces her bid and a winning bidder is paid at least her bid. They differ from standard auctions in that the auction volume is variable. As an important consequence, there will always be at least one losing bidder in the auction (if at least one company participates and there is no volume floor), irrespective of the relationship between k and n.

ER intends to keep the payments low in case of low supply. However, it creates a strong adverse effect on participation.

Proposition 1. *In an ER auction with volume k and limit $\underline{\mu}$, the cutoff costs $\hat{x}$ and the participants are the same as in a standard auction with the auction volume $\underline{\mu}$. In particular, participation depends only on the lower bound $\underline{\mu}$ at which rationing stops, and participation will be zero if $\underline{\mu} = 0$.*

Proof: The cutoff costs $\hat{x}$ determine the participants. These are the same in the ER auction with volume k and in the standard auction with volume $\underline{\mu}$. In the ER auction, the bidder with $\hat{x}$ submits the highest bid and will only win if the total number of bidders is not above $\underline{\mu}$. Otherwise, the number of goods ($k < m$) or the rationing ($\kappa(m) < m$) prevents her from winning. Because her bid wins only if she faces no competition, her payment is r. Therefore, she has the same expected profit as from a standard auction with the auction volume $\underline{\mu}$ (see (2.1)) and participates if and only if

$$(r - \hat{x}) \sum_{i=0}^{\min\{\underline{\mu},n\}-1} \tbinom{n-1}{i} F(\hat{x})^i \big(1 - F(\hat{x})\big)^{n-1-i} - c \geq 0. \tag{2.2}$$

This proves Proposition 1. ■

According to Proposition 1, even though the ER auction puts a larger volume k out to tender than a standard auction with volume $\underline{\mu} < k$, the number of bids is the same in both auctions. Note that participation in the ER auction does not depend on the allocation function $\kappa(m)$ for $\underline{\mu} < m \leq \bar{\mu}$ but only on the lower bound $\underline{\mu}$. Participation is zero when $\underline{\mu} = 0$, i.e., when rationing holds for every $m \leq \bar{\mu}$.

Let us emphasize that choosing $\underline{\mu} > 0$ implies to accept outcomes in which all bidders win, which contradicts the main motivation for using ER. The natural choice $\underline{\mu} = 0$, however, implies no participation, such that auctions with ER clearly perform worse than standard auctions with respect to any measure.

Rules applied in practice, like the 80%-rule, may implement $\underline{\mu} > 0$. Therefore, let us compare such an ER auction with the standard auction with volume k. Take the optimally designed standard auction as the appropriate point of comparison. In Section 2.3 we show that the auction that maximises the auctioneer's surplus or welfare can be implemented as a standard auction with optimal ceiling price (Proposition 2). Thus, this standard auction provides higher surplus or welfare than any auction with ER.

2.3 Conflicting objectives and measures that contribute to all of them

ER is motivated by the desire to ensure proportionality of support payments. Indeed, if only reduced support payments are a goal, ER might appear advantageous because payments could be lower than in the standard auction.[19] Even if participation were higher in real-world auctions than theory predicts, the ER auction can perform worse than the standard auction with respect to multiple performance measures because of its negative effect on participation and number of goods allotted. Albeit, with empirical auction data, such comparisons might be hampered by the unobservability of the number of potential bidders, e.g., in the context of RE support the companies that potentially might develop a project and register for an auction. Theoretical analysis has highlighted conflicts between ensuring proportionality through ER auctions and other performance measures. To shed further light on these conflicts, we derive optimal mechanisms for three auctioneer's objectives which are prevalent in procurement auctions, particularly those organized by the government or other public institutions:

- O1 Maximise the auctioneer's expected surplus
- O2 Maximise the expected social welfare (at lowest payments)
- O3 Maximise the expected number of goods allotted, given k (at lowest payments)

O1 and O2 require that prior to the auction the auctioneer assigns a value to acquiring goods. For example, in an auction for RE support, the government's value for a good is the social value of the energy produced

---

[19] No payments because of no awarded projects are lower than payments of many awarded projects.

by the RE plants. We assume that every acquired unit of the good has the same value v and that $c+\underline{x} < v$, so that the production of the goods can increase social welfare.

An optimal auction for O1 maximises the auctioneer's expected surplus, and thus trades off the value generated by acquiring goods with the payments to the companies. Switching the objective to social welfare O2 shifts the focus from support payments to companies' total costs. According to objective O3, the auctioneer aims to acquire as many as possible of the demanded goods k. In the context of RE support, this objective corresponds to a commitment to achieve the development goals. For objectives O2 and O3, we break ties among optimal mechanisms in favour of those with the lowest auctioneer's payments.

Proposition 2 presents auctions that implement optimal mechanisms for objectives O1 to O3. The UP auction in the proposition could be replaced by any standard auction due to payoff equivalence (Lemma 2).

Proposition 2. *An optimal symmetric mechanism for objective* Oj*,* $j \in \{1, 2, 3\}$*, implements a unique optimal cutoff type* $\hat{x}^{Oj}$*. It can be implemented by a UP auction with an optimal ceiling price* r_s^{Oj} *where all participating companies receive* s *in reimbursement for their costs* c*. The optimal cutoff type* $\hat{x}^{Oj}$ *and ceiling prices* r_s^{Oj} *are the following.*

O1 *Assume* $x+\frac{F(x)}{f(x)}$ *is increasing. If* $n > k$ *or* $v < \bar{x}+\frac{1}{f(\bar{x})}+c$*, then* $\hat{x}^{O1}$ *is given by* $\left(v - \hat{x}^{O1} - \frac{F(\hat{x}^{O1})}{f(\hat{x}^{O1})}\right)\left(1 - F_{(k,n-1)}(\hat{x}^{O1})\right) = c$*, and the ceiling price is* $r_s^{O1} = v - \frac{F(\hat{x}^{O1})}{f(\hat{x}^{O1})} - \frac{s}{1-F_{(k,n-1)}(\hat{x}^{O1})}$ *for all* $s \in [0, c]$*. Otherwise, if* $n \leq k$ *and* $v \geq \bar{x} + \frac{1}{f(\bar{x})} + c$*, then* $\hat{x}^{O1} = \bar{x}$ *and* $r_s^{O1} = \hat{x}^{O1} + c - s$ *for all* $s \in [0, c]$*.*

O2 *If* $n > k$ *or* $v < \bar{x}+c$*, then* $\hat{x}^{O2}$ *is given by* $(v-\hat{x}^{O2})\left(1 - F_{(k,n-1)}(\hat{x}^{O2})\right) = c$*, and the ceiling price is* $r_s^{O2} = v - \frac{s}{1-F_{(k,n-1)}(\hat{x}^{O2})}$ *for all* $s \in [0, c]$*.*

Otherwise, if $n \leq k$ *and* $v \geq \bar{x}+c$*, then* $\hat{x}^{O2} = \bar{x}$ *and* $r_r^{O2} = \hat{x}^{O2}+c-s$ *for all* $s \in [0, c]$*.*

O3 *If* $n > k$*, then only the auction with* $s = c$ *is optimal, and* $\hat{x}^{O3} = \bar{x}$ *and* $r_{s=c}^{O3} = \hat{x}^{O3}$*. If* $n \leq k$*, then* $\hat{x}^{O3} = \bar{x}$ *and* $r_s^{O3} = \hat{x}^{O3} + c - s$ *for all* $s \in [0, c]$*.*

The optimal mechanism is determined by the optimal cutoff type and the payments to implement this cutoff. An ER auction cannot implement the optimal cutoff type with the associated payments and is therefore not optimal for any of the objectives.

In case of no competition ($n \leq k$) and sufficiently high value v, the optimal mechanism is the same for all three objectives and maximises participation. All companies participate ($\hat{x}^{Oj} = \bar{x}$ for $j \in \{1, 2, 3\}$) because every company wins and receives the ceiling price $r_s^{Oj} = \bar{x}+c-s$ plus the reimbursement s. Every bid is awarded and generates value. This contributes to O3 and, if $v \geq \bar{x} + c$, to O2. If $v \geq \bar{x} + 1/f(\bar{x}) + c$, the trade-off between efficiency and surplus disappears, and incentivising full participation is optimal also for O1.

In contrast, in the case of competition ($n > k$) or sufficiently low value v, optimal mechanisms for the three objectives differ and involve trade-offs between participation, total participation costs, and total payments. Unlike in auctions without participation costs, the optimal ceiling prices for O1 and O2 depend on $\hat{x}$, and, therefore, on n. To get some intuition for the optimal mechanisms, consider the cases $s = c$ and $s = 0$, i.e., a UP auction with an optimal ceiling price $r_{s=c}$ and a reimbursement c to all participating companies and a UP auction with an optimal ceiling price $r_{s=0}$ and no reimbursement. Participants in these auctions have a weakly dominant strategy to bid their costs. According to Proposition 2, the cutoff type $\hat{x}^{Oj}$ is the same in the optimal auction with $s = c$ and

$s = 0$ for the respective objective $j \in \{1, 2, 3\}$. In the optimal auction with $s = c$, the reimbursement of c makes participation costless, and the ceiling price $r^{Oj}_{s=c} = \hat{x}^{Oj}$ guarantees that companies with $x > \hat{x}^{Oj}$ do not participate. In the optimal auction with $s = 0$, the incentive to participate is provided by higher expected payments in the auction due to a higher ceiling price $r^{Oj}_{s=0} > r^{Oj}_{s=c}$ (for $j \in \{1, 2\}$) that gives the same expected payoffs to all bidder types as in the auction with $s = c$. [20] Each objective may be achieved with an auction with $s = c$, whereas with an auction with $s < c$ it is impossible to achieve objective O3. This is because O3 requires full participation, which cannot be achieved with $s < c$ because type $\bar{x}$ receives the payoff zero from the auction if all companies participate and thus cannot cover the participation costs (compare Lemma 1).

For any $s \in [0, c]$, the objectives' optimal cutoffs can be ordered by size. The optimal cutoffs for O1 and O2 are lower than $\bar{x}$, i.e., the optimal cutoff for O3, and the optimal cutoff for O1 is lower than that for O2. As the ceiling prices with $s = c$ are equal to the cutoff types, they are ordered in the same way. The same order of ceiling prices applies if $s < c$, but then optimal mechanisms exist only for O1 and O2. Corollary 1 summarizes these findings.

Corollary 1. *Assume* $x + \frac{F(x)}{f(x)}$ *is increasing. If* $n > k$ *or* $v < \bar{x} + c$ *then* $\hat{x}^{O3} > \hat{x}^{O2} > \hat{x}^{O1}$, $r^{O3}_s > r^{O2}_s > r^{O1}_s$ *for* $s = c$, *and* $r^{O2}_s > r^{O1}_s$ *for all* $s \in [0, c)$. *If* $n \leq k$ *and* $v \geq \bar{x} + \frac{1}{f(\bar{x})} + c$ *then* $\hat{x}^{Oj} = \bar{x}$ *and* $r^{Oj}_s = \bar{x} + c - s$ *is optimal for* $s \in [0, c]$, $j \in \{1, 2, 3\}$.

---

[20] For $k = 1$, several studies identified optimal auctions and mechanisms for objectives O1 and O2. Samuelson (1985) derives the optimal auction with $s = 0$ for O1 and O2 and Menezes et al. (2000) show that the optimal auction with $s = c$ is an optimal mechanism for O1. Lu (2009a) derives the implementation of the optimal mechanisms as an auction with $s \in [0, c]$ for O1 and Lu (2009b) the implementation with $s = c$ for O2. Stegemann (1996) shows that equilibria with asymmetric participation can improve efficiency. Tan et al. (2006) provide conditions under which only symmetric participation occurs in the welfare-maximising auction.

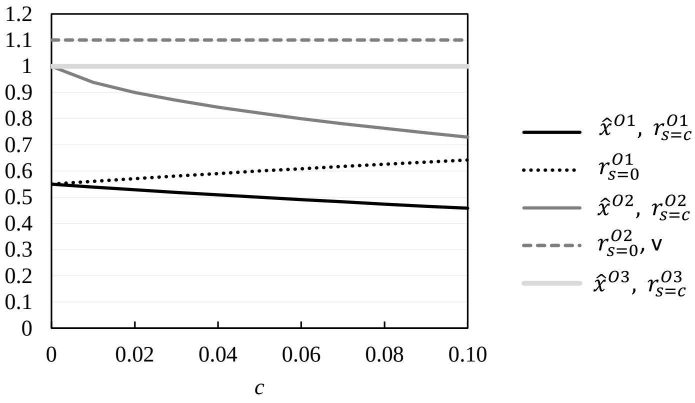

Figure 2.1: Cutoff costs $\hat{x}^{O1}$, $\hat{x}^{O2}$, and $\hat{x}^{O3}$, ceiling prices $r^{O1}_{s=c}$, $r^{O2}_{s=c}$, and $r^{O3}_{s=c}$, and ceiling prices $r^{O1}_{s=0}$ and $r^{O2}_{s=0}$ for $k = 1$, $n = 2$, $v = 1.1$, and for different levels of c with a uniform distribution on $[0, 1]$

Figure 2.1 illustrates these rankings using a uniform distribution F on $[0, 1]$.[21]. It also illustrates some general properties of how cutoffs and ceiling prices change with c. If c increases, the surplus-maximising cutoff $\hat{x}^{O1}$ and ceiling price $r^{O1}_{s=c}$ (which are equal) decrease and are always below the valuation. The cutoff $\hat{x}^{O1}$ and the ceiling price $r^{O1}_{s=0}$ diverge when c increases by the assumption that $x + F(x)/f(x)$ increases (whereas $r^{O1}_{s=0}$ increases or decreases depending on whether the reverse hazard rate $F(x)/f(x)$ decreases or increases).[22] Furthermore, independent of c and F we have that $\hat{x}^{O3} = \bar{x}$ and $r^{O2}_{s=0} = v$, and for all F we have that $\hat{x}^{O2}$ and $r^{O2}_{s=c}$ decrease in c.

Among the optimal auctions, the welfare-maximising auction without reimbursement stands out because it can be implemented for every number of companies n and goods k without knowing the cost distribution F by setting the ceiling price equal to the auctioneer's valuation for a good, $r^{O2}_{s=0} = v$. On the other hand, the auctions with reimbursement

---

[21] Note that with this distribution, the optimal ceiling price r^{O1}_{r} and cutoff value $\hat{x}^{O1}$ add up to the auctioneer's valuation: $r^{O1}_{r} + \hat{x}^{O1} = v - F(\hat{x}^{O1})/f(\hat{x}^{O1}) + \hat{x}^{O1} = v$.

[22] The same applies to the effect of the number of potential bidders n on cutoff type and ceiling price. Proposition 3 will, however, show that the influence of increasing n and c on the value of the objective function can differ.

$s = c$ distinguish themselves by providing weakly dominant strategies for participation and bidding (cp. Lu, 2009b): companies participate iff $x_i \leq \hat{x}$ and bid their costs x_i, independent of the other companies' participation or bidding decisions.

The designs in Proposition 2 are not the only ways to implement the optimal mechanisms. Corollary 2 lists further mechanisms conceivable for renewable energy auctions.[23]

Corollary 2. *The optimal mechanism for Oj, $j \in \{1, 2\}$, can be implemented (i) by a UP auction and a reimbursement $s \in [0, c]$ to all winning bidders; (ii) by a UP auction and a reimbursement $s \in [0, c]$ to all losing bidders. The optimal mechanism for O3 can be implemented by an auction of type (ii) with $s = c$.*

If only winning or losing bidders receive a reimbursement, a company's bid is lower or higher, respectively, than its cost by the amount of the reimbursement. As a result, the optimal auction in which only winning bidders receive the reimbursement is ex-post payoff equivalent to the optimal auction in which no one receives a reimbursement and the optimal auction in which only losing bidders receive the reimbursement is equivalent to the optimal auction in which all bidders receive a reimbursement. Consequently, the optimal auction in which only the successful bidders receive a refund is ex-post payoff equivalent to the optimal auction in which no one receives a refund, and the optimal auction in which only the losing bidders receive a refund is equivalent to the optimal auction in which all bidders receive a refund.

Hence, these designs endow the auctioneer with options to shift payments between the categories award payments and reimbursement payments. However, they cannot address the conflict of objective.

---

[23] Technically, auctions with entry fees (i.e., $s < 0$) are another option (Menezes et al., 2000).

The considerations on optimal mechanisms in this section highlight the common finding that, while it is possible to design the auction optimally for specific goals, it is impossible to create a panacea in form of a design that is optimal for multiple goals. Adjusting the ceiling price will shift weight between objectives. However, determining an optimal ceiling price can be a challenging task, which is also often up to lobbying and political restrictions.

Against this background the question arises if there are other policies that support all objectives. Without participation costs, increasing the number of bidders n is a measure that improves all three dimensions. With participation costs, however, increasing n can increase or decrease surplus and welfare depending on F, c, and v.[24] The optimal auction formats with $s = c$ highlight the relevance of the participation costs. Indeed, reducing these costs supports all three objectives.

Proposition 3. *Consider participation costs c and c' with $c' < c$. The expected auctioneer's surplus (O1), expected social welfare (O2), and the expected number of goods allotted (O3) in a standard auction with ceiling price $r \leq v$ and no reimbursement are with c' strictly higher than with c if $n > k$.*

Proposition 3 states that, with any standard auction with ceiling price below the valuation, surplus, welfare, and number of allotted goods benefit from a decrease in participation costs.[25] For a given ceiling price, decreasing c has the direct effect of decreasing participation costs for all companies that participate with c but in addition it increases the cutoff costs and more (higher) cost types participate (Lemma 1). Therefore, the expected number of goods allotted increases, the expected payment

---

[24] Samuelson (1985) and Menezes et al. (2000) provide examples for both objectives.

[25] The restriction $r \leq v$ is sufficient but not necessary. It is chosen because it is a plausible restriction in applications. For $r > v$ there exist examples where the result does not hold. The restriction to $n > k$ is because for $n \leq k$, surplus and number of goods allotted do not change in c.

per good decreases, and the welfare contribution of all types increases. Proposition 3 implies that the positive effect of decreasing c is robust to non-optimal specifications of the ceiling price and that all three objectives benefit from decreasing c even if the original ceiling price is chosen optimally for only one of them.

From Proposition 3 follows directly that surplus and welfare in the respective optimal mechanism for $n > k$ increase if participation costs decrease because a standard auction with optimal ceiling price below the valuation is an optimal mechanism for these objectives. Further improvements in surplus and welfare are achieved by optimally adjusting the ceiling price to the higher optimal cutoff. If $n \leq k$, welfare in the optimal mechanism increases directly due to the lower participation costs and surplus increases by the reduction of the optimal ceiling price. Corollary 3 summarizes this result. The optimal mechanism for O3 achieves full participation, and therefore the value of the objective function does not change in the participation costs.

Corollary 3. *Consider participation costs c and c' with $c' < c$. The expected auctioneer's surplus (O1) and expected social welfare (O2) in the respective optimal mechanism with c' are strictly higher than with c.*

A straightforward policy implication of Proposition 3 is to reduce the participation costs. Even if the objectives are in conflict, such a measure contributes to three different objectives. It also contributes to the determination of proportionality because the likelihood that competition determines the auction price increases. Thus, any factors that unnecessarily increase participation costs should be eliminated. Factors that may influence participation costs in auctions for RE support include administrative obstacles, limited availability of zones for building the plant, lack of acceptance in the population, species and nature protection laws, and legal disputes that may lengthen or hinder the planning and the permit processes. Speeding up administrative processes, pre-planning sites, changing laws to extend the available zones, using more exemptions by species protection laws or adjusting bird protection (e.g., from an individual analysis to a species aggregate), and inclusion, or even compensation of citizens in order to reduce their refusal of RE projects close to their homes are among the measures discussed to address hindering factors. Of course, any measure that reduces the companies' participation costs can involve costs for its implementation. Further, any measure that reduces participation costs by mitigating participation requirements needs to consider detrimental effects on project quality. Hence, it is not advised to abrogate the participation requirements that cause the participation costs, but to find a reasonable balance between entry barriers that ensure the seriousness of bids and attractive conditions for participating in the auction.

2.4 Conclusion

ER has been suggested as a means to ensure proportionality and increase competition in the case of low participation in auctions. However, the theoretical analysis in this chapter shows that the primary effect of ER in auctions with costly participation is a large reduction in participation, which impairs welfare and volume goals. The implementation of ER in auctions for RE support is therefore detrimental to the goal of expanding RES in energy production.

In general, the objectives to maximise the auctioneer's surplus, social welfare, or the number of goods allotted, and ensuring proportionality conflict. However, one policy measure that contributes to all three objectives for any number of potential bidders – assuming it absorbs its implementation costs and does not adversely affect project quality – is to reduce the costs of participation. Especially for auctions for RE support, this implies revisiting the legal framework for prequalification measures or site approvals.

Chapter 3

Experimental analysis of auctions with endogenous rationing

3.1 Introduction

In recent years, auctions for RE support have been established worldwide. While most auctions have been a success, there are also cases where the auctioned volume has not been met or where only high prices have been achieved (AURES II, 2022). To counteract these problems, different strategies have been suggested (Hanke et al., 2020). A popular potential solution is the implementation of ER and has so far been implemented in several countries, e.g., in Germany (BNetzA, 2019). Under this rule, the auction volume is reduced when there is a lack of competition in the auction, so that only a certain percentage of the original submitted bids is actually awarded.

The rationale behind this suggestion is that there are more submitted bids than awarded ones, supposedly guaranteeing competition in the auction. In Chapter 2 it is shown, that in the game-theoretic equilibrium no potential bidder would actually participate. Experiments e.g., regarding beauty contests (Nagel, 1995) have shown that the game-theoretic extreme solution does not manifest itself right from the beginning, but is rather approached gradually over the course of repeated games, when players anticipate their opponents' behaviour in more depth. Applying iterative reasoning (Camerer et al., 2004), bidders guess competitors' (non-equilibrium) bidding strategies and in how far competitors anticipate the bidders' own behaviour.

Thus, while the theoretic predictions are unambiguous, the real-world behaviour in auctions might differ significantly. Therefore, we conduct a laboratory experiment to test whether participants in the experiment behave according to theory. If the equilibrium strategy is applied, it is a further strong indication that auctions with ER negatively effect the market in the long run and should be avoided.

In this chapter, we experimentally study ER by comparing ER auctions with standard auctions. In Section 3.2 give a detailed description of the experimental design. Section 3.4 shows the experimental results, both in regarding to descriptive as well as inferential statistics. In Section 3.5 we shortly discuss the results and conclude the chapter.

3.2 Experimental design

The laboratory experiment consists of two treatments: *ER Treatment* and *Control Treatment*, both of which were conducted at the KD2lab (Karlsruhe Decision and Design Lab) in Karlsruhe, Germany.[1] In the ER Treatment, the subjects play a DP auction with endogenous adaption of the auction volume, as described and analysed in Section 2.2.2. Thus, if competition is too low, not all goods in an auction are actually awarded. The subjects in the Control Treatment play a standard DP auction (see Section 2.2).

---

[1] The KD2lab is DFG-funded and situated at the Karlsruhe Institute of Technology. For further information see https://www.kd2lab.kit.edu/english/index.php.

Table 3.1: Experimental design parameters

Number of goods per auction	$k = 6$
ceiling price (maximum bid price)	$r = 77$ ExCU
Pricing rule	Pay as bid
Number of potential bidders per auction	$n = 9$
Private costs	$x_i \sim U[50, 75]$ ExCU
Participation costs	$c = 5$ ExCU

The experimental design parameters in Table 3.1 apply to both treatments. We refer to the game that nine subjects play in a round (including the decision to participate) as an auction. In each auction, six goods (projects) are demanded. Each subject can supply one good. The auction is organised as follows: First, the nine subjects receive their private cost signals x_i (with two decimals) i.i.d. drawn from the uniform distribution on the interval [50, 75] experimental currency units (ExCU). One ExCU is equal to 50 Euro Cent. Second, the nine subjects simultaneously decide whether to participate in the auction or not. Participation costs 5 ExCU. Subjects who decide against bidding accrue no costs, but also do not receive any payment. We refer to those subjects who participate in the auction as bidders. The number of bidders is not revealed prior to bidding. Third, the auction is conducted and each bidder submits one bid (with two decimals). The lowest bids are awarded (according to the rules of the respective treatment). DP pricing applies. Bidders, whose bids are awarded, receive a payment equal to the difference between their bid and their costs minus the participation costs. Bidders, whose bids are not awarded, make a loss equal to the participation costs.

In the auctions in the ER Treatment, endogenous volume adaption is implemented by the following rule: If eight or nine bids are submitted, the six lowest bids are awarded. If seven or fewer bids are submitted, two bids less are awarded. That is, if seven bids are submitted, the five lowest bids are awarded; if six bids are submitted, the four lowest bids are awarded and so on. If one or two bids are submitted, no bid is awarded. That is, there is no lower bound at which rationing stops, i.e., $\underline{\mu} = 0$ following the notation in Chapter 2. In the standard auctions in the Control Treatment, if seven or more bids are submitted, the six lowest bids are awarded. If six or fewer bids are submitted, all bids are awarded.

A subject is assigned to either the ER treatment or the control treatment. 72 subjects participate in each treatment and are divided into four matching groups of 18 subjects each.[2] Each matching group participates in 15 consecutive rounds. In each round, two groups of nine participants from the matching group are formed at random. Each group plays one auction. Thus, 120 auctions are played in each treatment and each subject participates in 15 consecutive auctions with alternating opponents.[3]

3.3 Experimental hypothesis

In the experiment, the lower limit of participation $\underline{\mu} = 0$, so Proposition 1 in Chapter 2 predicts no participation in the equilibrium of the one-shot ER auction. Since this is an extreme result requiring sophisticated coordination of beliefs, we derive a weaker hypothesis involving learning. That is, we do not expect low participation right at the beginning, but rather a downward spiral, i.e., participation that gradually decreases over the course of repeated auctions. This hypothesis of gradual development

---

[2] At the beginning of the experiment, written instructions were read out aloud (see a translation of the instructions in C.3). Before the experiment started, subjects had to answer questions on the instructions (see C.4). At the end of the experiment, the subjects execute the Holt-Laury task to measure their risk aversion (Holt et al., 2002). Each session lasted around 45 minutes. The experiment was programmed in oTree (D. L. Chen et al., 2016) and the experiment was organised and recruited with the software hroot (Bock et al., 2014).

[3] A subject's final payment consists of a show-up fee of 8 Euro, the subject's average profits of five randomly drawn auction rounds and a payment from the risk-aversion task. The average payment was 11.00 EUR. The lowest and highest payment were 5.00 EUR and 16.30 EUR.

is in line with experimental results for example on the beauty contest game (e.g., Nagel, 1995). Camerer et al. (2004) provide a model that captures such non-equilibrium behaviour in which players use different depths of iterative reasoning for deriving their strategies and in which their beliefs about their competitors' behaviour might not represent the equilibrium strategy.

3.4 Experimental results

First, we analyse subjects' behaviour in the control treatment. If this behaviour were to be decisively different than theory predicts, outcomes of the ER treatment could only be considered to an extent, as some effects then might be linked to experiment design itself, and not ER. Second, we observe the behavioural difference between treatments, both cumulated over all treatments and per matching group. Thirdly, we conduct statistical analyses of experimental data.

3.4.1 Behaviour in the Control Treatment

The experimental parameters in Table 3.1 in Section 3.2 yield, by Equation (A.6), the cutoff $\hat{x} = 64.92$. That is, theory predicts that subjects with private costs x below 64.92 participate in the auction and submit the equilibrium bid $\beta^{DP}(x)$ in Lemma 3 in Chapter 2, whereas subjects with higher private costs do not to participate.

Table 3.2 shows how subjects decide on their participation in the auction with respect to the relation between their private costs x and the theoretical cutoff $\hat{x}$. In 690 (of 1080) cases, the private costs x are lower than $\hat{x}$. In these cases, we observe 655 (94.9%) participations. In 390 (of 1080) cases the private costs x are higher than $\hat{x}$ and we observe 288 (73.8%) non-participations. Thus, a total of 943 (87.3%) of the 1080 participation decisions are in line with theory, i.e., either a subject with $x \leq \hat{x}$ participates in the auction or a subject with $x > \hat{x}$ does not participate. Figure 3.1 indicates for both cases an increase of the share of participation decisions in line with theory over the rounds.

Table 3.2: Distribution of the participation decisions in the Control Treatment

		Private costs x		
		$x \leq \hat{x}$	$x > \hat{x}$	Sum
Participation	Yes	655 (60.6%)	102 (9.4%)	757 (70.1%)
	No	35 (3.2%)	288 (26.7%)	323 (29.9%)
	Sum	690 (63.9%)	390 (36.1%)	1080 (100 %)

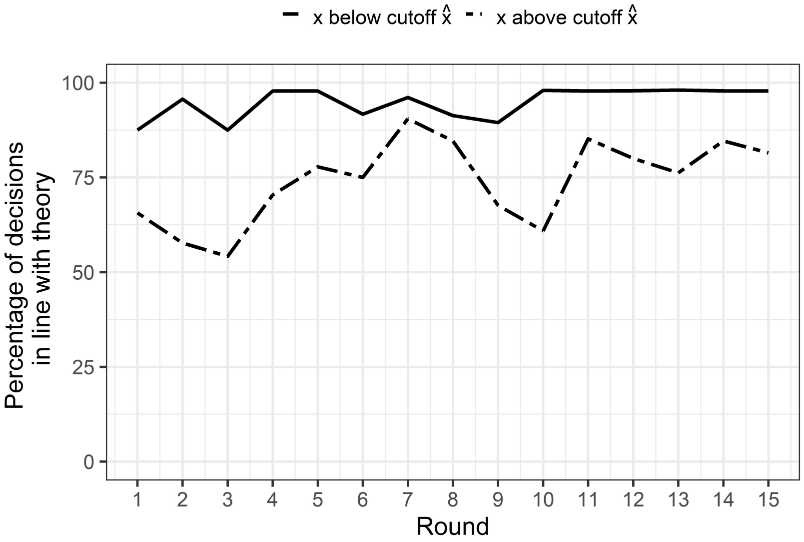

Figure 3.1: Development of the percentage of participation decisions in line with theory in the Control Treatment: percentage of participation for $x \leq \hat{x}$ (solid line) and percentage of non-participation for $x > \hat{x}$ (dotted line)

The average submitted bid (after participation in line with theory) is 68.35, while the average corresponding equilibrium bid is 68.86. Thus, the submitted bids deviate on average (median) from the equilibrium bids only by -0.50 (0.23), which amounts to 1.85% (0.85%) of the range from the lower interval limit to the ceiling price $[\underline{x}, r]$. Figure 3.2 shows the development of these differences over the rounds. After negative deviations in the first rounds, the bid level reaches the equilibrium level and remains there in the following rounds (see also Figure 3.4 in Section 3.4).

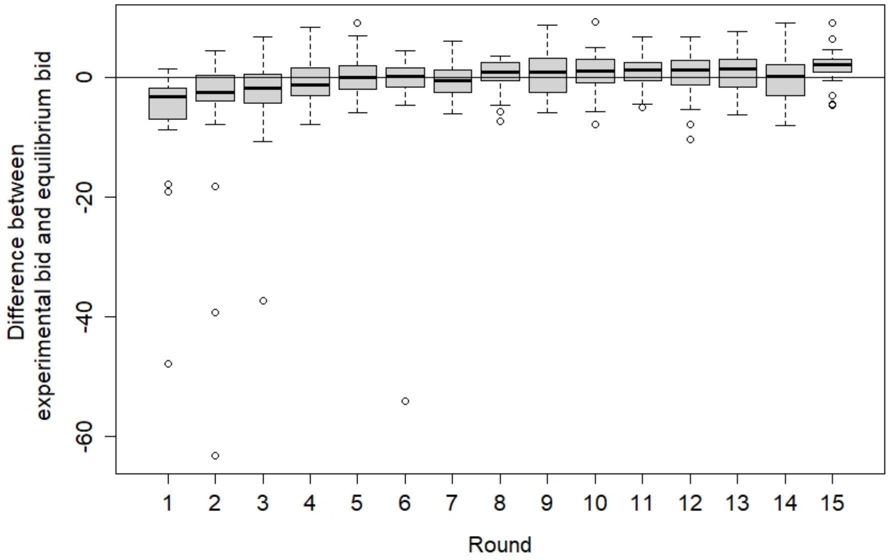

Figure 3.2: Box-and-whisker plots of the difference between equilibrium bids and submitted bids in the rounds of the Control Treatment conditional on participation in line with theory: median, IQR, whiskers (outliers at max 1.5×IQR), and outliers more than 1.5×IQR.

We conclude that the subjects' behaviour in the Control Treatment is largely in line with the equilibrium strategy derived in Section 2.2, both with respect to participation and bids. This indicates that the experimental design is well fit to trigger (close to) equilibrium behaviour in the Control Treatment.

3.4.2 Difference in treatments

Table 3.3 shows the means (over all groups) of different variables in all rounds (1–15), in the first round (1), and in the last round (15). The calculation of the auctioneer's surplus and the social welfare requires to assign the auctioneer a valuation v. We use $v = r$, which is the valuation for which r is the welfare-maximising ceiling price in the Control Treatment (see Proposition 2 in Chapter 2).

Table 3.3: Experimental results of the auctions

Treatment	ER			Control		
Rounds	1–15	1	15	1–15	1	15
Avg. number of submitted bids	4.03	5.13	2.75	6.31	5.75	6.13
Avg. number of awarded bids	2.13	3.13	1.00	5.63	5.75	5.50
Avg. value of submitted bids	62.13	57.74	63.10	69.91	65.23	71.41
Avg. value of awarded bids	56.65	47.84	55.91	69.43	65.23	71.03
Avg. auctioneer's surplus	41.51	83.63	18.38	42.88	67.63	32.73
Avg. social welfare	105.55	167.45	34.31	366.90	376.91	358.21

Figure 3.3 shows that the number of submitted bids (i.e., the participation level) and the number of awarded bids are lower in the ER Treatment than in the Control Treatment and decrease in the ER Treatment, while they show no trend in the Control Treatment.

3.4.2.1 Detailed results

In this section, we analyse whether the results in Section 3.4.2 also hold for each matching group or whether one group has majorly different results. Table 3.4 shows for each matching group of each treatment when the session was conducted and how the matching groups are labeled.

In each matching group of 18 subjects, in 15 consecutive rounds two randomly assigned groups of nine subjects play the same type of auction (either the ER auction in the ER Treatment or the standard auction in the Control Treatment). Tables 3.5 and 3.6 present the aggregated results in Table 3.3 for all rounds (1–15), the first round (1) and the last round (15) per matching group.

In the two ER matching groups ER-2 and ER-3 some bids are smaller

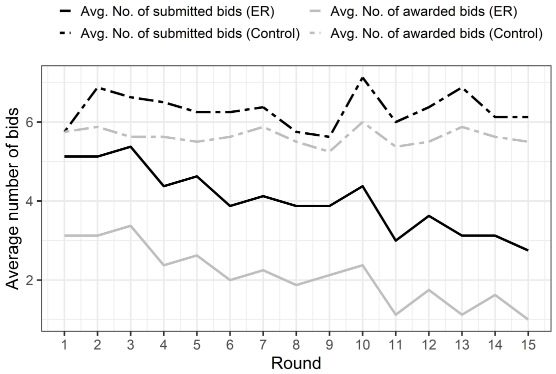

Figure 3.3: Development of the numbers of submitted and awarded bids

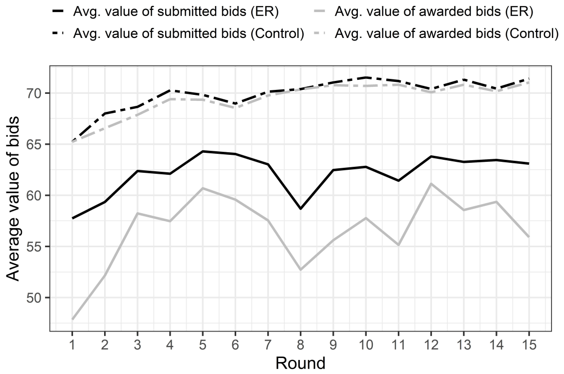

Figure 3.4: Development of the means of submitted and awarded bids

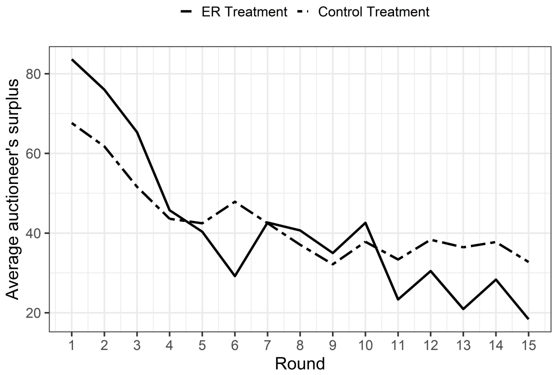

Figure 3.5: Development of the auctioneer's surplus

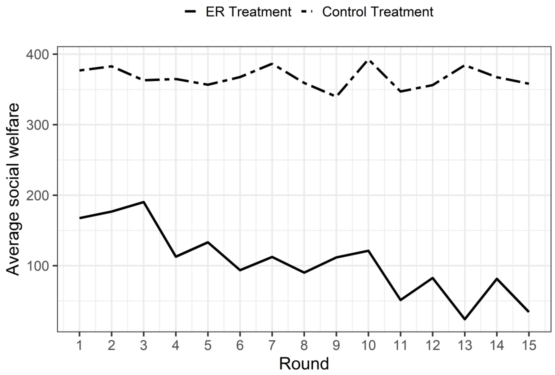

Figure 3.6: Development of the social welfare

than 50, i.e., the lowest possible cost signal. As a consequence, in several rounds of these two matching groups the average submitted bid and the average awarded bid are lower than 50 (Table 3.5 and Figure 3.8). This is also the reason why the average awarded bid in the first round of the ER Treatment in Table 3.3 is below 50. Figure 3.8 shows that in the matching groups ER-1 and ER-3 there are rounds where no bid is awarded because in both groups of the matching group less than three bids are submitted (ER-1: rounds 11, 12 and 15; ER-3: round 11). In

Table 3.4: Overview of sessions

Date and time of session	Treatment	Matching group label
07-02-2019, 10.30 a.m.	Control	Control-1
07-02-2019, 10.30 a.m.	ER	ER-1
07-30-2019, 10.30 a.m.	Control	Control-2
07-30-2019, 10.30 a.m.	ER	ER-2
07-30-2019, 02.00 p.m.	ER	ER-3
10-08-2019, 10.30 a.m.	Control	Control-3
10-08-2019, 10.30 a.m.	ER	ER-4
10-09-2019, 10.30 a.m.	Control	Control-4

all matching groups of the Control Treatment, the average number of awarded bids is close to six, i.e., the highest possible number (Table 3.6). Figures 3.9 and 3.10 show that in all matching groups, the average submitted bid and the average awarded bid (after an increase in the first rounds in some matching groups) remain on the same level of about 70 (see also 3.4.1). Thus, while in the Control Treatment the matching groups' behaviour is relatively similar over all groups, some bidders in the ER Treatment do behave differently than others. This contributes to the lower submitted and awarded bids in the aggregated results. Still, even in groups without unusual low bids, bids are on average lower than in the matching groups of the Control Treatments. The effects of the single matching group behaviour thus seems to intensify a difference which exists in all groups, in some only to a smaller extent.

3.4.2.2 Statistical analyses

To test the effects of the treatments and the rounds on the variables in Table 3.3, we apply linear mixed-effects models and additionally Wilcoxon rank sum tests for inter-treatment comparisons in the first and the last round. Throughout the statistical analysis we use the significance level $\alpha = 0.05$.

Table 3.5: Results of the auctions in the matching groups of the ER Treatment

Matching group	ER-1			ER-2		
Rounds	1–15	1	15	1–15	1	15
Avg. number of submitted bids	2.63	5.00	2.00	4.33	5.00	2.50
Avg. number of awarded bids	0.93	3.00	0.50	2.33	3.00	0.50
Avg. value of submitted bids	62.63	67.60	60.15	56.36	53.42	55.28
Avg. value of awarded bids	60.41	65.00	60.00	45.10	39.41	30.50
Avg. auctioneer's surplus	14.04	36.00	8.50	64.41	100.85	23.25
Avg. social welfare	35.71	160.41	4.85	112.25	153.74	5.49

Matching group	ER-3			ER-4		
Rounds	1–15	1	15	1–15	1	15
Avg. number of submitted bids	3.97	5.50	3.00	5.17	5.00	3.50
Avg. number of awarded bids	2.03	3.50	1.00	3.20	3.00	2.00
Avg. value of submitted bids	63.95	49.07	68.65	65.52	60.88	68.31
Avg. value of awarded bids	59.05	35.46	62.95	62.23	51.50	63.14
Avg. auctioneer's surplus	39.64	125.19	14.06	47.94	72.50	27.72
Avg. social welfare	96.02	196.57	7.95	178.23	159.07	118.94

First, we apply a linear mixed-effects model (Gałecki et al., 2013) to test the influence of the treatment and the round on the dependent variables in Table 3.3. We use the R-packages *lme4* (Bates et al., 2015) and *lmerTest* (Kunzetsova et al., 2017) on R 4.0.3 (R Core Team, 2020).

The vector of the dependent variables is denoted by y. We include the fixed effects treatment and round, and an interaction effect between treatment and round to test whether the influence of these variables has an interdependence. The parameters for the constant, the two main effects, and the interaction effect are denoted by β_j for $j \in \{0, 1, 2, 3\}$. An advantage of linear mixed-effects models is the inclusion of dependencies in the data (Müller et al., 2013). We include this in our model by taking the matching group as a random effect with parameter g (Brown, 2021), since subjects are randomly put into these groups at the start of the

Table 3.6: Results of the auctions in the matching groups of the Control Treatment

Matching group	Control-1			Control-2		
Rounds	1–15	1	15	1–15	1	15
Avg. number of submitted bids	5.90	6.00	4.50	6.40	6.00	5.50
Avg. number of awarded bids	5.37	6.00	4.50	5.73	6.00	5.50
Avg. value of submitted bids	70.03	67.37	71.86	68.62	63.96	68.63
Avg. value of awarded bids	69.68	67.37	71.86	68.04	63.96	68.63
Avg. auctioneer's surplus	39.29	57.78	22.86	51.83	78.23	45.80
Avg. social welfare	348.22	399.69	285.51	375.02	396.51	362.75

Matching group	Control-3			Control-4		
Rounds	1–15	1	15	1–15	1	15
Avg. number of submitted bids	6.27	5.00	7.50	6.67	6.00	7.00
Avg. number of awarded bids	5.57	5.00	6.00	5.87	6.00	6.00
Avg. value of submitted bids	70.33	64.96	72.61	70.67	64.61	72.53
Avg. value of awarded bids	69.83	64.96	71.67	70.16	64.61	71.95
Avg. auctioneer's surplus	39.96	60.19	32.00	40.42	74.32	30.32
Avg. social welfare	361.32	317.04	390.25	383.03	394.39	394.33

experiment and do not change their matching group in the course of the experiment, and this might have an influence as examined in Section 3.4.2.1. With the vector of residual errors ε, the model is as follows:

$$\begin{aligned} y = {} & \beta_0 + \beta_1 \cdot TreatER + \beta_2 \cdot Round + \beta_3 \cdot TreatER \cdot Round \\ & + g \cdot Matchinggroup + \varepsilon. \end{aligned} \tag{3.1}$$

The results of the statistical calculations are presented in Table 3.7. The parameter estimates for the fixed effects are given, with information on the p-value of the t-test. The standard errors are in brackets.

Table 3.7 reveals the following results: There is no evidence of a trend in the number of submitted bids in the Control Treatment, while the round has a significant negative effect on the number of submitted bids in the ER treatment. The number of awarded bids is significantly

Table 3.7: Effect of treatment and round on different variables

Dependent variable	Number of observations	TreatER	Round	$\text{TreatER} \cdot \text{Round}$	Constant
Number of submitted bids	240	-0.965 (0.633)	-0.003 (0.028)	-0.165^{***} (0.039)	6.333^{***} (0.448)
Number of awarded bids	240	-2.401^{**} (0.531)	-0.010 (0.020)	-0.138^{***} (0.028)	5.712^{***} (0.376)
Value of submitted bids	1,240	-7.160^{*} (2.084)	0.298^{***} (0.074)	-0.071 (0.120)	67.601^{***} (1.445)
Value of awarded bids	931	-12.343^{**} (3.251)	0.328^{***} (0.077)	-0.176 (0.154)	66.779^{***} (2.234)
Private costs of submitted bids	1,240	-2.230^{*} (0.954)	-0.142^{**} (0.046)	0.024 (0.075)	60.296^{***} (0.650)
Private costs of awarded bids	931	-3.198^{*} (1.120)	-0.156^{*} (0.045)	-0.024 (0.088)	59.732^{***} (0.728)
Auctioneer's surplus	240	13.333 (11.993)	-1.939^{***} (0.438)	-1.838^{*} (0.619)	58.387^{***} (8.480)
Social welfare	240	-190.723^{***} (34.366)	-0.627 (1.437)	-8.828^{***} (2.032)	371.909^{***} (24.301)

$^{*}p<0.05$; $^{**}p<0.01$; $^{***}p<0.001$

lower in the ER Treatment than in the Control Treatment, with an increasing divergence over the rounds. The submitted bids as well as the awarded bids significantly increase over the rounds and are significantly lower in the ER Treatment than in the Control Treatment. The private costs of the submitted bids significantly decrease over the rounds and are significantly lower in the ER Treatment than in the Control Treatment. This also applies to the private costs of the awarded bids. The auctioneer's surplus significantly decreases over the rounds, with a significantly stronger decrease in the ER Treatment. The social welfare is significantly lower in the ER Treatment than in the Control Treatment, with an increasing divergence over the rounds.

We additionally apply Wilcoxon rank sum tests (Wilcoxon, 1945) to compare the two treatments' variables in Table 3.3 both in the first round and in the last round. For the calculation of the Wilcoxon rank sum tests, the R-package *stats* is used on R 4.0.3 (R Core Team, 2020). We provide the p-values for two-tailed tests. Thus, in all tests, the null hypothesis is that there is no difference between the treatments.

The test results are presented in Table 3.8. The first column presents the variable, the second to fourth columns the test results for the first round (*round 1*), and the fifth to last columns the test results for the last round (*round 15*). The number of observations, the test statistics W, and the p-value are given. We find a significant difference between the treatments both in the first and last round for the number of awarded bids, the value of the awarded bids, the average private costs of the awarded bids, and the social welfare. We find a significant difference between the treatments in the last but not the first round for the number of submitted bids, the value of submitted bids, and the average private costs of the submitted bids.[4] For the auctioneer's surplus, there is neither a significant difference in the first round nor in the last round.

The two approaches of testing complement each other. Together with the descriptive approach presented in Table 3.3, we derive at the following results.

Result 1. *In the ER Treatment, the number of submitted bids is significantly lower than in the Control Treatment (overall and last round) and significantly decreases in the ER Treatment. This also applies to the number of awarded bids, where there is already a significant difference in the first round.*

This result supports the weakened hypothesis in Section 3.3 and reveals the expected strong negative effect of ER on participation.

Result 2. *The submitted bids and the awarded bids are significantly lower in the ER Treatment than in the Control Treatment, which also*

---

[4] When we apply the rather conservative Bonferroni correction to address the multiple comparisons problem, all differences except those for the private costs remain significant.

Table 3.8: Wilcoxon tests for the comparison of ER and Control Treatment in first and last round

	Round 1 (first round)			Round 15 (last round)		
	Number of observations	W	p-value	Number of observations	W	p-value
Number of submitted bids	16	44	0.192	16	60.5	0.003
Number of awarded bids	16	63	< 0.001	16	63.5	< 0.001
Value of submitted bids	87	1138	0.098	71	934.5	< 0.001
Value of awarded bids	71	874.5	< 0.001	52	374.5	< 0.001
Private costs of submitted bids	87	1099.5	0.185	71	597	0.038
Private costs of awarded bids	71	747.5	0.038	52	254	0.048
Auctioneer's surplus	16	22	0.328	16	49	0.082
Social welfare	16	63	< 0.001	16	64	< 0.001

applies to the last round and for the awarded bids also to the first round (Figure 3.4).

The lower bids can be attributed to a selection effect since the lower participation in the ER Treatment is mainly due to higher-cost types staying out.[5]

Result 3. *The auctioneer's surplus significantly decreases in both treatments, where the decrease in the ER treatment is stronger than in the Control Treatment (Figure 3.5).*

There is no significant treatment difference in the amount of the auctioneer's surplus.

Result 4. *Social welfare is significantly lower in the ER Treatment than*

---

[5] The private costs of the bidders who submit bids and of those whose bids are awarded are significantly lower in the ER Treatment than in the Control Treatment and significantly decrease over the rounds in the ER Treatment (see Table 3.7) .

in the Control Treatment, which also applies to the first and to the last round. Also, social welfare significantly decreases in the ER Treatment (Figure 3.6).

We conclude that the experiment supports the theoretical predictions: the participation level and the social welfare under ER are lower than in the corresponding standard auction and strongly decrease over the rounds. Although ER generates lower payments than the standard auction, a higher auctioneer's surplus cannot be identified.

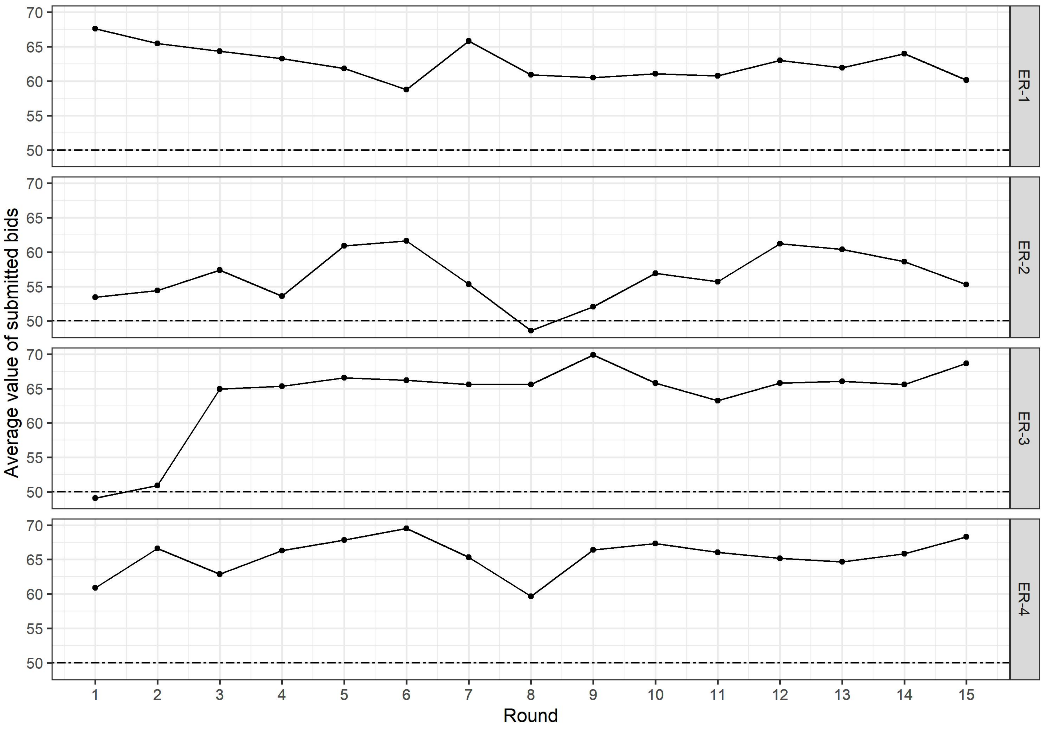

Figure 3.7: Development of the average value of submitted bids in the matching groups of the ER Treatment

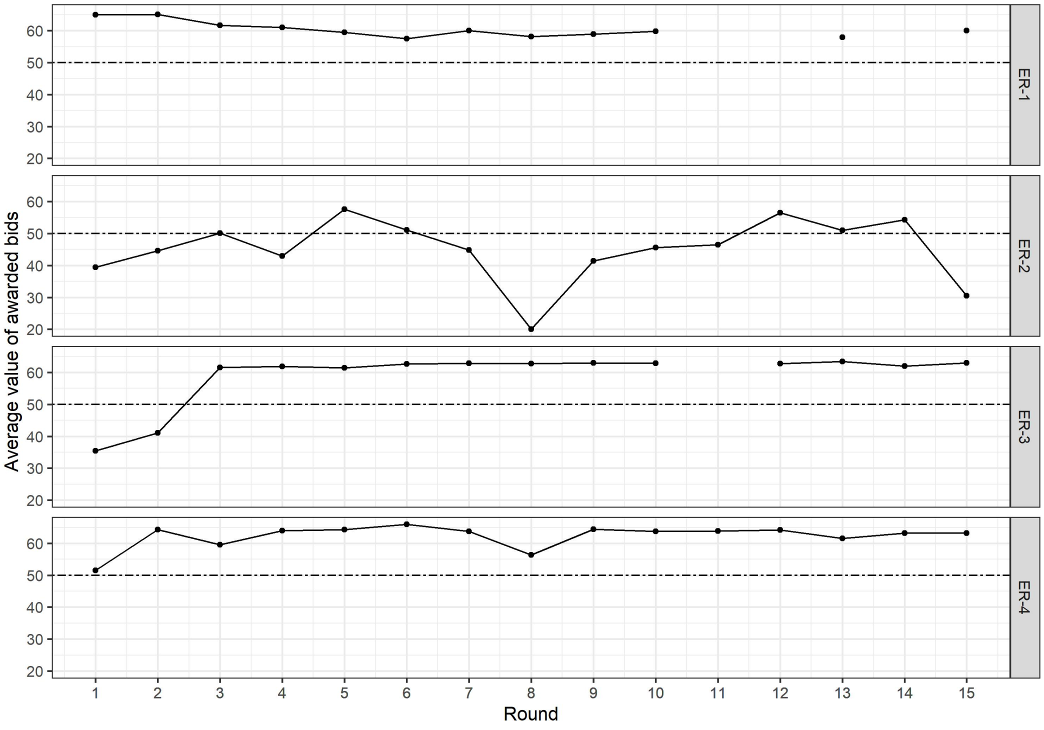

Figure 3.8: Development of the average value of awarded bids in the matching groups of the ER Treatment

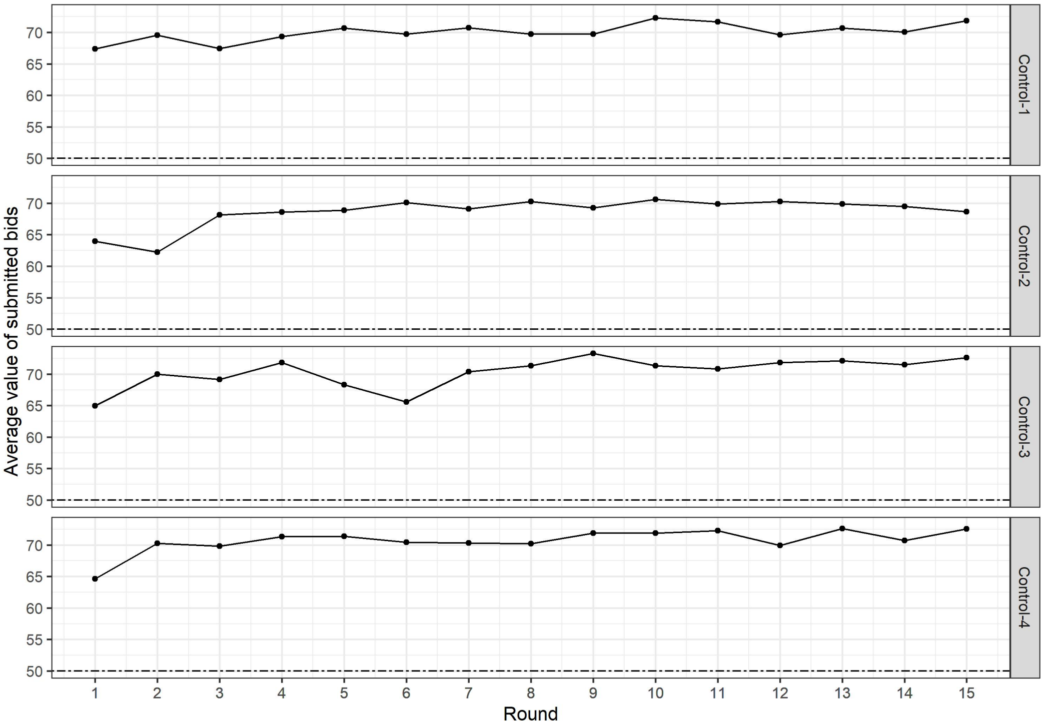

Figure 3.9: Development of the average value of submitted bids in the matching groups of the Control Treatment

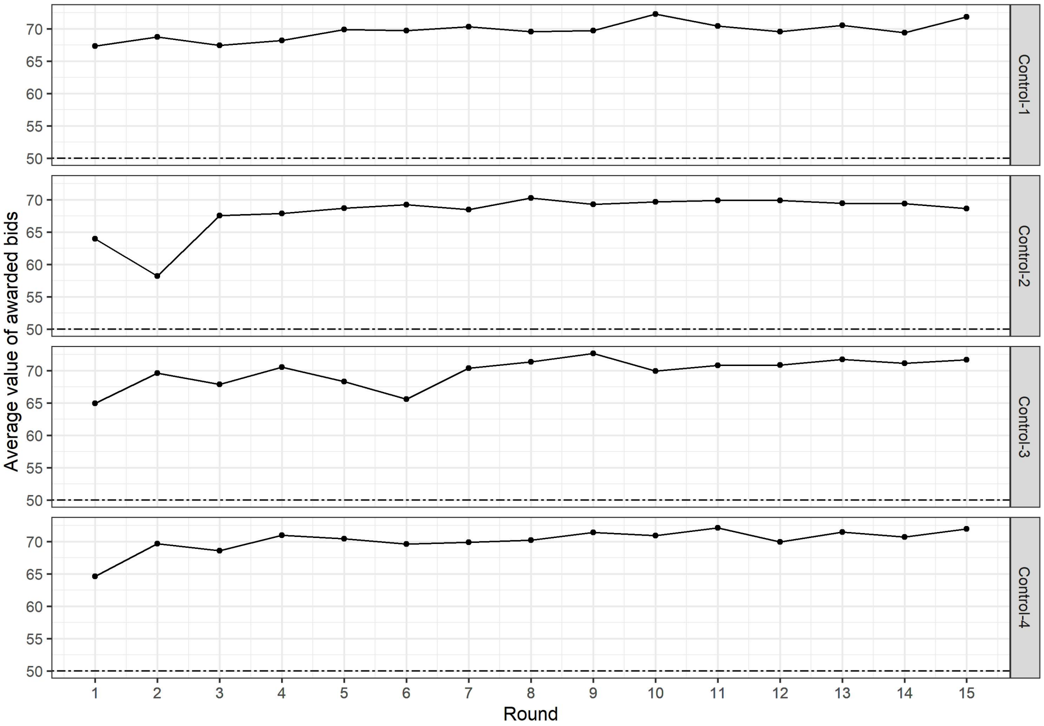

Figure 3.10: Development of the average value of awarded bids in the matching groups of the Control Treatment

3.5 Discussion and conclusion

Theory has suggested that by implementing ER measures, no participation of potential bidders is expected. To test whether this extreme result actually would manifest in real-world applications, an experiment was conducted. Subjects' behaviour in the Control Treatment of the experiment had only minor deviations from equilibrium strategies with regard to participation and bid decisions. Thus, the experiment design is suitable in reflecting theoretic behaviour. Nevertheless, especially in the ER Treatment, some bidders tend to underbid their costs. This can be seen, since some bids are even below the lower limits of costs, resulting in a definite loss of money, if the bid is awarded. This bidding behaviour is in line with behaviour in other experiments (see Chapter 5), where underbidding seems to occur occasionally as well. While lower prices do have a positive effect on the auctioneer's surplus, no significant difference can be found between the treatments.

While the number of auctions without any participating bidders is rather low, a significant downwards spiral of participation can be seen in auctions with ER. Further, standard auctions without ER have higher social welfare than auctions with ER. Thus, theoretic predictions (Chapter 2) and the experimental hypothesis (Section 3.3) are met.

Subjects participating in the experiment are incentivised to bid optimally for maximising their profit by linking their decisions with real payments. The rationale behind this, is that companies in real-world auctions often follow the same line of thought. Still, subjects cannot be ruined by wrong decisions as their counterpart can. Thus, a laboratory experiment cannot be transferred wholly to real-world applications. With this limitations in mind, we nevertheless strongly advise against implementing ER measures in auctions. Both theory and experiment predict a worse outcome for auctioneer's surplus and social welfare when ER is implemented, even though support payments in the ER Treatment are lower than in the Control Treatment.

To counteract the problematic of low competition, other options might be favourable. Hanke et al. (2020) make several suggestions, e.g., a (temporarily) pre-announced reduction of the auction volume might mitigate the problem. Further, high auction prices send positive signals for potential bidders, such that in the future, a more stable market with more competition might be realised. Thus, when designing auctions for RES, sometimes the long-term positive effects outweigh the short-term negative results.

Chapter 4

Auction-theoretic aspects of cross-border auctions

4.1 Introduction

Though auctions for RE support have been applied in a growing number of countries (AURES II, 2022), a relatively new and rather unused facet in this field is the implementation of so-called cross-border auctions, i.e., auctions that are held not only for projects situated in the auction-conducting country, but also for projects located in a foreign country. Until now only one cooperation of this kind has been conducted, namely two cross-border pilot auctions for PV in Denmark and Germany in 2016 (Roth et al., 2022). Both Denmark and Germany conducted a cross-border auction, while Germany opened all of the 50 MW tender volume for Danish projects, whereas Denmark only opened $2,4$ MW of the 20 MW tender volume for German projects. Due to the lower prices in the German opened auction compared to the national German tenders, this auction can be considered a success in terms of lower support costs (von Blücher et al., 2019). Furthermore, many EU Member States, e.g. Germany and Hungary, were obliged by the EU Commission to perform cross-border auctions (European Commission, 2014). In addition, the recently introduced revised Renewable Energy Directive (RED II) encourages countries to open at least 5% of their annual volume of auctions for RES to the participation of projects from other countries in the future (European Commission, 2018). Although no other cross-border auctions were conducted in Europe, several countries were interested in the participation in a case study in Blücher et al. (2020), where hypothetical cross-border auctions were analysed with regard to the newly introduced EU RES financing mechanism (European Parliament, 2018). It is therefore vital to understand the underlying theoretical framework in order to conduct cross-border auctions whose outcomes achieve the goals in the best possible way and to help countries design well-performing cross-border auctions.

In this chapter, we examine three different ways to design cross-border auctions. Each scenario represents a different level of openness between two countries. So far, countries have conducted national auctions, only open to projects in their own country. These two *Separate Auctions* serve as a benchmark case in our analysis. A possibility of implementing cross-border auctions is the opening of one of these Separate Auctions for bidders with projects in the other country, which we call a *Unilateral Auction*. Further openness is achieved when both countries open their auctions to projects from the other country. Then bidders from both countries can decide whether they want to participate in their original country or the other (e.g. the German-Danish case). This is called a *Mutual Auction*. Complete openness is guaranteed by a *Joint Auction* conducted by both countries, which is also explicitly mentioned as a possibility by European Commission, 2018. To achieve this, the countries have to decide upon one auction design. Therefore, a Joint Auction can be understood as the hardest auction format to implement. In all other scenarios, the countries decide on the auction design on their own and thus have more freedom, even if they decide to open the auction for other nationalities. All formats are auction-theoretically analysed and their outcome is compared regarding the expected rent for the auctioneer, i.e., the prices the auctioneer will have to pay (this is also often referred to as support cost efficiency), and the expected efficiency, i.e., if this format guarantees that only the bidders with the lowest costs of producing energy are awarded (generation cost/allocative efficiency). For simplicity, we assume that a country can only open their scheme completely, and not only for a percentage of the total auction volume, like this is the case in the Danish cross-border auction. We will refer to auction volume reserved for domestic projects as an outside option for those bidders, since they can compete in both auctions, the cross-border scheme as well as the country-specific one.

The rest of this chapter is structured as follows. In Section 4.2 we will introduce the different design possibilities for cross-border auctions and their individual characteristics. Section 4.3 will give an overview over the existing theoretical and practical literature on these auction types. In Section 4.4 we will develop our theoretical model. First we will introduce our basic model in Section 4.4.1, followed by the individual analysis on Joint (4.4.2), Separate (4.4.3), Mutual (4.4.4) and Unilateral Auctions (4.4.5). When bidders can decide in which auction they want to participate, we differentiate further between Simultaneous and Sequential Auctions. All analyses will examine efficiency and prices as main auction outcomes. We will compare the different formats in Section 4.4.6. Afterwards, we will present possible extensions of the model, which can be analysed in further work, in Section 4.4.7. We will conclude this chapter in Section 4.5.

4.2 Types of cross-border auctions

In this section we want to analyse the difficulties and choices the implementation of the different cross-border scenarios entails. Our non-cross-border benchmark case, the complete separation of RES auctions between countries is the easiest form of auction design and implementation. Each country can then set its own design without having to interact with the other country. The awarded bidders will receive the support payment from the country their project is located in. Furthermore, it is clear that the support payments, i.e., in the European context the feed-in premiums, are based on the domestic electricity market price, so all bidders regardless of their project have the same basis for their calculations.

This is not the case if an auction is opened for projects in other countries. If the auctions are unilaterally or mutually opened for bidders from a different country, the first decision bidders have to face is in which country they want to participate. Since we first analyse auctions which take place at the same time and in coordination of each other, it is usually not economically feasible to participate in these auctions at the same time. One of the first question for the auctioneer as well as the bidders that arises from this, is which market price is the basis for the determination of the height of the support payments. The easiest way is to take the market price from the country or region the project is located in, as the energy produced is sold in this market. This can result in different calculations the bidders have to make while calculating their bid. For example, a bidder with a project located in country A but participating in country B must potentially bid differently for a fixed market premium than a bidder with a project located in country B.[1]

---

[1] Another possibility is to take the market price of the country conducting the auction, but this goes hand

Nevertheless, it is still possible to have different design variants in the different countries, e.g. most likely regarding different prequalification requirements and penalties. In the German-Danish case, there were for example different financial prequalifications and ceiling prices in each auction (von Blücher et al., 2019). Further the two countries of course have different market characteristics apart from the auction design, e.g., in Germany farmland is largely excluded from PV development whereas in Denmark this is not the case. This is not explicitly part of the auction design, but part of the permits which need to be obtained in order to realise the project. These different country-specific framework conditions still persist, even if the auction designs are completely harmonised.

The by far most complex auction design for cross-border auctions is the Joint Auction. We will consider this as the cross-border benchmark case. The most intuitive form of a Joint Auction is when the two countries need to agree on one design, independently of whether they apply different designs in their country-specific auctions. In this case it cannot be distinguished which country was responsible for the award. Thus, first of all, a challenge might be the distribution of support payments between the two countries. One possibility is that the bidders are paid from a common budget, into which both countries have to pay. The easiest form here is to share the costs evenly among the participating countries, but of course all other forms of splitting costs is possible. The decision upon a fair cost distribution and auction characteristics might be hard for countries wanting to participate. Furthermore, an auction design which might be ideally adapted to the domestic market structure might not be appropriate for the neighbouring circumstances. Thus, compromises need to be found which can be rather challenging in the

---

in hand with higher administrative effort, since apart from the calculation of the support payment, also the difference between the two market prices has to be considered under a sliding feed-in premium. As this is rather complicated, its implementation is unlikely.

political and economic context. Nevertheless, we will show that the Joint Auction with a completely harmonised design is efficient and will lead to the lowest possible prices.

Another possibility to conduct a Joint Auction is to take into consideration the market differences and, e.g., implement different pricing rules for the different countries, i.e., different remuneration schemes. This auction is similar to a Mutual Auction but with the difference that bidders are allowed to emit two bids, one for being awarded from country A and one for being awarded from country B. In the Mutual Auction bidders have to decide in which country they want to participate in the first place and can thus only place one bid. The bidders in this kind of Joint Auction can, similarly to the Mutual auction, only be awarded with one of their bids, i.e., either they fall under the remuneration scheme of country A or under the scheme of country B. A huge advantage of this system is that they do not have to pay penalties for the bid which is not awarded. This would not have been the case if they participated in two completely separate auctions, since then there was the possibility that they were awarded in both with the same project.

A satisfying pricing mechanism for this Joint Auction which allows only one bid per participant to be awarded can be hard to find. We will propose a solution in Section 4.4.7.2. The awarded bids here not only determine the height of the support payment, but also the country which has to pay for it, namely the country for which this bid was placed. Again, this procedure is overall efficient and the cheapest feasible outcome. Nevertheless, this can lead to major disadvantages for one country, resulting in very high costs, while the other country has very low costs. This will be discussed later in this chapter.

For all types of openness, we assume that either all of the auction

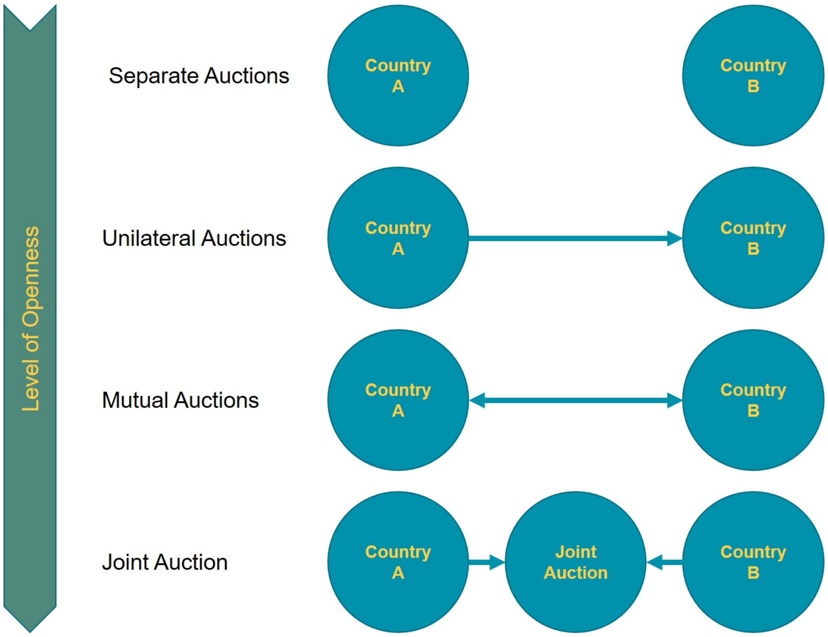

Figure 4.1: Overview of types of cross-border auctions

volume is opened to foreign projects, or none. We will not consider cases where only a percentage $\delta\%$ of the auction volume is opened for foreign projects, while the rest of the volume is reserved for domestic plants. [2]

An overview of the different types of cross-border auctions can be found in Figure 4.1, where the different levels of openness of the auctions is displayed. Since there only is one auction in the joint scheme, this can be considered the scenario with the highest level of openness, and, going hand in hand with that, also the scenario with the highest level of required cooperation of the countries. The benchmark cases thus serve as boundaries of the level of openness between the countries.

---

[2] In the auction-theoretic model, this percentage scenario can easily be transformed into a scenario where there are two auctions: one for projects from both countries (and the total auction volume equal to the percentage $\delta\%$), and one only for bidders from the domestic country with the remaining auction volume. This assumption simplifies the analyses, as the calculation of the equilibrium participation probability is slightly different, while the bidding behaviour of the participants itself is equal in both variants. The results can thus be transferred, and need not be explained in detail in this chapter.

4.3 Related literature

In von Blücher et al., 2019 a more conceptional approach of understanding cross-border auctions is applied, examining the different design options for cross-border auctions and presenting the economic rationale for their introduction. One of the most important arguments in favour of cross-border auctions is the support cost efficiency, which can be observed in the context of the German-Danish auctions. Out of the overall 52.4 MW of auctioned volume in both auctions, only Danish projects were awarded. On the one hand, this is explained with the more favourable conditions in Denmark, e.g., the possibility to erect plants on farmland in Denmark whereas in Germany this type of location was limited. Furthermore, the Danish authorities granted much easier permits for the PV plants (Sorge, 2016) and thus preparation was easier for Danish projects, which also led to lower costs. Another factor is the market environment in both countries. In Germany, bidders had an outside option to bid in the country-specific auctions, which were conducted parallel to the cross-border auction. At that time, no Danish RE support system existed and thus, Danish bidders only had the chance of receiving support in the cross-border auctions. Subsequently, the Danish projects submitted lower bids than their German counterparts (Kahles, 2017) and thus, were in an economic sense more efficient. Furthermore, as a result, Germany did not have to pay support to the awarded bidders in most months, due to the high market values in Denmark (von Blücher et al., 2019), which is a further positive aspect from the German conducting authority's [3] point of view. We will deepen the research of von Blücher et al., 2019 in an auction-theoretical way and examine

---

[3] The conducting agency is the Federal Network Agency (Bundesnetzagentur) on behalf of the German Ministry of Economic Affairs and Climate Action (Bundesministerium für Wirtschaft und Klimaschutz).

whether this apparent efficiency increase can theoretically be expected in all future cross-border auctions.

The theoretic literature on Joint Auctions is manifold, since they can be interpreted as the standard case where there are two bidder groups participating in one auction. This is for example examined in Krishna, 2009. The most important finding is that an auction need not be efficient if bidder groups use different bidding strategies, i.e., if a higher bid does not necessarily correspond with higher costs, which is important when deciding on the auction design. We will use this case as a benchmark case for the cross-border auctions, in addition to the case of two Separate Auctions. The Separate Auctions themselves also can serve as the benchmark model examined in the standard literature (e.g. Myerson, 1981) when considered by themselves. Then this corresponds to a standard IPV-model (i.e., independent private values) with a homogenous set of bidders for each auction. In this setting, each auction taken only for itself is efficient and yields the same prices and awarded bidders independently of the pricing mechanism (Revenue Equivalence Theorem; Vickrey, 1961; Myerson, 1981). This efficiency need not be the case in our setting, since we examine the groups of bidders as a whole, independently of their origin, and then it is not guaranteed that the bidders with the overall lowest costs are awarded, as we will discuss later on.

The Joint Auction is can also be connected to the literature on whether to bundle objects in one auction or to conduct Separate Auctions (Palfrey, 1983; Leszczyc et al., 2010). In contrast to e.g. Leszczyc et al., 2010, we analyse the case where even in a Joint Auction the goods can be awarded to different bidders, i.e., can be bought from different project developers. A very practical case of centralised, i.e., Joint, auctions instead of multiple local ones can be found in Houde et al., 2017, where the market for sanitary services in Dakar (Senegal) is examined. The authors find that a centralised auction can lead up to 73% of price reductions compared to the situation where the market is not optimised. They explain this result with the increased competition due to the centralisation.

In order to be able to compare the different auction formats, we analyse two auctions being conducted at the same time but independently of each other in contrast to one single auction with a joint set of bidders. This approach can also be found in Moldovanu et al., 2006, where the authors study competing auctions compared to a centralised market place. In this paper two sellers decide whether they want to conduct one single or two separate auctions. Bidders can decide where they want to participate, but only afterwards learn their true values. One result of this paper is that there only exists an equilibrium in pure strategies in the centralised auction. We will transfer this result to the cross-border context. Another paper which deals with the auction selection problem is Delnoij et al., 2018, where they conclude there is an symmetric equilibrium in mixed strategies. The focus of this paper is the design decision of the pricing mechanism, which we will not focus on, but show that this approach can be applied to mutually opened auctions as well.

A huge thread of literature related to our topic deals with the mechanism behind auctions on the internet platform ebay. Here there are many different sellers offering their goods, while bidders decide in which sales auction they participate. This is e.g. examined in Peters et al., 2006 with the result that in all auctions the price is identical. Further Anwar et al., 2006 describe that bidders tend to bid always in the auction with the lowest price and change auctions often. We in contrast consider a procurement auction, and bidders cannot participate in more than one auction at once. Hernando-Veciana, 2005 show that if there are several auctions, in the symmetric equilibrium it is optimal for an auctioneer to choose the ceiling price close to his production costs. This result can i.a. also be found in Virag, 2010. For both papers the number of bidders is an important factor. We will use this result as one of the reasons why we do not focus on the optimal setting of the ceiling price in this paper. A general study on the multiple bidders/multiple sellers model can be found in R. P. McAfee, 1993. He shows that bidders randomize their choice which auction they participate in.

The literature on Unilateral Auctions is rather scarce. Larue et al., 2013 examine Canadian hog auctions. Here bidders from Ontario were allowed to buy Quebec hogs in an auction, but Quebec bidders did not have a chance to buy hogs from Ontario. The authors find that the increased competition was not in favour for the auctioneers since they received lower prices. Also, Gerding et al., 2008 analyse the optimal strategy for a global player who can participate in numerous local auctions, competing against local bidders. Again, in our scenario, bidders can only participate in one auction at a time. A similar setting with local bidders is considered in auctions for radio-frequency in Krishna et al., 1996. One of the results is, that increasing the number of global bidders leads to less aggressive bidding. All of these analyses consider the possibility to buy the goods in an alternative way. This is often called an *outside option*. Outside options can have numerous different effects on auction outcomes and optimal design variables. Kirchkamp et al., 2009 show in a laboratory experiment that a first-price auction tends to generate more revenue than a second-price auction when there are outside options. This can be explained as bidders tend to be risk-averse in real life, instead of risk-neutral which is often assumed in theory. An optimal auction with outside options is charging an entry fee (Ledyard, 2007). Nevertheless, this auction may not be efficient since it prevents bidders from participation. Reiss, 2008 finds that it is optimal for an auctioneer to lower the competitiveness of his auction when bidders have an outside option.

We will combine all of these different approaches into one model in order to compare the different scenarios. The outside option in our case will be that bidders can decide to participate in another auction, or if this option is not given, need to participate in the auction even though they face higher competition if they want to realise their project and receive support. This is the equivalent to the German-Danish cross-border cooperation, where German bidders had the chance to compete in the German-only auctions, whereas the Danish did not have the opportunity to participate in another auction or receive funds in any other way.

4.4 Theoretic analysis

In this section, we present first theoretic analyses of different forms of cross-border auctions and their implications with regard to efficiency and awarded prices. In Section 4.4.1 we introduce the basic model underlying all following analyses. As a cross-border benchmark model to compare efficiency and prices, the free competition between two countries in a so-called Joint Auction is analysed in Section 4.4.2. Since typically, auctions are conducted - at least in the EU - on a national level (AURES II, 2022), we consider this scenario of Separate Auctions in Section 4.4.3, which serves as our non-cross-border benchmark case. We also analyse Mutual Auctions (Section 4.4.4) and Unilateral Auctions (Section 4.4.5). For both forms, we differentiate between simultaneous auctions (Sections 4.4.4.1 and Sections 4.4.5.1) and sequential auctions (Sections 4.4.4.2 and Sections 4.4.5.2).

Auctions are analysed by game-theoretic methods. This approach is based on Vickrey (1961). A comprehensive overview and introduction to auction theory is provided by the books of Menezes et al. (2005), Milgrom (2007), and Krishna (2009). The application of auctions theory to the field of renewable energy support is discussed by, e.g., Kreiss et al. (2017) and Haufe et al. (2018).

4.4.1 Basic model

Consider two multi-unit procurement auctions A and B for k_A and k_B units of a homogenous good, $k_A, k_B \geq 1$. Thus, overall there are at least two goods auctioned.

There are two groups of risk-neutral bidders (companies) N_A and N_B with $n_A = |N_A|$ and $n_B = |N_B|$, $n_A, n_B \geq 1$. Moreover, $N = N_A \cup N_B$, $n = |N| = n_A + n_B$.

All bidders have single-unit supply, i.e., each bidder participates with one project in the auctions. The symmetric independent private values (IPV) approach applies to the two bidder sets N_A and N_B (e.g., Krishna, 2009). In Group A, each company $i \in N_A$ has private costs x_i for supplying the good, and the companies' supply costs are independently drawn from the same distribution F_A with the density f_A and full support [4] on $[\underline{a}, \overline{a}]$. The same applies to Group B: each company $j \in N_B$ has private costs x_j for supplying the good, and the companies' supply costs are independently drawn from the same distribution F_B with the density f_B and full support on $[\underline{b}, \overline{b}]$.

In both auctions, the auctioneers set a ceiling price (maximum price) r_A in Auction A and r_B in Auction B, which the bidders are not allowed to exceed with their bids. In this chapter, we assume ceiling prices r_A and r_B to be non-restrictive for participation, i.e., $\min\{r_A, r_B\} \geq \max\{\overline{a}, \overline{b}\}$.

The auctions are conducted as sealed-bid auctions in which each bidders i submits a bid b_i. Bids are submitted simultaneously. Let m_t denote the number of bidders who actually participate in Auction $t \in \{A, B\}$. If the ceiling price does not restrict participation, $m_A + m_B = n_A + n_B$.

In the auctions the LRB-UP rule applies, that is, in both auctions the lowest rejected bid determines the uniform award price p_t[5] if $m_t > k_t$. If $m_t \leq k_t$, the price is determined by the ceiling price, that is, $p_t = r_t$. For bidders who participate in a single auction, an auction with LRB-UP is incentive compatible. That is, it is a weakly dominant strategy for each bidder to bid exactly her costs x, i.e., $b = x$ (Weber, 1983).

In our analyses in the following sections, we consider cases where bidders from N_A are awarded in Auction B and vice versa. If A and B refer to different countries, Country A and Country B, this means

---

[4] Full support means that all probability mass is concentrated on this interval.

[5] For simplification purposes, the award prices in our study, i.e., the prices paid to the awarded bidders, correspond to a FiT.

that the awarded A-bidder will build her project in Country A and will receive the price (i.e., monetary support) from Country B (see Section 4.2).

The following auction-theoretic analyses also base on order statistics, which we introduce here. Consider a set N of n bidders, whose cost signals are independently drawn from distribution F with density f. The kth order statistic $X_{(k,n)}$ describes the random variable of kth lowest cost signal of all n signals (e.g., Ahsanullah et al., 2013), that is,

$$X_{(1,n)} \leq X_{(2,n)} \leq \ldots, \leq X_{(n,n)} .$$

The distribution function of $X_{(k,n)}$ is denoted by $F_{(k,n)}$, $1 \leq k \leq n$, and is given by[6]

$$F_{(k,n)}(x) = \sum_{i=k}^{n} \binom{n}{i} F(x)^i \big(1 - F(x)\big)^{n-i} \tag{4.1}$$

and the density function by

$$f_{(k,n)}(x) = \binom{n}{k} k f(x) F(x)^{k-1} \big(1 - F(x)\big)^{n-k} . \tag{4.2}$$

4.4.2 Joint Auction

In the Joint Auction, Auction A and Auction B are put together to one auction, in which both bidder groups N_A and N_B participate. Thus, the set of bidders in the Joint Auction is given by $N = N_A \cup N_B$ with $n = n_A + n_B$ and the number of auctioned goods is given by $k = k_A + k_B$. The Joint Auction serves as the reference point for the evaluation of the results of other formats in the following sections.

---

[6] Binomial coefficient:

$$\binom{n}{k} = \frac{n!}{(n-k)!k!}$$

Let N_{eff} denote the set of bidders with the lowest costs: $N_{eff} \subset N$ and $|N_{eff}| = k$. Since it is optimal for the bidders to reveal their cost signals in their bids (Section 4.4.1), the k bidders with the lowest cost signals, i.e., the bidders in N_{eff}, are awarded. Hence, the auction outcome is efficient, i.e., the total demand k is met by the lowest-cost supply. The uniform price p_J in the Joint Auction is determined by the $(k+1)$th lowest cost signal $x_{(k+1,n)}$, i.e., $p_J = x_{(k+1,n)}$. That is, the auction outcome is efficient and the expected price is $E[P] = E\left[X_{(k+1,n)}\right]$.[7] The auctioneer's costs in the Joint Auction are $c_J^0 = kx_{(k+1,n)}$. Since this cannot be determined prior to the auction, it is sensible to consider the auctioneer's expected costs $E[C_J^0] = kE[X_{(k+1,n)}]$.

The implementation in practice of a Joint Auction may be difficult and problematic and, thus, a challenge, particularly when the auction is conducted in two Countries A and B with different market characteristics and auction designs for their domestic RES auctions. Under the current rules (Sections 4.2 and 4.4.1), awarded projects of A-bidders are built in Country A and awarded projects of B-bidders in Country B. Here, the question arises, how the payments for the k awarded projects are distributed between the two countries, particularly if the number of awarded A-bidders does not match the number of demanded projects k_A in Country A. A simple rule is to allocate the payments for the best (i.e., lowest) bids from N_t to Country t until k_t is reached, $t \in \{A, B\}$. If, for example, the number of awarded A-bidders is higher than k_A and, thus, the number of awarded B-bidders in lower than k_B by the same amount, the payments for the remaining awarded A-bidders are allocated to Country B.

---

[7] This applies to a large set of auction formats including the DP auction in which the (different) award prices are equal to the bids (Engelbrecht-Wiggans, 1988). This result refers to the so-called revenue equivalence theorem (Myerson, 1981; Riley et al., 1981), which states that under certain conditions any auction format that allocates the goods to the same bidders generates the same outcome including the same expected bidder profits and the same expected (average) price and auction revenue (auctioneer's costs).

4.4.3 Separate Auctions

In Separate Auctions, bidders from group N_A, i.e., with projects in Country A, are only allowed to enter Auction A, whereas bidders from group N_B can only enter Auction B. Since auction entry accrues no costs, all bidders will participate and thus $m_A = n_A$ and $m_B = n_B$. Therefore, for each auction, the results of the Joint Auction applies (Section 4.4.2). That is, the k_t bidders with the lowest costs are awarded and the price is determined by the $(k_t + 1)$th lowest cost signal $x_{(k_t+1,n_t)}$, i.e., $p = x_{(k_t+1,n_t)}$, $t \in \{A, B\}$. Thus, the expected price in Auction A is $E[P_A] = E\left[X_{(k_A+1,n_A)}\right]$ and the expected price in Auction B is $E[P_B] = E\left[X_{(k_B+1,n_B)}\right]$.

An efficient outcome is reached if and only if the $k = k_A + k_B$ bidders with the lowest costs, i.e., the bidders in the set N_{eff}, are awarded, which is met in the Joint Auction (4.4.2). Note that it is irrelevant for an efficient outcome in the Separate Auctions how the k bidders in N_{eff} are distributed among the two auctions A and B, i.e. which bidder participates in which auction. The only condition that has to be fulfilled is that k_A bidders in N_{eff} participate in Auction A and k_B bidders in N_{eff} participate in Auction B.

For analysing efficiency in the Separate Auctions, we consider the case of equal cost distributions in the two auctions, i.e., $F_A \equiv F_B \equiv F$. Since the distributions F_A and F_B are equal, the set N_A of the A-bidders can be modelled by n_A independent draws from F and the set N_B of the B-bidders by n_B independent draws from F. As pointed out before, an efficient outcome will be reached if exactly k_A bidders of N_{eff} are among the n_A bidders who participate in Auction A and, thus, k_B bidders of N_{eff} are among the n_B bidders who participate in Auction B. The probability that this happens is[8]

$$\frac{\binom{k}{k_A}\binom{n-k}{n_A-k_A}}{\binom{n}{n_A}}\,. \tag{4.3}$$

The probability in (4.3) includes all efficient allocations of the k bidders in N_{eff}, so that k_A of these bidders participate in Auction A and k_B of these bidders participate in Auction B. Table 4.1 shows the efficiency probabilities for symmetric auctions with $n_A = n_B = 25$ and $k_A = k_B$.

Table 4.1: Probability of efficient outcome in the Separate Auctions for $n_A = n_B = 25$

$k_A = k_B$	1	2	3	4	5	10	15	20
Probability	51.0%	39.1%	33.3%	29.8%	27.5%	22.7%	22.7%	27.5%

How are the prices and auctioneer's costs in the Separate Auctions compared to the Joint Auction (Section 4.4.2)? In an efficient outcome in the Separate Auctions, the bidder with the cost signal $x_{(k+1,n)}$ either determines the price in Auction A, i.e., $p_A = x_{(k+1,n)}$, or in Auction B, i.e., $p_B = x_{(k+1,n)}$, but not in both Auctions. That is, the prices are different in the two auctions and the higher price is $x_{(k+2,n)}$ or higher. If the bidder with $x_{(k+1,n)}$ participates in Auction A, we have $p_B > p_A = p_J = x_{(k+1,n)}$, and if the bidder with $x_{(k+1,n)}$ participates in Auction B, we have $p_A > p_B = p_J = x_{(k+1,n)}$ As a consequence the auctioneer's total costs $c^0_{Sim} = c^0_A + c^0_B = k_A p_A + k_B p_B$ in the Separate Auctions are higher than the auctioneer's costs c^0_J in the Joint Auction: $c^0_{Sim} > c^0_J$.

Now consider the prices if the outcome of the Separate Auctions is inefficient. Since there are also bidders awarded, which do not belong

---

[8] The efficiency probability (4.3) can be equivalently expressed by

$$\frac{\binom{k}{k_B}\binom{n-k}{n_B-k_B}}{\binom{n}{n_B}}\,.$$

to N_{eff}, i.e., do not have the lowest costs und thus the lowest bids, the price in one of the two Auctions is higher than the price of the Joint Auction $x_{(k+1,n)}$. In this Auction, w.l.o.g.[9] let this be Auction A, less than k_A bidders from N_{eff} did participate. Thus, in the other Auction B, more than k_B bidders from N_{eff} did participate. Therefore not all bidders from N_{eff} are awarded, and in B a bidder with a lower bid than $x_{(k+1,n)}$ determines the price. Hence, the price in this Auction is lower than in the Joint Auction. As a consequence, in an inefficient outcome, the auctioneer's total costs can be equal or even lower than in the Joint Auction, but also higher, depending on the exact realisations of the cost signals and the actual bidder distribution over Auctions A and B.

4.4.4 Mutual Auctions

In Mutual Auctions, the bidders in N_A and in the bidders in N_B can participate in both auctions A and B. In the case of the Simultaneous Mutual Auctions (Sections 4.4.4.1), the two auctions A and B are conducted simultaneously and bidders can only participate in one of the auctions. The bidders simultaneously decide in which auction they participate, i.e., either in Auction A or in Auction B.[10] For the case of the Sequential Mutual Auctions (Section 4.4.4.2), in which the two auctions A and B are conducted consecutively, we assume that the bidders are allowed to participate in both auctions. Bidders, who are not awarded in the first auction, are allowed to participate in the second auction.

---

[9] without loss of generality

[10] This also includes the case where auctions are not conducted at exactly the same time, but in the same time range so it is not possible to participate in both. This happened for example in the German-Danish case where only a few weeks were in between the auctions.

4.4.4.1 Simultaneous Mutual Auctions

In the following we derive for the Simultaneous Mutual Auctions the game-theoretic solution in form of a symmetric mixed Bayes-Nash-equilibrium. Since the bidders simultaneously decide on the auction in which they will bid (a bidder cannot observe other bidders' decisions), a symmetric equilibrium has to be in mixed strategies, where the probability distribution of the mixed equilibrium strategy applies to participation decision. The mixed equilibrium strategy $\beta = (\beta_A, \beta_B)$ with $\beta_t(x) = (q_t, b_t)$, $t \in \{A, B\}$, consists of two components, one for the A-bidders and the other for the B-bidders, each consists of (1) the probability q_t for participating in Auction A (and thus $1 - q_t$ for Auction B) and (2) the bid b_t. Symmetry refers to both decisions: (1) All bidders in N_A participate with same probability q_A in Auction A and, thus, with probability $1-q_A$ in Auction B. The same applies to the bidders in N_B, that is, all bidders in N_B participate with probability q_B in Auction A and with probability $1-q_B$ in Auction B. (2) All bidders apply the same bidding strategy in form of bidding their costs x, that is, $b_t = x$, $t \in \{A, B\}$.

For determining the participation probabilities q_A and q_B, we consider a representative A-bidder with costs $x \in [\underline{a}, \overline{a}]$, who bids $b_A = x$ in the auction in which she participate and a representative B-bidder with costs $z \in [\underline{b}, \overline{b}]$, who bids $b_B = z$ in the auction in which she participates.

If each of the other $n_A - 1$ A-bidders' participation probabilities are $(q_A, 1 - q_A)$ and those of each of the n_B B-bidders are $(q_B, 1 - q_B)$ and all bidders bids their costs, the representative A-bidder's expected profit of bidding in Auction A is

$$\begin{aligned}&\Pi_A(x, n_A, n_B, k_A, r_A, q_A, q_B) = \\ &\sum_{i=0}^{n_A-1} \sum_{j=0}^{n_B} \binom{n_A-1}{i} \binom{n_B}{j} q_A^i (1-q_A)^{n_A-1-i} q_B^j (1-q_B)^{n_B-j} \\ &\qquad\qquad\qquad\qquad \cdot I(x, k_A, r_A, i, j)\,,\end{aligned} \tag{4.4}$$

with

$$I(k_A, r_A, i, j) = \begin{cases} \int_x^{r_A} (y-x) f_{(k_A,i,j)}(y) dy & : i+j \geq k_A \\ r_A - x & : i+j < k_A \end{cases} \tag{4.5}$$

and her expected profit of bidding in Auction B is

$$\begin{aligned}&\Pi_A(x, n_A, n_B, k_B, r_B, 1-q_A, 1-q_B) = \\ &\sum_{i=0}^{n_A-1} \sum_{j=0}^{n_B} \binom{n_A-1}{i} \binom{n_B}{j} q_A^{n_A-1-i} (1-q_A)^{i} q_B^{n_B-j} (1-q_B)^{j} \\ &\qquad\qquad\qquad\qquad \cdot I(x, k_B, r_B, i, j)\,,\end{aligned} \tag{4.6}$$

with

$$I(k_B, r_B, i, j) = \begin{cases} \int_x^{r_B} (y-x) f_{(k_B,i,j)}(y) dy & : i+j \geq k_B \\ r_B - x & : i+j < k_B\,, \end{cases} \tag{4.7}$$

where $F_{(k,i,j)}$ and $f_{(k,i,j)}$ denote the distribution function and density function of the kth order statistics (i.e., random variable of the k-lowest costs) if i cost signals are drawn from F_A and j cost signals are drawn from F_B.

Analogously, the same applies to the representative B-bidder with costs z, who bids $b_B = z$ in the auction in which she participate. Her expected profit of bidding in Auction A is

$$\begin{aligned}&\Pi_B(z, n_A, n_B, k_A, r_A, q_A, q_B) = \\ &\sum_{i=0}^{n_A}\sum_{j=0}^{n_B-1}\binom{n_A}{i}\binom{n_B-1}{j} q_A^i (1-q_A)^{n_A-i} q_B^j (1-q_B)^{n_B-1-j} \\ &\qquad\qquad\qquad\qquad \cdot I(z, k_A, r_A, i, j)\,,\end{aligned} \tag{4.8}$$

with

$$I(k_A, r_A, i, j) = \begin{cases} \int_z^{r_A} (y-z) f_{(k_A,i,j)}(y)dy & : i+j \geq k_A \\ r_A - z & : i+j < k_A \end{cases} \tag{4.9}$$

and her expected profit of bidding in Auction B is

$$\begin{aligned}&\Pi_B(z, n_A, n_B, k_B, r_B, 1-q_A, 1-q_B) = \\ &\sum_{i=0}^{n_A}\sum_{j=0}^{n_B-1}\binom{n_A}{i}\binom{n_B-1}{j} q_A^{n_A-i} (1-q_A)^{i} q_B^{n_B-1-j} (1-q_B)^{j} \\ &\qquad\qquad\qquad\qquad \cdot I(z, k_B, r_B, i, j)\,,\end{aligned} \tag{4.10}$$

with

$$I(k_B, r_B, i, j) = \begin{cases} \int_z^{r_B} (y-z) f_{(k_B,i,j)}(y)dy & : i+j \geq k_B \\ r_B - z & : i+j < k_B\,. \end{cases} \tag{4.11}$$

The equilibrium probabilities q_A and q_B are determined by

$$\begin{aligned}\Pi_A(x, n_A, n_B, k_A, r_A, q_A, q_B) &= \Pi_A(x, n_A, n_B, k_B, r_B, 1-q_A, 1-q_B)\,, \\ \Pi_B(z, n_A, n_B, k_A, r_A, q_A, q_B) &= \Pi_B(z, n_A, n_B, k_B, r_B, 1-q_A, 1-q_B)\,.\end{aligned} \tag{4.12}$$

In the symmetric case with $k_A = k_B$, $r_A = r_B$, $n_A = n_B$, and $F_A \equiv F_B$, by (4.4), (4.6), (4.8), and (4.10), the equilibrium conditions (4.12) are fulfilled with $q_A = q_B = \frac{1}{2}$. Thus, the symmetric equilibrium strategy is given by $\beta = (\beta_A, \beta_B)$ with $\beta_t(x) = (\frac{1}{2}, x)$, $t \in \{A, B\}$.

Equal Cost Distribution Functions

Any case of the Simultaneous Mutual Auction with $F_A \equiv F_B \equiv F$ can be analysed by a model of two auctions and one bidder set. The demand volumes and the ceiling prices in the two auctions A and B may differ, that is, $k_A \neq k_B$ and/or $r_A \neq r_B$. Since the distributions F_A and F_B are equal, there exists a symmetric equilibrium with $q_A = q_B$, independent of n_A and n_B, which can be different. This case can be simplified by joining the two bidder sets N_A and N_B to one set $N = N_A \cup N_B$ with $n = n_A + n_B$, where the n bidders' signals are independently drawn from F.

The mixed equilibrium strategy $\beta(x) = (q, b)$ consists of two components. All bidders participate with same probability q in Auction A and, thus, with probability $1 - q$ in Auction B. For determining the participation probabilities q, we consider a representative bidder with costs x, who bids $b = x$ in the auction in which she participates. If each of the other $n - 1$ bidders' participation probabilities are $(q, 1 - q)$ and all bidders bids their costs, the representative bidder's expected profit of bidding in Auction A, given by (4.4), (4.5), (4.8), and (4.9), reduces to

$$\Pi(x, k_A, r_A, q) = \sum_{i=k_A}^{n-1} \binom{n-1}{i} q^i (1-q)^{n-1-i} \int_x^{r_A} (y - x) f_{(k_A,i)}(y) dy \\ + (r_A - x) \sum_{i=0}^{k_A - 1} \binom{k_A - 1}{i} q^i (1-q)^{n-1-i} \tag{4.13}$$

and her expected profit if she bids in Auction B, given by (4.6), (4.7), (4.10), and (4.11), reduces to

$$\begin{aligned}\Pi(x,k_B,r_B,1-q) = &\sum_{i=k_B}^{n-1}\binom{n-1}{i}q^{n-1-i}(1-q)^i\int_x^{r_B}(y-x)f_{(k_B,i)}(y)dy\\ &+(r_B-x)\sum_{i=0}^{k_B-1}\binom{k_B-1}{i}q^{n-1-i}(1-q)^i \qquad (4.14)\end{aligned}$$

The probability q for the mixed equilibrium strategy $\beta(x)=(q,x)$ is determined by

$$\Pi(x,k_A,r_A,q)=\Pi(x,k_B,r_B,1-q)\,. \qquad (4.15)$$

In the case $k_A=k_B$ and $r_A=r_B$, by (4.13) and (4.14), the equilibrium condition (4.15) is fulfilled with $q=\frac{1}{2}$. Thus, the symmetric equilibrium strategy is given by $\beta(x)=(\frac{1}{2},x)$. All A-bidders and all B-bidders flip a coin to decide in which auction they will bid.

Obviously, for $k_A>k_B$ and $r=r_A=r_B$, $q>\frac{1}{2}$, since with a higher number of auctioned goods the probability of winning and thus, the expected profit in this auction rises.

The same applies for $k=k_A=k_B$ and $r_A>r_B$. To show this, we consider (4.13) and (4.14) for $q=\frac{1}{2}$. Then, the representative bidder's expected profit 4.13 in Auction A can we written as

$$\begin{aligned}\Pi(x,k,r_A,\frac{1}{2}) = &\sum_{i=k}^{n-1}\binom{n-1}{i}\left(\frac{1}{4}\right)^{i(n-1-i)}\\ &\cdot\left(\int_x^{r_B}(y-x)f_{(k,i)}(y)dy+\int_{r_B}^{r_A}(y-x)f_{(k,i)}(y)dy\right)\\ &+(r_B+(r_A-r_B)-x)\sum_{i=0}^{k-1}\binom{k-1}{i}\left(\frac{1}{4}\right)^{i(n-1-i)} \qquad (4.16)\end{aligned}$$

and her expected profit in Auction B can be written as

$$\Pi(x,k,r_B,\frac{1}{2}) = \sum_{i=k}^{n-1} \binom{n-1}{i} \left(\frac{1}{4}\right)^{i(n-1-i)} \int_x^{r_B} (y-x) f_{(k,i)}(y)dy + (r_B - x) \sum_{i=0}^{k-1} \binom{k-1}{i} \left(\frac{1}{4}\right)^{i(n-1-i)} . \tag{4.17}$$

Since

$$\Pi(x,k,r_A,\frac{1}{2}) - \Pi(x,k,r_B,\frac{1}{2}) = \sum_{i=k}^{n-1} \binom{n-1}{i} \left(\frac{1}{4}\right)^{i(n-1-i)} \cdot \int_{r_B}^{r_A} (y-x) f_{(k,i)}(y)dy + (r_A - r_B) \sum_{i=0}^{k-1} \binom{k-1}{i} \left(\frac{1}{4}\right)^{i(n-1-i)} > 0 \,,$$

$q = \frac{1}{2}$ cannot be the equilibrium probability, but $q > \frac{1}{2}$.

Efficiency and Prices

An efficient outcome is reached if and only if the $k = k_A + k_B$ bidders with the lowest costs are awarded, which is met in the Joint Auction (4.4.2). As in the Separate Auctions (Section 4.4.3), efficiency does not depend on how the bidders in N_{eff} are distributed among the two auctions A and B, but only that k_A bidders in N_{eff} participate in Auction A and the remaining k_B bidders in N_{eff} participate in Auction B.

For the Mutual Auctions, we consider the symmetric case with the same equilibrium strategy $\beta(x) = (q, x)$ for all bidders in the joint set N. Then, the probability of an efficient outcome is

$$\binom{k}{k_A} q^{k_A} (1-q)^{k_B} \,. \tag{4.18}$$

The probabilities in (4.18) includes all efficient allocations of the k bidders in N_{eff}, so that k_A of these bidders participate in Auction A and k_B of these bidders participate in Auction B. Note that, contrary to the efficiency probabilities for the Separate Auction (Section 4.4.3), the efficiency probabilities for the Mutual Auctions do not depend on the number of bidders n_A and n_B in the two auctions. Table 4.2 shows these probabilities for symmetric auctions with $k_A = k_B$ and $q = \frac{1}{2}$.

Table 4.2: Probability of efficient outcome in the Mutual Auctions for $q = \frac{1}{2}$

$k_A = k_B$	1	2	3	4	5	10	25	50
Probability	50.0%	37.5%	31.3%	27.3%	24.6%	17.6%	11.2%	8.0%

To analyse and evaluate the distribution of the awarded bidders among the two bidder sets N_A and N_B in an efficient outcome, we apply the following simplifying approach. Define $\Phi = \frac{n_B}{n_A}$. In an efficient outcome, $\frac{1}{\Phi+1}(k)$ A-bidders are awarded and $\frac{\Phi}{\Phi+1}(k)$ B-bidders. This approach can be justified by an a priori view before the cost signals are drawn or by considering the average in a long-run view. For example, if $n_A = n_B$, in an efficient outcome, we expect the awarded bidders to be distributed evenly between A and B, i.e., half of the awarded bidders are from N_A and the other half from N_B.

For the prices in the Mutual Auctions the same applies as for the Separate Auctions (Section 4.4.3). In an efficient outcome in the Mutual Auctions, the bidder with the cost signal $x_{(k+1,n)}$ either determines the price in Auction A, i.e., $p_A = x_{(k+1,n)}$, or in Auction B, i.e., $p_B = x_{(k+1,n)}$, but not in both Auctions. That is, the prices are different in the two auctions and the higher price is $x_{(k+2,n)}$ or higher. If the bidder with $x_{(k+1,n)}$ participates in Auction A, we have $p_B > p_A = p_J = x_{(k+1,n)}$, and if the bidder with $x_{(k+1,n)}$ participates in Auction B, we have $p_A > p_B = p_J = x_{(k+1,n)}$ Hence, the auctioneer's total costs $c_M^0 = c_A^0 + c_B^0 =$

$k_A p_A + k_B p_B$ in the Mutual Auctions are higher than the auctioneer's costs c_J^0 in the Joint Auction: $c_M^0 > c_J^0$.

If the outcome of the Mutual Auctions is inefficient, the price in one of the two auctions is lower than $x_{(k+1,n)}$, while in the other auction, the price is higher than $x_{(k+1,n)}$. The auctioneer's total costs in the Mutual Auctions can be equal or even lower than in the Joint Auction, but also higher.

4.4.4.2 Sequential Mutual Auctions

In Sequential Mutual Auctions, the two auctions A and B are conducted sequentially. W.l.o.g. we assume that Auction A is conducted before Auction B. All bidders from N_A and N_B are allowed to participate with their project in both auctions. More precisely, all bidders are allowed to participate in Auction A, while only those bidders are allowed to participate in the B-Auction who either were not successful in Auction A or did not participate in the Auction A. We assume that the bids and results of Auction A are observable before Auction B is conducted.

In this sequential auction there exists a unique symmetric Bayes equilibrium in pure strategies. [11] In this equilibrium, each bidder submits a bid in Auction A, and if this bid is not awarded, the bidder will submit a bid in Auction B. Hence, the equilibrium bidding strategy $\beta(x)$ of a representative bidder (from N_A or N_B) with cost signal x consists of two components, $\beta(x) = (\beta_A(x), \beta_B(x))$, where $\beta_A(x)$ denotes the bid in Auction A and $\beta_B(x)$ the bids in Auction B. By transferring and extending the results of a sequential sales auction with one good in each auction (e.g. Krishna, 2009) to a sequential procurement auction with k_A goods in the first auctions and k_B goods in the second auction, we

---

[11] This is a standard result in game theory, see e.g. Krishna (2009).

get the following equilibrium strategy $\beta(x) = (\beta_A(x), \beta_B(x))$ with

$$\beta_A(x) = E[X_{(k+1,n)} \,|\, X_{(k_A,n)} < x < X_{(k+1,n)}]\,, \tag{4.19}$$

$$\beta_B(x) = x\,. \tag{4.20}$$

Since the equilibrium strategy components $\beta_A(x)$ and $\beta_B(x)$ are strictly monotone, i.e., strictly increasing in x, the outcome of the sequential auction is efficient. That is, the k bidders with the lowest cost signals are awarded. Strict monotonicity also implies that in the first auction A the k_A bidders with the lowest costs are awarded and in the second auction B the k_B bidders with the (k_A+1)-lowest costs up to the k-lowest costs. Thus, the "best" projects are awarded in Auction A.

Due this different bidding behaviour in Auction A and Auction B, the expected prices are the same in both auctions and equal to $E[X_{(k+1,n)}]$, i.e., the expected value of the $(k+1)$-lowest cost signal. This price, which reflects the overall scarcity in the joint market, is the same as in the free competition scenario in the Joint Auction (4.4.2): $E[P_{Seq,A}] = E[P_{Seq,B}] = E[P_J] = E[X_{(k+1,n)}]$. The same applies to the auctioneer's expected costs: $E[C^0_{Seq}] = E[C_{Seq,A}] + E[C^0_{Seq,B}] = k_A E\left[X_{(k+1,n)}\right] + k_B E\left[X_{(k+1,n)}\right] = kE\left[X_{(k+1,n)}\right] = E[C^0_J]$.

Since the two equilibrium strategy components are monotone and, by (4.20), the bidders truthfully bid their costs in the second auction B, it is obvious that in the LRB-UP auction B the price is equal to the $(k+1)$-lowest cost signal, i.e., the cost signal of the "best" bidder who is not awarded. In the first auction A, by (4.19), the bidders do not reveal their true costs but exaggerate their costs in their bids. The incentive for this form of "bid shading" is generated by the additional chance for an award in the subsequent Auction B. More precisely, a bidder's equilibrium bid for Auction A is equal to the expected value of the $(k+1)$-lowest cost signal under the condition that the bidder's own cost signal is between the k_A-lowest and the $(k+1)$-lowest cost signal. This exaggeration of the costs in the bids implies that the bidders with the k_A-lowest costs are awarded in Auction A and that the expected price in this auction is also equal to expected value of the $(k+1)$-lowest cost signal.

However, there is some empirical evidence that real sequential procurement auctions the price tends to decrease, i.e., the price in Auction B is higher than in Auction A (Ashenfelter, 1989; Ashenfelter et al., 1992; Gallegati et al., 2011; R. McAfee et al., 1993). Possible reasons for this phenomenon are risk aversion or myopic thinking. The latter refers to the fact that the bidders do not fully account for the additional chance in Auction B when calculating their bid for Auction A.

4.4.5 Unilateral Auctions

For the Unilateral Auctions, w.l.o.g. we assume that A-bidders are allowed to bid either in Auction A or in Auction B, while the B-bidders are only allowed to participate in Auction B.

4.4.5.1 Simultaneous Unilateral Auctions

Since in a Simultaneous Unilateral Auction the A-bidders simultaneously decide on the auction in which they will bid, a A-bidders' symmetric equilibrium strategy has to be in mixed strategies. As in the Mutual Auction (Section 4.4.4), the probability distribution of the mixed equilibrium strategy applies to participation decision, where q_A is an A-bidder's probability for participating in Auction A, and, thus, $1-q_A$ is an A-bidder's probability for participating in Auction B. As before, an A-bidder bids her cost signal in the auction in which she participates. That is, $\beta_A(x) = (q_A, x)$ The B-bidders' equilibrium strategy is simple because they cannot choose the auction. They participate in Auction B where they bid their cost signal. That is, $q_B = 0$ and, thus, $\beta_B(x) = (0, x)$.

For determining the participation probabilities q_A, we consider a representative A-bidder with costs $x \in [\underline{a}, \overline{a}]$. If each of the other $n_A - 1$ A-bidders' participation probabilities are $(q_A, 1 - q_A)$ and those of each of the n_B B-bidders are $(q_B, 1 - q_B)$ and all bidders bid their costs, the representative A-bidder's expected profit of bidding in Auction A is

$$\Pi_A(x, n_A, k_A, r_A, q_A) = \\ \sum_{i=0}^{n_A-1} \binom{n_A - 1}{i} q_A^i (1 - q_A)^{n_A-1-i} I(x, k_A, r_A, i)\,, \tag{4.21}$$

$$I(k_A, r_A, i) = \begin{cases} \int_x^{r_A} (y - x) f_{(k_A,i)}(y) dy & : i \geq k_A \\ r_A - x & : i < k_A \end{cases} \tag{4.22}$$

and her expected profit of bidding in Auction B is

$$\Pi_A(x, n_A, n_B, k_B, r_B, 1 - q_A) = \\ \left(\sum_{i=0}^{n_A-1} \binom{n_A - 1}{i} q_A^{n_A-1-i} (1 - q_A)^i + n_B \right) I(x, k_B, r_B, i, n_B)\,, \tag{4.23}$$

$$I(k_B, r_B, i, n_B) = \begin{cases} \int_x^{r_B} (y - x) f_{(k_B,i+n_B)}(y) dy & : i \geq k_B \\ r_A - x & : i + n_B < k_B \end{cases} \tag{4.24}$$

where $F_{(k,n_B+i)}$ and $f_{(k,n_B+i)}$ denote the distribution function and density function of the kth order statistics (i.e., random variable of the k-lowest costs) if i cost signals are drawn from F_A and n_B cost signals are drawn from F_B.

The equilibrium probability q_A is determined by

$$\Pi_A(x, n_A, k_A, r_A, q_A) = \Pi_A(x, n_A, n_B, k_B, r_B, 1 - q_A)\,. \tag{4.25}$$

That is, every A-bidder is indifferent (with respect to her expected profits) between participating in Auction A or in Auction B.

Equal Cost Distributions

The case of an equal cost distribution is given by $F_A \equiv F_B$. For simplicity, we further assume $r_A = r_B$ and $k_A = k_B$.

If $n_A \leq n_B$, we have $q_A = 1$ and, thus, $1 - q_A = 0$ because

$$\Pi_A(x, n_A, k_A, r_A, q_A) > \Pi_A(x, n_A, n_B, k_B, r_B, 1 - q_A) \tag{4.26}$$

for all $q_A \in [0, 1]$. That is, no A-bidder participates in Auction B because an A-bidders expected profit (4.21) from participating in Auction A is always higher than her expected profit (4.23) from participating in Auction B, independent of the other A-bidders' decision. This holds because actual number of competitors the Auction B is always higher than in Auction A. Thus, this case is equal to the case of two separate auctions (Section 4.4.3).

Only for $n_A > n_B$, $q_A < 0$ and, thus, $1 - q_A > 0$, i.e., the A-bidders also participate with a positive probability in Auction B. Given a fixed n_B, it follows from (4.21), (4.23), and 4.25 that q_A decreases in n_A. That is, the higher the number of A-bidders, the higher is the probability that they participate in Auction B. For these cases, with regard to efficiency, expected prices and costs, the argumentation and results of the Simultaneous Mutual Auctions (4.4.4.1) apply. That is, there is a high probability that the outcome is inefficient and that the prices and costs are higher than in efficient outcome of the Joint Auction (Section

4.4.2).

4.4.5.2 Sequential Unilateral Auctions

When analysing Sequential Unilateral Auctions, we have to distinguish between the case that Auction A is conducted before Auction B and the opposite case that Auction B is conducted before Auction A. Since B-bidders are only allowed to participate in Auction B, it is optimal for them to bid their cost signal independent of the sequence of the auctions. For the A-bidders it is optimal to participate in both auctions by bidding truthfully in the second auction and exaggerating their costs in the first auctions. This is the same bid pattern as in the Sequential Mutual Auctions (Section 4.4.4.2). However, the degree of exaggeration in the first auction differs from (4.19).

The award prices p_A and p_B depend on the sequence of the auctions.

If Auction A is conducted before Auction B, $p_B \leq x_{(k+1,n)}$. The case $p_B = x_{(k+1,n)}$ holds if and only if the outcome of the Sequential Unilateral Auction is efficient, i.e., the k bidders with the lowest costs are awarded, i.e., the bidders in set N_{eff}. In this case, in Auction A, k_A of these bidders are awarded, and in the subsequent auction B, the remaining k_B bidders.

If k_A or more A-bidders are in N_{eff}, the outcome is efficient and $p_B = x_{(k+1,n)}$ because all bidders in N_{eff} are awarded and the bidder with $x_{(k+1,n)}$ determines the price in Auction B. If in this case, the A-bidders beliefs about N_{eff} are correct, $E[P_{Uni,A}] = E\left[X_{(k+1,n)}\right]$. That is, the expected price in both auctions are equal and equal to the expected price in the Joint Auction 4.4.2: $E[P_{Uni,A}] = E[P_{Uni,A}] = E[P_J] = E\left[X_{(k+1,n)}\right]$. Thus, this also applies to the auctioneer's expected costs: $E[C_{Uni}] = E[C_{Uni,A}] + E[C_{Uni,B}] = k_A E\left[X_{(k+1,n)}\right] + k_B E\left[X_{(k+1,n)}\right] =$

$kE\left[X_{(k+1,n)}\right] = E[C_J]$.

If at least one of the k_A bidders, who are awarded in Auction A, does not belong to N_{eff}, i.e., more than k_B bidders are in N_{eff}, the outcome is inefficient and $p_B < x_{(k+1,n)}$. This happens because not the bidder with $x_{(k+1,n)}$ determines the price in Auction B, but a bidder in N_{eff} with a lower cost signal than $x_{(k+1,n)}$. This case occurs if fewer than k_A A-bidders and, thus, more than k_B B-bidders are in N_{eff}. In this case, the price p_A differs from p_B. In Auction A, the price-determining A-bidder's cost signal is higher than $x_{(k+1,n)}$. Since A-bidders exaggerate their costs in their bids, $p_A > x_{(k+1,n)}$. Therefore, in this case, $p_B < x_{(k+1,n)} < p_A$.

If Auction B is conducted before Auction A, p_A is ambiguous, i.e., all cases $p_A = x_{(k,n)}$, $p_A < x_{(k,n)}$, or $p_A > x_{(k,n)}$ are possible. Moreover, the equivalence between efficiency and $p_A = x_{(k+1,n)}$ does not hold as in the opposite sequence. The Sequential Unilateral Auction is efficient if the k bidders with the lowest costs are awarded. In this case, in Auction B, k_B of these bidders are awarded, and in the subsequent auction A, the remaining k_A bidders. However, since the A-bidders and B-bidders behave differently in the B auction – the B-bidders bid truthfully, whereas the A-bidders exaggerate their costs – it is possible that in Auction B, a B-bidder, who is not N_{eff}, is awarded. As a consequence, the outcome is inefficient and $p_A < x_{(k,n)}$ because the price in Auction A is determined by a bidder with a cost signal $x < x_{(k+1,n)}$. On the other side, if more than k_B bidders are in N_{eff}, the outcome is also inefficient and $p_A > x_{(k+1,n)}$ because the price in Auction A is determined by a bidder with a cost signal $x > x_{(k+1,n)}$. Also in theses cases, the prices p_A and p_B may differ.

4.4.6 Comparison of the different auctions

In order to decide on an optimal design for cross-border auctions, it is important to compare the different auction scenarios and their individual outcomes. In Section 4.4.2 we showed that a Joint Auction is always efficient and yields an expected price of $E[P] = E\left[X_{(k+1,n)}\right]$ when bidders from the two countries can be assumed to have similar costs. If one conducts Separate Auctions, the probability of an efficient outcome is much smaller as calculated in Section 4.4.3, and if this auction is efficient, the price in one of the auctions will in all cases be higher than the price of the Joint Auction. If the auctions end inefficient, i.e., if not the k projects with the lowest costs are awarded, the outcome cannot be determined before. The overall costs for the auctioneers can be higher than, lower than or equal to the costs of the joint auction. This is because in one of the auctions the auctioneer will have to pay less than in an efficient outcome, but the other one has to pay more. Depending on this exact ratio, the overall costs can be determined. One argument in favour of Separate Auctions is the relatively easy implementation for each country, since they do not need to cooperate.

Mutual Auctions can be conducted both simultaneously and sequentially. When conducted simultaneously, the problem is the same as with Separate Auctions, since the probability for an efficient outcome is rather small for a high number of auctioned goods (Section 4.4.4.1) and efficiency leads to higher prices than in the ideal case of the Joint Auction. Again, if the auction outcome is inefficient, no concrete statement about the resulting prices can be made. When the Mutual Auctions are conducted sequentially, the outcome is efficient and the prices in both auctions are equal to the price of the Joint Auction (Section 4.4.4.2). This constitutes a real alternative for the Joint Auction. The outcomes are identical, but the Mutual Auctions leaves much more liberties for the conducting countries, since each country is responsible for only one auction independently of the design of the other. Of course, if the designs are too different, this will have effects on the prices as well. A further advantage is that it is clear which country gave the award for which bidder and thus has to pay for the support.

The Unilateral Auctions are comparable to the Separate Auctions if the cost structure and auction design is identical (or considerably similar) in both countries (Section 4.4.5.1). In this case, nobody will enter the auction in the foreign country and the results are those from Section 4.4.3. If the market characteristics or the auction design are different in both countries, again an equilibrium in mixed strategies is constituted and the result is the same as Section 4.4.4.1 for Simultaneous Mutual Auctions. The Sequential Unilateral Auctions need to be distinguished into two scenarios: one, the opened auction is conducted first, and two, it is conducted second. If it is conducted first, there is a high chance that the auctions will be overall inefficient, since in the first auction two different bidding strategies are apparent: the bidders only allowed to participate in this auction will bid their true costs while the others will apply bid-shading (Section 4.4.5.2). Thus, depending on the cost structure of the bidders, the prices can differ in both directions. What is clear is that both auctions will in most cases not achieve the same prices.

If the opened auction is conducted second, the auctions can be efficient. This is the case if more than k_A A-bidders are in the group of the overall lowest costs projects (Section 4.4.5.2), as this secures that in both auctions only the bidders with the lowest costs are awarded. In this case, the price in both auctions will be equal to the price achieved in the Joint Auction. If this is not the case, i.e., if there are bidders awarded in the first auction who do not belong to the group with the lowest costs, the auction outcome is inefficient and the prices of the two auctions differ from the reference price $E\left[X_{(k+1,n)}\right]$, where the price in the first auction is higher, and the price in the second auction is lower than $E\left[X_{(k+1,n)}\right]$.

To put it in a nutshell, the Joint Auctions has a guaranteed efficient outcome and no dangers of too high prices due to unfavourable bidder structures in the different countries. Nevertheless, it is harder to conduct. An alternative would be the Sequential Mutual Auction, where the same outcome regarding awards and prices can be expected, but with more liberties for the auctioneers in their individual auction design. The other auction types can yield lower overall prices, but only together with an inefficient outcome. Furthermore, there is also a high chance that the prices will turn out to be higher than in a Joint Auction.

4.4.7 Extensions

In the following we discuss some extensions of the models in the previous sections.

4.4.7.1 Other auction formats

How do the results of our analyses change instead of the LRB-UP rule the DP rule or the HAB-UP rule are applied? In Section 4.4.2, we mention the so-called revenue equivalence theorem (Myerson, 1981; Riley et al., 1981; Engelbrecht-Wiggans, 1988), which (to a certain degree) can be applied to different pricing rules in the auctions considered in the previous sections. Accordingly, the expected equilibrium outcomes under other pricing rule are considered to be the same or at least similar to theses derived under LRB-UP.

4.4.7.2 Systematic cost differences between countries

Assume that Auction A is conducted in Country A and Auction B is conducted in Country B and that there are systematically different conditions in the two countries. These differences may be caused by differences in the monetary support systems in the two countries. Due to these differences, bidders have different costs for a similar project depending where the project is built.

W.l.o.g. we assume that the costs are higher in Country B than in Country A. We model this cost difference by an additive constant d. That is, if a bidder has costs x when she is awarded in Auction A, the bidders has costs $x + d$ when she is awarded in Auction B. As a consequence, the bidder submits a higher bid in Auction B than in Auction A. In the case of the simultaneous auctions (Sections 4.4.4.1 and Section 4.4.5.1), the different bids are $b = x$ in Auction A and $b = x + d$ in Auction B. Generally, in the Separate Auctions (Section 4.4.3, Mutual Auctions (Section 4.4.4), and Unilateral Auctions (Section 4.4.5), the price in Auction B is expected to be d higher than in the case of equal costs with $d = 0$ considered so far. The results about efficiency and expected costs remain except for the auctioneer's costs in Auction B, which increase by $k_B d$.

The Joint Auction is a challenge because the two auction demands k_A and k_B are put together and are allocated in one auction, in which each bidder submits one bid for her project. Therefore, for the Joint Auction, we recommend that the two countries agree on one award system, so that it does not matter for the bidders whether they are awarded in Country A or B.

Nevertheless, it is possible to design a reasonable and applicable mechanism for the Joint Auction which takes the systematic cost differences between the two countries into consideration. It is obvious that the allocation procedure described in Section 4.4.2 cannot be applied because it does not account for the cost differences. The proposed design for the Joint Auction contains is based on the Generalized Vickrey Auction (GVA) or Vickrey-Clarke-Groves (VCG) mechanism (e.g., Ausubel et al., 2006; Krishna, 2009). Each bidders submits two bids for her project. The first bid, the A-bid, applies to Country A and the second bid, the B-bid, applies to Country B. From all submitted bids, the set of all feasible combinations of bids is computed. A feasible bid combination contains (1) at maximum one bid of each bidder and (2) k_A A-bids and k_B B-bids. The winning bids are determined by the feasible bid combination that minimizes the total sum of bids. For the pricing rule, the Vickrey rule e.g., Ausubel et al., 2006 or the DP rule can be taken into consideration, whereas the UP rule (LRB or HAB) is considered to be less suited. Although the Vickrey Auction is incentive-compatible, i.e., it is a weakly dominant strategy for the bidders to reveal their true costs in their bids b_A and b_B, due to the weaknesses of this auction format, we consider the application of the DP rule to be the better choice.

4.4.8 Multiple countries

In the future, it might be considered to not only conduct cross-border auctions between two countries, but between multiple ones, e.g., the implementation of region-wide cross-border auctions can be of interest. This can for example be sensible in the Baltic Region, since the countries are relatively small and the introduction of an auction scheme can be administratively challenging. Our results can easily be extended to multiple countries. The Joint Auction and Separate Auctions will maintain their effects. For the Mutual and Unilateral Auctions, there are just a few cases added, for example when one country decides to open for all other countries while another one decides to open only for one foreign country. Nevertheless, the principle problems and underlying structures remain, i.e., the auctions will with a high probability be inefficient and the overall costs for the auctioneers, i.e., the different countries, might be much higher than with a cooperative design like the Joint or Sequential Mutual Auction.

4.5 Conclusion

In this chapter, we have theoretically analysed the implications of various degrees of openness of cross-border auctions on the allocative efficiency and the resulting award prices. We compared the results of a Joint Auction, Separate Auctions, a Unilateral Auction and Mutual Auctions. In our approach, we assume an adequate auction design and sufficient competition in all auctions.[12]

We find that the Joint Auction is the most promising type of cross-border auction with regard to efficiency, our modelling result showing efficient allocation, as well as moderate awarded prices. Nevertheless, implementing this type of auction is quite complicated due to a high degree of cross-border integration and regulatory coordination.

Mutual Auctions can be conducted either simultaneously or sequentially. In the first case, we find that the probability of achieving an efficient outcome is rather small and the resulting prices are higher than in the Joint Auction. Sequential Mutual Auctions, on the other hand, lead to an efficient result as well as to the same prices as in the Joint Auction. This type of cross-border auction, which has already been used in the German-Danish PV auctions, can thus be a role-model for future design choices. Policymakers do not face the same difficulties as in the Joint Auctions: each country can decide on its own auction design and thus no coordination efforts are needed. In addition, each country can be responsible for the support payments awarded in its own auction, and no complex formula is needed to divide the support payments, as required in the Joint Auction. Nevertheless, as studies have shown, in reality lower costs might be expected in the first Mutual Auction compared to the second one, thus this has to be accounted for when countries establish

---

[12] Note that the specific design implications of each type of auction is not the focus of this chapter.

their cross-border cooperation.

Unilateral (both the Simultaneous and Sequential cases), as well as the Separate Auctions are shown to have a relatively low probability of achieving an efficient outcome and are thus inferior to both the Joint and the (Sequential) Mutual Auctions. More generally, the analysis shows that parallel auctions (where project developers must chose in which auction they want to participate and cannot participate in both) tend to decrease the efficiency of a support scheme.

Therefore, based on our theoretical analysis, we can recommend to policymakers to consider Sequential Mutual Auctions when designing cross-border auctions. This auction type combines the benefits of relatively straightforward implementation with the allocative efficiency of a Joint Auction.

Chapter 5

Analysing multi-technology auctions - experimental evidence

5.1 Introduction

With ongoing climate change, the need for RE especially in the electricity sector is higher than ever (Qazi et al., 2019). Though technology costs have been decreasing for RES in the last years (Steffen et al., 2020), not all RE plants can compete with market prices (Timilsina, 2021). Thus, RES have been given a support payment additional to market prices to help transition into a sustainable future. Before 2014, this add-on was mostly a fixed FiT on top of the market price. Since 2014, the procedure for determining support payments in the EU has to be changed to a competitive environment, i.e., auctions (European Commission, 2014). In these auctions for RE support, project developers compete for payments made by a country or state-authority, while only a certain number of projects are awarded. In most cases, the award is based solely on the price, i.e., projects with the lowest price bids are awarded (AURES II, 2020). These auctions are called procurement auctions, and since mostly not only one project, or, more generally speaking, one unit of the auction product (e.g., capacity) is awarded, the auctions are multi-unit auctions.

When designing an auction, the auctioneer, i.e., in most cases the state or a state-authority, has to decide on which technologies to be eligible for award. A follow-up decision is then whether to award all technologies in a single auction (*multi-technology* auction), or in one auction per technology (*technology-specific* auction) (Winkler, 2021). There has been an ongoing discussion about which of the two approaches is to be favoured when designing auctions for RES (Jerrentrup et al., 2016; Winkler, 2021), though in the long term, the EU favours the implementation of multi-technology auctions except for a few exemptions (European Commission, 2014). This chapter experimentally analyses the differences between multi-technology and technology-specific multi-unit auctions in terms of prices, bidding behaviour, efficiency, and outcomes for auctioneer and society as a whole. It thus contributes to the complexity of deciding on an auction design by providing valuable insights in the advantages and disadvantages of the two different ways of awarding multiple technologies. Further, the most commonly used pricing rules in RE auctions (AURES II, 2020) are analysed, DP and UP. To account for different characteristics of project developers, both developers with only one project as well as those with multiple projects are represented in the experiment.

So far, a large strand of experimental literature regarding the electricity market since the early 2000s has been dealing with the wholesale electricity market and its price determination (e.g., Schulze et al., 2000; Mount et al., 2001; Oh et al., 2003; Chirkin et al., 2016). Auctions for renewable energy support are different: the determination of awards is independent from the wholesale market.[1] RE projects can participate at the wholesale market independently of award, awarded projects just

---

[1] although payments may dependent on the wholesale market price, depending on the remuneration scheme (Mora et al., 2017).

can receive an additional payment.[2] The RE auctions thus are more related to the field of repeated static sealed-bid auctions. Since multiple technologies with different cost structures are analysed, the theory of asymmetric bidders where one bidder stochastically dominates the other (e.g., Leoni et al., 2017) can be applied here. First studies of asymmetric bidders appear in Vickrey, 1961. Griesmer et al., 1967, Plum, 1992, Krishna, 2003, Reny et al., 2004 and Kaplan et al., 2012 study bidding strategies and equilibria in auctions with asymmetric bidders under different pricing rules. Waehrer, 1999 analyses collusion among bidders with different cost structures, while Güth et al., 2005 and Avery et al., 1997 experimentally analyse the outcome of asymmetric auctions. A calculation of expected revenues can be found in Cantillon, 2008. A comparison between different pricing rules in auctions with asymmetric bidders is examined in Mares et al., 2014 and Kirkegaard, 2012. A theoretic analysis of different pricing rules with symmetric bidders can be found in many papers (e.g., Engelbrecht-Wiggans, 1988; Engelbrecht-Wiggans et al., 1998b; Hudson et al., 2000). Other approaches studying different pricing rules in the electricity market or other public sectors include agent-based modelling (Xiong et al., 2004; Guerci et al., 2012), empirical data analysis (Tenorio, 1993; Wolfram, 1998; Heim et al., 2013; Umlauf, 1993) or other experiments (Rassenti et al., 2003). Though some of these papers were published years ago, theoretic results hold still today.

When considering multi-demand in sales auctions, the equivalent to multi-supply in procurement auctions, theory becomes far more complicated than in the single-demand case (Engelbrecht-Wiggans et al., 1998a; Ausubel et al., 2014). Still, experiments have been conducted to test bid-

---

[2] Depending on the remuneration scheme and the exact market situation, bidders not always actually receive a payment, e.g., with a one-sided CfD, bidders only receive a payment when the wholesale market price drops below a threshold, and this difference is then compensated.

ding behaviour and auction results. Works that analyse multi-demand with independent private values are Alsemgeest et al., 1998; Kagel et al., 2001; Manelli et al., 2006 and Engelmann et al., 2009. All of them have in common, that they analyse different pricing rules regarding efficiency and revenue. Results differ based on the analysed pricing rules and the different levels of competition. Kagel et al., 2001 and Alsemgeest et al., 1998 find that UP has higher revenue, and efficiency is similar (Alsemgeest et al., 1998) or higher in the Ausubel auction (Kagel et al., 2001). Manelli et al., 2006 find the highest revenue in Vickrey auctions, while Engelmann et al., 2009 have the highest revenue in DP auctions.

This chapter intersects at the presented strands of literature: while asymmetric bidders have been studied theoretically and experimentally in single- and multi-demand, no experimental comparison has been made so far. A further contribution is the comparison between auctions conducted for asymmetric bidders together, and auctions conducted for each bidder type separately. To also include possible learning effects (Casari et al., 2007), this chapter studies the same auctions conducted over multiple rounds. Experimental results show the degree of efficiency is higher in multi-technology auctions than technology-specific auctions. In this experiment, multi-technology auctions lead to lower prices and higher auctioneer's surplus and social welfare than technology-specific prices. DP auctions have lower award prices and higher auctioneer's surplus and social welfare than UP auctions. Irrational bidding behaviour is more common in UP auctions, and participants do not seem to adapt their bidding behaviour in the course of the experiment.

The rest of the chapter is structured as follows. Section 5.2 sets the theoretic basis for the experiment. Section 5.3 introduces the experiment and presents its results, which are discussed in Section 5.4. Section 5.5

concludes the chapter.

5.2 Theoretic analyses

In this chapter, different forms of multi-unit procurement auctions are examined and compared. For this purpose, we analyse single-supply bidders as well as multi-supply bidders. Single-supply bidders have exactly one project to participate in an auction, and multi-supply bidders have exactly two projects. The approach in this chapter is similar to that in Chapter 4, where different types of cross-border auctions are analysed. In contrast to these calculations, it is assumed that bidding accrues no participation costs. Without participation costs bidders do not face sunk costs in case of non-award, and will thus participate without the risk of losing money with all possible projects.

Consider two different types of bidders A and B which differ regarding their projects' underlying cost structure. There are n_a bidders with role A and n_B bidders with role B, and thus a total of $n = n_A + n_B$ bidders. Each project i of a bidder is assigned individual realisation costs x_i. Costs of type A are drawn from the interval $[\underline{a}, \overline{a}]$ and costs of type B are drawn from the interval $[\underline{b}, \overline{b}]$. Within these intervals the costs are identically and independently distributed with distribution functions F_j and density functions f_j for types $j \in \{A, B\}$. Since there are two different bidder types, we speak of asymmetric bidder groups, while within the group, the symmetric independent private value approach (IPV, see e.g., Krishna, 2009) can be applied. W.l.o.g. assume the distribution function F_B stochastically dominates F_A, i.e., $F_B(t) - F_A(t) \geq 0$ for all values of t. The probability of costs being lower than t is higher for costs of type A than for costs of type B. Projects of type A can thus be considered cheaper than projects of type B. Multi-supply bidders have two projects of the same type. Assume a total of $k \geq 2$ homogenous goods, i.e., projects, to be auctioned. In this chapter, two different scenarios are compared:

(J) One single (*joint*) auction where k homogenous goods are auctioned. All bidders can participate.

(S) Two *separate* auctions A and B where k_A and k_B homogenous goods are auctioned. Bidders of type A can only participate in auction A, while bidders of type B can only participate in auction B.

The joint auction here represents the multi-technology auction with two technologies eligible for award, while the separate auctions represent the technology-specific auctions.

Further, a ceiling price r which is the same in the joint auction as well as in both auctions A and B in the separate case is introduced. This prevents excessively high bidding. To not exclude bidders from the auction by setting a too low ceiling price, let $r \geq \max\{\overline{a}, \overline{b}\}$. Thus, all realisation costs are below the ceiling price and bidders can participate without underbidding their costs.

In order to determine the expected outcome, i.e., awards, prices, and rents, the concept of order statistics (Ahsanullah et al., 2013) is important. The kth order statistic is the random variable of the kth lowest cost signal out of all n signals and is denoted with $X_{(k,n)}$. Thus, the order statistics can be sorted, where the first order statistic is the lowest and the nth is the highest random variable:

$$X_{(1,n)} \leq X_{(2,n)} \leq \cdots \leq X_{(n,n)}$$

All auctions are conducted as sealed-bid auctions, where all bidders

i simultaneously submit their bids b_i. Bidders do not have a chance to see bids of others before submitting their own bid. Multi-supply bidders thus submit a bid pair (b_{i1}, b_{i2}) consisting of one bid for each of their projects. Each bid can unambiguously be linked to a specific project. In the following analysis, two different pricing rules are examined: UP and DP. In an UP auction, all awarded bidders receive the same price, namely the lowest non-awarded bid. In a DP auction, awarded bidders receive their own bid.

5.2.1 Joint Auction

In scenario J with single-supply bidders, the k lowest from the n submitted bids are awarded. In scenario J with multi-supply bidders, the $2k$ lowest from the $2n$ submitted bids are awarded. For the single-supply bidders, Ehrhart et al., 2019b give the expected price in a UP auction as the expected value of the $(k+1)$th lowest order statistic:

$$E[p_J] = E[X_{(k+1,n)}].$$

Since all bidders participate in the auction, and have the incentive to bid their own costs, the bidder with the k lowest costs will be awarded in a single-supply auction. Auction J ends efficient[3] in the equilibrium, even if bidders are asymmetric. This auction outcome can also be expected for other pricing rules when bidders are symmetric, including the discriminatory or pay-as-bid auction (Engelbrecht-Wiggans, 1988). This result follows the revenue equivalence theorem (Myerson, 1981), which states that if the goods are allocated to the same bidders under different pricing rules (and under certain conditions), the same auction outcome including prices, profits and auctioneer's surplus can be expected. The

---

[3] In this chapter, we use *efficiency* in the sense of auction-theoretic efficiency, i.e., correctly awarding the projects with the lowest resalisation costs.

equilibrium bidding strategies of course differ in different auctions, e.g., the equilibrium bidding strategy β^{DP} of a procurement auction with single-unit supply is $\beta^{DP}(x) = E[X_{(k+1,n)} \mid X_{(k+1,n)} > x]$. Thus, in the symmetric equilibrium of the DP auction the bidder submits a bid in height of the expected value of the competitor he has to beat in order to be awarded. With asymmetric bidders, this result cannot be transferred. Since weaker bidders have a different bidding strategy than stronger bidders, i.e., a higher signal does not automatically lead to higher bids, the auction does not always end efficient (Krishna, 2009; Ausubel et al., 2014). Therefore, different revenues in DP and UP auctions may occur, where the exact ranking of pricing rules regarding revenues highly depends on the asymmetry (Mares et al., 2014; Kirkegaard, 2012).

Further, when introducing multi-supply bidders to DP or UP auctions, in general there exist multiple Bayes-Nash equilibria, which are inefficient even for symmetric bidders (Krishna, 2009). One way to avoid this, is the introduction of bid constraints (Holmberg et al., 2018). S. Chen et al., 2022 use the assumption of linear strategies and show, that the price and awards in DP auctions are indeterminate compared to UP auctions. The only general rational bidding strategy, is to submit a higher bid for the project with the higher realisation costs than for the project with lower realisation costs independently of pricing rules (Krishna, 2009).[4] Further, it is a weakly dominant strategy to bid one's own realisation costs, but only for the project with the lower realisation costs, and only in UP auctions (Krishna, 2009).

5.2.2 Separate Auctions

In scenario S there are two auctions with two disjoint groups of bidders. Refer to the auctions as A and B, respectively. Thus, bidders with

---

[4] One exception might be for special cases, where the bids are the same (Krishna, 2009).

different roles do not compete against each other. Only bidders with the same role compete against each other in one auction. In UP auctions with single-supply bidders, the price is determined by the (k_A+1)th and (k_B+1)th lowest bids, respectively. The bidding strategy is again the (weakly) dominant strategy to bid the costs. Thus, the k_A lowest bidders of type A are awarded in auction A for the price of the (k_A+1)th lowest bid:

$$E[p_A] = E[X_{(k_A+1,n_A)}].$$

In auction B the k_b bidders with the lowest costs of type B are awarded and receive the payment in height of the (k_B+1)th lowest bid:

$$E[p_B] = E[X_{(k_B+1,n_B)}].$$

This result holds for the DP auction as well, due to the revenue equivalence theorem and the symmetric bidders in auctions A and B. Considered only for themselves, each separate auction is efficient, because in each auction t the lowest bidders with role t are awarded for $t \in \{A, B\}$. If one takes into account all bidders, the picture is different. We refer to the separate auctions A and B as an *auction unit*. In each auction unit, there are n bidders, where n_A bidders have role A and n_B bidders have role B.[5] Following the argumentation from Ehrhart et al., 2019b, the auction only ends efficient if the k overall cheapest projects divides exactly into the k_A cheapest projects in auction A and the k_B cheapest projects in auction B. Let $f_{k_t}(x) := f_{t(k_t,n_t)}(x)$ be the density function of the k_tth order statistic for distributions $t \in \{A, B\}$. Then the probability

---

[5] A joint auction is therefore an auction unit as well.

for an efficient outcome in the separate auctions is given by

$$\begin{aligned}&\int_{\underline{a}}^{\overline{a}} f_{k_A}(a_1) \int_{a_1}^{\overline{b}} f_{k_B+1}(b_2) \int_{\underline{b}}^{b_2} f_{k_B}(b_1)\\ &\quad\int_{b_1}^{\overline{a}} f_{k_A+1}(a_2 \mid a_2 \geq a_1)\ da_2\ db_1\ db_2\ da_1,\end{aligned} \tag{5.1}$$

i.e., the probability that the k_Ath lowest costs in auction A are smaller than the (k_B+1)th lowest costs in auction B, and at the same time the k_Bth lowest costs in auction B are smaller than the (k_A+1)th lowest costs in auction A. This probability is clearly lower than one, and thus, there is a chance that the separate auctions will not award all bidders with the cheapest projects.[6]

In auctions A and B with multi-supply bidders, the reasoning of the joint auction with symmetric bidders, who each have multiple projects, holds. That is, the auction in general does not end efficient and the rank of prices is indeterminate (Section 5.2.1).

5.2.3 Comparison

Comparing the separate and joint auctions with single-supply bidders regarding price and efficiency from an auctioneer's perspective, the joint auction clearly is to be favoured. First, the joint auction always ends efficient in the symmetric equilibrium of the UP auction. This is not the case in the separate auctions, which only end efficient with the probability calculated in (5.1), which is smaller than 1. Further, the different scenarios yield different prices. If scenario S is efficient, the prices are higher than in scenario J. This is because the price-determining bidder in auction J is either of type A or of type B. W.l.o.g. assume the price determining bidder in J is of type A. This bidder cannot participate in

---

[6] This does not mean that separate auctions cannot end efficient. Further, an auction either ends efficient or not efficient. The probability here does not indicate "how much" efficient the auction is, but rather in how many cases one can expect an efficient outcome.

both auctions, and will thus only set the price in auction A: $p_A = p_J$. The price of auction B is then determined by the next lowest bid, i.e., the realisation costs $x_{(k+2,n)}$, $p_B = E[X_{(k+2,n)}]$. Thus, the auctioneer's surplus Π_S^0, which is the difference between the auctioneer's valuation v for the projects, and the payments (i.e., auctioneer's costs) that accrue, is lower than in the joint auction:

$$\begin{aligned}\Pi_S^0 &= v - (k_A \cdot p_A + k_B \cdot p_B) = v - (k_A \cdot p_J + k_B \cdot p_B)\\ &\leq v - (k_A \cdot p_J + k_B \cdot p_J)\\ &= \Pi_J^0.\end{aligned}$$

If the separate auctions end inefficient, it is hard to make a statement. Depending on the exact realisations of the costs, and on the ratio between k_A and k_B, the auctioneer's surplus can be lower or higher in the separate auctions than in the joint auction. Overall, the conduction of the joint auction is cheaper for the auctioneer than the conduction of separate auctions if

$$k_A \cdot p_A + k_B \cdot p_B > k \cdot p_J. \tag{5.2}$$

As evident from (5.2), it is possible, that prices in one separate auction (w.l.o.g. A) are lower than in the joint auction, and still overall the joint is cheaper, because of comparably too high prices in auction B. This imbalance is based on the stochastic dominance, i.e., in auction A it is expected that bidders have lower costs compared to auction B. The more asymmetrical those relations are, the lower the chances of an efficient outcome.[7] The same line of argumentation can be applied to auctions with multi-supply bidders, as these do not necessarily end efficient, and prices are indeterminate.

---

[7] For example if $\overline{a} < \underline{b}$, the separate auctions will in no case end efficient.

To compare the efficiency of the different auction formats, define N_{awd} as the set of awarded projects, and N_{eff} as the set of projects with the lowest costs, i.e., which would lead to an efficient outcome if awarded. As efficiency is a binary variable, it is sensible to calculate either the probability (5.1) or a degree of efficiency, i.e., the percentage of efficient outcomes when conducting the same auction(s) multiple times. Let thus be m the number of conducted auction rounds, where for the sake of comparability each auction unit is only counted once, i.e., also separate auctions A and B are only counted as one.

The most conservative way to determine the degree of efficiency is to only count an auction efficient, if all projects are awarded that should be awarded. If only one project is awarded that does not belong to the set of projects with the lowest costs N_{eff}, the auction is not efficient. This is called the *binary* approach, and the corresponding degree of efficiency is referred to as D_{eff}^{bin}. It corresponds to the probability calculated in (5.1). This measure can be calculated as

$$D_{eff}^{bin} = \frac{1}{m} \sum_{j=1}^{m} \prod_{i \in N_{awd}^{j}} \mathbb{1}(i \in N_{eff}), \tag{5.3}$$

where N_{awd}^{l} is the subset of awarded projects in auction round j. Another possibility to compare auctions regarding the degree of efficiency D_{eff} is to calculate the percentage of projects who are correctly awarded in the auction. Refer to this as the *relative* approach, as it does not consider the auction as a whole (binary), but just projects on an individual level. Thus, the degree of efficiency under this approach is defined by

$$D^{rel}_{eff} = \frac{1}{m \cdot k} \sum_{i \in N_{awd}} \mathbb{1}(i \in N_{eff}). \tag{5.4}$$

The least conservative option to calculate the degree of efficiency D^{rge}_{eff} is to take into account the range of realised cost signals. This range approach measures the loss of money that emerges from the award of the wrong projects. It can be calculated as

$$D^{rge}_{eff} = \frac{1}{m} \sum_{j=1}^{mk} \sum_{i \in N^j_{awd}} \left(1 - \frac{x^j_i - x^j_{(i,n)}}{x^j_{(n,n)} - x^j_{(1,n)}} \right). \tag{5.5}$$

The ratio in the last part of (5.5) has a value of 1 when the bidder with the lowest costs was awarded, and 0, when the bidder with the highest costs was awarded. This is a weaker definition of the degree of efficiency, since it is relative to the cost signals. Again, this is more relaxed than e.g., calculating on an auction round basis, since this treats projects individually and counts stronger deviations from the ideal outcome more than minor deviations. Proposition 4 orders the different ways of measuring the degree of efficiency.

Proposition 4. *Compare m auction rounds with k auctioned goods and n participating bidders in each auction round. Then for all possible allocations of goods it holds for the degrees of efficiency defined in* (5.3), (5.4) *and* (5.5)*:*

$$0 \leq D^{bin}_{eff} \leq D^{rel}_{eff} \leq D^{rge}_{eff} \leq 1.$$

Since the social welfare is calculated as the difference between the valuation of the auctioneer gained by the transfer of projects/goods from bidders to auctioneer, and the realisation costs of the awarded projects, social welfare does not depend on auction prices but on efficiency. An efficient auction results in a higher social welfare than an inefficient one.

5.3 Experiment

As seen from Section 5.2, no clear equilibria and thus, auction outcomes, can be determined in multi-unit auctions with asymmetric bidders. Therefore, to test which auction format and which pricing rule offer the highest degree of efficiency, auctioneer's surplus, and social welfare, as well as the lowest prices, an experiment was conducted. The experiment was programmed in oTree (D. L. Chen et al., 2016). The first half of the experiment was conducted at the KD2lab[8] (Karlsruhe Decision and Design Lab) at Karlsruhe Institute of Technology, Germany in November 2019. The second half of the experiment was conducted online in March 2022.[9] For both settings, on overall of 240 participants were recruited via hroot (Bock et al., 2014). Participants received an average payment of 12.73 €, while the experiment lasted on average 52 minutes. Before the experiment itself, bidders had instructions read out to them and they had to answer a questionnaire to ensure their understanding of the experimental rules.[10] Out of the 12 planned online sessions, 4 sessions could not be completed due to participants quitting before the end of the session and the need for a fixed number of 12 participants in each session. [11] Participants in the affected sessions were paid a fixed

---

[8] The KD2lab is DFG-funded. For more information, see `https://www.kd2lab.kit.edu/english/index.php`.

[9] The time gap between experimental halves and the change of conduction mode to online was due to the Covid-19 pandemic.

[10] A translation of the instructions as well as the questionnaire can be found in C.3 and C.4. The experiment itself was conducted in German.

[11] Reasons for quitting include connection problems additional to untold reasons. Presumably participants were not willing to finish the experiment although being told about length and payment at registration.

show-up fee based on their already spent time.

5.3.1 Experimental design

Participants are assigned projects with randomly determined realisation costs. The award and thus, realisation, of the projects is determined in an award procedure, i.e., a procurement auction. Each experiment session consists of 40 rounds. In each round, each participant participates in exactly one award procedure. Each bidder in an award procedure submits one bid for each project he is assigned. To account for bidder asymmetries, participants are assigned different roles (A and B) at the beginning of a session. These roles change after each 10 rounds, so participants play 20 round with role A and 20 rounds with role B. The realisation costs of bidders with role A are uniformly and independently distributed over the interval A $[300, 400]$, while those of bidders with role B are uniformly and independently distributed over the interval B $[350, 450]$. The height of bids is limited in all auctions by the ceiling price $r = 500$. In 20 consecutive rounds out of the 40 overall rounds, participants compete with 2 other participants for award (*separate auction*), and in the remaining consecutive 20 rounds, they compete with 5 other participants (*joint auction*). To ensure an equal level of competition, twice as many awards are given in the joint than in the separate auction. In the separate auctions, only bidders with the same role compete against each other. In the joint auctions, exactly 3 bidders of each role compete against each other. Thus, $n_A = n_B = 3$. Bidders in neither joint nor separate auction do know who exactly their competitors are, or whether they competed in the same auction in the last round(s). Sessions differ in the order of conducted auctions, i.e., in 11 sessions participants competed in separate auctions first, while in 9 sessions participants competed in joint auctions first.[12] Each session consists of 12 participants. In one part of the experiment, participants have one project each, for which they submit a bid. This represents a *single-supply auction* with single-supply bidders. In the second part of the experiment, participants are assigned two projects, and submit a bid for each. This represents a *multi-supply auction* with multi-supply bidders. In single-supply auctions, when competing in the separate auctions, only the lowest bid is awarded ($k_A = k_B = 1$). When competing in the joint auctions, the two projects with the lowest bids are awarded ($k = 2$). In multi-supply auctions, which are conducted in separate auctions, the two lowest bids are awarded. When competing in joint auctions, the four lowest bids are awarded. The price determination for successful, i.e., awarded, projects, differs between sessions. Exactly half of the session used the *DP* pricing rule, where bidders receive a payment in height of their bid, if this bid was awarded. In the second half of the sessions, the *UP* rule was used. In this case, bidders receive a payment in height of the lowest non-awarded bid for their awarded bid. In the case of multi-supply auctions, this can also be their own bid for their other project. These design choices result in multiple layers of design variables: type of bidders (single- or multi-supply), sequence of auction types (separate first or joint first) and different pricing rules (DP or UP). Table 5.1 gives an overview over the different sessions and when they were conducted.

Bidders' profits are determined based on the award of their bids. If a bid is awarded, bidders receive the payment for this bid based on the pricing rule, and must pay their realisation costs of the corresponding project. If no bid is awarded in the award procedure, the profit in this round is 0. In the case of multi-supply bidders, a bidder's overall round

---

[12] It was planned to conduct 12 sessions for each order. The imbalance in number is due to the dropout of participants in the online sessions.

Date	Name	Sequence	Bidder type	Pricing rule
06.11.2019	SPS1	separate first	single-supply	DP
06.11.2019	SPS2	separate first	single-supply	DP
06.11.2019	SPS3	separate first	single-supply	DP
06.11.2019	SPJ1	joint first	single-supply	DP
06.11.2019	SPJ2	joint first	single-supply	DP
06.11.2019	SPJ3	joint first	single-supply	DP
07.11.2019	SUS1	separate first	single-supply	UP
07.11.2019	SUS2	separate first	single-supply	UP
07.11.2019	SUS3	separate first	single-supply	UP
07.11.2019	SUJ1	joint first	single-supply	UP
07.11.2019	SUJ2	joint first	single-supply	UP
07.11.2019	SUJ3	joint first	single-supply	UP
07.03.2022	MPJ1	joint first	multi-supply	DP
07.03.2022	MPJ2	joint first	multi-supply	DP
08.03.2022	MPS1	separate first	multi-supply	DP
08.03.2022	MPS2	separate first	multi-supply	DP
09.03.2022	MUJ1	joint first	multi-supply	UP
10.03.2022	MUS1	separate first	multi-supply	UP
10.03.2022	MUS2	separate first	multi-supply	UP
10.03.2022	MUS3	separate first	multi-supply	UP

Table 5.1: Overview of conducted sessions and corresponding design differences

profit is the sum of both profits for the individual projects. If bidders bid below their costs and are awarded, their profit can be negative, if the payment they receive is also below their costs. Bidders receive information about all submitted and awarded bids from the award procedure they were participating in, but not the underlying realisation costs (apart from their own, naturally). They do only get information about their own profit, but not any other bidder's profit. Participants' payoff was determined as the sum of a show-up fee of 5 € and a variable amount which is performance based. The variable amount is the average of the respective bidder's profit of 20 randomly selected rounds, where always 5 rounds are selected from 10 consecutive rounds.

5.3.2 Experimental results

For the comparison of auction performance, different result parameters were analysed. Parameters include the *bid*, i.e., all submitted bids by all participants independently of the award status, the *price*, i.e., the payments awarded bidders received (equal to their bids in DP auctions, and equal to the lowest rejected bid in UP auctions), and the bid *surcharge*, which is the difference between a bidder's bid and their realisation costs. Furthermore, the auctioneer's *surplus*, i.e., the difference between gained value and the payments made to bidders, as well as the social *welfare*, i.e., the difference between gained value of the auctioneer and realisation costs of awarded bidders, are calculated. Since more awarded goods typically lead to higher surplus and welfare, the benchmark is the single-supply separate auction, were only one good is awarded. To ensure comparability, in all other auctions, the resulting surplus and welfare is divided by the number of awarded goods to calculate the average surplus and welfare per awarded good.

Additionally, the different degrees of efficiency D_{eff}^{bin}, D_{eff}^{rel}, and D_{eff}^{rge} presented in Section 5.2 are calculated for each auction unit, i.e., either for one joint auction or two separate auctions belonging to the same unit.

All computations in this Section were done under R 4.0.3 (R Core Team, 2020) and with the packages *lme4* (Bates et al., 2015) and *lmerTest* (Kunzetsova et al., 2017). The significance level used is $\alpha = 0.05$.

Relevance of sequence and auction unit

A first aspect to consider are the auction units, which were randomly assigned during the experiment. To ensure this random assignment does not lead to different results for the auction efficiency compared to effi-

Design parameters			Results (Average over all auctions)				
			Bid	Price	Surcharge	Surplus	Welfare
Single-supply	Joint	DP	390.09	355.95	14.39	144.05	160.75
		UP	369.32	361.58	-6.10	138.42	160.16
	Separate	DP	387.05	362.67	11.95	137.34	147.42
		UP	370.85	371.76	-3.15	128.24	148.55
Multi-supply	Joint	DP	385.42	350.35	10.58	150.44	163.02
		UP	367.71	356.96	-6.62	143.04	161.92
	Separate	DP	386.80	359.26	10.93	140.74	150.55
		UP	371.14	365.00	-2.92	135.00	151.24

Table 5.2: Average experimental results over all conducted auctions

ciency resulting from a different assignment, the efficiency for all possible auction units was calculated and statistically analysed. The results presented in C.1 find no statistical difference between different approaches. Therefore, the original auction units from the experiment were used in the following analysis.

A second aspect to consider while calculating differences between auctions results with different design parameters, is to exclude the sequence effect. For this purpose, statistical tests were run to determine whether auction results were different dependent on whether separate auctions were played first by bidders, or joint auctions. The results are presented in detail in C.1. No statistical significance of sequence could be found, and the hypotheses that there is no difference in sequence could not be rejected. As a result, the sequence of auctions was not considered as an explaining variable in the following analysis.

Aggregated results

Table 5.2 gives an overview of the average bid, the average price, the average surcharge, as well as average surplus and welfare of all auctions conducted with the same design parameters.

For all these parameters, a linear-mixed model (Gałecki et al., 2013) is used to test whether the differences are statistically significant. Hereby, the dependent variables are the result parameters. The vector of those is denoted by y. As fixed effects, the different (design) parameters *auction type*, *pricing rule*, *round*, and *bidder type* are used and represented with parameters β_j with $j \in \{1, 2, 3, 4\}$. Further, an interaction effect between auction type and pricing rule is introduced with parameter β_5. The constant is included with parameter β_0. As the advantage of a linear-mixed model is the introduction of dependencies between different observations (Müller et al., 2013), a random effect for the conducted session is also included with parameter g. This takes into account that participants were randomly assigned for one session without the chance of changing their competitors. All participants in one session are thus affected by the same fixed effects (Brown, 2021). The model is thus of the following form

$$\begin{aligned} y = \; & \beta_0 + \beta_1 \cdot Auctiontype + \beta_2 \cdot Pricingrule + \beta_3 \cdot Round \\ & + \beta_4 \cdot Biddertype + \beta_5 \cdot Auctiontype : Pricingrule \\ & + g \cdot Session + \varepsilon. \end{aligned} \tag{5.6}$$

The test results can be found in Table 5.3.[13] Participants' bids are significantly lower in UP auctions, and significantly increase over the rounds, though only to a small amount (see Figure 5.1). Auction prices are significantly higher in separate auctions, compared to joint auctions, and significantly lower in multi-supply auctions than in single-supply auctions. UP auctions lead to significantly higher prices than DP auc-

---

[13] The number of submitted bids from all participants is 13440. The number of conducted auctions is 2400. These numbers lead to the different number of observations in Table 5.3. In the case of prices, the average price in the auction is considered.

Table 5.3: Linear-mixed model to test effects of design parameters on different dependent variables

	Dependent variable:				
	Bid	Price	Surcharge	Surplus	Welfare
Auction type	−0.514	7.594*	−0.848	−7.907*	−12.990*
separate	(1.218)	(1.861)	(0.835)	(1.455)	(1.637)
Pricing rule	−19.300*	6.025*	−18.840*	−6.338*	−0.790
UP	(3.351)	(2.455)	(3.149)	(2.197)	(1.890)
Round	1.500*	−0.054	−0.050	0.053	0.005
	(0.075)	(1.730)	(0.026)	(0.084)	(0.095)
Bidder type	1.559	5.089*	1.278	−5.219*	−2.615*
single-unit	(3.290)	(1.752)	(3.149)	(1.751)	(1.114)
Auction type:	3.127	1.732	3.943*	−1.419	1.743
Pricing rule	(1.722)	(2.632)	(1.190)	(2.058)	(2.315)
Constant	371.100*	351.224*	12.860*	149.187*	163.200*
	(3.158)	(2.323)	(2.956)	(2.073)	(1.795)
Observations	13440	2400	13440	2400	2400

Note: $^{*}p<0.05$

Design parameters			Degree of efficiency (Average over all units)		
			D_{eff}^{bin}	D_{eff}^{rel}	D_{eff}^{rge}
Single-supply	Joint	DP	69.58%	84.38%	96.40%
		UP	16.67%	56.88%	83.92%
	Separate	DP	74.58%	86.25%	96.20%
		UP	14.58%	55.63%	84.53%
Multi-supply	Joint	DP	55.00%	86.56%	97.70%
		UP	3.75%	59.84%	89.12%
	Separate	DP	54.38%	86.09%	96.76%
		UP	1.88%	57.66%	87.05%

Table 5.4: Average degree of efficiency over all 1600 units

tions. The surcharge on participants' costs is significantly lower in UP auctions, i.e, bidders in UP auctions significantly underbid their costs. Further there is a significant interaction effect: the surcharge is the significantly lowest in UP, joint auctions, and the highest in DP, joint auctions (for interpretation of interaction terms, see e.g., Brambor et al., 2006). Auctioneer's surplus is significantly higher in joint auctions and with multi-unit bidders, as well as in DP auctions. Social welfare is significantly higher in joint auctions and significantly higher with multi-supply bidders.

Table 5.4 gives the average degrees of efficiency over all 1600 auction units. For each of the three possible ways to determine the degree of efficiency, also the linear-mixed model (5.6) is used to test significant influences of design parameters. The results of those tests are presented in Table 5.5. For all three possibilities to determine the degree of efficiency, the degree is significantly higher in joint auctions, though the difference is the highest for D_{eff}^{bin}, and the lowest for D_{eff}^{rge}. For the binary and relative approach, the degree of efficiency increases significantly over the rounds, though only very small. Auctions with single-supply bidders

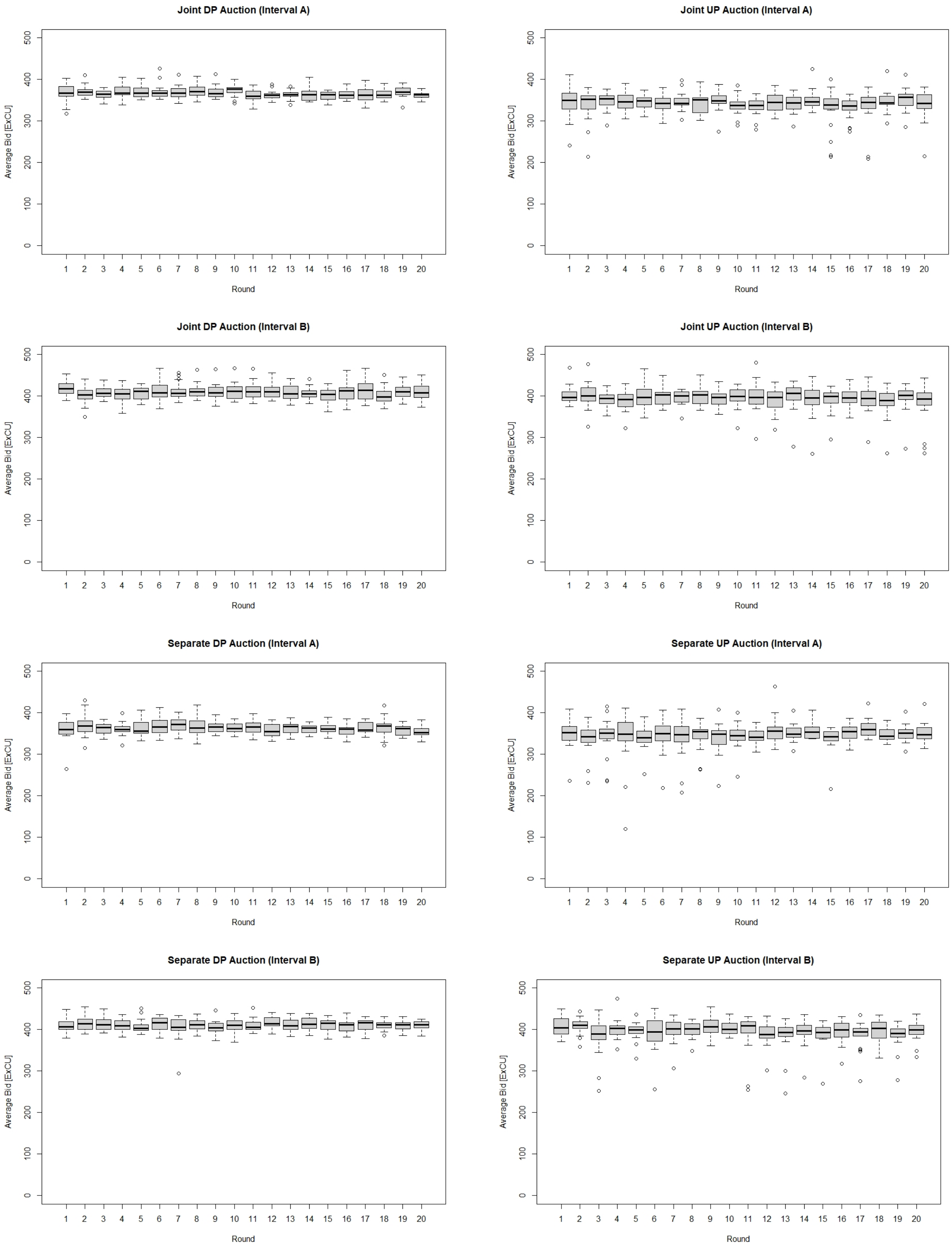

Figure 5.1: Box-and-whisker plots of average bids in different auctions over the rounds: median, interquartile range IQR, whiskers (outliers at max 1.5×IQR), and outliers more than 1.5×IQR.

have a significantly higher binary degree of efficiency, while they have a significantly lower range degree of efficiency.

Table 5.5: Linear-mixed model to test effects of design parameters on degrees of efficiency

	Dependent variable:		
	D_{eff}^{bin}	D_{eff}^{rel}	D_{eff}^{rge}
Auction type separate	−0.523* (0.028)	−0.272* (0.014)	−0.109* (0.007)
Pricing rule UP	0.028 (0.033)	0.009 (0.020)	−0.005 (0.010)
Round	0.004* (0.002)	0.002* (0.001)	0.001 (0.000)
Bidder type single-unit	0.151* (0.027)	−0.018 (0.018)	−0.024* (0.010)
Auction type: Pricing rule	−0.048 (0.039)	−0.026 (0.020)	0.000 (0.009)
Constant	0.501* (0.033)	0.838* (0.020)	0.975* (0.010)
Observations	1600	1600	1600
Note:			*p<0.05

Bidding behaviour

The most striking bidding behaviour is that bidders in all 20 sessions do underbid their costs. A total of 154 participants out of 240 at least once bid below their costs. As seen in Figure 5.2, even bids below the lowest possible realisation cost 300 ExCU in interval A are submitted. These bids are present in all rounds of the UP auctions, but also in a few rounds of DP auctions. Bids above the highest possible realisation costs (450 ExCU in interval B) are also present in all rounds (Figure

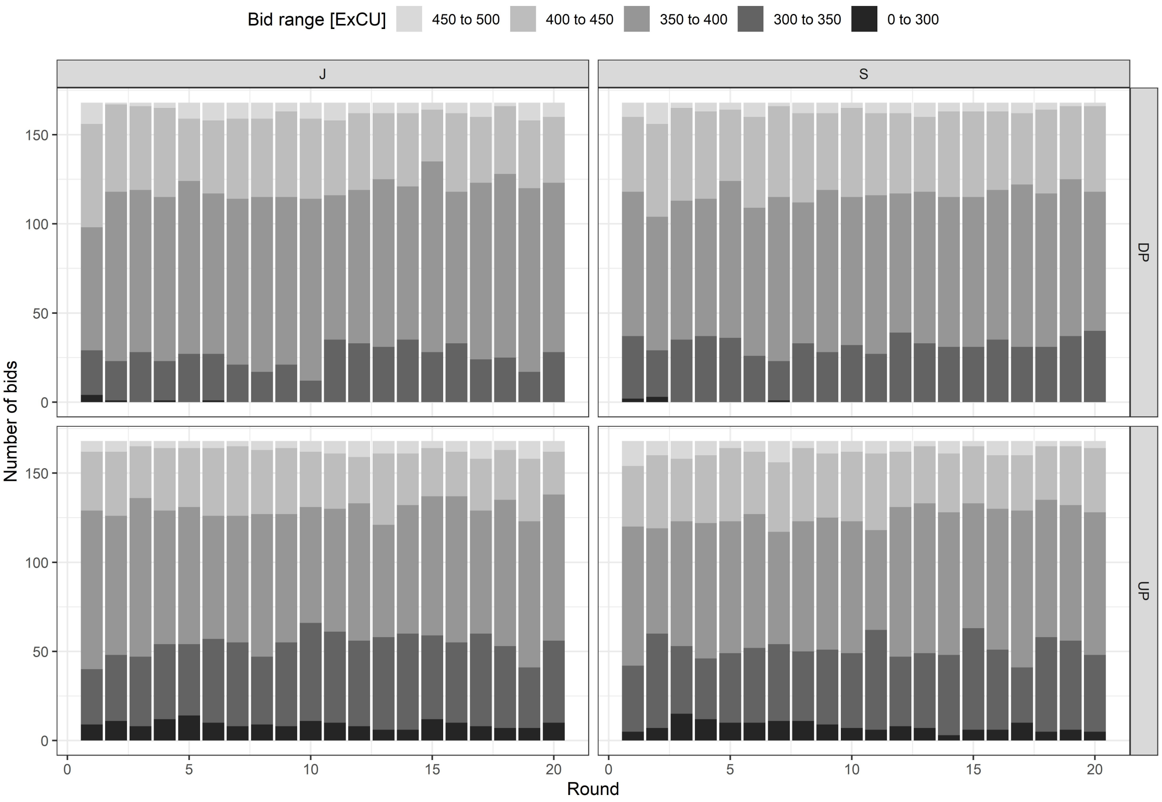

Figure 5.2: Bid distributions differentiated between joint and separate auctions, as well as DP and UP auctions

5.2). The large majority of bids stems from the interval between 350 and 400 ExCU.

The UP auctions are hereby more divers regarding bidding behaviour: bids are spread over a wider interval than in DP auctions for both joint and separate auctions and for both bidder roles (A or B, Figure 5.1). Bidders with role B bid higher than bidders with role A, but otherwise do not differ regarding bidding behaviour (Figure 5.1).

A second kind of irrational bidding behaviour can be analysed in auctions with multi-supply bidders. W.l.o.g. refer to the project with a bidder's lowest realisation costs as Project 1, and the project with the higher costs as Project 2. Then irrational behaviour is submitting a higher bid for Project 1 than for Project 2 (Section 5.2). In the experiment, 2.6% of all possible bid pairs are irrational. Irrationality appears in all 8 session with multi-supply bidders, and 46.9.% of multi-supply bidders at least once submit an irrational bid pair. The average difference between the bid for Project 1 and Project 2 is 47 ExCU, i.e., bidders that behave irrationally submit a bid for Project 2 that is on average 47 ExCU lower than the bid for Project 1.

When analysing the surcharge of the single bids in a bid pair statistically, and comparing it to the surcharge of the bids of single-unit bidders, no statistical difference between Project 1, Project 2 and the project from the single-unit bidder can be found (see C.1). Thus, it cannot be deduced that single- or multi-supply bidders behave differently when deciding on their bid. Also, it cannot be deduced that multi-supply bidders in general behave differently when deciding on their bid for the first and second project.

5.4 Discussion of results

In all considered relevant aspects for an auctioneer, especially a state authority conducting RES auctions, joint auctions perform better than separate auctions. Prices are lower, and surplus, welfare, as well as the degree of efficiency are higher in joint auctions. This is true for both pricing rules and bidder types. The results in Section 5.3.2 thus support the theory in Section 5.2.3. Since the binary approach of measuring efficiency, which is the most prominent one in auction theory (Krishna, 2009), is rather conservative, two different approaches to measure the degree of efficiency are presented. Though the degrees differ in absolute values, the significant result of higher degrees of efficiency for joint auctions are the same for all approaches. The results thus seem robust.

Though pricing rules do not have an effect on efficiency, bidders seriously underbid their costs in UP auctions, while only occasionally in DP auctions. This resulted in losses when those bidders were awarded. Though participants in the experiments were only students, with less to no experience in auction participation, results show dangers of implementing UP auctions. Further, results in real-world auctions hint that the problematic of wrongfully underbidding can be a problem in auctions for RES (Rio, 2016).

The irrationality of some multi-supply bid pairs, though present, do not seem to affect auction outcomes in a significant way. This might be due to the relatively small percentage of occurrences. So, while bidders might increase their profit by optimizing bidding strategies and avoiding obvious irrational choices, this is not a major risk compared to underbidding. Further, an auctioneer has no measures to counteract in order to prevent bidders from choosing this strategy, since the problematic appeared with all auction types and pricing rules.

Still, in some individual cases the underbidding or wrongful bidding also can be due to mistakes while manually submitting the bid. Two participants specifically mentioned this while giving feedback. Further, the change of conduction method from a lab experiment to an online experiment might be the reason for some (missing) differences in auction results for single- and multi-supply bidders. Participants only needed an active internet connection and technical equipment (e.g., mobile phone, tablet or computer) in order to take part in the experiment, the surroundings and thus the exclusive focus on the experimental task could not be observed. As several participants dropped out during four sessions, those sessions could not be finished, and it can be assumed that participants were not concentrated on their task and preferred to drop out. For this reason, online experiments where a large fixed group is needed to finish, and that take longer than a few minutes, are not advised in the future.

Additionally, no differences in bidding behaviour for single-supply, or multi-supply bidders for their different projects could be found. In absence of a equilibrium bidding strategy (Section 5.2), and the absence of a clear learning effect over the rounds (except for a slight increase in bids overall), multi-supply bidders seem to choose a similar strategy as single-supply bidders.

Although results are rather straightforward, the number of participants is still relatively small (240 participants). Nevertheless, all participants needed to play 40 auction rounds, thus giving at least a satisfying number of decisions. To strengthen results, more session of the experiment might still need to be conducted.

5.5 Conclusion and further research

Auctions have been and are still playing an important role in establishing RES in the electricity generation. When designing an auction for RE support, an important decision is whether to conduct multi-technology or technology-specific auctions. This chapter experimentally analyses both auction types under two different pricing rules, DP and UP, and with both single- and multi-supply bidders. The results show an advantage of multi-technology auctions in regards of efficiency, prices, surplus, and welfare. Further, DP auctions perform better than UP auctions in terms of prices, surplus, and welfare as well. Another drawback of UP auctions is the significantly higher irrationality of bidders, since the underbidding of bidders' realisation costs is far higher in absolute terms as well as frequency. Not only is this disadvantageous for the bidders themselves, since losses or even bankruptcy can result, but also for the society as a whole through lower social welfare and the potential loss of these project developers in the long run, since they might be needed for a sustainable future in later years.

The clear advice for policy makers who aim for efficiency and low support payments is to conduct multi-technology auctions with the DP rule. Still, these results are derived in a laboratory setting, and their limitations should thus be considered. For future research, more participants should be present and conducting the experiment to strengthen statistical results. Further, it is advised to also consider real-world auction results of multi-technology and technology-specific auctions, though they might not be easily comparable due to different conduction methods and market characteristics. At last, efficiency might not be the sole policy objective a country has, so studies regarding effectiveness or green growth can be interesting in supplementing the findings of this chapter.

Chapter 6

Conclusions and outlook

With the impending challenge of limiting effects of the climate change, the expansion of RE and an increasing share of electricity produced from RES are inevitable. A major tool in the transition period from fixed support for RE projects to a no-subsidy world in the long term is the use of auctions. However, the design of these auctions for RE support is not an easy task and policy makers face great challenges in deciding on an adequate auction design. Therefore, design elements need to be adjusted carefully and decisions on a certain element can have long-term damaging or enhancing effects on the market. This thesis provides a guideline for policy makers deciding on the conduction of auctions for RE support and how the design may differ based on their goals.

6.1 Summary

This thesis analyses different choices of auction design elements which have not been studied in the literature before. Firstly, the proposed solution to low competition in auction, an automatic reduction of the auction volume is examined both theoretically and experimentally. Secondly, different options of conducting cross-border auctions are analysed and compared. Thirdly, a laboratory experiment to test the different performances of multi-technology and technology-specific auctions is conducted and analysed.

The automatic reduction of auction volume in cases of low competition has been suggested from multiple sources and formalised in different countries worldwide. Still, this design element had not been addressed adequately in existing literature. Chapter 2 shows that auction-theory predicts no participation in auctions where ER is implemented. Though support payments from the auctioneer are predicted to be lower, social welfare, auctioneer's surplus, and the number of awarded goods are lower in auctions with ER compared to standard auctions. Therefore, the implementation of ER has no theoretic advantages, and is further actually harmful for the establishment of RES in the long term. With the help of mechanism design, Chapter 2 further proposes measures to optimise auctions for RE support. In the case of no competition, the ceiling price should be high enough to cover even the highest costs of the bidders. If the valuation for the good is high enough, incentivising full participation is beneficial for all considered objectives. In the case of competition, the optimal choices of a ceiling price and a possible reimbursement of bidders depends on the distribution of bidders' costs and the number of participants. In this case, it is not possible to optimise the auction for all possible goals. Thus, policy makers need to prioritise their goals. A possible compromise can be the decrease of participation costs, which means revisiting entry barriers and prequalification criteria.

Chapter 3 supplements the previous findings by the conduction of a laboratory experiment, where the effects of ER in regards to participation, prices, auctioneer's surplus and social welfare are measured. Though extreme auction outcomes with no participation, like predicted by theory, are rare, they do exists. Further, over the course of different auction rounds, participation, surplus, and welfare decrease steadily and the difference between standard auctions and auctions with ER increases. Although auction prices, and, consequently, support payments, are lower with ER, it is advised against such a measure. Long term negative effects can be deduced from experimental results as well as the theoretical findings, hindering an early establishment of the RE market.

With the goal of a common European market, in the long term, cross-border auctions need to be implemented. Chapter 4 analyses different options for designing cross-border auctions and compares them with regard to efficiency and auction prices. Here, different levels of openness are considered. Unilateral Auctions, where only one country opens their auction for bidders from other countries, and Mutual Auctions, where both countries open their auctions, are easier to implement than Joint Auctions, as a Joint Auction requires a deeper level of cooperation. Further, the time sequence of the auctions is of importance. When bidders have to decide which auction to participate in to prevent penalty charges if awarded in both, this comes with higher prices and a loss of efficiency. The Joint Auction has the highest level of efficiency and the lowest auction prices, but needs a high level of integration. A compromise here are Sequential Mutual Auctions, where bidders can participate in the second auction, if they were not awarded in the first, resulting in an efficient outcome as well. This design choice can thus be seriously considered for future cross-country cooperations.

A similar question is the choice of eligible technologies in an auction. While the theoretic modelling is similar to cross-border auctions, Chapter 5 includes a different aspect to evaluate the inclusion of multiple technologies in one auction, namely analyses the goals of efficiency, prices, surplus, and welfare in an experimental setting. To better reflect the reality of auctions for RE support, both single-supply as well as multi-supply bidders are considered. A striking result, that answers the current discussion on which pricing rule to use, is that DP performs better in every aspect compared to UP auctions. Particularly, the theoretic advantage of UP auctions with the dominant strategy of bidding one's own costs does not show in the experiment, as bidders more often show irrational behaviour in UP auctions, increasing the risk of bankruptcy. Further, multi-technology auctions increase efficiency, surplus and welfare, and lead to lower auction prices. Thus, if policy makers do not aim for a certain percentage or the special support of one technology, it is advised to conduct multi-technology auctions with DP, regardless whether single- or multi-supply bidders participate.

6.2 Critical discussion and further research

The topic of RE will continue to be important in the next years. Without the use of RES in electricity generation, climate change effects cannot be mitigated. Thus, a thorough understanding of auctions for RE support is vital. This thesis supports this understanding by providing an in-depth auction-theoretical and experimental analysis of certain design elements. Still, there is room for further examinations.

A standard assumption in auction-theoretic analyses is rationality of bidders. As shown in literature, and also in the experiments in this thesis, bidders not always behave rationally. Especially the analysis of ER is based on the assumption of rather sophisticated, rational behaviour of bidders, so theoretical results cannot be expected to a full extent in real-world applications, but need to be transferred carefully. Though the conduction of experiments hints at the same direction as theoretical results, actual auctions for RE support might show unexpected outcomes.

With the growing number of conducted auctions, econometric analysis, such as Anatolitis et al., 2022, can supplement the theoretical and experimental results, to capture prior unobserved effects and adapt the auction design accordingly.

Nevertheless, auction-theoretic measures will remain to be one of the key elements of auction analyses. Particularly in a sector where political decisions affect not only industrial companies and project developers, but also society as a whole, it is important to examine mechanisms in a scientific and unbiased way. Lobbying activities or limited understanding of market fundamentals might otherwise influence decisions and create undesired outcomes. This is especially true for design elements which reduce bidders' uncertainties or, more generally speaking, favour one group of bidders over another. All those decisions need to be made with the best possible knowledge of the situation and its affected parties.

Experimental economics are also an important part of evaluating auctions. Though there is a difference between students participating in a laboratory experiment and gaining money, and project developers in large ventures, similar behaviour of both groups can be expected. Albeit, laboratory experiments (as well as theoretic analyses) often simplify real market characteristics, thus not including all possible drivers for bidding behaviour. This can be e.g. applied to cross-border auctions, where the general recommendation of this thesis to conduct Sequential Mutual Auctions can also depend on the exact design of the participating countries. Another cornerstone of analysing auctions for RE support can be agent-based modelling (Welisch et al., 2019), where more characteristics can be implemented.

Lastly, new occurrences and market developments need to be analysed swiftly. Like the suggestion of implementing ER in answer to low levels of competition, new short-term solutions might be proposed. Only after several warnings based on the evaluation presented in this thesis, the large scale application of such measures could be prevented. It cannot be ruled out that future propositions by industry or politics might actually worsen the market in the long-run, due to a lack of theoretical background.

Future research on auctions for RE will thus be conducted for sure in the next years, until RE are fully integrated into the electricity market without need of further support.

6.3 Policy implications

The most striking implication is that policy makers need to be aware of their most important objective, regardless of the design elements they want to implement. An auction is not a panacea and cannot achieve every objective to the fullest, though an optimisation can be made under certain circumstances. With this limitation in mind, this thesis analyses the most common objectives of efficiency, effectiveness[1], auction prices, auctioneer's surplus, and social welfare, and advises policy makers on this basis.

A clear recommendation is to not implement measures which endogenously limit awards in cases of low competition. Instead, policy makers should aim for the establishment of favourable framework conditions for project developers to encourage investments in the market. Short-term undesired auction results promise a better incentive for long-term market commitment, than short-sighted actions which destroy long-term trust and reliability.

Further, bidders seem to perform better and with less risk of irrational

---

[1] The number of awarded goods is only relevant in cases of low competition.

behaviour under DP, whereas theory predicts the same outcomes. Also, the introduction of DP is more transparent for awarded bidders, since it is directly linked to their price bid. Keeping overall social welfare in mind, as well as increasing competition, the use of cross-border auctions and multi-technology auctions for already established technologies and markets can be favourable for policy makers.

Overall, auctions are a suitable instrument to support RE projects, which are not yet competitive with fossil sources in the energy market. When designed carefully, they make an important contribution to a sustainable future with a reliable energy supply from RES.

Appendix A

Appendix to Chapter 2

A.1 Proofs

The proofs of Lemma 1 and Proposition 2 will make use of the following lemma.

Lemma 4.

$$\begin{aligned}&\sum_{i=0}^{k}\binom{n}{i}F(x)^{i-1}(1-F(x))^{n-i-1}(i-nF(x))\\&=-n\binom{n-1}{k}F(x)^{k}(1-F(x))^{n-k-1}\end{aligned}\tag{A.1}$$

$$\begin{aligned}&\sum_{i=0}^{k}\binom{n}{i}(i-k)F(x)^{i-1}(1-F(x))^{n-i-1}(i-nF(x))\\=&\sum_{i=1}^{k}\binom{n}{i}iF(x)^{i-1}(1-F(x))^{n-i}\end{aligned}\tag{A.2}$$

Proof of Lemma 4: We will use the identities

$$\binom{n}{i}i=n\binom{n-1}{i-1}\qquad\text{and}\qquad\binom{n}{i}(n-i)=n\binom{n-1}{i}\tag{A.3}$$

and the binomial theorem

$$\textstyle\sum_{i=0}^{n}\binom{n}{i}F(x)^{i}(1-F(x))^{n-i}=(F(x)+1-F(x))^{n}=1\,.\tag{A.4}$$

Proof of (A.1) via simplifying a telescoping sum.

$$\begin{aligned}
& \Sigma_{i=0}^{k} \binom{n}{i} F(x)^{i-1}(1-F(x))^{n-i-1}(i-nF(x)) \\
= \quad & \Sigma_{i=0}^{k} \binom{n}{i} \left(iF(x)^{i-1}(1-F(x))^{n-i} - (n-i)F(x)^{i}(1-F(x))^{n-i-1} \right) \\
\underset{(A.3)}{=} \quad & n \left(\Sigma_{i=1}^{k} \binom{n-1}{i-1} F(x)^{i-1}(1-F(x))^{n-i} \right. \\
& \left. - \Sigma_{i=0}^{k} \binom{n-1}{i} F(x)^{i}(1-F(x))^{n-i-1} \right) \\
= \quad & n \left(\Sigma_{i=0}^{k-1} \binom{n-1}{i} F(x)^{i}(1-F(x))^{n-i-1} \right. \\
& \left. - \Sigma_{i=0}^{k} \binom{n-1}{i} F(x)^{i}(1-F(x))^{n-i-1} \right) \\
= \quad & -n \binom{n-1}{k} F(x)^{k}(1-F(x))^{n-k-1}
\end{aligned}$$

Proof of (A.2) via induction. For $k=1$, $n(1-F(x))^{n-1} = n(1-F(x))^{n-1}$, which proves the base case. For the induction step assume (A.2) holds for k. Now look at $k+1$.

$$\begin{aligned}
& \Sigma_{i=0}^{k+1} \binom{n}{i} F(x)^{i-1}(1-F(x))^{n-i-1}(i-nF(x))(i-k-1) \\
= \quad & \Sigma_{i=0}^{k} \binom{n}{i} F(x)^{i-1}(1-F(x))^{n-i-1}(i-nF(x))(i-k) \\
& - \Sigma_{i=0}^{k} \binom{n}{i} F(x)^{i-1}(1-F(x))^{n-i-1}(i-nF(x)) \\
\underset{IH}{=} \quad & \Sigma_{i=0}^{k} \binom{n}{i} iF(x)^{i-1}(1-F(x))^{n-i} \\
& - \Sigma_{i=0}^{k} \binom{n}{i} iF(x)^{i-1}(1-F(x))^{n-i-1} \\
& + \Sigma_{i=0}^{k} \binom{n}{i} nF(x)^{i}(1-F(x))^{n-i-1} \\
= \quad & - \Sigma_{i=0}^{k} \binom{n}{i} iF(x)^{i}(1-F(x))^{n-i-1} + \Sigma_{i=0}^{k} \binom{n}{i} nF(x)^{i}(1-F(x))^{n-i-1} \\
= \quad & \Sigma_{i=0}^{k} \binom{n}{i} (n-i)F(x)^{i}(1-F(x))^{n-i-1} \\
= \quad & \Sigma_{i=1}^{k+1} \binom{n}{i-1} (n-i+1)F(x)^{i-1}(1-F(x))^{n-i} \\
= \quad & \Sigma_{i=1}^{k+1} \binom{n}{i} iF(x)^{i-1}(1-F(x))^{n-i}
\end{aligned}$$

■

Proof of Lemma 1: Note that $F(\hat{x}) < 1$ iff $\hat{x} < \bar{x}$ and that $F(\hat{x})$ increases iff $\hat{x}$ increases.

First we show that $\hat{x} < \bar{x}$ if $n > k$ or $r < \bar{x} + c$. If a company with costs $\bar{x}$ participates, the other $n-1$ companies also participate. If a company with costs $\bar{x}$ is wins a good, it receives a payment of r by (P4). A company with $\bar{x}$ wins a good with probability 0 if $n > k$ and with probability 1 if $n \leq k$. A company participates iff its expected profit from participating is non-negative. Thus, if $n > k$, a company with $\bar{x}$ does not participate because $(r - \bar{x}) \cdot 0 - c < 0$. If $n \leq k$, a company with $\bar{x}$ does not participate iff $(r - \bar{x}) \cdot 1 - c < 0$.

If, to the contrary, $n \leq k$ and $r \geq \bar{x} + c$, then the expected payoff of the worst-off type $\bar{x}$ is positive, $r - \bar{x} - c \geq 0$, and all companies participate, $\hat{x} = \bar{x}$ and $F(\hat{x}) = 1$.

To prove the remaining properties, consider the expected profit of the company $\hat{i}$ who receives a good only if no more than $k-1$ other companies participate if $n > k$ or who receives a good for sure if she participates if $n \geq k$. Her expected profit is (see (2.1))

$$\begin{aligned}
\Pi(\hat{x}, r, c, n) &= (r - \hat{x})(1 - F_{(k,n-1)}(\hat{x})) - c && \text{(A.5)}\\
&= \begin{cases} (r - \hat{x}) \sum_{i=0}^{k-1} \binom{n-1}{i} F(\hat{x})^i \big(1 - F(\hat{x})\big)^{n-i-1} - c & \text{if } n > k \\ r - \hat{x} - c & \text{if } n \leq k. \end{cases}
\end{aligned}$$

Since company $\hat{i}$ participates only if $\Pi(\hat{x}, r, c, n) \geq 0$ and since $c > 0$, it follows that $\hat{x} < r$.

If not all companies participate ($\hat{x} < \bar{x}$), company $\hat{i}$ is indifferent between participating and not participating in the auction. Since company $\hat{i}$ is indifferent if and only if her expected profit from participating is zero, the cutoff costs $\hat{x}$ are determined by

$$\Pi(\hat{x}, r, c, n) = 0\,. \tag{A.6}$$

There exists a unique $\hat{x}$ that fulfills property (A.6), since the derivative of (A.5) with respect to $\hat{x}$ is negative for all $\hat{x} \leq r$:[1]

$$\begin{aligned} &\frac{\partial \Pi(\hat{x}, r, c, n)}{\partial \hat{x}} \\ &= \begin{cases} -\sum_{i=0}^{k-1} \binom{n-1}{i} F(\hat{x})^i \big(1 - F(\hat{x})\big)^{n-i-1} & \\ -(r - \hat{x}) k \binom{n-1}{k} f(\hat{x}) F(\hat{x})^{k-1} \big(1 - F(\hat{x})\big)^{n-k-1} & \text{if } n > k \\ -1 & \text{if } n \leq k \end{cases} \\ &< 0\,. \end{aligned} \tag{A.7}$$

To determine how $\hat{x}$ depends on r and c, we apply the implicit function theorem. With (A.6) and (A.7) we get

$$\begin{aligned} \frac{d\hat{x}}{dr} &= -\frac{\frac{\partial \Pi(\hat{x},r,c,n)}{\partial r}}{\frac{\partial \Pi(\hat{x},r,c,n)}{\partial \hat{x}}} = -\frac{\sum_{i=0}^{\min\{k,n\}-1} \binom{n-1}{i} F(\hat{x})^i \big(1 - F(\hat{x})\big)^{n-i-1}}{\frac{\partial \Pi(\hat{x},r,c,n)}{\partial \hat{x}}} > 0\,, \\ \frac{d\hat{x}}{dc} &= -\frac{\frac{\partial \Pi(\hat{x},r,c,n)}{\partial c}}{\frac{\partial \Pi(\hat{x},r,c,n)}{\partial \hat{x}}} = \frac{1}{\frac{\partial \Pi(\hat{x},r,c,n)}{\partial \hat{x}}} < 0\,. \end{aligned}$$

The cutoff costs $\hat{x}$ increase in k if $n > k$ because the probability in (A.5) increases in k.

Further, $\hat{x}$ decreases in n if $n \geq k$. For given $\hat{x}$, the probability of getting a good in (A.5) decreases in n because $F_{(k,n-1)}(\hat{x}) < F_{(k,n)}(\hat{x})$. Take the $\hat{x}$ that fulfills (A.6) for n companies. All companies with $x < \hat{x}$ would have a positive expected payoff from behaving like the company with $\hat{x}$. If there were $n + 1$ companies and the company with costs $\hat{x}$ was the cutoff type, its probability of getting a good would be lower and

---

[1] The second term of the derivative stems from simplifying a telescoping sum (see Lemma 4(A.1)).

the payoff in (A.5) would be negative. Thus, the cutoff costs with $n+1$ companies must be smaller than with n companies. ■

Proof of Lemma 2: companies participate in the auction iff $x_i \leq \hat{x}$. If $n > k$, type $\hat{x}$ wins iff $m \leq k$ and, by (P4), type $\hat{x}$ can then bid to receive the maximum payment r. Type $\hat{x}$'s expected profit from the auction is, with $G(x) = F_{(k,n-1)}(x)$, $\pi(\hat{x}, r, c, n) = (r - \hat{x})(1 - G(\hat{x})) = c$ (see (2.1) and the proof of Lemma 1). If $n \leq k$, $\pi(\hat{x}, r, c, n) = r - \hat{x}$.

If $n > k$, we assume symmetric, strictly increasing equilibrium bidding functions (P5). Denote by $\pi(x, z)$ the expected profit of a company of type $x \leq \hat{x}$ who bids as if her type was z. Let $p(z)$ denote the payment to a company who bids like type z. To maximize

$$\pi(x,z) = p(z) - (1 - G(z))x \qquad \text{for all } x, z \in [\underline{x}, \hat{x}]\,,$$

we derive the first-order condition

$$\frac{\mathrm{d}}{\mathrm{d}z}\pi(x,z) = \frac{d}{dz}p(z) + g(z)x = 0 \qquad \text{for all } x, z \in [\underline{x}, \hat{x}]\,.$$

In equilibrium, $z = x$, and, thus

$$\begin{aligned} \frac{\mathrm{d}}{\mathrm{d}y}p(y) &= -g(y)y && \text{for all } y \in [\underline{x}, \hat{x}] \\ \implies p(x) &= \text{const} + \int_x^{\hat{x}} g(y)y\,\mathrm{d}y \\ &= (1 - G(\hat{x}))\,r + \int_x^{\hat{x}} g(y)y\,\mathrm{d}y && \text{for all } x \in [\underline{x}, \hat{x}]\,. \end{aligned}$$

Therefore, the expected profit

$$\pi(x,r,c,n) = (1 - G(\hat{x}))\,r + \int_x^{\hat{x}} g(y)y\,\mathrm{d}y - (1 - G(x))\,x \quad \text{for all } x \in [\underline{x}, \hat{x}]\,, \tag{A.8}$$

is the same for all auctions that assign goods to the same types (P5) and in which a company can bid to receive r if $m \leq k$ (P4).

If $n \leq k$, $\pi(x, r, c, n) = r - x$ for all $x \in [\underline{x}, \hat{x}]$ in all auctions with property (P4). ■

Proof of Lemma 3: The proof uses payoff equivalence (Lemma 2).

Consider first the case $n > k$. In a pay-as-bid auction, if all companies choose β^{PaB}, a company with type $x \leq \hat{x}$ wins, has costs x, and receives the payment $\beta^{PaB}(x, r)$ iff she is among the k lowest types, which has probability $1 - G(x)$ with $G(x) = F_{(k,n-1)}(x)$. Therefore, her expected payment is

$$\begin{aligned}(1 - G(x))\beta^{PaB}(x, r) =& (1 - G(x))\, x + (1 - G(\hat{x}))(r - \hat{x}) \\ &+ \int_x^{\hat{x}} (1 - G(y))\, \mathrm{d}y \\ =& (1 - G(\hat{x}))\, r + \int_x^{\hat{x}} g(y) y \, \mathrm{d}y \,,\end{aligned}$$

using partial integration $\int_x^{\hat{x}} (1 - G(y))\, \mathrm{d}y = [(1 - G(y))y]_x^{\hat{x}} + \int_x^{\hat{x}} g(y) y \, \mathrm{d}y$. Thus, her expected profit is equal to (A.8) in the proof of Lemma 2.

In a uniform-price auction, if all companies choose $\beta^{UP}(x, r) = x$, a company with type $x \leq \hat{x}$ wins and has costs x if she is among the k lowest types, which has probability $1 - G(x)$. She receives the payment r if no more than k companies participate, which has probability $1 - G(\hat{x})$. Her payment is equal to her opponents' k-th lowest bid if more than k companies participate and she is among the k lowest types. Her expected payment from these cases is $\int_x^{\hat{x}} g(y) y \, \mathrm{d}y$. Thus, her expected profit is equal to (A.8).

If $n \leq k$, $\pi(x, r, c, n) = r - x$ for all $x \in [\underline{x}, \hat{x}]$ by payoff equivalence. Bidders receive the payment r by bidding r in a pay-as-bid auction and by bidding x (or r) in a uniform-price auction. ■

Proof of Proposition 2: We will prove parts O1 to O3 of Proposition 2 consecutively.

O1 Auctioneer's surplus We use standard mechanism design arguments (e.g., Myerson, 1981; Krishna, 2009) to derive optimal mechanisms when companies have to bear participation costs in order to bid. Let $q^p(x_i)$, $q^p : [\underline{x}, \bar{x}] \to [0, 1]$, define a company's participation probability as a function of her costs x_i, let $q_i^g(\mathbf{x})$, $q_i^g : [\underline{x}, \bar{x}]^n \to [0, 1]$ denote company i's probability of getting an item when the costs $\mathbf{x}$ are announced conditional on i's participation, and let $p_i(\mathbf{x})$, $p_i : [\underline{x}, \bar{x}]^n \to \mathbb{R}$ denote the payment to company i when the costs $\mathbf{x}$ are announced. The companies send messages $\mathbf{x}$ to the mechanism. The mechanism designer chooses a mechanism $(q^p, (q_1^g, q_2^g, \ldots, q_n^g), (p_1, p_2, \ldots, p_n))$ to maximize his expected surplus, taking the companies' (interim) individual rationality (IR) and incentive compatibility (IC) constraints into account. His problem is

$$\max_{(q^p,(q_1^g,q_2^g,\ldots,q_n^g),(p_1,p_2,\ldots,p_n))} \int \sum_{i=1}^{n} \left[q^p(x_i) q_i^g(\mathbf{x}) v - p_i(\mathbf{x})\right] \, \mathrm{d}H(\mathbf{x})$$

$$\text{s.t. (IR), (IC)}$$

$$0 \leq q^p(x_i) \leq 1, 0 \leq q_i^g(\mathbf{x}) \leq 1 \quad \forall i = 1, 2, \ldots, n, \sum_{i=1}^{n} q_i^g(\mathbf{x}) \leq k$$

where $H(\mathbf{x})$ denotes the joint distribution of the individual cost distributions, $H(\mathbf{x}) = \Pi_{i=1}^n F(x_i)$ and $H_{-i}(\mathbf{x}_{-i}) = \Pi_{j \neq i} F(x_j)$.

A company i's (interim) expected payoff from reporting x_i when costs are x_i is

$$\Pi_i(x_i) = \int \left[p_i(\mathbf{x}) - q^p(x_i) \left(q_i^g(\mathbf{x}) x_i + c\right)\right] \mathrm{d}H_{-i}(\mathbf{x}_{-i}) \,. \qquad \text{(A.9)}$$

The IR constraint and the IC constraint, which ensure truthful reporting of x_i, are

$$\Pi_i(x_i) \geq 0 \qquad \forall x_i \in [\underline{x}, \bar{x}] \qquad \text{(IR)}$$

$$\Pi_i(x_i) \geq \int [p_i(x_i', \mathbf{x}_{-i}) - q^p(x_i') \left(q_i^g(x_i', \mathbf{x}_{-i})x_i + c\right)] \mathrm{d}H_{-i}(\mathbf{x}_{-i}) \qquad \forall x_i, x_i' \in [\underline{x}, \bar{x}] \,. \qquad \text{(IC)}$$

Furthermore, define company i's (interim) expected probability of getting a good conditional on i's participation

$$Q_i(x_i) := \int q_i^g(\mathbf{x}) \mathrm{d}H_{-i}(\mathbf{x}_{-i}) \,.$$

Condition (IC) implies, for all x_i and x_i'

$$\begin{aligned}
\Pi_i(x_i) &= \int \left[p_i(x_i, \mathbf{x}_{-i}) - q^p(x_i) \left(q_i^g(x_i, \mathbf{x}_{-i})x_i + c\right)\right] \mathrm{d}H_{-i}(\mathbf{x}_{-i}) \\
&\geq \int \left[p_i(x_i', \mathbf{x}_{-i}) - q^p(x_i') \left(q_i^g(x_i', \mathbf{x}_{-i})x_i + c\right)\right] \mathrm{d}H_{-i}(\mathbf{x}_{-i}) \\
&= \int \left[p_i(x_i', \mathbf{x}_{-i}) - q^p(x_i') \left(q_i^g(x_i', \mathbf{x}_{-i})x_i' + c\right)\right] \mathrm{d}H_{-i}(\mathbf{x}_{-i}) \\
&\qquad + \int \left[q^p(x_i')\, q_i^g(x_i', \mathbf{x}_{-i})(x_i' - x_i)\right] \mathrm{d}H_{-i}(\mathbf{x}_{-i}) \\
&= \Pi_i(x_i') + q^p(x_i')Q_i(x_i')(x_i' - x_i) \,.
\end{aligned}$$

Thus, for $x_i > x_i'$,

$$\frac{\Pi_i(x_i) - \Pi_i(x_i')}{x_i - x_i'} \geq -q^p(x_i')Q_i(x_i')$$

and for $x_i < x_i'$,

$$\frac{\Pi_i(x_i) - \Pi_i(x_i')}{x_i - x_i'} \leq -q^p(x_i')Q_i(x_i') \,.$$

Therefore, (IC) implies that

$$\frac{\mathrm{d}\Pi_i(x_i)}{\mathrm{d}x_i} = -q^p(x_i)Q_i(x_i)$$

and, by integration,

$$\Pi_i(x_i) = \text{const}_i + \int_{x_i}^{\bar{x}} q^p(z) Q_i(z)\,\mathrm{d}z. \tag{A.10}$$

Using (A.9) and (A.10) we can rewrite the auctioneer's expected surplus with incentive compatible payoffs of companies as

$$\begin{aligned}
\Pi_0 &= \int \sum_{i=1}^{n} q^p(x_i) q_i^g(\mathbf{x}) v - p_i(\mathbf{x})\,\mathrm{d}H(\mathbf{x}) \\
&= \int \Bigg[\sum_{i=1}^{n} q^p(x_i) q_i^g(\mathbf{x}) v - p_i(\mathbf{x}) \\
&\quad + \int p_i(\mathbf{x}) - q^p(x_i)\left(q_i^g(\mathbf{x}) x_i + c\right) \mathrm{d}H_{-i}(\mathbf{x}_{-i}) \Bigg] \mathrm{d}H(\mathbf{x}) \\
&\quad - \int \sum_{i=1}^{n} \Pi_i(x_i)\,\mathrm{d}H(\mathbf{x}) \\
&= \int \sum_{i=1}^{n} q^p(x_i)\left[q_i^g(\mathbf{x})(v - x_i) - c\right] \mathrm{d}H(\mathbf{x}) - \sum_{i=1}^{n} \text{const}_i \\
&\quad - \int \sum_{i=1}^{n} \int_{x_i}^{\bar{x}} q^p(z) Q_i(z)\,\mathrm{d}z\,\mathrm{d}H(\mathbf{x}) \\
&= \int \sum_{i=1}^{n} q^p(x_i)\left[q_i^g(\mathbf{x})(v - x_i) - c\right] \mathrm{d}H(\mathbf{x}) - \sum_{i=1}^{n} \text{const}_i \\
&\quad - \sum_{i=1}^{n} \int \frac{F(x_i)}{f(x_i)} q^p(x_i) Q_i(x_i)\,\mathrm{d}H(\mathbf{x}) \\
&= \int \sum_{i=1}^{n} q^p(x_i)\left[q_i^g(\mathbf{x})\left(v - x_i - \frac{F(x_i)}{f(x_i)}\right) - c\right] \mathrm{d}H(\mathbf{x}) - \sum_{i=1}^{n} \text{const}_i\,,
\end{aligned}$$

where in the next-to-last step we interchanged the order of integration in the hindmost integral.[2] To maximize his surplus, the auctioneer will choose const_i as low as possible, which is zero because (IC) (i.e., (A.10)) and (IR) bound const_i to zero from below.

---

[2] $\int \int_{x_i}^{\bar{x}} q^p(z) Q_i(z)\,\mathrm{d}z\,\mathrm{d}H(\mathbf{x}) = \int \int_{\underline{x}}^{\bar{x}} \int_{x_i}^{\bar{x}} q^p(z) Q_i(z)\,\mathrm{d}z\,\mathrm{d}F(x_i)\,\mathrm{d}H_{-i}(\mathbf{x}_{-i}) =$
$\int \int_{\underline{x}}^{\bar{x}} \int_{\underline{x}}^{z} q^p(z) Q_i(z) \mathrm{d}F(x_i)\,\mathrm{d}z\,\mathrm{d}H_{-i}(\mathbf{x}_{-i}) = \int \int_{\underline{x}}^{\bar{x}} q^p(z) Q_i(z) F(z)\,\mathrm{d}z\,\mathrm{d}H_{-i}(\mathbf{x}_{-i}) =$
$= \int \int_{\underline{x}}^{\bar{x}} \frac{q^p(z) Q_i(z) F(z)}{f(z)}\,\mathrm{d}F(z)\,\mathrm{d}H_{-i}(\mathbf{x}_{-i}) = \int \frac{q^p(x_i) Q_i(x_i) F(x_i)}{f(x_i)}\,\mathrm{d}H(\mathbf{x}).$

Thus, the auctioneer's problem can be written as

$$\max_{(q^p,(q_1^g,q_2^g,\ldots,q_n^g),(p_1,p_2,\ldots,p_n))} \int \sum_{i=1}^{n} q^p(x_i)\left[q_i^g(\mathbf{x})\left(v - x_i - \frac{F(x_i)}{f(x_i)}\right) - c\right] \mathrm{d}H(\mathbf{x})$$

$$\text{s.t.}\quad 0 \le q^p(x_i) \le 1, \quad 0 \le q_i^g(\mathbf{x}) \le 1 \quad \forall i = 1,2,\ldots,n, \quad \sum_{i=1}^{n} q_i^g(\mathbf{x}) \le k$$

We assume that $x_i + \frac{F(x_i)}{f(x_i)}$ is increasing in x_i. Thus, either there exists a unique $\tilde{x} < \bar{x}$ such that $v - \tilde{x} - \frac{F(\tilde{x})}{f(\tilde{x})} = 0$ and $v - x_i - \frac{F(x_i)}{f(x_i)} \ge 0$ for all $x_i \le \tilde{x}$, or we have that $v - x_i - \frac{F(x_i)}{f(x_i)} \ge 0$ for all $x_i \in [\underline{x}, \bar{x}]$, in which case $\tilde{x} = \bar{x}$. Conditional on participation, the auctioneer will choose $q_i^g(\mathbf{x}) = 1$ for the at most $\min\{n,k\}$ companies with the lowest $x_i \le \tilde{x}$, and $q_i^g(\mathbf{x}) = 0$ for the remaining companies. Thus, for companies that participate and have $x_i \le \tilde{x}$, we get

$$\begin{aligned} Q_i(x_i) &= \int q_i^g(\mathbf{x}) \mathrm{d}H_{-i}(\mathbf{x}_{-i}) \\ &= \mathrm{Prob}\{x_i \text{ is among the } \min\{n,k\} \text{ lowest costs}\} \\ &= \sum_{j=0}^{\min\{k,n\}-1} \binom{n-1}{j} F(x_i)^j (1 - F(x_i))^{n-j-1}\,. \end{aligned}$$

The auctioneer maximizes

$$\max_{(q^p,(p_1,p_2,\ldots,p_n))} \sum_{i=1}^{n} \int q^p(x_i)\left[Q_i(x_i)\left(v - x_i - \frac{F(x_i)}{f(x_i)}\right) - c\right] \mathrm{d}F(x_i)$$

$$\text{s.t.} \qquad 0 \le q^p(x_i) \le 1$$

by choosing $q^p(x_i) = 1$ if $Q_i(x_i)\left(v - x_i - \frac{F(x_i)}{f(x_i)}\right) \ge c$ and $q^p(x_i) = 0$ if the inverse holds. Because $x_i + \frac{F(x_i)}{f(x_i)}$ and $Q_i(x_i)$ are increasing in x_i for all $x_i < \bar{x}$, there exists a unique $\hat{x} \le \tilde{x}$ such that $q^p(x_i) = 1$ if $x_i \le \hat{x}$ and $q^p(x_i) = 0$ if $x_i > \hat{x}$. For $n > k$, $\hat{x}$ is determined by $Q_i(\hat{x})\left(v - \hat{x} - \frac{F(\hat{x})}{f(\hat{x})}\right) = c$. For $n \le k$, $Q_i(x_i) = 1$ for all $x_i \in [\underline{x}, \bar{x}]$ (by the binomial theorem (A.4)). Then, either $\hat{x}$ is the solution of $v - \hat{x} - \frac{F(\hat{x})}{f(\hat{x})} = c$, in which case $\hat{x} \leq \bar{x}$, or we have that $v - \bar{x} - \frac{1}{f(\bar{x})} > c$, in which case $\hat{x} = \bar{x}$. Summarizing, and, for convenience, setting $Q_i(x_i) = 0$ if $q^p(x_i) = 0$, we have

$$q^p(x_i) = \begin{cases} 0 & \text{if } x_i > \hat{x} \\ 1 & \text{if } x_i \leq \hat{x} \end{cases} \tag{A.11}$$

$$Q_i(x_i) = \begin{cases} 0 & \text{if } x_i > \hat{x} \\ \sum_{j=0}^{\min\{k,n\}-1} \binom{n-1}{j} F(x_i)^j (1 - F(x_i))^{n-j-1} & \text{if } x_i \leq \hat{x}\,. \end{cases} \tag{A.12}$$

It remains to determine payment functions $p_1, p_2, \ldots, p_n$ such that the payoff (A.9) satisfies incentive compatibility (A.10):

$$\Pi_i(x_i) = \int p_i(\mathbf{x}) - q^p(x_i)\left(q_i^g(\mathbf{x}) x_i + c\right) \mathrm{d}H_{-i}(\mathbf{x}_{-i}) = \int_{x_i}^{\bar{x}} q^p(z) Q_i(z)\, \mathrm{d}z\,.$$

Plugging in (A.11) and (A.12) gives

$$\Pi_i(x_i) = \begin{cases} \int p_i(\mathbf{x}) \mathrm{d}H_{-i}(\mathbf{x}_{-i}) = 0 & \text{if } x_i > \hat{x} \\ \int p_i(\mathbf{x}) \mathrm{d}H_{-i}(\mathbf{x}_{-i}) - Q_i(x_i) x_i - c = \int_{x_i}^{\hat{x}} Q_i(z)\, \mathrm{d}z & \text{if } x_i \leq \hat{x} \end{cases}$$

and we get

$$\int p_i(\mathbf{x}) \mathrm{d}H_{-i}(\mathbf{x}_{-i}) = \begin{cases} 0 & \text{if } x_i > \hat{x} \\ \int_{x_i}^{\hat{x}} Q_i(z)\, \mathrm{d}z + Q_i(x_i) x_i + c & \text{if } x_i \leq \hat{x}\,. \end{cases} \tag{A.13}$$

In the case of $n > k$, let $y_{(k,n-1)}$ denote the k-th lowest of i's opponents' realised costs $\mathbf{x}_{-i}$ if $k < n$ and let $F_{(k,n-1)}$ denote the distribution of the random variable $X_{(k,n-1)}$. Note that $F_{(k,n-1)}(z) = 1 - Q_i(z)$. (The zero probability event $y_{(k,n-1)} = x_i$ is ignored in what follows and can be resolved by random tie-breaking.) In the case of $n \leq k$, for ease of notation define $y_{(k,n-1)} > \hat{x}$ and $F_{(k,n-1)}(z) = 1 - Q_i(z) = 0$ for all $z \in [\underline{x}, \bar{x}]$.

Payment functions that fulfill (A.13) if $\hat{x} < \bar{x}$ are, for all $s \in [0, c]$,

$$p_i(\mathbf{x}) = \begin{cases} 0 & \text{if } x_i > \hat{x} \\ v - \frac{F(\hat{x})}{f(\hat{x})} - \frac{s}{Q_i(\hat{x})} + s & \text{if } x_i \leq \hat{x} < y_{(k,n-1)} \\ y_{(k,n-1)} + s & \text{if } x_i < y_{(k,n-1)} \leq \hat{x} \\ s & \text{if } y_{(k,n-1)} < x_i \leq \hat{x} \end{cases} \tag{A.14}$$

Obviously, (A.14) fulfills (A.13) for $x_i > \hat{x}$. For $x_i \leq \hat{x}$ and (A.14), we get

$$\begin{aligned} \int p_i(\mathbf{x}) \mathrm{d}H_{-i}(\mathbf{x}_{-i}) =& s + (1 - F_{(k,n-1)}(\hat{x})) \left(v - \frac{F(\hat{x})}{f(\hat{x})} - \frac{s}{Q_i(\hat{x})} \right) \\ & + \int_{x_i}^{\hat{x}} z \mathrm{d}F_{(k,n-1)}(z) \\ =& s + Q_i(\hat{x}) \left(v - \frac{F(\hat{x})}{f(\hat{x})} - \frac{s}{Q_i(\hat{x})} \right) + \left[z F_{(k,n-1)}(z) \right]_{x_i}^{\hat{x}} \\ & - \int_{x_i}^{\hat{x}} F_{(k,n-1)}(z) \mathrm{d}z \\ =& Q_i(\hat{x}) \left(v - \frac{F(\hat{x})}{f(\hat{x})} \right) - Q_i(\hat{x})\hat{x} + Q_i(x_i) x_i \\ & + \int_{x_i}^{\hat{x}} Q_i(z) \mathrm{d}z \\ =& c + x_i Q_i(x_i) + \int_{x_i}^{\hat{x}} Q_i(z) \mathrm{d}z \,. \end{aligned}$$

According to Stegemann (1996, Lemma 1), every direct mechanism in which each company announces its type is associated with an outcome-equivalent semi-direct mechanism in which only participating companies announce their type.

In the semi-direct mechanism associated with (A.14), companies participate in the auction iff $x_i \leq \hat{x}$, participating companies reveal their true costs x_i and receive a fixed payment of s, and the assignment and payments are determined by a uniform-price rule with the ceiling price

$v - \frac{F(\hat{x})}{f(\hat{x})} - \frac{s}{1-F_{(k,n-1)}(\hat{x})}$. By independence of the bidding strategy from the reimbursement and by payoff equivalence (Lemma 2), the pricing rule could be replaced by any pricing rule with a monotonic symmetric equilibrium, i.e., the uniform-price auction can be replaced by any standard auction.

If $\hat{x} = \bar{x}$, a payment function that fulfills (A.13) is $p_i(\mathbf{x}) = c+\bar{x}$, which can be implemented by a uniform-price auction with ceiling price $c+\bar{x}-s$ and reimbursement s for $s \in [0, c]$. Then, all companies participate and receive the ceiling price $c + \bar{x} - s$ and the reimbursement s.

O2 Social welfare We first determine the socially optimal cutoff value $\hat{x}$, which by the assumption of symmetry is the same for all companies. Second, we determine the ceiling price $r_{s=0}$ in a uniform-price auction without reimbursement that induces socially optimal participation. Third, we describe auctions with a reimbursement $s \in (0, c]$ that generate the same expected welfare.

The expected social welfare S given a cutoff $\hat{x}$ is

$$\begin{aligned} S = &- ncF(\hat{x}) - \textstyle\sum_{i=1}^{\min\{k,n\}} E[X_{(i,n)} | X_{(i,n)} \leq \hat{x}]\, F_{(i,n)}(\hat{x}) \\ &+ v \min\{k, n\} \\ &- v \textstyle\sum_{i=0}^{\min\{k,n\}-1} (\min\{k, n\} - i) \binom{n}{i} F(\hat{x})^i (1 - F(\hat{x}))^{n-i}\,. \end{aligned}$$

First, assume $v \geq \bar{x} + c$ and $n \leq k$. Then, participation by all companies is socially optimal and the auctioneer attracts participation by all companies with a ceiling price $r_{s=0} \geq \bar{x} + c$. The same participation can be achieved by a ceiling price $r_s \geq \bar{x} + c - s$ and a reimbursement $s \in (0, c]$ to all participants. The auctioneer's payments are lowest with the ceiling prices $r_s = \bar{x} + c - s$ for all $s \in [0, c]$.

Second, assume $v < \bar{x} + c$ or $n > k$. The first-order condition of the problem to maximize S is $\partial S/\partial\hat{x} = 0$, where

$$\begin{aligned}\frac{\partial S}{\partial \hat{x}} =& -ncf(\hat{x}) - \sum_{i=1}^{\min\{k,n\}} \hat{x} f_{(i,n)}(\hat{x}) - vf(\hat{x}) \\ &\cdot \sum_{i=0}^{\min\{k,n\}-1} \tbinom{n}{i} (\min\{k,n\} - i) F(\hat{x})^{i-1} (1 - F(\hat{x}))^{n-i-1} (i - nF(\hat{x}))\,,\end{aligned}$$

which with $f_{(i,n)}(\hat{x}) = nf(\hat{x})\binom{n-1}{i-1}F(\hat{x})^{i-1}(1-F(\hat{x}))^{n-i}$ and Lemma 4 (A.2) and (A.3) leads to

$$(v - \hat{x}) \sum_{i=1}^{\min\{k,n\}} \tbinom{n-1}{i-1} F(\hat{x})^{i-1} (1 - F(\hat{x}))^{n-i} - c = 0\,. \tag{A.15}$$

For $v = r$, Condition (A.15) equals Condition (2.1) to determine the cutoff costs $\hat{x}$ of equilibrium participation. Thus, $r^{O2}_{s=0} = v$ attracts the participation that generates the social optimum. (Second-order conditions can be straightforwardly checked.)

One socially optimal mechanism is therefore a uniform-price auction with the ceiling price $r_{s=0} = v$. Other auctions that achieve socially optimal participation of all types $x \leq \hat{x}$ are a uniform-price auction with $r_s = v - s/(1 - F_{(k,n-1)}(\hat{x}))$ and an additional payment of s to all participants, where $s \in (0, c]$. In such an auction, type $\hat{x}$'s expected payoff is $(v - s/(1 - F_{(k,n-1)}(\hat{x})) - \hat{x})(1 - F_{(k,n-1)}(\hat{x})) + s - c = (v - \hat{x})(1 - F_{(k,n-1)}(\hat{x})) - c$, which is zero by Condition (2.1). $\hat{x}$ is thus indeed the highest type that will participate.

O3 Number of goods allotted The maximum number of goods allotted is k if $n > k$ or n if $n \leq k$. A mechanism that guarantees $\max\{n, k\}$ participants, which with symmetric entry requires $\hat{x} = \bar{x}$, is therefore optimal. If $n \leq k$, as with O1, full participation can be achieved by a uniform-price auction with ceiling price $r_s \geq \bar{x} + c - s$ and a reimbursement $s \in (0, c]$ to all participants. Among these options, the one with $r_s = \bar{x} + c - s$ has the lowest payments. If $n > k$ and all companies participate, type $\bar{x}$ will not win in the auction. Thus, with a uniform-price auction and reimbursement $s \in [0, c)$, type $\bar{x}$ will not participate, independent of the ceiling price (Lemma 1). However, with a uniform-price auction with $r \geq \bar{x}$ and a reimbursement c, the auctioneer achieves full participation. Among these options, the one with $r_s = \bar{x}$ has the lowest payments. ■

Proof of Corollary 1: The part on the case $n \leq k$ and $v \geq \bar{x} + \frac{1}{f(\bar{x})} + c$ follows directly from Proposition 2. The part on the case $n > k$ or $v < \bar{x} + c$ follows from direct comparisons using the results in Proposition 2. The cutoff $\hat{x}^{O3}$ is equal to $\bar{x}$, and $\bar{x} > \hat{x}^{O2}$ because $\bar{x}$ violates the equation to determine $\hat{x}^{O2}$: $(v - \bar{x})(1 - F_{(k,n-1)}(\bar{x})) = (v - \bar{x}) \cdot 0 < c$. Further, we have $\hat{x}^{O2} > \hat{x}^{O1}$ because otherwise the equations to determine $\hat{x}^{O2}$ and $\hat{x}^{O1}$ are violated. Assume to the contrary that $\hat{x}^{O2} \leq \hat{x}^{O1}$. Then $1 - F(\hat{x}^{O2}) \geq 1 - F(\hat{x}^{O1})$, and fulfilling $(v - \hat{x}^{O2})(1 - F(\hat{x}^{O2})) = c = (v - \hat{x}^{O1} - F(\hat{x}^{O1})/f(\hat{x}^{O1}))(1 - F(\hat{x}^{O1}))$ requires $(v - \hat{x}^{O2}) \leq (v - \hat{x}^{O1} - F(\hat{x}^{O1})/f(\hat{x}^{O1}))$. This implies $F(\hat{x}^{O1})/f(\hat{x}^{O1}) \leq \hat{x}^{O2} - \hat{x}^{O1} \leq 0$, a contradiction. We get that $r_s^{O2} > r_s^{O1}$ for all $s \in [0, c)$ again from the equations to determine $\hat{x}^{O2}$ and $\hat{x}^{O1}$. Assume to the contrary that $r_s^{O2} \leq r_s^{O1}$, i.e., $v - s/(1 - F_{(k,n-1)}(\hat{x}^{O2})) \leq v - F(\hat{x}^{O1})/f(\hat{x}^{O1}) - s/(1 - F_{(k,n-1)}(\hat{x}^{O1}))$. Replacing $(1 - F_{(k,n-1)}(\hat{x}^{O2}))$ and $(1 - F_{(k,n-1)}(\hat{x}^{O1}))$ using the equations to determine the optimal cutoffs yields $v - s(v - \hat{x}^{O2})/c \leq v - F(\hat{x}^{O1})/f(\hat{x}^{O1}) - s(v - F(\hat{x}^{O1})/f(\hat{x}^{O1}) - \hat{x}^{O1})/c$. Rearranging gives $(1 - s/c)F(\hat{x}^{O1})/f(\hat{x}^{O1}) \leq s(\hat{x}^{O1} - \hat{x}^{O2})/c < 0$, a contradiction. Finally, $r_s^{O3} > r_s^{O2} > r_s^{O1}$ for $s = c$ because in this case $r_s^{Oj} = \hat{x}^{Oj}$ for all $j \in \{1, 2, 3\}$ and we have already proven the order of the cutoffs. ■

Proof of Corollary 2: Let r_s^{Oj} denote the optimal ceiling price for objective j when all participants receive a reimbursement s. The optimal mechanism for Oj with $j \in \{1,2\}$ can be implemented (i) by a uniform-price auction with a ceiling price $r_{w,\tilde{s}}^{Oj} = r_{s=0}^{Oj} - \tilde{s}$ and a reimbursement $\tilde{s} \in [0,c]$ to all winning bidders; (ii) by a uniform-price auction with a ceiling price $r_{l,\tilde{s}}^{Oj} = r_{s=\tilde{s}}^{Oj} + \tilde{s}$ and a reimbursement $\tilde{s} \in [0,c]$ to all losing bidders. The optimal mechanism for O3 can be implemented by an auction of type (ii) with $\tilde{s} = c$. We show that with these auctions, participating companies receive the same payments as with the optimal auctions in Proposition 2.

In a uniform-price auction with a reimbursement $\tilde{s}$ only to winners, the weakly dominant strategy is to bid $x_i - \tilde{s}$, because at a price equal to this bid, a company is indifferent between winning and losing. If the ceiling price is $r_{w,\tilde{s}}^{Oj} = r_{s=0}^{Oj} - \tilde{s}$, then participating companies receive the total payment $r_{s=0}^{Oj}$ if they win and the ceiling price determines the price, $y_{(k,n-1)}$ if a competitor determines the price, and zero if they do not win. These are the same payments as with $r_{s=0}^{Oj}$ and no reimbursement.

In a uniform-price auction with a reimbursement $\tilde{s}$ only to losers, the weakly dominant strategy is to bid $x_i + \tilde{s}$, because at a price equal to this bid, a company is indifferent between winning and losing. If the ceiling price is $r_{l,\tilde{s}}^{Oj} = r_{s=\tilde{s}}^{Oj} + \tilde{s}$, then participating companies receive the total payment $r_{s=\tilde{s}}^{Oj} + \tilde{s}$ if they win and the ceiling price determines the price, $y_{(k,n-1)} + \tilde{s}$ if a competitor determines the price, and $\tilde{s}$ if they do not win. These are the same payments as with $r_{s=\tilde{s}}^{Oj}$ and a reimbursement $\tilde{s}$. ■

Proof of Proposition 3: Consider $n > k$, participation costs c, and a standard auction with ceiling price $r \leq v$. Note that $\hat{x} < \bar{x}$ by Lemma 1 and $\hat{x} > \underline{x}$ by property P2 of a standard auction ($r > \underline{x} + c$). Therefore, and by Lemma 1, $\hat{x}$ strictly increases if c decreases to c'. Denote the equilibrium cutoff costs associated with c' by $\hat{x}'$. Thus, the additional types that participate with c' are the types in $(\hat{x}, \hat{x}']$.

Consider any profile of types $\mathbf{x}$. Given $\mathbf{x}$, surplus is weakly higher with c' than with c because weakly more goods are allotted at a weakly lower price. First, if with c we have that $m \leq k$, then with c' either the same types participate and the price remains at level r or more types enter, the number of allotted goods increases, and the price is weakly below r (strictly below r if with c' we have $m' > k$). Second, if with c we have that $m > k$, then with c' we have the same allocation and price. Taking the expectation over all profiles $\mathbf{x}$, the cases with strict increase of surplus have positive probability, and, thus, surplus is strictly higher with c'.

Expected welfare is strictly higher with c' than with c because all companies have a weakly higher contribution to welfare and some have a strictly higher contribution. First, types $x \in (\hat{x}, \hat{x}']$ contribute nothing to welfare if participation costs are c. With c' their expected payoff from participation is positive and thus, with $r \leq v$, their expected contribution to social welfare is positive. Second, types $x \in [\underline{x}, \hat{x}]$ for a given profile $\mathbf{x}$ either are auction winners both with c and with c' or do not win in the auction both with c and with c'. Thus, their contribution to welfare after participation is either $v - x$ or 0 before and after the decrease in participation costs but their total contribution to welfare is strictly higher after the decrease because their participation costs are strictly lower.

Finally, the expected number of goods allotted increases strictly if c decreases to c' because the cutoff costs increase strictly. ■

A.2 Endogenous ceiling price

ER cannot only be conducted by an *endogenous auction volume (EAV)* also by an *endogenous ceiling price (ECP)*, in which the submitted bids determine a ceiling price below the original ceiling price such that there is at least on unsuccessful bid. Only bids below the ECP are successful. Variations differ in the way the bids determine the ECP, e.g., by the bids' mean or median. ECPs are applied in France (Ministre de l'Europe, 2019) and Peru (Comité, 2015).

An ECP is derived from the submitted bids. In the first step, the companies decide about their participation. Then, participating companies submit their bids, which may not exceed the default ceiling price r. The bids of the $m \leq n$ participating companies are denoted by $\mathbf{b} = (b_1, b_2, \ldots, b_m)$. Next, the ECP $\varrho(\mathbf{b})$ is calculated on the basis of $\mathbf{b}$, where $\min_{i\in\{1,\ldots,m\}}\{b_i\} \leq \varrho(\mathbf{b}) \leq \max_{i\in\{1,\ldots,m\}}\{b_i\}$ and $1 \geq \frac{\partial\varrho(\mathbf{b})}{\partial b_i} \geq 0$ for all $i \in \{1,\ldots,m\}$. For the award, only bids $b < \varrho(\mathbf{b})$ are taken into consideration, or alternatively, $b \leq \varrho(\mathbf{b})$ and $b < \max_{i\in\{1,\ldots,m\}}\{b_i\}$.[3] We call these *accepted bids* and denote their number by m', $m' \leq m$. The payment rule is applied as if only the accepted bids were submitted and as if the ECP was the ceiling price.[4]

We complement the ECP rule by a floor $\underline{\mu}$ and a ceiling $\bar{\mu}$, with $0 \leq \underline{\mu} < k \leq \bar{\mu}$. (The case of no floor or ceiling is included by $\underline{\mu} = 0$ or $\bar{\mu} = \infty$, respectively.) Floor and ceiling override rationing. If $m \geq \underline{\mu} > m'$, then the $\underline{\mu}$ lowest bids win (with random tie-breaking) and the ceiling price equals the highest of the winning bids. If $m \leq \underline{\mu}$ or $m > \bar{\mu}$,

---

[3] To enforce rationing if $n \leq k$ or $m \leq k$, the ECP winner-determination rule must prevent that all bids win if all bidders bid the same, e.g., r. This is met by both forms of the ECP rule.

[4] That means, if $m' \leq k$, in the uniform-price auction, the price is equal to $\varrho(\mathbf{b})$.

all bids are accepted and the payment rule is applied with the ceiling price $\max_{i \in \{1,\ldots,m\}}\{b_i\}$ or r, respectively.

We focus on ECP rules with the property that for all $b_i \in (\underline{x}, \bar{x})$ there exist combinations of the other bidders' bids $\mathbf{b}_{-i}$ such that $\frac{\partial \varrho(\mathbf{b})}{\partial b_i} > 0$. Examples for ECP rules $\varrho(\mathbf{b})$ are the mean rules that determine the ECP based on the mean of the submitted bids, $\varrho(\mathbf{b}) = \alpha \frac{1}{m} \sum_{i=1}^{m} b_i$ with $\alpha \in (0, 1]$, and the median rules that determine the ECP based on the median of the submitted bids, $\varrho(\mathbf{b}) = \alpha \cdot \text{median}(\mathbf{b})$ with $\alpha \in (0, 1]$.[5]

With an ECP, it is not an equilibrium that all bidders bid r.[6] Therefore, we focus on symmetric and strictly increasing bidding functions and assume the existence of an equilibrium in symmetric pure strategies (5).

Proposition 5. *In an auction with ECP* $\varrho(\mathbf{b})$*, the cutoff costs* $\hat{x}$ *and the participants are the same as in a standard auction with the auction volume* $k = \underline{\mu}$*.*

A company $\hat{i}$ with the cutoff costs $\hat{x}$ receives a good if and only if the number of bidders m is $\underline{\mu}$ or less. If $m > \underline{\mu}$, her bid will not win because the other bidders submit lower bids, and thus, company $\hat{i}$'s bid $b_{\hat{i}} = \max_{i \in \{1,\ldots,m\}}\{b_i\}$ is not below $\varrho(\mathbf{b})$. If $m \leq \underline{\mu}$, company $\hat{i}$'s bid wins and, furthermore, determines $\varrho(\mathbf{b})$ and, therefore, her payment. Thus, company $\hat{i}$ participates and bids $b_{\hat{i}} = r$ iff (2.2) holds. This proves Proposition 5.

The fact that company $\hat{i}$'s decision problem is the same in an EAV

---

[5] A different auction with median-price rule is the Medicare auction analysed by Cramton et al. (2015) and widely criticised by auction experts (see http://www.cramton.umd.edu/papers2010-2014/further-comments-of-concerned-auction-experts-on-medicare-bidding.pdf, accessed 09/16/2019). One of the reasons why the Medicare auction was predicted to perform badly is that it is not ex post individually rational in that winning bidders' payments can be below their bids: the k lowest bids win and the median of the winning bids is the payment to each winner. All auctions that we analyse are ex post individually rational. Further differences to our setting are that in the Medicare auction bids are non-binding, bids have to be above a bid floor (assumed to be below $\underline{x}$ and necessitated by the incentives evoked by the design), and participation costs are absent.

[6] Only if the bidders knew that $m \leq \underline{\mu}$, all bidders bidding r would be an equilibrium.

auction as in an ECP auction reveals a parallelism between the two instruments. If $\underline{\mu} > 0$, then $\hat{x} > \underline{x}$, and all companies with $\hat{x} \geq x_i \geq \underline{x}$ participate in the auction. If the ECP is a quantile of the bids, then there is an EAV rule under which the same companies win and their payments are the same. For example, the median rule for the ECP corresponds to an EAV of 50 %.[7] However, there are also differences, where the ECP rules do not correspond to any EAV rule. Consider, for example, the ECP that is equal to the mean. With this rule, adding a bid can increase or decrease the number of winning bidders, which is impossible under an EAV rule. Furthermore, in the uniform-price auction, bidders have an incentive to bid above their costs because an increase in their bid may increase the ECP and may therefore increase their payment. In contrast, bidders cannot influence their payment in the uniform-price EAV auction, in which it is optimal for the bidders to bid their costs. Payoff equivalence does not hold for different auctions (e.g., pay-as-bid vs. uniform pricing) with the same ECP rule because different payment rules may determine different sets of winners due to the differences in the bidding strategies.

Auctions with ER may also be plagued by strategic manipulations. ECP auctions are susceptible to actions that artificially increase supply in order to profit from a higher probability of award and higher prices. A company may participate with a serious bid and with an additional bid (either because multiple bids are feasible or under a different identity) that equals the ceiling price to increase the probability of an award for the serious bid. The participation costs reduce the attractiveness or availability of such strategic supply expansion.

---

[7] Concretely, the median rule with $\alpha = 1$ that chooses the higher of the two middle values in case of an even number of bids as the ECP (i.e., $\rho(\mathbf{b}) = b_{(\lceil 0.5m \rceil)}$ where $b_{(j)}$ denotes the j-th lowest bid) corresponds to the 50 %-EAV rule that rejects the bid at the 50 % boundary in case of an odd number of bids (i.e., $\kappa(m) = \lfloor 0.5m \rfloor$).

Appendix B

Appendix to Chapter 3

B.1 Experimental instructions

Text in blue is displayed in the instructions of the EAV treatment only. Text in red is displayed in the instructions of the Control treatment only.

Instructions

Welcome to the experiment!

In this experiment, you can earn money which will be paid to you at the end of the experiment in cash and anonymously. In the experiment the fictive currency "ExCU" will be used. 1 ExCU equals 50€-Cent. Your payment at the end of the experiment is composed of a fixed amount of 8€ and a variable amount, which you achieve owing to the experiment and the subsequent task.

Conduction of the experiment

The experiment consists of **15 rounds**. In each of the 15 rounds, out of a **group of 18** participants, where you belong to as well, **two groups of 9 participants each are formed randomly**. Thus, in each round you and 8 other participants form a **group of 9**. The composition of both groups of 9 is determined newly and randomly in each round. You do not know who the other participants are and you have no means of communication with them.

In each of the 15 rounds you participate in an **award procedure** within your group of 9 to determine the realisation of projects.

You (and every other member of your group of 9) have **one project** per round, which can be realized. If your project is realized or not is determined in the award procedure of the round.

Realisation costs:[1] The realisation costs of your project are individual and are drawn randomly at the beginning of the round and then disclosed to you. Every value between **50 and 75 ExCU** inclusive is equally likely. The realisation costs accrue only if the project is realized.

Bid for your project: At first you decide if you want to participate with your project in the award procedure, i.e., submit a bid. Submission of a bid costs **5 ExCU**. If you have decided in favor of submission, you have to submit a bid for your project.

Award and realisation: If your project is **awarded** in the award procedure, it will be **realized**. In this case you **receive your bid** and **pay the realisation costs** of the project. Your **result** of this round therefore is the **difference between your bid for the project and its total costs**. The total costs of a realized project are the **submission costs plus the realisation costs**.

If your bid is **not awarded**, you neither receive your bid nor you pay the realisation costs, because your project will not be realized. The **submission costs** accrue nevertheless. Therefore, your result of a round in which you submit a bid that is not awarded, is a **loss of 5 ExCU**.

---

[1] In the experiment, the potential bidders' private costs are referred to as realisation costs.

If you do not submit a bid, no costs accrue. Your result of this round is therefore **0 ExCU**.

Please notice that with the project that is available to you in a round you can **participate only once in the award procedure**, namely in this round. If your bid is **not awarded** or you **do not participate in the award procedure of this round** by not submitting a bid, you **cannot participate again with this project in award procedures of the following rounds**.

The following rules apply in the award procedure of each round:

Submission of bid: You can submit for your project a bid with **maximum two decimal places**. A bid must be **higher than or equal** to **0 ExCU** and **lower than or equal** to **77 ExCU**. The submission of a bid costs **5 ExCU**.

Award rule: If **8 or 9 bids** are submitted, the **6 lowest bids are awarded**. If **7 or fewer bids** are submitted, **2 bids less than submitted are awarded**. Thus, if 7 bids are submitted, the 5 lowest bids are awarded; with 6 submitted bids, the 4 lowest bids are awarded, etc. If 2 or 1 bids are submitted, no bid is awarded.

Award rule: Out of the submitted bids in your group of 9, the **6 lowest bids are awarded**. If **6 or fewer bids** are submitted, **all submitted bids are awarded**.

If **several bids** considered for award are **equal**, awards are **selected randomly**.

Payment for an awarded bid: If your bid for your project is awarded, you receive a **payment in the amount of your bid**.

Realisation costs: If your bid for a project is awarded, this project will be realized. Therefore, the realisation costs of this project accrue. If a bid is not awarded, no realisation costs accrue.

Result of a round

The **total costs** of a realized project consist of the submission costs and the realisation costs of the project:

Total costs of a realized project =
submission costs + realisation costs of the project

Your **result** of a round in which your project is realized is the difference between the bid for the project and its total costs:

Round result = awarded bid of project − total costs of project

Payment

After the 15 rounds of the experiment, **5 rounds relevant for your payment are randomly selected**. Out of these results of the 5 rounds, the **mean** is calculated. This mean is converted into Euro and results together with the fixed payment and your payment from the subsequent task in your total payment. This total payment will be paid out out you in cash and anonymously directly after the end of the experiment.

Please notice that negative round results are possible, and thus, a negative mean out of the selected rounds is possible. In this case, the mean will be subtracted from your fixed payment and the payment from the subsequent task. A negative total payment is not possible. You cannot lose money in this experiment.

Overview of the procedure of the experiment

The experiment consists of 15 rounds. Each round consists of 4 steps:

Step 1: You receive your randomly drawn realisation costs of your project and decide whether you want to participate with this project in the award procedure.

Step 2: You can submit a bid for your project. Only when all participants carried out this step, the experiment continues.

Step 3: You receive information whether your project is awarded and will thus be realized and what your round result is.

Step 4: You receive further information about the award procedure: the number of submitted bids, the number of awarded bids, the lowest bid, the highest bid, the mean submitted bid and the mean awarded bid.

Information about the subsequent task

You receive an additional payment for the completion of the subsequent task.

You will be presented 10 decisions on your monitor. Each of these decisions consists of a choice between “Option A” and “Option B”. While the amounts for payment in the two options are the same in each decision, the probability to get the higher amount varies between decisions.

After you finished all decisions, one out of the 10 decisions is randomly selected for your payment. For your choice of option “A” or “B” in this decision and according to the respective probabilities, the higher or lower amount is randomly selected for your payment.

Summary: You make 10 decisions; in each of these decisions you choose between “Option A” and “Option B”. You can choose “A” in some rows, and “B” in others. When you made all your decisions, one of the 10 decisions is randomly selected for your payment. Based on your choice (“A” or “B”) a random selection decides if the higher or lower amount is paid to you.

When you completed the task, the experiment is finished for you. Please stay calmly in your cabin, until you are picked up by the experimenters.

Please mute your phone now, if not already done. Do not use your phone in the course of the experiment, and do not browse the internet.

Thank you for your participation in the experiment!

B.2 Experimental questionnaire

Text in blue is displayed in the instructions of the EAV treatment only. Text in red is displayed in the instructions of the Control treatment only.

Note: The error message appears only if a wrong answer is chosen.

Question 1: How many rounds will be played in the experiment?
Options: All integers.
Error message: Your answer is wrong. 15 rounds will be played in the experiment.

Question 2: How many other participants interact with you in each round?
Options: All integers.
Error message: Your answer is wrong. 8 other participants interact with you in each round.

Question 3: Which of the following statements is true?
Options:

- The composition of the group of 9 you belong to is the same in all 15 rounds. This means, you will interact with the same 8 participants in each round.
- The composition of the group of 9 you belong to is newly and randomly determined each round.

Error message: Your answer is wrong. The composition of the group of 9 you belong to is newly and randomly determined each round.

Question 4: Which of the following statements is true?
Options:

- In every round you have exactly one project.

- In every round you have several projects by default.
- From round 2 on, you also have your non-awarded projects from previous rounds.

Error message: Your answer is wrong. In every round you have exactly one project.

Question 5: Which of the following statements about the realisation costs of your projects in the different rounds is true?
Options:

- The realisation costs of the projects are always 5 ExCU.
- The realisation costs of all projects of the 9 participants are equal and are drawn randomly from the interval [50,75] at the beginning of each round.
- The realisation costs of the project of each participant are drawn independently and randomly from the interval [50,75] at the beginning of each round. Thus, realisation costs of the 9 participants can differ.

Error message: Your answer is wrong. The realisation costs of the project of each participant are drawn independently and randomly from the interval [50,75] at the beginning of each round. Thus, realisation costs of the 9 participants can differ.

Question 6: What is the first decision you have to make in each of the 15 rounds?
Options:

- If you want to submit a bid for your project in the award procedure in this round.
- What bid you submit for your project in the award procedure in this round.
- If you realize your project.

Error message: Your answer is wrong. In each round, you first decide if you want to submit a bid for your project in the award procedure in this round.

Question 7: What are the costs of submitting a bid?
Options: All integers (in ExCU).

Error message: Your answer is wrong. Submitting a bid always costs 5 ExCU.

Question 8: How many bids and thus, projects, are awarded at maximum in each round?
Options: All integers.
Error message: Your answer is wrong. In each round, at maximum the 6 lowest bids are awarded.

Question 9: How many bids and thus, projects, are awarded, if 6 or less bids are submitted?
Options:

- The number of awards is determined randomly.
- None of them.
- All of them.

Error message: Your answer is wrong. If 6 bids or less are submitted, all bids are awarded.

Question 9: How many bids and thus, projects, are awarded, if 7 or less bids are submitted?
Options:

- All of them.
- None of them.
- Two bids less than submitted are awarded.

Error message: Your answer is wrong. If 7 bids or less are submitted, two bids less than submitted are awarded.

Question 10: Which bids and thus, projects, are awarded?
Options:

- The projects with the lowest bids are awarded.
- The projects with the highest bids are awarded.
- The awards are determined randomly.

Error message: Your answer is wrong. The projects with the lowest bids are awarded.

Question 11: In one round, you submitted a bid for your project, which has realisation costs of 60 ExCU. How high are the total costs in this round, if your bid for this project is awarded?

Options: All integers (in ExCU).
Error message: Your answer is wrong. The participation costs for submitting a bid are 5 ExCU. Together with the realisation costs of 60 ExCU, your total costs sum up to 5 ExCU + 60 ExCu = 65 ExCU.

Question 12: In one round, you submitted a bid for your project, which has realisation costs of 60 ExCU. How high are the total costs in this round, if your bid for this project is not awarded?
Options: All integers (in ExCU).
Error message: Your answer is wrong. As your bid for this project has not been awarded, your project will not be realized and the realisation costs do not accrue. Thus, only the participation costs for submitting a bid accrue, which are 5 ExCU.

Question 13: In one round, you submitted a bid with 69 ExCU for your project. This project has realisation costs of 60 ExCU. What is your round result, if your bid for this project is awarded?
Options: All integers (in ExCU).
Error message: Your answer is wrong. Your total costs sum up to 65 ExCU (5 ExCU participation costs plus 60 ExCU realisation costs). As your bid was awarded, you receive a payment in the amount of your bid, 69 ExCU. Thus, your round result is 69 ExCU − 65 ExCU = 4 ExCU.

Question 14: In one round, you submitted a bid with 69 ExCU for your project. This project has realisation costs of 60 ExCU. What is your round result, if your bid for this project is not awarded?
Options: All integers (in ExCU).
Error message: Your answer is wrong. Your total costs sum up to 5 ExCU (participation costs). As your bid was not awarded, you do not have to pay the realisation costs. Also, you do not receive a payment. Thus, your round result is −5 ExCU.

Question 15: You decide not to submit a bid. What is your round result?
Options: All integers (in ExCU).
Error message: Your answer is wrong. As you did not submit a bid, you do not have to pay the participation costs, but do not receive any

payments. Thus, your round result is 0 ExCU.

Question 16: How is your payment for the 15 rounds at the end of the experiment determined?
Options:

- You receive the sum of your 15 round results.
- You receive the mean of your 15 round results.
- You receive the mean of your round results of 5 randomly selected rounds.

Error message: Your answer is wrong. You receive the mean of your round results of 5 randomly selected rounds.

Appendix C

Appendix to Chapter 5

C.1 Statistical analysis

Table C.1 shows the results of the linear-mixed models used to determine whether the randomly assigned auction units of the separate auctions in the experiment have an effect on the degrees of efficiency .[1] For this purpose, first the degrees of efficiency for both the original composition as well as the new (artifical) composition were calculated. The original composition here is that the three participants in group 1 (2) with role A are in the same auction unit as participants in group 1 (2) with role B. In the new composition, one auction unit consists of the participants in group 1 (2) with role A, and participants in group 2 (1) with role B. The vector of dependent variables y includes the three degrees of efficiency. Parameters for the independent variable *Composition* as well as the constant are denoted by β_j, $j \in \{0, 1\}$. Further a random effect to account for the session with parameter g was included in the model, as well as the vector of residual errors ε:

$$y = \beta_0 + \beta_1 \cdot Composition + g \cdot Session + \varepsilon.$$

From the results, no statistical difference between the different ways of composing auction units can be deduced for neither degree of efficiency.

Tables C.2 and C.3 show linear-mixed model results for tests whether the sequence of auctions has any effect on the dependent variables intro-

---

[1] The joint auctions are a fixed auction unit, since all participant in this setting are competing in the same auction.

Table C.1: Linear-mixed model to test whether composition of auction unit has an effect on degrees of efficiency in separate auctions (Standard errors in brackets)

	Dependent variable:		
	D_{eff}^{bin}	D_{eff}^{rel}	D_{eff}^{rge}
New composition	−0.010	−0.003	0.002
	(0.015)	(0.001)	(0.006)
Constant	0.115*	0.576*	0.856 *
	(0.019)	(0.009)	(0.002)
Observations	1600	1600	1600
Note:			*p<0.05

duced in Section 5.3.2. Again, the model is of the form

$$\begin{aligned} y = \; & \beta_0 + \beta_1 \cdot Auctiontype + \beta_2 \cdot Pricingrule \\ & + \beta_3 \cdot Sequence + \beta_4 \cdot Biddertype + g \cdot Session + \varepsilon, \end{aligned}$$

where y is the vector of dependent variables, β_j with $j \in \{0, 1, 2, 3, 4\}$ the parameter for the fixed effects, g the parameter for the random effect as well as the vector of residual errors ε.

For all dependent variables, no statistical influence of the sequence of auctions can be deduced.

Table C.4 shows the linear-mixed model results on the bid surcharge. The linear-mixed model has the form

$$\begin{aligned} y = \; & \beta_0 + \beta_1 \cdot Auctiontype + \beta_2 \cdot Pricingrule + \beta_3 \cdot Round \\ & + \beta_4 \cdot Project1 + \beta_5 \cdot Project2 + \beta_6 \cdot Auctiontype : Pricingrule \\ & + g \cdot Session + \varepsilon, \end{aligned}$$

where y is the vector of dependent variables. The parameters β_j with $j \in \{0, \ldots, 7\}$ are the parameters for the constant, the explaining fixed variables auction type, pricing rule, round, and project type, as well as the interaction term auction type:pricing rule. The project type has

Table C.2: Linear-mixed model to test whether sequence of auctions has an effect on different dependent variables (Standard errors in brackets)

	Dependent variable:				
	Bid	Price	Surcharge	Surplus	Welfare
Auction type separate	1.050 (0.874)	8.460* (1.316)	1.265* (0.591)	−8.617* (1.029)	−12.114* (1.158)
Pricing rule UP	−17.776* (3.354)	7.380* (1.708)	−16.903* (3.202)	−7.490* (1.703)	0.351 (1.097)
Sequence separate first	0.344 (3.398)	−2.002 (1.730)	0.327 (3.244)	2.063 (1.729)	0.206 (1.111)
Bidder type single-unit	1.602 (3.415)	4.839* (1.748)	1.319 (3.269)	−4.961* (1.743)	−2.589* (1.122)
Constant	385.917* (3.678)	351.227* (2.071)	10.607* (3.513)	149.025* (1.992)	162.525* (1.430)
Observations	13440	2400	13440	2400	2400

Note: $^{*}p<0.05$

Table C.3: Linear-mixed model to test whether sequence of auctions has an effect on efficiency in auction units (Standard errors in brackets)

	Dependent variable:		
	D_{eff}^{bin}	D_{eff}^{rel}	D_{eff}^{rge}
Auction type	-0.546^{*}	-0.285^{*}	-0.109^{*}
separate	(0.020)	(0.010)	(0.005)
Pricing rule	0.002	0.005	-0.005
UP	(0.026)	(0.018)	(0.010)
Sequence	0.022	0.015	0.006
separate first	(0.027)	(0.018)	(0.010)
Bidder type	0.154^{*}	0.016	-0.023^{*}
single-unit	(0.027)	(0.018)	(0.010)
Constant	0.546^{*}	0.861^{*}	0.980^{*}
	(0.031)	(0.020)	(0.011)
Observations	1600	1600	1600
Note:			*p<0.05

three different outcomes: a single project for single-supply bidders, and Project 1 and Project 2 for multi-supply bidders. The parameters β_4 und β_5 refer to both projects of the multi-supply bidders. Further, a parameter g for the fixed session effect and the vector of residual errors ε is included.

Table C.4: Linear-mixed model to test of significant differences in bid surcharge (Standard errors in brackets)

	Dependent variable:
	Surcharge
Auction type separate	−0.848 (0.835)
Pricing rule UP	−18.840* (3.149)
Round	0.049 (0.026)
Project 1	−1.307 ((3.173)
Project 2	−1.249 (3.173)
Auction type: Pricing rule	3.943* (1.190)
Constant	14.140* (2.622)
Observations	13440
Note:	*p<0.05

As seen in Table C.4, the hypotheses that surcharges do not differ based on the project type cannot be rejected.

C.2 Proof of Proposition

Proof of Proposition 4: Let D_{eff}^{bin}, D_{eff}^{rel} and D_{eff}^{rge} be defined as in (5.3), (5.4)and (5.5). For simplicity assume $m = 1$, the argumentation for $m > 1$ is identical.

Assume the auction is efficient. Thus, every project that should be awarded is awarded. It follows

$$\begin{aligned} D_{eff}^{abs} &= \frac{1}{k}\sum_{i=1}^{k} 1 &&= 1 \\ D_{eff}^{rel} &= \prod_{i=1}^{k} 1 &&= 1 \\ D_{eff}^{rge} &= \frac{1}{k}\sum_{i=1}^{k}\left(1 - \frac{0}{x_{(n,n)} - x_{(1,n)}}\right) &&= 1, \end{aligned}$$

i.e., the highest possible value for all measures is 1. In this case $D_{eff}^{bin} = D_{eff}^{rel} = D_{eff}^{rge} = 1$.

Assume the auction is inefficient. Then clearly $D_{eff}^{abs} = 0$. If there is no project correctly awarded, $D_{eff}^{rel} = 0$. For all other cases it holds:

- If a project is awarded correctly the term of the sum is 1 in both $D_{eff}^{rel} > 0$ and $D_{eff}^{rge} > 0$.
- If a project is wrongly awarded, the term of the sum is smaller than 1, but larger than 0 in D_{eff}^{rge} while it is surely equal to 0 in D_{eff}^{rel}.

Thus, when the auction is inefficient, $0 = D_{eff}^{bin} \leq D_{eff}^{rel} \leq D_{eff}^{rge} < 1$ where $D_{eff}^{bin} = D_{eff}^{rel}$ only holds when there are no project correctly awarded, and $D_{eff}^{rel} = D_{eff}^{rge}$ only holds when there is just one project auctioned, and the award is given to the project with the highest costs, since then the sum is 0. This completes the proof. ■

C.3 Experimental instructions

C.3.1 Single-supply bidders

Text in blue is displayed in the instructions of the DP treatments only. Text in magenta is displayed in the instructions of the UP treatments only. Text in green is displayed in the instructions of the joint first treatments only. Text in red is displayed in the instructions of the separate first treatments only.

Instructions

Welcome to the experiment!

In this experiment, you can earn money that will be paid to you at the end of the experiment in cash and anonymously. In the experiment the fictive currency “ExCU” will be used. **1 ExCU** equals **1 €**. Your payment at the end of the experiment is composed of a fixed amount of **5 €** and a variable amount, which you achieve owing to the experiment.

Conduction of the Experiment

This experiment consists of **two sections**. Each of them consists of **20 rounds**. You are a member of a group of **12 participants**. You do not know who the other participants are and you have no way to communicate with them. At the beginning of the experiment, all participants of your group will be randomly assigned to **types A and B: 6 participants** will be of **type A** while the other **6 participants** will be of **type B. After 10 rounds** each participant will **change** the type: A participant of type A will be of type B for the next 10 rounds and vice versa. Therefore, at the beginning of the second section, all participants regain the type they had at the beginning of the experiment and after 10 rounds switch to the other type again.

In each of the 20 rounds in both sections, you will take part in an **award procedure** for realisation of projects. You (as well as other 11 member of your group of 12) will have **one project** in each round, which can be realised. Whether your project will be realised or not, is decided by the

award procedure in the round.

Realisation costs: The realisation costs of your project are individual and will be drawn randomly at the beginning of each round and informed to you. The realisation costs of a participant of **type A** will be drawn randomly from the interval **A** = [**300,400**]. Any amount between **300** and **400 ExCU** is equally likely. The realisation costs of a participant of **type B** will be drawn randomly from the interval **B** = [**350,450**]. Any amount between **350** and **450 ExCU** is equally likely. The realisation costs will be incurred if and only if the project is realised. In order to realise the project, you have to submit a **bid** for this project. This bid is used in the **award procedure** to decide whether your project will be realised.

Award and realisation: If your project is awarded in the award procedure, it will be realised. In this case, you will receive your bid and pay the project realisation costs. Therefore, your result of this round will be the difference between your bid for the project and its realisation costs.

Award and realisation: If your project is awarded in the award procedure, it will be realised. In this case, you will receive the lowest non-accepted bid from your competitors and pay the realisation costs of your project. Therefore, your result of this round is the difference between the lowest non-awarded bid from your competitors and the realisation costs of your project.

If your bid is **not awarded**, then you will neither receive a payment nor pay the realisation costs, since your project will not be realised. Thus, your **result** of this round, in which your bid is not accepted, is **0 ExCU**. Please note that, you can participate with the project, which is available to you in this round, **only once in the award procedure**. In the next round a new project will be available to you, whose realisation costs will be again determined randomly at the beginning of the next round.

The following rules will be applied to the award procedure in each round:

Submission of bid: You can submit **a positive bid** for your project with **maximum two decimal places**. A bid can be **at most 500 ExCU**.

1. Section of the experiment: In the first part of the experiment, i.e. in the first 20 rounds, **in each round**, the 6 participants of the same type will be **randomly assigned into two groups**. This means, that in each round the 6 participants of type A will be assigned in two group of three and at the same time, the 6 participants of type B will be assigned in two group of three as well. As a result, you will always interact with participants, who are of the same type as you during the first 20 rounds. You will participate in the award procedure in one of the **groups of three** of your own type. Only the **lowest bid** of all bids, which are submitted in a round from your group of three, **will be awarded**.

1. Section of the experiment: In the first part of the experiment, i.e. in the first 20 rounds, **in each round**, the 12 participants in your group will be **randomly assigned in two groups of six.** Exactly **3 participants of type A** and **3 participants of type B** will be assigned to each of these two groups. This means that in each group of six, there are 3 participants of type A and 3 participants of type B. You will participate in the award procedure in one of groups of six. The **two lowest bids** of all bids, which are submitted in a round from your group of six, **will be awarded**.

2. Section of the experiment: In the second part of the experiment, i.e. in the second 20 rounds, **in each round**, the 6 participants of the same type will be **randomly assigned into two groups**. This means, that in each round the 6 participants of type A will be assigned in two group of three and at the same time, the 6 participants of type B will be assigned in two group of three as well. As a result, you will always interact with participants, who are of the same type as you during the first 20 rounds. You will participate in the award procedure in one of the **groups of three** of your own type. Only the **lowest bid** of all bids, which are submitted in a round from your group of three, **will be awarded**.

2. Section of the experiment: In the second part of the experiment, i.e. in the second 20 rounds, **in each round**, the 12 participants in your group will be **randomly assigned in two groups of six.** Exactly **3 participants of type A** and **3 participants of type B** will be assigned to each of these two groups. This means that in each group of six, there are 3 participants of type A and 3 participants of type B. You will participate in the award procedure in one of groups of six. The **two lowest bids** of all bids, which are submitted in a round from your group of six, **will be awarded**.

If **several bids** are **equally relevant for being awarded**, then the award will be **chosen randomly**.

Payment for an accepted bid: If your bid is awarded for a prepared project, then you will receive a payment in the amount of your bid.

Payment for an accepted bid: If your bid is awarded for a prepared project, then you will receive a payment in the amount of the lowest non-awarded bid from your competitors.

Realisation cost: If your bid is awarded for a project, then this project will be realised, which will incur the realisation costs of this project to you. If a project is not awarded and realised, then no costs will occur.

Result of a round:

Your **result** of a round, in which your **bid is awarded** and therefore your project is realised, will be determined as the difference between your bid for the project and its realisation costs.

Round result = awarded bid for the project – realisation cost of the project

If your **bid is not awarded**, then your result of this round is **zero**.

Your **result** of a round, in which your **bid is awarded** and therefore your project is realised, will be determined as the between the lowest non-awarded bid and the realisation costs of your project.

Round result = lowest non-awarded bid – realisation cost of

the project
If your **bid is not awarded**, then your result of this round is **zero**.

Payment

After completing the 20 rounds twice, **from each** of the 4 blocks with 10 rounds, **5 rounds will be selected randomly** for your payment. The **mean** of your results in these 20 chosen rounds will be converted into Euros, and together with your fixed amount, form your total payment. This will be paid out to you in cash and anonymously after the experiment. Please notice that negative round results are possible, and thus, a negative mean out of the selected rounds is possible. In this case, the mean of the 20 rounds will be deducted from your fixed payment. A negative payment in total is not possible. You cannot lose money in this experiment.

Overview of the procedure of the experiment

This experiment consists of two sections each with 20 rounds. Each round consists of 3 steps:

- Step 1: You receive the randomly drawn realisation costs of your project.
- Step 2: You have to submit a bid for your project. Only when all participants carried out this step, the experiment continues.
- Step 3: You receive information whether your project is awarded and therefore realised, as well as the round result you have achieved. Besides, you receive further information about the bids from other participants in your group, who have participated in the same award procedure as you.
- Step 3: You receive information whether your project is awarded and therefore realised, the payment you have received as well as the round result you have achieved. Besides, you receive further information about the bids from other participants in your group, who have participated in the same award procedure as you.

In each of the 20 rounds in the first section, you take part in the award procedure with 2 other participants. In each of the 20 rounds in the second section, you take part in the award procedure with 5 other participants.

In each of the 20 rounds in the first section, you take part in the award procedure with 5 other participants. In each of the 20 rounds in the second section, you take part in the award procedure with 2 other participants.

Your type (A or B) remains the same in the first 10 rounds in a section. For the next 10 rounds in a section, your type switches (from A to B or from B to A) and remains the same during these 10 rounds.

When the last round is finished, you have finished this experiment. Please remain seated in your cabin quietly until you are picked up by the experimenters.

Please turn your mobile phone on silent mode. Please do not use your mobile phone during the experiment and do not surf the Internet.

Thank you for your participation in this experiment!

C.3.2 Multi-supply bidders

Text in blue is displayed in the instructions of the DP treatments only. Text in magenta is displayed in the instructions of the UP treatments only. Text in green is displayed in the instructions of the joint first treatments only. Text in red is displayed in the instructions of the separate first treatments only.

Instructions

Welcome to the experiment!

In this experiment, you can earn money that will be paid to you at the end of the experiment anonymously. In the experiment the fictive currency "ExCU" will be used. **1 ExCU** equals **1 €**. Your payment at the end of the experiment is composed of a fixed amount of **5 €** and a variable amount, which you achieve owing to the experiment.

Conduction of the experiment

This experiment consists of **two sections**. Each of them consists of **20 rounds**. You are a member of a group of **12 participants**. You do not know who the other participants are and you have no way to communicate with them. At the beginning of the experiment, all participants of your group will be randomly assigned to **types A and B: 6 participants** will be of **type A** while the other **6 participants** will be of **type B. After 10 rounds** each participant will **change** the type: A participant of type A will be of type B for the next 10 rounds and vice versa. Therefore, at the beginning of the second section, all participants regain the type they had at the beginning of the experiment and after 10 rounds switch to the other type again.

In each of the 20 rounds in both sections, you will take part in an **award procedure** for realisation of projects. You (as well as other 11 member of your group of 12) will have **two projects** in each round, which can be realised. Whether your project will be realised or not, is decided by the **award procedure** in the round.

Realisation costs: The realisation costs of your projects are individual and will be drawn randomly at the beginning of each round and informed to you. The realisation costs of a participant of **type A** will be drawn randomly from the interval **A** = [**300**,**400**]. Any amount between **300** and **400 ExCU** is equally likely. The realisation costs of a participant of **type B** will be drawn randomly from the interval **B** = [**350**,**450**]. Any amount between **350** and **450 ExCU** is equally likely. The realisation costs will be incurred if and only if the project is realised. In order to realise the project, you have to submit a **bid** for this project. This bid is used in the **award procedure** to decide whether your project will be realised. You have to submit one bid per project. Thus, you have to submit two bids in the award procedure.

Award and realisation: None, one or both of your bids for your projects can be awarded. If one of your projects is awarded in the award procedure, it will be realised. In this case, you will receive your bid and pay the project realisation costs. Therefore, your result of this round for this projects will be the difference between your bid for the project and its realisation costs.

Award and realisation: None, one or both of your bids for your projects can be awarded. If one of your projects is awarded in the award procedure, it will be realised. In this case, you will receive the lowest non-accepted bid and pay the realisation costs of your project. The lowest non-accepted bid can be from your competitors, or from you for your other project, if that is not accepted. Therefore, your result of this round for this project is the difference between the lowest non-awarded bid and the realisation costs of your project.

If your bid is **not awarded**, then you will neither receive a payment nor pay the realisation costs, since your project will not be realised. Thus, your **result** of this round, in which your bid is not awarded, is **0 ExCU**.

If your bid is **not awarded**, then you will neither receive a payment nor pay the realisation costs, since your project will not be realised. Thus, your **result** of this round, in which your bid is not awarded, is **0 ExCU**.

Your **total round result** is the **sum of the single results** of both of your projects. Please note that, you can participate with the projects, which are available to you in this round, **only once in the award procedure**. In the next round new projects will be available to you, whose realisation costs will be again determined randomly at the beginning of the next round.

The following rules will be applied to the award procedure in each round:

Submission of bid: You can submit **a positive bid** for your projects with **maximum two decimal places**. A bid can be **at most 500 ExCU**.

1. Section of the experiment: In the first part of the experiment, i.e. in the first 20 rounds, **in each round**, the 6 participants of the same type will be **randomly assigned into two groups**. This means, that in each round the 6 participants of type A will be assigned in two group of three and at the same time, the 6 participants of type B will be assigned in two group of three as well. As a result, you will always interact with participants, who are of the same type as you during the first 20 rounds. You will participate in the award procedure in one of the **groups of three** of your own type. Only the **two lowest bids** of all bids, which are submitted in a round from your group of three, **will be awarded**.

1. Section of the experiment: In the first part of the experiment, i.e. in the first 20 rounds, **in each round**, the 12 participants in your group will be **randomly assigned in two groups of six.** Exactly **3 participants of type A** and **3 participants of type B** will be assigned to each of these two groups. This means that in each group of six, there are 3 participants of type A and 3 participants of type B. You will participate in the award procedure in one of groups of six. The **four lowest bids** of all bids, which are submitted in a round from your group of six, **will be awarded**.

2. Section of the experiment: In the second part of the experiment, i.e. in the second 20 rounds, **in each round**, the 12 participants in your group will be **randomly assigned in two groups of six.** Exactly **3 participants of type A** and **3 participants of type B** will be assigned to each of these two groups. This means that in each group of six, there are 3 participants of type A and 3 participants of type B. You will participate in the award procedure in one of groups of six. The **two lowest bids** of all bids, which are submitted in a round from your group of six, **will be awarded**.

2. Section of the experiment: In the second part of the experiment, i.e. in the second 20 rounds, **in each round**, the 6 participants of the same type will be **randomly assigned into two groups**. This means, that in each round the 6 participants of type A will be assigned in two group of three and at the same time, the 6 participants of type B will be assigned in two group of three as well. As a result, you will always interact with participants, who are of the same type as you during the first 20 rounds. You will participate in the award procedure in one of the **groups of three** of your own type. Only the **two lowest bid** of all bids, which are submitted in a round from your group of three, **will be awarded**.

If **several bids** are **equally relevant for being awarded**, then the award will be **chosen randomly**.

Payment for an awarded bid: If your bid is awarded for a prepared project, then you will receive a payment in the amount of your bid.

Payment for an awarded bid: If your bid is awarded for a prepared project, then you will receive a payment in the amount of the lowest non-awarded bid from your competitors or from you for your other bid.

Realisation cost: If your bid is awarded for a project, then this project will be realised, which will incur the realisation costs of this project to you. If a project is not awarded and realised, then no costs will occur.

Result of a round:

Your **result** of a round, in which your **bid is awarded** and therefore your project is realised, will be determined as the difference between your bid for the project and its realisation costs.

Round result = awarded bid for the project - realisation cost of the project

If your **bid is not awarded**, then your result of this round is **zero**.

Your **result** of a round, in which your **bid is awarded** and therefore your project is realised, will be determined as the between the lowest non-awarded bid and the realisation costs of your project.

Round result = lowest non-awarded bid - realisation cost of

the project
If your **bid is not awarded**, then your result of this round is **zero**.

Your **total round result** is the **sum of the single round results** of both of your projects.
Total Round result = Round result for project 1 + Round result for project 2

Payoff

After completing the 20 rounds twice, **from each** of the 4 blocks with 10 rounds, **5 rounds will be selected randomly** for your payment. The **mean** of your results in these 20 chosen rounds will be converted into Euros, and together with your fixed amount, form your total payoff. This will be paid out to you in cash anonymously after the experiment. Please note that, negative round results are possible, and thus, a negative mean of the selected rounds is possible. In this case, the mean of the 20 rounds will be set to 0.

Overview of the procedure of the experiment

This experiment consists of two sections each with 20 rounds. Each round consists of 3 steps:

- Step 1: You receive the randomly drawn realisation costs of your projects.
- Step 2: You have to submit a bid for each of your projects. Only when all participants carried out this step, the experiment continues.

- Step 3: You receive information whether your projects are awarded and therefore realised, as well as the round results you have achieved. Besides, you receive further information about the bids from other participants in your group, who have participated in the same award procedure as you.
- Step 3: You receive information whether your projects are awarded and therefore realised, the payment you have received as well as the round results you have achieved. Besides, you receive further information about the bids from other participants in your group, who have participated in the same award procedure as you.

In each of the 20 rounds in the first section, you take part in the award procedure with 2 other participants. In each of the 20 rounds in the second section, you take part in the award procedure with 5 other participants.

In each of the 20 rounds in the first section, you take part in the award procedure with 5 other participants. In each of the 20 rounds in the second section, you take part in the award procedure with 2 other participants.

Your type (A or B) remains the same in the first 10 rounds in a section. For the next 10 rounds in a section, your type switches (from A to B or from B to A) and remains the same during these 10 rounds.

When the last round is finished, you have finished this experiment. Once you see the end screen, you can leave the experiment. Please enter the token you received at the beginning of the experiment and then your bank details under the link displayed. Failure to do so will result in our inability to complete your payment.

Please turn your mobile phone on silent mode. Please do not use your mobile phone during the experiment and do not surf the Internet.

Thank you for your participation in this experiment!

C.4 Experimental questionnaire

C.4.1 Single-supply bidders

Text in blue is displayed in the quiz pages of the DP treatments only. Text in magenta is displayed in the quiz pages of the UP treatments only. Text in green is displayed in the quiz pages of the joint first treatments only. Text in red is displayed in the quiz pages of the separate first treatments only.

Note: the respective error message will certainly only appear, if the correct answer was not selected.

Question 1: How many rounds does each of the two sections of this experiment consist of?
Options: All integers.
Error message: Your answer is wrong. Each of the two sections of this experiment consist of 20 rounds.

Question 2: How many other participants will you interact with in each round in the first section of the experiment?
Options: All integers.
Error message: Your answer is wrong. You will interact with 2 other participants in each round in the first section.

Question 2:
How many other participants will you interact with in each round in the first section of the experiment?
Options: All integers.
Error message: Your answer is wrong. You will interact with 5 other participants in each round in the first section.

Question 3: How many other participants will you interact with in each round in the second section of the experiment?
Options: All integers.
Error message: Your answer is wrong. You will interact with 5 other participants in each round in the second section.

Question 3: How many other participants will you interact with in each round in the second section of the experiment?
Options: All integers.
Error message: Your answer is wrong. You will interact with 2 other participants in each round in the second section.
[1ex] **Question 4:** Which of the following statements is correct?
Options:

- The composition of the group in the award procedure, to which you belong, is the same in all 20 rounds. In other words, you will interact with the same participants in each of the 20 rounds.
- The composition of the group in the award procedure, to which you belong, will be randomly redetermined in each round.

Error message: Your answer is wrong. The composition of the group in the award procedure, to which you belong, will be randomly redetermined in each round.

Question 5: Which of the following statements is correct?
Options:

- In each round you will have exactly one project.
- In each round you will have several project in principle.
- From the second round onwards, you will have the non-awarded projects from the previous rounds as well.

Error message: Your answer is wrong. In each round you will have exactly one project.

Question 6: Which of the following statements is correct?
Options:

- The types (A or B) of a participant will not change during the experiment.
- The types (A or B) of a participant will remain the same in the first section and switch in the second section.
- The types (A or B) of a participant will switch after every 10 rounds, not only in the first section but also in the second section of the experiment.

Error message: Your answer is wrong. The types (A or B) of a participant will switch after every 10 rounds, not only in the first section but also in the second section of the experiment.

Question 7: At the beginning of the experiment you are of type A. Which of the following statements about the realisation costs of the project, which is available to you in one of the first 10 rounds of the experiment, is correct?

Options:

- The realisation costs of your project will always be 300 ExCU.
- In each round, the realisation costs of the project will be the same for all 3 participants in your group and drawn randomly from the interval A = [300,400] at the beginning of the round.
- The realisation costs of the project of a participant will be drawn individually randomly from the interval A = [300,400] at the beginning of the round. Thus, the realisation costs of the 3 participants may differ.

Error message: Your answer is wrong. The realisation costs of the project of a participant will be drawn individually randomly from the interval A = [300,400] at the beginning of the round. Thus, the realisation costs of the 3 participants may differ.

Question 7: At the beginning of the experiment you are of type A. Which of the following statements about the realisation costs of the project, which is available to you in one of the first 10 rounds of the experiment, is correct?

Options:

- The realisation costs of your project will always be 300.
- In each round, the realisation costs of the project will be the same for all 5 participants in your group and drawn randomly from the interval [300,400] at the beginning of the round.
- The realisation costs of the project of a participant will be drawn individually randomly from the interval A = [300,400] at the beginning of the round. Thus, the realisation costs of the 5 participants may differ.

Error message: Your answer is wrong. The realisation costs of the project of a participant will be drawn individually randomly from the interval A = [300,400] at the beginning of the round. Thus, the realisation costs of the 5 participants may differ.

Question 8: From which interval will the realisation cost of a participant of type B be drawn?
Options:
- B = [350,450]
- B = [300,400]
- B = [350,400]

Error message: Your answer is wrong. The realisation costs of a participant of type B will be drawn from the interval B = [350,450].

Question 9: How many bids will be accepted (and therefore the projects will be awarded) per round in the first section of the experiment?
Options: All integers.
Error message: Your answer is wrong. In each round in the first section, only the lowest bid will be accepted.

Question 9: How many bids will be accepted (and therefore the projects will be awarded) per round in the first section of the experiment?
Options: All integers.
Error message: Your answer is wrong. In each round in the first section, the two lowest bids will be accepted.

Question 10: How many bids will be accepted (and therefore the projects will be awarded) per round in the second section of the experiment?
Options: All integers.
Error message: Your answer is wrong. In each round in the second section, the two lowest bids will be accepted.

Question 10: How many bids will be accepted (and therefore the projects will be awarded) per round in the second section of the experiment?
Options: All integers.
Error message: Your answer is wrong. In each round in the second section, only the lowest bid will be accepted.

Question 11: Which bid will be accepted and which project will be

awarded?
Options:

- The project with the highest bid will be awarded.
- The project with the lowest bid will be awarded.
- The acceptance of the bid and the awarding of the project will be chosen randomly.

Error message: Your answer is wrong. The project with the lowest bid will be awarded.

Question 12: You have submitted a bid in the amount of 369 ExCU for your project in one round. The realisation costs of this project are 360 ExCU. What is your round outcome, if your bid for this project is accepted?
Options: All integers (in ExCU).
Error message: Your answer is wrong. Your realisation costs are 360 ExCU. Since your bid has been accepted, you will receive your bid in the amount of 369 ExCU. Thus, your round outcome is 369 ExCU - 360 ExCU = 9 ExCU.

Question 12: You have submitted a bid in the amount of 365 ExCU for your project in one round. The realisation costs of this project are 360 ExCU. What is your round outcome, if your bid for this project is accepted and the lowest non-accepted bid from your 5 competitors is 369 ExCU?
Options: All integers (in ExCU).
Error message: Your answer is wrong. Your realisation costs are 360 ExCU. Since your bid has been accepted, you will receive a payment in the amount of the lowest non-accepted bid from your competitors, namely 369 ExCU. Thus, your round outcome is 369 ExCU - 360 ExCU = 9 ExCU.

Question 13: You have submitted a bid in the amount of 369 ExCU for your project in one round. The realisation costs of this project are 360 ExCU. What is your round outcome, if your bid for this project is not accepted?
Options: All integers (in ExCU).

Error message: Your answer is wrong. Since your bid has not been accepted, no realisation costs will incur and you will not receive your bid. Thus, your round outcome is 0 ExCU.

Question 13: You have submitted a bid in the amount of 370 ExCU for your project in one round. The realisation costs of this project are 360 ExCU. What is your round outcome, if your bid for this project is not accepted and the lowest non-accepted bid from your 5 competitors is 369 ExCU?
Options: All integers (in ExCU).
Error message: Your answer is wrong. Since your bid has not been accepted, no realisation costs will incur and you will not receive any payment. Thus, your round outcome is 0 ExCU.

Question 14: How will your payoff be calculated from the two times 20 rounds of the experiment?
Options:

- You will receive the sum of all round outcomes in the two times 20 rounds.
- You will receive the average of all round outcomes in the two times 20 rounds.
- You will receive the average of your round outcomes in the first section of the experiment.
- You will receive the average of your round outcomes in 20 randomly chosen rounds, whereby every 5 rounds are chosen from 10 consecutive rounds.

Error message: Your answer is wrong. You will receive the average of your round outcomes in 20 randomly chosen rounds, whereby every 5 rounds are chosen from 10 consecutive rounds.

C.4.2 Multi-supply bidders

Text in blue is displayed in the quiz pages of the DP treatments only. Text in magenta is displayed in the quiz pages of the UP treatments only. Text in green is displayed in the quiz pages of the joint first treatments only. Text in red is displayed in the quiz pages of the separate first treatments *only.*

Note: the respective error message will certainly only appear, if the correct answer was not selected.

Question 1: How many rounds does each of the two sections of this experiment consist of?
Options: All integers.
Error message: Your answer is wrong. Each of the two sections of this experiment consist of 20 rounds.

Question 2: How many other participants will you interact with in each round in the first section of the experiment?
Options: All integers.
Error message: Your answer is wrong. You will interact with 2 other participants in each round in the first section.

Question 2: How many other participants will you interact with in each round in the first section of the experiment?
Options: All integers.
Error message: Your answer is wrong. You will interact with 5 other participants in each round in the first section.

Question 3: How many other participants will you interact with in each round in the second section of the experiment?
Options: All integers.
Error message: Your answer is wrong. You will interact with 5 other participants in each round in the second section.

Question 3: How many other participants will you interact with in each round in the second section of the experiment?
Options: All integers.
Error message: Your answer is wrong. You will interact with 2 other participants in each round in the second section.

Question 4: Which of the following statements is correct?

Options:

- The composition of the group in the award procedure, to which you belong, is the same in all 20 rounds. In other words, you will interact with the same participants in each of the 20 rounds.
- The composition of the group in the award procedure, to which you belong, will be randomly redetermined in each round.

Error message: Your answer is wrong. The composition of the group in the award procedure, to which you belong, will be randomly redetermined in each round.

Question 5: Which of the following statements is correct?
Options:

- In each round you will have exactly one project.
- In each round you will have exactly two projects.
- From the second round onwards, you will have projects from the previous rounds as well.

Error message: Your answer is wrong. In each round you will have exactly two projects.

Question 6: Which of the following statements is correct?
Options:

- The types (A or B) of a participant will not change during the experiment.
- The types (A or B) of a participant will remain the same in the first section and switch in the second section.
- The types (A or B) of a participant will switch after every 10 rounds, not only in the first section but also in the second section of the experiment.

Error message: Your answer is wrong. The types (A or B) of a participant will switch after every 10 rounds, not only in the first section but also in the second section of the experiment.

Question 7: At the beginning of the experiment you are of type A. Which of the following statements about the realisation costs of the project, which is available to you in one of the first 10 rounds of the experiment, is correct?

Options:

- The realisation costs of your projects will always be 300 ExCU.
- In each round, the realisation costs of the projects will be the same for all 3 participants in your group and drawn randomly from the interval A = [300,400] at the beginning of the round.
- The realisation costs of the project of a participant will be drawn individually randomly from the interval A = [300,400] at the beginning of the round. Thus, the realisation costs of the 3 participants may differ. Also, the realisation costs of the the projects of one participant may differ.

Error message: Your answer is wrong. The realisation costs of the project of a participant will be drawn individually randomly from the interval A = [300,400] at the beginning of the round. Thus, the realisation costs of the 3 participants may differ. Also, the realisation costs of the the projects of one participant may differ.

Question 7: At the beginning of the experiment you are of type A. Which of the following statements about the realisation costs of the project, which is available to you in one of the first 10 rounds of the experiment, is correct?

Options:

- The realisation costs of your projects will always be 300.
- In each round, the realisation costs of the projects will be the same for all 5 participants in your group and drawn randomly from the interval [300,400] at the beginning of the round.
- The realisation costs of the projects of a participant will be drawn individually randomly from the interval A = [300,400] at the beginning of the round. Thus, the realisation costs of the 5 participants may differ. Also, the realisation costs of the the projects of one participant may differ.

Error message: Your answer is wrong. The realisation costs of the project of a participant will be drawn individually randomly from the interval A = [300,400] at the beginning of the round. Thus, the realisation costs of the 5 participants may differ. Also, the realisation costs of the the projects of one participant may differ.

Question 8: From which interval will the realisation cost of a participant of type B be drawn?
Options:

- B = [350,450]
- B = [300,400]
- B = [350,400]

Error message: Your answer is wrong. The realisation costs of a participant of type B will be drawn from the interval B = [350,450].

Question 9: How many bids will be accepted (and therefore the projects will be awarded) per round in the first section of the experiment?
Options: All integers.
Error message: Your answer is wrong. In each round in the first section, only the two lowest bids will be accepted.

Question 9: How many bids will be accepted (and therefore the projects will be awarded) per round in the first section of the experiment?
Options: All integers.
Error message: Your answer is wrong. In each round in the first section, the four lowest bids will be accepted.

Question 10: How many bids will be accepted (and therefore the projects will be awarded) per round in the second section of the experiment?
Options: All integers.
Error message: Your answer is wrong. In each round in the second section, the four lowest bids will be accepted.

Question 10: How many bids will be accepted (and therefore the projects will be awarded) per round in the second section of the experiment?
Options: All integers.
Error message: Your answer is wrong. In each round in the second section, only the two lowest bids will be accepted.

Question 11: Which bids will be accepted and which projects will be awarded?
Options:

- The projects with the highest bids will be awarded.
- The projects with the lowest bids will be awarded.
- The acceptance of the bids and the awarding of the projects will be chosen randomly.

Error message: Your answer is wrong. The projects with the lowest bids will be awarded.

Question 12: You have submitted a bid in the amount of 369 ExCU for your project in one round. The realisation costs of this project are 360 ExCU. What is your round outcome, if your bid for this project is accepted?
Options: All integers (in ExCU).
Error message: Your answer is wrong. Your realisation costs are 360 ExCU. Since your bid has been accepted, you will receive your bid in the amount of 369 ExCU. Thus, your round outcome is 369 ExCU - 360 ExCU = 9 ExCU.

Question 12: You have submitted a bid in the amount of 365 ExCU for your project in one round. The realisation costs of this project are 360 ExCU. What is your round outcome, if your bid for this project is accepted and the lowest non-accepted bid from your 5 competitors is 369 ExCU?
Options: All integers (in ExCU).
Error message: Your answer is wrong. Your realisation costs are 360 ExCU. Since your bid has been accepted, you will receive a payment in the amount of the lowest non-accepted bid from your competitors, namely 369 ExCU. Thus, your round outcome is 369 ExCU - 360 ExCU = 9 ExCU.

Question 13: You have submitted a bid in the amount of 369 ExCU for your project in one round. The realisation costs of this project are 360 ExCU. What is your round outcome, if your bid for this project is not accepted?
Options: All integers (in ExCU).
Error message: Your answer is wrong. Since your bid has not been accepted, no realisation costs will incur and you will not receive your

bid. Thus, your round outcome is 0 ExCU.

Question 13: You have submitted a bid in the amount of 370 ExCU for your project in one round. The realisation costs of this project are 360 ExCU. What is your round outcome, if your bid for this project is not accepted and the lowest non-accepted bid from your 5 competitors is 369 ExCU?
Options: All integers (in ExCU).
Error message: Your answer is wrong. Since your bid has not been accepted, no realisation costs will incur and you will not receive any payment. Thus, your round outcome is 0 ExCU.

Question 14: You have submitted a bid in the amount of 369 ExCU for your first project and a bid of 380 ExCU for your second project in one round. The realisation costs of the first project are 360 ExCU and the realisation costs of the second project are 370 ExCU. What is your total round outcome, if both of your bids are accepted?
Options: All integers (in ExCU).
Error message: Your answer is wrong. Your realisation costs of the first project are 360 ExCU. Since your bid has been accepted, you will receive your bid in the amount of 365 ExCU. Thus, your round outcome for the first project is 365 ExCU - 360 ExCU = 5 ExCU. Your realisation costs of the second project are 370 ExCU. Since your bid has been accepted, you will receive your bid in the amount of 380 ExCU. Thus, your round outcome for the second project is 380 ExCU - 370 ExCU = 10 ExCU. Thus, your total round outcome is the sum of the individual round outcomes, which are 5 ExCU + 10 ExCU = 15 ExCU.

Question 14: You have submitted a bid in the amount of 365 ExCU for your first project and a bid of 380 ExCU for your second project in one round. The realisation costs of the first project are 360 ExCU and the realisation costs of the second project are 370 ExCU. The lowest non-accepted bid is 382 ExCU. What is your total round outcome, if both of your bids are accepted?
Options: All integers (in ExCU).
Error message: Your answer is wrong. Your realisation costs of the

first project are 360 ExCU. Since your bid has been accepted, you will receive the lowest non-accepted bid in the amount of 382 ExCU. Thus, your round outcome for the first project is 382 ExCU - 360 ExCU = 22 ExCU. Your realisation costs of the second project are 370 ExCU. Since your bid has been accepted, you will receive the lowest non-accepted bid in the amount of 382 ExCU. Thus, your round outcome for the second project is 382 ExCU - 370 ExCU = 12 ExCU. Thus, your total round outcome is the sum of the individual round outcomes, which are 22 ExCU + 12 ExCU = 34 ExCU.

Question 15: How will your payoff be calculated from the two times 20 rounds of the experiment?

Options:

- You will receive the sum of all round outcomes in the two times 20 rounds.
- You will receive the average of all round outcomes in the two times 20 rounds.
- You will receive the average of your round outcomes in the first section of the experiment.
- You will receive the average of your round outcomes in 20 randomly chosen rounds, whereby every 5 rounds are chosen from 10 consecutive rounds.

Error message: Your answer is wrong. You will receive the average of your round outcomes in 20 randomly chosen rounds, whereby every 5 rounds are chosen from 10 consecutive rounds.

References

Abylkairova, Bayan (2018). *The first renewable energy auctions in Kazakhstan. Lessons learned and recommendations to improve the environment for private investments in renewable energy*. Accessed:11/29/2019. URL: `http://ptfcar.org/wp-content/uploads/2018/07/Day-2_Bayan-Abylkairova_RE-workshop_Tashkent_day-2_July-12_En.pdf`.

Adam, Zakia et al. (2020). *Global Energy review 2020: The impacts of the Covid 19 crisis on global energy demand and CO2 emissions*. Accessed: 03/29/2021. URL: `https://www.iea.org/reports/global-energy-review-2020/renewables`.

Ahsanullah, Mohammad, Valery B Nevzorov, and Mohammad Shakil (2013). *An introduction to order statistics*. Atlantis Press. DOI: `10.2991/978-94-91216-83-1`.

Alsemgeest, Paul, Charles Noussair, and Mark Olson (1998). "Experimental comparisons of auctions under single-and multi-unit demand". In: *Economic Inquiry* 36.1, pp. 87–97. DOI: `10.1111/j.1465-7295.1998.tb01697.x`.

Amazo, Ana, Felix von Blücher, Bastian Lotz, and Martin Jakob (2020). *Auctions and renewable energy communities*. Accessed. 10/24/2022. URL: `http://aures2project.eu/wp-content/uploads/2020/02/AURES_II_D4_2_energy_communities.pdf`.

Anatolitis, Vasilios, Alina Azanbayev, and Ann-Katrin Fleck (2022). "How to design efficient renewable energy auctions? Empirical insights from Europe". In: *Energy Policy* 166, p. 112982. DOI: `10.1016/j.enpol.2022.112982`.

Anwar, Sajid, Robert McMillan, and Mingli Zheng (2006). "Bidding behavior in competing auctions: Evidence from eBay". In: *European Economic Review* 50.2, pp. 307–322. DOI: `10.1016/j.euroecorev.2004.10.007`.

Ashenfelter, O.C. (1989). "How auctions work for wine and art". In: *Journal of Economic Perspectives* 3, pp. 23–36. DOI: `10.1257/jep.3.3.23`.

Ashenfelter, O.C. and D. Genesove (1992). "Testing for price anomalies in real estate auctions". In: *American Economic Review* 80, pp. 501–505. DOI: `10.3386/w4036`.

Asker, John and Estelle Cantillon (2010). "Procurement when price and quality matter". In: *The RAND Journal of Economics* 41.1, pp. 1–34. ISSN: 07416261. DOI: `10.1111/j.1756-2171.2009.00088.x`.

AURES (2016a). *Auctions for Renewable Energy Support: Cash Flow Model Simulations of Past RES Auctions in Germany, Spain and Denmark, Report D5.1, Technical University of Denmark (DTU)*. Accessed:11/05/2019. URL: `http://aures2project.eu/wp-content/uploads/2021/07/d5-1_report_model_application_final.pdf`.

— (2016b). *Auctions for Renewable Energy Support: Lessons learnt from International Experiences, Report D4.2*. Accessed: 11/05/2019. URL: `http://aures2project.eu/wp-content/uploads/2021/07/aures_wp4_synthesis_report.pdf`.

AURES (2017). *Auctions for Renewable Energy Support: Taming the beast of competitive bidding, Report D9.2.* Accessed: 11/05/2019. URL: `https://orbit.dtu.dk/files/142941994/aures_finalreport.pdf`.

AURES II (2020). *Auction Database.* Internet database. Accessed: 07/19/2020. URL: `http://aures2project.eu/auction-database/`.

— (2022). *Auction Database.* Internet database. Accessed: 10/14/2022. URL: `http://aures2project.eu/auction-database/`.

Ausubel, Lawrence M., Peter Cramton, Marek Pycia, Marzena Rostek, and Marek Weretka (2014). "Demand Reduction and Inefficiency in Multi-Unit Auctions". In: *The Review of Economic Studies* 81.4, pp. 1366–1400.

Ausubel, Lawrence M. and Paul Migrom (2006). "The Lovely but Lonely Vickrey Auction". In: *Combinatorial Auctions.* Ed. by Peter Cramton, Yoav Shoham, and Richard Steinbegr. The MIT Press, pp. 17–40. DOI: `10.7551/mitpress/9780262033428.003.0002`.

Avery, Christopher and John H. Kagel (1997). "Second-Price Auctions with Asymmetric Payoffs: An Experimental Investigation". In: *Journal of Economics & Management Strategy* 6.3, pp. 573–603. DOI: `10.1111/j.1430-9134.1997.00573.x`.

Back, Kerry and Jaime F. Zender (2001). "Auctions of divisible goods with endogenous supply". In: *Economics Letters* 73, pp. 29–34. DOI: `10.1016/S0165-1765(01)00465-7`.

Bates, Douglas, Martin Mächler, Ben Bolker, and Steve Walker (Oct. 2015). "Fitting Linear Mixed-Effects Models Using lme4". In: *Journal of Statistical Software* 67.1, pp. 1–48. DOI: `10.18637/jss.v067.i01`.

Blücher, Felix von, Malte Gephart, Fabian Wigand, and Gustav Resch (Aug. 2020). *The new renewable energy financing mechanism of the EU in practice - a cooperation case study.* AURES II Report. Acessed: 02/22/2022. URL: `http://aures2project.eu/wp-content/uploads/2020/11/AURES_II_D6_3_EU.pdf`.

BNetzA (2019). *Bundesnetzagentur (BNetzA): Ausschreibungen für EE- und KWK-Anlagen.* Accessed: 10/09/2019. URL: `https://www.bundesnetzagentur.de/DE/Sachgebiete/ElektrizitaetundGas/Unternehmen_Institutionen/Ausschreibungen/Ausschreibungen_node.html`.

— (2022). *Bundesnetzagentur (BNetzA): Ausschreibungen für EE- und KWK-Anlagen.* Accessed: 01/14/2022. URL: `https://www.bundesnetzagentur.de/DE/Sachgebiete/ElektrizitaetundGas/Unternehmen_Institutionen/Ausschreibungen/start.html`.

Bock, Olaf, Ingmar Baetge, and Andreas Nicklisch (2014). "hroot: Hamburg registration and organization online tool". In: *European Economic Review* 71, pp. 117–120. DOI: `10.1016/j.euroecorev.2014.07.003`.

BP p.l.c (2020). *BP Statistical Review of World Energy.* Accessed: 03/29/2021. URL: `https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2020-full-report.pdf`.

Brambor, Thomas, William Roberts Clark, and Matt Golder (2006). "Understanding interaction models: Improving empirical analyses". In: *Political analysis* 14.1, pp. 63–82. DOI: `10.1093/pan/mpi014`.

BReg (2019). *Deutsche Bundesregierung (BReg): Klimaschutzprogramm 2030 der Bundesregierung zur Umsetzung des Klimaschutzplans 2050.* Accessed: 11/06/2019. URL: `https://www.bundesregierung.de/resource/blob/974430/1679914/e01d6bd855f09bf05cf7498e06d0a3ff/2019-10-09-klima-massnahmen-data.pdf?download=1`.

Broom, Douglas (2022). *Europe is beating its renewable energy targets. Which countries are leading the charge?* World Economic Forum. Acccessed: 10/13/2022. URL: `https://www.weforum.org/agenda/2022/02/europe-overachieving-net-zero/`.

Brown, Violet A (2021). “An Introduction to Linear Mixed-Effects Modeling in R”. In: *Advances in Methods and Practices in Psychological Science* 4.1, p. 2515245920960351. DOI: `10.1177/2515245920960351`.

Bundesamt für Energie (2019). *Wettbewerbliche Ausschreibungen – ProKilowatt.* Accessed: 10/16/2019. URL: `https://www.bfe.admin.ch/bfe/de/home/foerderung/energieeffizienz/wettbewerbliche-ausschreibungen-prokilowatt.html#kw-83176`.

Bundesnetzagentur (2022). *Statistiken: Windenergieanlagen an Land - Ausschreibungen.* Accessed: 26/10/2022. URL: `https://www.bundesnetzagentur.de/SharedDocs/Downloads/DE/Sachgebiete/Energie/Unternehmen_Institutionen/Ausschreibungen/Statistiken/Statistik_Onshore.xlsx?__blob=publicationFile&v=23`.

Camerer, Colin F, Teck-Hua Ho, and Juin-Kuan Chong (2004). “A cognitive hierarchy model of games”. In: *The Quarterly Journal of Economics* 119.3, pp. 861–898. DOI: `10.1162/0033553041502225`.

Campbell, Colin M. (1998). “Coordination in Auctions with Entry”. In: *Journal of Economic Theory* 82 (2), pp. 425–450. DOI: `10.1006/jeth.1995.2452`.

Cantillon, Estelle (2008). “The effect of bidders’ asymmetries on expected revenue in auctions”. In: *Games and Economic Behavior* 62.1, pp. 1–25. DOI: `10.1016/j.geb.2006.11.005`.

Cao, Xiaoyong, Guofu Tan, Guoqiang Tian, and Okan Yilankaya (2018). “Equilibria in second-price auctions with private participation costs”. In: *Economic Theory* 65, pp. 231–249. DOI: `10.1007/s00199-016-1028-6`.

Cao, Xiaoyong and Guoqiang Tian (2010). “First Price Auctions with Participation Costs”. In: *Games and Economic Behavior* 69, pp. 258–273. DOI: `10.1016/j.geb.2009.11.006`.

— (2013). “Second Price Auctions with Differentiated Participation Costs”. In: *Journal of Economics & Management Strategy* 22 (1), pp. 184–205. DOI: `10.1111/jems.12004`.

Casari, Marco, John C Ham, and John H Kagel (2007). “Selection bias, demographic effects, and ability effects in common value auction experiments”. In: *American Economic Review* 97.4, pp. 1278–1304. DOI: `10.1257/aer.97.4.1278`.

Celik, Gorkem and Okan Yilankaya (2009). “Optimal Auctions with Simultaneous and Costly Participation”. In: *The B.E. Journal of Theoretical Economics* 9.1. DOI: `10.2202/1935-1704.1522`.

Chen, Daniel L., Martin Schonger, and Chris Wickens (2016). “oTree—An open-source platform for laboratory, online, and field experiments”. In: *Journal of Behavioral and Experimental Finance* 9, pp. 88–97. ISSN: 2214-6350. DOI: `10.1016/j.jbef.2015.12.001`.

Chen, Shiying, Zhenhuan Dong, Chunming Cao, and Changjun Zheng (2022). “Strategy and design of multi-unit auction in grouped asymmetric setting”. In: *Managerial and Decision Economics*. DOI: `10.1002/mde.3606`.

Chirkin, V. et al. (2016). “Gaming Experiments for Analysis of Pricing Mechanisms at Electricity Markets”. In: *IFAC-PapersOnLine* 49.32. Cyber-Physical & Human-Systems CPHS 2016, pp. 13–18. ISSN: 2405-8963. DOI: `10.1016/j.ifacol.2016.12.182`.

Comité para la conducción del proceso de la cuarta subasta de suministro de electricidad con recursos energéticos renovables (2015). *Circular No.5.* Accessed: 05/06/2019. URL:

http://www.osinergmin.gob.pe/seccion/centro_documental/energias-renovables/Subastas/Circular%5C%20N05_%5C%20Precio%5C%20M%5C%C3%5C%A1ximo.pdf.

Cramton, Peter, Sean Ellermeyer, and Brett Katzman (2015). "Designed to Fail: The Medicare Auction for Durable Medical Equipment". In: *Economic Inquiry* 53.1, pp. 469–485. DOI: 10.1111/ecin.12101.

Damianov, Damian S. (2005). "The Uniform Price Auction with Endogenous Supply". In: *Economics Letters* 88, pp. 152–158. DOI: 10.1016/j.econlet.2005.02.004.

Damianov, Damian S. and Johannes Gerd Becker (2010). "Auctions with variable supply: Uniform price versus discriminatory". In: *European Economic Review* 54.4, pp. 571–593. DOI: 10.1016/j.euroecorev.2009.09.002.

Delnoij, Joyce and Kris De Jaegher (2018). "Competing first-price and second-price auctions". In: *Economic Theory* XX, pp. 1–34. DOI: 10.1007/s00199-018-1161-5.

Deutscher Bundestag (2017). *EEG 2017. Gesetz für den Ausbau erneuerbarer Energien (Erneuerbare-Energien-Gesetz -EEG 2017).* Accessed: 09/22/2017. URL: https://www.gesetze-im-internet.de/eeg_2014/BJNR106610014.html.

Ehrhart, Karl-Martin, Ann-Katrin Fleck, and Marion Ott (2022). "A Small Volume Reduction that Melts Down the Market: Auctions with Endogenous Rationing". In: *under review in Games and Economic Behaviour.*

Ehrhart, Karl-Martin, Ann-Katrin Hanke, Vasilios Anatolitis, and Jenny Winkler (2019a). *Auction-theoretic aspects of cross-border auctions.* Accessed:05/05/2022. URL: http://aures2project.eu/wp-content/uploads/2020/02/MultiAuctions_final_anv.pdf.

Ehrhart, Karl-Martin and Jan Kreiss (2019b). "Multi-unit common value auctions – theoretical and experimental analysis". working paper.

Enerdata (2021). *Italy awards only 821 MW of renewable capacity in a 3.3 GW tender.* Accessed: 02/21/2022. URL: https://www.enerdata.net/publications/daily-energy-news/italy-awards-only-821-mw-renewable-capacity-33-gw-tender.html.

Engelbrecht-Wiggans, Richard (1988). "Revenue equivalence in multi-object auctions". In: *Economics Letters* 26.1, pp. 15–19. ISSN: 0165-1765. DOI: 10.1016/0165-1765(88)90044-4.

Engelbrecht-Wiggans, Richard and Charles M. Kahn (Sept. 1998a). "Multi-unit auctions with uniform prices". In: *Economic Theory* 12.2, pp. 227–258. DOI: 10.1007/s001990050220.

— (Apr. 1998b). "Multi-Unit Pay-Your-Bid Auctions with Variable Awards". In: *Games and Economic Behavior* 23.1, pp. 25–42. DOI: 10.1006/game.1997.0599.

Engelmann, Dirk and Veronika Grimm (2009). "Bidding behaviour in multi-unit auctions–an experimental investigation". In: *The Economic Journal* 119.537, pp. 855–882. DOI: 10.1111/j.1468-0297.2009.02249.x.

European Commission (2014). *Guidelines on State aid for environmental protection and energy 2014-2020 (2014/C 200/01).* Accessed: 11/25/2019. URL: http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52014XC0628(01).

— (2018). *Renewable Energy Directive II.* URL: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32018L2001&from=EN#d1e1885-82-1.

— (2020). *Stepping up Europe's 2030 climate ambition. Investing in a climate-neutral future for the benefit of our people. Communication from the commission to the European parliament, the council, the European economic and social committee and the committee of* *the regions.* URL: `https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020DC0562&from=EN`.

— (2022). *Guidelines on State aid for climate, environmental protection and energy.* URL: `https://ec.europa.eu/competition-policy/sectors/energy-and-environment/legislation_en`.

European Parliament (2018). *Regulation (EU) 2018/1999 of the European Parliament and of the Council of 11 December 2018 on the Governance ofthe Energy Union and Climate Action.* Accessed: 02/22/2022. URL: `https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018R1999&from=EN`.

European Parliament and Council of the EU (2021). *Proposal for a Directive of the European Parliament and of the Council amending Directive (EU) 2018/2001 of the European Parliament and of the Council, Regulation (EU) 2018/1999 of the European Parliament and of the Council and Directive 98/70/EC of the European Parliament and of the Council as regards the promotion of energy from renewable sources, and repealing Council Directive (EU) 2015/652.* URL: `https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52021PC0557&from=EN`.

European Parliament, Council of the European Union (2009). *Directive 2009/28/EC.* Accessed: 07/08/2017. URL: `http://data.europa.eu/eli/dir/2009/28/oj`.

Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) (2000). *Act on Granting Priority to Renewable Energy Sources (Renewable Energy Sources Act).* Accessed: 10/17/2022. URL: `https://web.archive.org/web/20160921012408/http://www.bmub.bund.de/fileadmin/bmu-import/files/pdfs/allgemein/application/pdf/res-act.pdf`.

Fleck, Ann-Katrin (2022). "Analysing Multi-Technology Auctions - Experimental Evidence". In: *Working Paper.*

Fleck, Ann-Katrin and Vasilios Anatolitis (2023). "Achieving the objectives of renewable energy policy - Insights from renewable energy auction design in Europe". In: *Energy Policy* 173, p. 113357. DOI: `10.1016/j.enpol.2022.113357`.

Gałecki, Andrzej and Tomasz Burzykowski (2013). "Linear mixed-effects model". In: *Linear mixed-effects models using R.* Springer, pp. 245–273. DOI: `10.1007/978-1-4614-3900-4_13`.

Gallegati, Mauro, Gianfranco Giulioni, Alan Kirman, and Antonio Palestrini (2011). "What's that got to do with the price of fish? Buyers behavior on the Ancona fish market". In: *Journal of Economic Behavior and Organization* 80.1, pp. 20–33. DOI: `10.1016/j.jebo.2011.01.011`.

Gerding, Enrico H., Rajdeep K. Dash, Andrew Byde, and Nicholas R. Jennings (2008). "Optimal Strategies for Bidding Agents Participating in Simultaneous Vickrey Auctions with Perfect Substitutes". In: *Journal of Artificial Intelligence Research* 32, pp. 939–982. URL: `https://dl.acm.org/doi/10.5555/1622673.1622697`.

Griesmer, James H, Richard E Levitan, and Martin Shubikt (1967). "Toward a study of bidding processes part IV-games with unknown costs". In: *Naval Research Logistics Quarterly* 14.4, pp. 415–433. DOI: `10.1002/nav.3800140402`.

Guerci, Eric and Mohammad Ali Rastegar (2012). "Comparing system-marginal-price versus pay-as-bid auctions in a realistic electricity market scenario". In: *Managing Market Complexity.* Springer, pp. 141–153. DOI: `10.1007/978-3-642-31301-1_12`.

Güth, Werner, Radosveta Ivanova-Stenzel, and Elmar Wolfstetter (2005). “Bidding behavior in asymmetric auctions: An experimental study”. In: *European Economic Review* 49.7, pp. 1891–1913. DOI: `10.1016/j.euroecorev.2004.09.003`.

Hanke, Ann-Katrin and Silvana Tiedemann (June 2020). *How (not) to respond to low competition in renewable energy auctions.* Accessed: 08/28/2022. URL: `http://aures2project.eu/2020/06/15/how-not-to-respond-to-low-competition-in-renewable-energy-auctions/`.

Haufe, Marie-Christin and Karl-Martin Ehrhart (2018). “Auctions for renewable energy support – Suitability, design, and first lessons learned”. In: *Energy Policy* 121, pp. 217–224. ISSN: 0301-4215. DOI: `10.1016/j.enpol.2018.06.027`.

Heim, Sven and Georg Götz (2013). “Do pay-as-bid auctions favor collusion? Evidence from Germany’s market for reserve power”. In: *Evidence from Germany’s Market for Reserve Power.* DOI: `10.1016/j.enpol.2021.112308`.

Held, Anne, Mario Ragwitz, Pablo del Río, Gustav Resch, Corinna Klessmann, Arndt Hassel, Milan Elkerbout, and James Rawlins (2019). “Do Almost Mature Renewable Energy Technologies Still Need Dedicated Support Towards 2030?” In: *Economics of Energy & Environmental Policy* 8.2. DOI: `10.5547/2160-5890.8.2.ahel`.

Hernando-Veciana, Angel (2005). “Competition among auctioneers in large markets”. In: *Journal of Economic Theory* 121, pp. 107–127. DOI: `10.1016/j.jet.2004.03.001`.

Hochberg, Michael and Rahmatallah Poudineh (2018). *Renewable Auction Design in Theory and Practice: Lessons from the Experiences of Brazil and Mexico.* Oxford Institute for Energy Studies Paper: EL 28, Accessed: 11/25/2019. URL: `https://www.oxfordenergy.org/wpcms/wp-content/uploads/2018/04/Renewable-Auction-Design-in-Theory-and-Practice-Lessons-from-the-Experiences-of-Brazil-and-Mexico-EL-28.pdf`.

Holmberg, Pär and Frank A Wolak (2018). “Comparing auction designs where suppliers have uncertain costs and uncertain pivotal status”. In: *The RAND Journal of Economics* 49.4, pp. 995–1027. DOI: `10.1111/1756-2171.12259`.

Holt, Charles A and Susan K Laury (2002). “Risk aversion and incentive effects”. In: *American economic review* 92.5, pp. 1644–1655. DOI: `10.1257/000282802762024700`.

Houde, Jean-Francois, Terence Johnson, Molly Lipscomb, and Laura Schechter (2017). “Pricing Winners: Optimizing Just-in-time Procurement Auctions in Dakar, Senegal”. unpublished manuscript.

Hudson, Randy et al. (2000). “Analysis of uniform and discriminatory price auctions in restructured electricity markets”. In: *Oak Ridge National Laboratory, Oak Ridge, TN.* URL: `https://stuff.mit.edu/afs/athena.mit.edu/course/other/esd.126/OldFiles/www/MktsAuctions/ORNL.pdf`.

IRENA (2013). *Renewable Energy Auctions in Developing Countries.* Accessed: 11/25/2019. URL: `https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2013/IRENA_Renewable_energy_auctions_in_developing_countries.pdf`.

— (2015). *Renewable Power Generation Costs in 2014.* Accessed: 11/23/2017. URL: `https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2015/IRENA_RE_Power_Costs_2014_report.pdf?rev=4dfc65cc95394824805d5449babc2c93` (visited on 11/23/2017).

— (2019). *Renewable energy auctions: Status and trends beyond price.* Accessed: 08/27/2019. URL: `https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Jun/IRENA_Auctions_beyond_price_2019_findings.pdf`.

Jerrentrup, Lars, Bastian Lotz, Silvana Tiedemann, and Lion Hirth (2016). "Technology-Neutral Auctions for Renewable Energy: EU Law vs. Member State Reality". In: *Centro* 2017. Accessed: 02/21/2020, p. 5. DOI: `10.1163/18760104-01604005`.

Jiménez, Mariana (2016). *CENACE Obtains Definitive Results for the First Long-Term Electricity Tender.* Accessed: 04/26/2019.

Kagel, John H and Dan Levin (2001). "Behavior in multi-unit demand auctions: experiments with uniform price and dynamic Vickrey auctions". In: *Econometrica* 69.2, pp. 413–454. DOI: `10.1111/1468-0262.00197`.

Kahles, Markus (2017). *The Implementation of Cross-Border Auctions in Germany.* Accessed: 05/05/2022. URL: `https://energie-fr-de.eu/de/veranstaltungen/leser/konferenz-zu-foerdermechanismen-fuer-windenergie-standortbestimmung-und-perspektiven.html?file=files/ofaenr/02-conferences/2017/171010_conference_eolienne_mecanismes_de_soutien/Presentations/08_Markus_Kahles_Stiftung_Umweltenergierecht_DFBEW_OFATE.pdf`.

Kaplan, Todd R and Shmuel Zamir (2012). "Asymmetric first-price auctions with uniform distributions: analytic solutions to the general case". In: *Economic Theory* 50.2, pp. 269–302. DOI: `10.1007/s00199-010-0563-9`.

Kazakh Government (2009). *Government of Kazakhstan: On support for the use of renewable energy source, The Law of the Republic of Kazakhstan dated 4 July 2009 No. 165-IV.* Accessed: 11/25/2019. URL: `http://adilet.zan.kz/eng/docs/Z090000165_`.

Kerres, Pia, Felix von Blücher, Bastian Lotz, Malte Gephart, and Fabian Wigand (2021). *Guidance on implementing cross-border renewable energy auctions.* Accessed: 10/26/2022. URL: `http://aures2project.eu/wp-content/uploads/2021/06/AURES_II_D6_4_guidance_document.pdf`.

Kirchkamp, Oliver, Eva Poen, and J. Philipp Reiß (2009). "Outside options: Another reason to choose the first-price auction". In: *European Economic Review* 53, pp. 153–169. DOI: `10.1016/j.euroecorev.2008.03.005`.

Kirkegaard, René (2012). "A mechanism design approach to ranking asymmetric auctions". In: *Econometrica* 80.5, pp. 2349–2364. DOI: `10.3982/ECTA9859`.

Kitzing, L. and H. Ravn (May 2013). "Support mechanisms and risk: Implications on the Nordic electricity system". In: *2013 10th International Conference on the European Energy Market (EEM)*, pp. 1–7. DOI: `10.1109/EEM.2013.6607341`.

Kreiss, Jan, Karl-Martin Ehrhart, and Marie-Christin Haufe (2017). "Appropriate design of auctions for renewable energy support – Prequalifications and penalties". In: *Energy Policy* 101, pp. 512–520. DOI: `10.1016/j.enpol.2016.11.007`.

Kreiss, Jan, Karl-Martin Ehrhart, Marie-Christin Haufe, and Emilie Rosenlund Soysal (2020). "Different cost perspectives for renewable energy support: Assessment of technology-neutral and discriminatory auctions". In: *Economics of Energy and Environmental Policy* (forthcoming). DOI: `10.5547/2160-5890.10.1.jkre`.

Krishna, Vijay (2003). "Asymmetric english auctions". In: *Journal of Economic Theory* 112.2, pp. 261–288. DOI: `10.1016/S0022-0531(03)00074-7`.

— (2009). *Auction Theory.* Academic Press.

Krishna, Vijay and Robert W. Rosenthalb (1996). “Simultaneous Auctions with Synergies”. In: *Games and Economic Behavior* 17, pp. 1–31. DOI: `10.1006/GAME.1996.0092`.

Kunzetsova, A, PB Brockhoff, and RHB Christensen (2017). “lmerTest package: tests in linear mixed effect models”. In: *J Stat Softw* 82, pp. 1–26. DOI: `10.18637/jss.v082.i13`.

Larue, Bruno, Mohamed Jeddy, and Sébastien Pouliot (2013). *On the number of bidders and auction performance: when more means less.* Working Paper. SPAA Network. URL: `https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2317268`.

Ledyard, John O. (2007). *Optimal Combinatoric Auctions with Single-Minded Bidders.* WorkingPaper. EC ’07 Proceedings of the 8th ACM conference on Electronic commerce. URL: `http://www.its.caltech.edu/~jledyard/John%27s%20Papers/jlC2.pdf`.

Legislation of Ukraine (2019). *On Alternative Energy Sources (Document 555-IV).* Accessed: 01/13/2020. URL: `https://zakon.rada.gov.ua/laws/show/555-15?lang=en`.

Leoni, Patrick and Frederik Lundtofte (2017). “Information, stochastic dominance and bidding: The case of Treasury auctions”. In: *Economics Letters* 153, pp. 80–82. DOI: `10.1016/j.econlet.2017.02.004`.

Leszczyc, Peter T.L. Popkowski and Gerald Häubl (2010). “To Bundle or Not to Bundle: Determinants of the Profitability of Multi-Item Auctions”. In: *Journal of Marketing* 74, pp. 110–124. DOI: `10.1509/jmkg.74.4.110`.

Levin, Dan and James L. Smith (1994). “Equilibrium in Auctions with Entry”. In: *The American Economic Review* 84.3, pp. 585–599.

Li, Tong and Xiaoyong Zheng (2009). “Entry and Competition Effects in First-Price Auctions: Theory and Evidence from Procurement Auctions”. In: *Review of Economic Studies* 76, pp. 1397–1429. DOI: `10.1111/j.1467-937X.2009.00558.x`.

LiCalzi, Marco and Alessandro Pavan (2005). “Tilting the supply schedule to enhance competition in uniform-price auctions”. In: *European Economic Review* 49, pp. 227–250. DOI: `0.1016/S0014-2921(02)00324-0`.

Lu, Jingfeng (2009a). “Auction design with opportunity cost”. In: *Economic Theory* 38, pp. 73–103. DOI: `10.1007/s00199-008-0331-2`.

— (2009b). “Why a simple second-price auction induces efficient endogenous entry”. In: *Theory and Decision* 66, pp. 181–196. DOI: `10.1007/s11238-007-9092-9`.

Manelli, Alejandro M., Martin Sefton, and Benjamin S. Wilner (2006). “Multi-unit auctions: A comparison of static and dynamic mechanisms”. In: *Journal of Economic Behavior & Organization* 61, pp. 304–323. DOI: `10.1016/j.jebo.2005.04.014`.

Mares, Vlad and Jeroen M Swinkels (2014). “Comparing first and second price auctions with asymmetric bidders”. In: *International Journal of Game Theory* 43.3, pp. 487–514. DOI: `10.1007/s00182-013-0392-8`.

McAdams, David (2007). “Adjustable supply in uniform price auctions: Non-commitment as a strategic tool”. In: *Economics Letters* 95, pp. 48–53. DOI: `10.1016/j.econlet.2006.08.035`.

McAfee, R. Preston (1993). “Mechanism Design by Competing Sellers”. In: *Econometrica* 61, pp. 1281–1312. DOI: `10.2307/2951643`.

McAfee, R. Preston and John McMillan (1987). “Auctions with a Stochastic Number of Bidders”. In: *Journal of Economic Theory* 43, pp. 1–19. DOI: `10.1016/0022-0531(87)90113-X`.

McAfee, R.P. and D. Vincent (1993). “The declining price anomaly”. In: *Journal of Economic Theory* 60, pp. 191–212. DOI: `10.1006/jeth.1993.1041`.

Menezes, Flavio M. and Paulo K. Monteiro (2000). “Auctions with endogenous participation”. In: *Review of Economic Design* 5, pp. 71–89. DOI: `10.1007/s100580050048`.

— (2005). *An Introduction to Auction Theory*. Oxford University Press, USA. DOI: `10.1093/019927598X.001.0001`.

Milgrom, Paul (2007). *Putting Auction Theory to Work*. Cambridge University Press. DOI: `10.1017/CBO9780511813825`.

Ministre de l’Europe et des Affaires étrangères (2018). *Soutien de l’effacement en France par appel d’offres, SA.48490 - France.* Accessed: 02/05/2020. URL: `https://ec.europa.eu/competition/elojade/isef/case_details.cfm?proc_code=3_SA_48490`.

— (2019). *Soutien par appel d’offres au développement d’installations de production d’électricité à partir de l’énergie solaire dans le département du Haut-Rhin, Aide d’État SA.51190 - France.* Accessed: 02/05/2020. URL: `https://ec.europa.eu/competition/state_aid/cases/274758/274758_2049151_113_2.pdf`.

Miralles, A. (2008). “Intuitive and noncompetitive equilibria in weakly efficient auctions with entry costs”. In: *Mathematical Social Sciences* 56, pp. 448–455. DOI: `10.1016/j.mathsocsci.2008.06.004`.

Moldovanu, Benny, Aner Sela, and Xianwen Shi (2006). “Competing Auctions with Endogenous Quantities”. In: *Journal of Economic Theory* 141, pp. 1–27. DOI: `10.1016/j.jet.2007.09.001`.

Mora, David et al. (2017). *Auctions for Renewable Energy Support: Taming the beast of competitive bidding, AURES Report D9.2.* Accessed: 11/05/2019. URL: `https://orbit.dtu.dk/files/142941994/aures_finalreport.pdf`.

Mount, Timothy D, WD Schulze, Robert J Thomas, and Raymond D Zimmerman (2001). “Testing the performance of uniform price and discriminative auctions”. In: *Rutger’s Center for Research in Regulated Industries 14th Annual Western Conference: Advanced Workshop in Regulation and Competition, Competitive Change in Network Industries.* Citeseer. URL: `https://e3rg.pserc.cornell.edu/files/Rutgers_Tim22.pdf`.

Müller, Samuel, Janice L Scealy, and Alan H Welsh (2013). “Model selection in linear mixed models”. In: *Statistical Science* 28.2, pp. 135–167. DOI: `10.1214/12-STS410`.

Myerson, Roger B. (1981). “Optimal Auction Design”. In: *Mathematics of Operations Research* 6.1, pp. 58–73. eprint: `http://dx.doi.org/10.1287/moor.6.1.58`.

Nagel, Rosemarie (1995). “Unraveling in guessing games: An experimental study”. In: *The American Economic Review* 85.5, pp. 1313–1326. URL: `https://www.jstor.org/stable/2950991`.

Nyborg, Kjell G., Kristian Rydqvist, and Suresh M. Sundaresan (2002). “Bidder Behavior in Multiunit Auctions: Evidence from Swedish Treasury Auctions”. In: *Journal of Political Economy* 110.2, pp. 394–424. DOI: `10.1086/338748`.

Oh, Hyung Seon, Robert J Thomas, Bernie Leiseutre, and Timothy D Mount (2003). “Comparing the behavior of agents to human subjects in a uniform price auction”. In: *36th Annual Hawaii International Conference on System Sciences, 2003. Proceedings of the.* IEEE, 7–pp. DOI: `10.1109/HICSS.2003.1173869`.

Palfrey, Thomas R. (1983). “Bundling Decisions by a Multiproduct Monopolist with Incomplete Information”. In: *Econometrica* 51, pp. 463–483. DOI: `10.2307/1912001`.

Papachristou, Dionysios, Panagiota Kapetana, Panagiotis Daliouris, and Thanassis Petmezas (2017). “The Pilot Tender for PV in Greece within 2016”. In: *33rd European Photovoltaic Solar Energy Conference and Exhibition* DOI: `10.4229/EUPVSEC20172017-7DV.1.35`.

Peters, Michael and Sergei Severinov (2006). “Internet auctions with many traders”. In: *Journal of Economic Theory* 130, pp. 220–245. DOI: `10.1016/j.jet.2005.04.005`.

Plum, Michael (1992). “Characterization and computation of Nash-equilibria for auctions with incomplete information”. In: *International Journal of Game Theory* 20.4, pp. 393–418. DOI: `10.1007/BF01271133`.

Qazi, Atika, Fayaz Hussain, Nasrudin ABD Rahim, Glenn Hardaker, Daniyal Alghazzawi, Khaled Shaban, and Khalid Haruna (2019). “Towards sustainable energy: a systematic review of renewable energy sources, technologies, and public opinions”. In: *IEEE access* 7, pp. 63837–63851. DOI: `10.1109/ACCESS.2019.2906402`.

Quentin, Jürgen (2015). *Wind-Studie zu Dauer und Kosten des Planungs- und Genehmigungsprozesses von Windenergieanlagen an Land (Fachagentur Windenergie an Land).* Accessed: 11/05/2019. URL: `https://www.fachagentur-windenergie.de/fileadmin/files/Veroeffentlichungen/dauer-kosten-wea-projektierung.pdf`.

R Core Team (2020). *R: A Language and Environment for Statistical Computing.* R Foundation for Statistical Computing. Vienna, Austria. URL: `https://www.R-project.org/`.

Rassenti, Stephen J, Vernon L Smith, and Bart J Wilson (2003). “Discriminatory price auctions in electricity markets: low volatility at the expense of high price levels”. In: *Journal of regulatory Economics* 23.2, pp. 109–123. DOI: `10.1023/A:1022250812631`.

Reiss, J. Philipp (2008). “Optimal Auctions with Outside Competition”. URL: `https://io.econ.kit.edu/downloads/Reiss_OptimalAuctionsWithOutsideCompetition.pdf`.

Reny, Philip J and Shmuel Zamir (2004). “On the existence of pure strategy monotone equilibria in asymmetric first-price auctions”. In: *Econometrica* 72.4, pp. 1105–1125. URL: `https://www.jstor.org/stable/3598780`.

Resch, Gustav, Jasper Geipel, and Lukas Liebmann (2021). *Modelling of European and cross-border RES auctions.* Accessed: 10/26/2022. URL: `http://aures2project.eu/wp-content/uploads/2022/04/AURES_II_D8_1_modelling_cross-border_auctions.pdf`.

Reuters (2021). *Denmark to pick winner of big offshore wind tender in lottery.* Accessed: 10/26/2022. URL: `https://www.reuters.com/business/energy/denmark-pick-winner-big-offshore-wind-tender-lottery-2021-11-25/`.

Riley, J.G. and W.F. Samuelson (1981). “Optimal Auctions”. In: *American Economic Review* 71, pp. 381–392. URL: `https://www.jstor.org/stable/1802786`.

Rio, Pablo del (2016). *Implementation of Auctions for Renewable Energy Support in Spain: a Case Study.* Accessed: 04/24/2022. URL: `http://aures2project.eu/wp-content/uploads/2021/07/wp7_-_case_study_report_spain_1.pdf`.

Río, Pablo del, Marie-Christin Haufe, Fabian Wigand, and Simone Steinhilber (2015). *Overview of Design Elements for RES-E Auctions.* URL: `http://aures2project.eu/wp-content/uploads/2021/07/design_elements_october2015.pdf`.

Robert, Aline and Frédéric Simon (2019). *French wind energy ‘in limbo’ for more than a year.* Accessed: 04/26/2019. URL: `https://www.euractiv.com/section/energy/news/french-wind-energy-in-limbo-for-more-than-a-year/`.

Rödl (2015). *Erneuerbare Energien: Erfahrungen und Trends weltweit.* Accessed: 12/09/2019. URL: `https://www.roedl.de/de-de/de/medien/publikationen/newsletter/erneuerbare-energien/documents/erneuerbare-energien_1504.pdf`.

Roth, Agustin, Felix von Blücher, and Fabian Wigand (2022). *Renewable energy cross-border auctions:benefits, models, and design recommendations.* Accessed: 05/24/2022. URL: `http://aures2project.eu/wp-content/uploads/2022/03/AURES_II_ES_cross-border_auctions.pdf`.

Samuelson, William F. (1985). "Competitive bidding with entry costs". In: *Economics Letters* 17, pp. 53–57. DOI: `10.1016/0165-1765(85)90126-0`.

Schulze, William D, Simon Ede, Ray Zimmerman, John Bernard, Timothy Mount, Robert Thomas, and Richard Schuler (2000). "Can Experimental Economics Help Guide Restructuring of Electric Power?" In: *Workshop Future Research Directions for Complex Interactive Electric Networks.* URL: `https://e3rg.pserc.cornell.edu/files/CAN_EXPERIMENTAL_ECONOMICS.pdf`.

Sorge, Nils-Viktor (2016). *Dänemark blamiert deutsche Ökostrom-Lobby.* Internet article. URL: `https://www.manager-magazin.de/unternehmen/energie/energiewende-daenemark-blamiert-deutschland-bei-solarstrom-a-1123455.html`.

Steffen, Bjarne, Martin Beuse, Paul Tautorat, and Tobias S Schmidt (2020). "Experience curves for operations and maintenance costs of renewable energy technologies". In: *Joule* 4.2, pp. 359–375. DOI: `10.1016/j.joule.2019.11.012`.

Stegemann, Mark (1996). "Participation Costs and Efficient Auctions". In: *Journal of Economic Theory* 71, pp. 228–259. DOI: `10.1006/jeth.1996.0116`.

Tan, Guofu (1992). "Entry and R & D in procurement contracting". In: *Journal of Economic Theory* 58.1, pp. 41–60. DOI: `10.1016/0022-0531(92)90100-V`.

Tan, Guofu and Okan Yilankaya (2006). "Equilibria in second price auctions with participation costs". In: *Journal of Economic Theory* 130, pp. 205–219. DOI: `10.1016/j.jet.2005.02.008`.

Tenorio, Rafael (1993). "Revenue equivalence and bidding behavior in a multi-unit auction market: an empirical analysis". In: *The Review of Economics and Statistics*, pp. 302–314. DOI: `10.2307/2109436`.

Timilsina, Govinda R (2021). "Are renewable energy technologies cost competitive for electricity generation?" In: *Renewable Energy* 180, pp. 658–672. DOI: `10.1016/j.renene.2021.08.088`.

Umlauf, Steven R (1993). "An empirical study of the Mexican Treasury bill auction". In: *Journal of Financial Economics* 33.3, pp. 313–340. DOI: `10.1016/0304-405X(93)90010-9`.

Umweltbundesamt (2016). *Klimaschutzplan 2050 der Bundesregierung.* Accessed: 11/25/2019. URL: `https://www.umweltbundesamt.de/publikationen/klimaschutzplan-2050-der-bundesregierung`.

United Nations Framework Convention on Climate Change (2015). *Paris Agreement.* Accessed: 11/23/2017. URL: `http://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf` (visited on 11/23/2017).

Vickrey, William (1961). "Counterspeculation, auctions, and competitive sealed tenders". In: *The Journal of Finance* 16, pp. 8–37. DOI: `10.1111/j.1540-6261.1961.tb02789.x`.

Virag, Gabor (2010). “Competing auctions: Finite markets and convergence”. In: *Theoretical Economics* 5, pp. 241–274. DOI: `10.3982/TE538`.

von Blücher, Felix, Malte Gephart, Fabian Wigand, Vasilios Anatolitis, Jenny Winkler, Anne Held, Jonas Khubute Sekamane, and Lena Kitzing (2019). *Design options for cross-border auctions*. Report D 6.1. Acessed: 09/25/2019. URL: `http://aures2project.eu/wp-content/uploads/2019/06/AURES_II_D6_1_final.pdf`.

Waehrer, Keith (1999). “Asymmetric private values auctions with application to joint bidding and mergers”. In: *International Journal of Industrial Organization* 17.3, pp. 437–452. DOI: `10.1016/S0167-7187(97)00043-X`.

Wallasch, Anna-Kathrin, Silke Lüers, and Knud Rehfeldt (2015). *Kostensituation der Windenergie an Land in Deutschland – Update (Deutsche WindGuard)*. Accessed: 11/07/2019. URL: `https://www.windguard.de/veroeffentlichungen.html?file=files/cto_layout/img/unternehmen/veroeffentlichungen/2015/Kostensituation%5C%20der%5C%20Windenergie%5C%20an%5C%20Land%5C%20in%5C%20Deutschland%5C%20-%5C%20Update.pdf`.

Weber, Robert J. (1983). “Multiple-Object Auctions”. In: *Auctions, Bidding, and Contracting: Uses and Theory*. Ed. by Martin Shubik, Robert M Stark, and Richard Engelbrecht-Wiggans. New York University Press. Chap. Issues in Theory of Auctions, pp. 165–191. URL: `http://hdl.handle.net/10419/220856`.

Welisch, Marijke and Jan Kreiss (2019). “Uncovering Bidder Behaviour in the German PV Auction Pilot: Insights from Agent-based Modeling”. In: *The Energy Journal (forthcoming)* 40.6. DOI: `10.5547/01956574.40.6.mwel`.

Widmann, Marc (2022). *Irgendwas ist immer*. Accessed:10/24/2022. URL: `https://www.zeit.de/2022/43/erneuerbare-energien-windenergie-solarenergie-foerderung-ausbau`.

Wilcoxon, Frank (1945). “Individual Comparisons by Ranking Methods”. In: *Biometrics Bulletin* 1.6, pp. 80–83. ISSN: 00994987. URL: `http://www.jstor.org/stable/3001968`.

Winkler, Jenny (2021). *The state of multi-technology auctions in Europe*. Accessed: 04/27/2022. URL: `http://aures2project.eu/wp-content/uploads/2022/04/AURES_II_D7_2_overview_multi_tech_auctions.pdf`.

Wolfram, Catherine D (1998). “Strategic bidding in a multiunit auction: an empirical analysis of bids to supply electricity in England and Wales”. In: *The RAND Journal of Economics*, pp. 703–725. URL: `https://www.jstor.org/stable/2556090`.

Xiong, Gaofeng, Shigeru Okuma, and Hideki Fujita (2004). “Multi-agent based experiments on uniform price and pay-as-bid electricity auction markets”. In: *2004 IEEE International Conference on Electric Utility Deregulation, Restructuring and Power Technologies. Proceedings*. Vol. 1. IEEE, pp. 72–76. DOI: `10.1109/DRPT.2004.1338471`.