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Auctions for Renewable Energy in Europe - Model-based analysis and beyond

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Marijke Welisch

January 16, 2018

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Institut für Energiesysteme und elektrische Anlagen
Energy Economics Group (EEG)

Dissertation

Auctions for Renewable Energy in Europe - Model-based analysis and beyond

Ausgeführt zum Zwecke der Erlangung der Doktorwürde in den Sozial- und Wirtschaftswissenschaften (Dr.rer.soc.oec) und eingereicht an der TU Wien, Fakultät für Elektrotechnik und Informationstechnik von

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Abstract

This thesis provides insights into the comparatively little studied field of renewable energy (RES) auctions. These insights are provided by three stand-alone modelling cases taking on three different markets - the UK, Germany and Denmark - and tackling one or several specific auction design questions relevant for each of these markets. Aside from geographical and structural differences, these markets also differ in the way their auction design is set and in its participant structure. Furthermore, the insights and data available vary from case to case. While in all cases, an agent-based model is applied, the research question requires different additional analyses in each case. Also, for each case the model was calibrated and extended in its design elements. Summarizing, the agent-based model developed and extended for this thesis has the following features: it can depict a variety of auction schemes and their respective design elements as well as regulatory features as e.g. restrictions to participation. Pay-as-bid and uniform pricing auctions can be modelled, either as a one-shot auction or a multi-round auction that allows participants and the auctioning entity to learn over auction rounds. It is further possible to model the agents in a highly detailed manner, to depict the respective auction participants in a country or to investigate a certain question concerning the auction outcome. In the following, each individual modelling case is outlined.

The first modelling case focuses on the technology neutral auctioning of Contracts for Difference (CfDs) in the UK, with a special focus on how pre-qualifications and penalties affect bidders' behaviour, risk aversion and bidding strategies and thus the auction outcomes in terms of prices and project implementation probability. The auctions are modelled to closely represent the auction design foreseen by the implementing agency, the Department for Business, Energy and Industrial Strategy (BEIS). Two alternative designs are presented: in the first one, bidders reveal their true costs, as a drop-out after being awarded would be penalized. The second one does not include a penalty. Here, bidders are modelled with a cost function that includes a higher level of uncertainty. The model results show that low pre-qualifications and low or no penalties lead to an increased drop-out of agents upon being awarded. For the policy-maker this implies a lower realisation rate for the auctions. Furthermore, the non-penalty case does not yield lower prices compared to a case with a stricter penalty/pre-qualification system in place.

The second modelling case investigates different criteria for the design of multi-unit RES auctions in small markets. The multi-technology RES auctions which are to be implemented in Denmark in 2018 serve as an exemplary case for the assessment. Focus of the assessment is how setting the auction schedule and the auctioned volume per round impacts the auction outcomes, accounting for the particular challenges of small markets. Agent-based modelling of the Danish auction scheme demonstrates that the Danish RES market provides sufficient competition to auction higher volumes and follow more ambitious expansion goals. Additionally, with a fixed budget, it is more effective in terms of deployment achieved, to hold fewer auctions with a larger volume. A flexibility mechanism that allows up to 50 % of the auction volume to be shifted between auction rounds in order to accommodate potential large-scale marginal bidders, proves to be a useful tool to increase deployment rates, without negatively affecting bid prices. Moreover, it was shown that at current cost levels, only onshore bidders would be awarded in the envisaged multi-technology scheme. Also, large-scale and multi-project bidders are likely to be the most cost competitive - indicating that further measures to maintain diversity could be useful.

The third and final modelling case analyses bidder behaviour with a focus on actor diversity in the German PV (photovoltaic) auction pilot. It combines insights from data analysis and game theory to optimize the agent based simulation model. A uniform pricing scheme, which serves as a benchmark case, and a pay-as-bid scheme, where agents adapt their bidding strategy is modelled. The findings are contrasted with empirical auction outcomes. The comparison shows that, especially in the early rounds, support costs could have been lower – possibly due to uncertainties and false expectations concerning competition. This is particularly visible in the first round. Adapting their expectations to a higher competition level, bidders in the pay-as-bid simulation subsequently decrease their bids. From simulating a separate auction for arable land bidders, it can be seen that this bidder type reduces support costs substantially and that an implicitly discriminatory auction furthermore yields more aggressive bids and can thus induce further cost reductions.

Summarizing, a variety of insights are provided over a large geographical spread, different variations of the pricing rule, different exemption rules and designs of bidder participation and also different levels of technology neutrality. Furthermore, different policy goals have been envisaged by the auctioning entities in the different countries selected, changing the criteria by which the auction outcome is evaluated. In a final section, the respective country-specific results from the modelling cases will be contrasted to derive some more general conclusions to the overarching question on how to optimally design renewable energy auctions.

Zusammenfassung

Diese Dissertation behandelt das relativ wenig erforschte Thema "Auktionen für Erneuerbare Energie". Sie besteht aus drei eigenständigen Kapiteln, die modellierte Fallstudien verschiedener Märkte - Großbrittanien, Deutschland und Dänemark - beinhalten. Jeder dieser Fälle beschäftigt sich mit einer oder mehreren Fragen zur Ausgestaltung des Auktionsdesigns im jeweiligen Markt. Neben geographischen und strukturellen Unterschieden, unterscheiden sich diese Märkte auch in der Ausgestaltung der Auktionen sowie der Zusammensetzung der Marktteilnehmer. In allen Fallstudien wird ein agentenbasiertes Modell angewendet. Die ergänzenden Untersuchungen variieren je nach zugehöriger Forschungsfrage, Datenverfügbarkeit und Einsichten in den Auktionsprozess, die die auktionierende Behörde ermöglichte. Weiterhin wurde das Modell für jede Fallstudie mit den entsprechenden Marktdaten kalibriert und auf bestimmte Auktionsdesign-Elemente hin erweitert.

Das agentenbasierte Modell lässt sich wie folgt beschreiben: Es kann eine Vielzahl von Auktionsdesigns und deren Designelemente abbilden, ebenso wie regulatorische Eigenschaften wie zum Beispiel Teilnahmebeschränkungen. Als Preisbildungsmechanismen lassen sich "Uniform Pricing" und "Pay-as-Bid" implementieren. Auktionen können als Einzelauktion oder über eine Mehrzahl von Runden durchgeführt werden. Weiterhin lassen sich die Agenten mit einem hohen Detaillierungsgrad modellieren, sodass die Akteurszusammensetzung in einem bestimmten Markt realitätsnah wiedergegeben werden kann. Im Folgenden werden alle drei Fallstudien kurz umrissen.

In der ersten Fallstudie werden die technologieübergreifenden "Contract for Difference" Auktionen in Großbrittanien modelliert. Die zu untersuchende Forschungsfrage ist der Einfluss von Präqualifikationskriterien und Pönalen auf das Bietverhalten in Auktionen. Analysiert werden dabei das Bietverhalten und die Risikoaversion von Auktionsteilnehmern und die resultierenden Auktionsergebnisse: Gebotspreise und die Realisierungswahrscheinlichkeit von bezuschlagten Projekten. Im Modell wird detailgetreu das Auktionsdesign der zuständigen Behörde (BEIS) dargestellt. Zwei alternative Szenarien werden dann simuliert: Zunächst wird ein Referenzfall gezeigt, in dem funktionierend Pönale die Bieter dazu anhalten ihre wahren Kosten zu bieten. Im Alternativfall gibt es keine Pönale, sodass die Bieter mit einer höheren Unsicherheit bezüglich ihrer Kostenfunktion modelliert werden. Die Modellergebnisse zeigen, dass niedrige oder keine Pönale oder - äquivalent - niedrige Präqualifikationsbedingungen die Realisierung von bezuschlagten Projekten gefährden können. Für die Regulierungsbehörde bedeutet das, dass Kapazitätsziele im Zweifel nicht erreicht werden.

Weiterhin ist zu sehen, dass die Auktionen ohne Pönale/Präqualifikationskriterien nicht zu niedrigeren Förderkosten führen.

Die zweite Fallstudie beschäftigt sich mit dem Design von Erneuerbarenauktionen in kleinen Märkten. Die technologieübergreifende Auktion, die in 2018 in Dänemark implementiert werden soll, dient dabei als Beispiel. Im Fokus der Analyse steht, wie das Ausschreibungsvolumen und die Frequenz der Auktionierung das Auktionsergebnis beeinflussen und wie diese in kleinen Märkten ausgestaltet werden sollten. Die agentenbasierte Simulation der dänischen Auktionen zeigt, dass der dänische Erneuerbaren-Markt genügend Wettbewerb aufweist um höhere Kapazitätsmengen zu auktionieren und somit ambitioniertere Erneuerbaren-Ausbauziele zu verfolgen. Wenn das Budget oder Volumen in einer Runde nicht flexibel ist, ist es zudem sinnvoll, weniger Auktionen mit einem größeren Volumen abzuhalten als umgekehrt. Ein Flexibilitätsmechanismus, der erlaubt einen Anteil des Budgets zwischen Runden zu verschieben und somit marginale Bieter, die das Budget überschreiten, ebenfalls zu bezuschlagen, ist ein nützliches Feature, das die Realisierungsraten von Auktionen verbessern kann, ohne die Gebotspreise zu erhöhen. Weiterhin wurde gezeigt, dass in Anbetracht der jetzigen Kostenniveaus nur Windkraftanbieter in der anvisierten Auktionsausgestaltung zum Zuge kommen würden. Weiterhin sind große Projekte oder solche Bieter, die mit mehreren Projekten teilnehmen, die kostengünstigsten. Dies deutet darauf hin, dass um Akteursvielfalt zu erhalten, ergänzende Maßnahmen nötig sein könnten.

Im dritten und letzten Fall wird das Bietverhalten mit einem Fokus auf Akteursdiversität im deutschen PV-Auktionspiloten untersucht. Das agentenbasierte Modell wurde für den Fall mit Ergebnissen einer umfangreichen statistischen Analyse der Auktionsergebnisse sowie mit Erkenntnissen aus der Auktionstheorie optimiert. Eine "Uniform Pricing"-Simulation dient als Benchmark, anschließend wird dann ein "Pay-as-Bid"-Auktionsdesign simuliert, in dem Akteure ihr Bietverhalten strategisch über die verschiedenen Runden anpassen. Die Modellergebnisse werden mit den empirischen Auktionsergebnissen verglichen. Der Vergleich zeigt, dass insbesondere in den ersten Runden des Piloten die Gebotspreise hätten niedriger sein können. Dies liegt womöglich an Unsicherheiten bezüglich des zu erwartenden Wettbewerbs in den Auktionen. Insbesondere in der ersten Runde ist dies gut ersichtlich. In der Simulation sieht man, wie die Akteure in Anbetracht des hohen Wettbewerbs ihre Gebotspreise kontinuierlich nach unten korrigieren. Aus einer separaten Simulation für Ackerflächen-Bieter, die im Piloten Ausnahmeregelungen unterlagen, zeigt sich, dass dieser Bietertyp die Förderkosten im Durchschnitt deutlich reduzieren kann. Eine implizit diskriminierende Auktion, wie sie im Piloten stattgefunden hat, kann den Wettbewerb innerhalb dieser Bietergruppe noch einmal erhöhen und noch weitere Kostensenkungen erzielen.

Zusammenfassend lässt sich sagen, dass eine Vielzahl an Erkenntnissen über einen weiten geographischen Raum hinweg gewonnen wurde. Die Preisfindungsregel wurde variiert, verschiedene Ausnahme- und Teilnahmeregelungen wurden modelliert ebenso wie verschiedene Levels an Technologieneutralität. Weiterhin wurden aus Sicht der Regulierungsbehörden unterschiedliche Politikziele abgebildet, die die Kriterien, nach denen das Auktionsergebnis bewertet wird, verändern. In einem abschließenden Kapitel werden alle Ergebnisse noch einmal kontrastiert und kritisch reflektiert um allgemeine Schlussfolgerungen zu ermöglichen, die der übergeordneten Forschungsfrage nach einem optimalen Design für Erneuerbaren-Auktionen Rechnung tragen sollen.

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Contents

Introduction

1

1.1 Motivation

Support for renewable energy (RES) has been subject to change in the last decade. We have seen support schemes become more market-oriented, as e.g. the sliding feed-in premium in Germany or contracts for difference in the UK which are oriented towards the market price, superseding previous fixed feed-in tariffs.[1] Due to this change, in many markets, renewable energy suppliers have to participate in direct marketing of their electricity. Additionally, we can to a certain extent talk about grid parity or maturity of renewable technologies like onshore wind and solar photovoltaics (PV).

Still, renewable energy has special features which will likely uphold its necessity for support for some more time: they are capital intensive, have zero or low running costs and they are mostly variable. This holds for the core technologies wind power and solar PV, which are also the technologies assessed in this thesis. Variable renewable energy sources induce a so called merit order effect, which puts downward pressure on electricity spot prices. This decreases the market value of these specific technologies, such that the market alone does not guarantee sufficient revenues to cover the costs of wind and solar power (see e.g Welisch et al., 2016). This view is the so-called system-integration perspective. Market orientation of support replacing fixed-feed-in tariffs already played a big role in making renewables competitive with conventional technologies. In this thesis, the focus will however be on the support cost perspective. Specifically, "competitive bidding processes" for allocating public support (European Commission, 2014) will be explored, that are aimed at increasing competition among renewable generators to tackle the information asymmetry in setting support levels.

The discussion on support of renewable energy has gone into several directions, but support expenditures have always been in the focus of the debate (compare e.g. Ragwitz et al. (2016)). As renewable energy technologies have matured, the discussion has partly shifted from support to market integration, as discussed above, but support continues to be an important topic, especially for less mature or still

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[1] In the following, I refer to electricity from renewable energy sources with the term "renewable energy", as a simplification.

maturing technologies. As the increased deployment of renewable energy has come at substantial costs not least for electricity consumers in some European Member States,[2] it is important to regularly review the need of further subsidizing. An important issue that policy makers, researchers but also the European people tend to forget during these discussions is the reason why we are subsidizing renewable energy and changing our electricity system in the first place. The European Commissions' 2020 and 2030 goals (European Parliament and Council Directive, 2009) have been set to contribute to a superordinate target: climate change mitigation. If we want to achieve these goals for renewable energy deployment, further expenditures have to be made. As it is hard to put a price on carbon emissions and in the view of very low prices in the EU emission trading scheme (ETS),[3] it is difficult to argue how much money should be spent on increasing renewable energy supply in Europe (as well as on all necessary accompanying measures needed to incorporate large shares of RES into the market). While renewable energy deployment comes at a cost, it also comes with benefits as local employment, technological innovation and reduced dependency on imported fossil fuels (Ragwitz et al., 2016). This just to name a few pro arguments in favour of continuing support of RES to strengthen the position of Europe globally and to support local economies in European member states.

Cutting this discussion short, leads us to an important conclusion. While the question if we need more RES in Europe is to some extent always a political one, the question on how to design its support in the most efficient and effective manner is not: auctions are a flexible support mechanism, which when implemented properly can lead to an effective and efficient outcome on the market for RES. Determining the allocation of support in a cost competitive way can help lowering costs of the energy transition. In theory, we will know that financial support is not needed anymore, if bidders start to bid for a premium of zero ct/kWh on top of the electricity spot price for their RES plants.[4] This obviously requires a functioning auction design to fit to the market's needs and to further help policy makers fulfil their (arguably again political) goals, which can range from solely achieving deployment at least cost over actor diversity or promotion of new technologies.

This thesis outlines the theoretical and political background needed to properly understand auctions for RES. It then provides insights into an agent-based model created to evaluate different questions on auction design. This agent-based model is then applied to three distinct European country analyses. Different issues concerning design and market features are assessed for Germany, the UK and Denmark. Whenever possible, questions are answered by modelling - in some cases, where the

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[2] See e.g. for Germany: Zeit online, October 2016.

[3] On overallocation of allowances see e.g. Oxford Journals, 2007.

[4] This holds for a fixed premium. A very low or zero sliding premium will show that financial support will only be required to guarantee a stable income for generators and to thus absorb the market risk to a certain extent. This differentiation will be explained in section 2.3.

model meets its limitations, the research is complemented by theoretical, statistical or qualitative analysis. The thesis concludes with policy recommendations derived from these model cases and an outlook into future auction design for Europe. The motivation to conduct this work was twofold: firstly, being in the middle of the political implementation process of auctions for renewable energy, the policy relevance of the topic is high. Secondly, the research gap to be filled is substantial - which will become clearer in section 3. The overall goal of this thesis is thus to contribute to the ongoing political discussion of market-based RES support, by answering an array of questions on auction design. This is motivated by the fact that past research has shown that the devil lies in the details, i.e. the choice of design elements is crucial for the success of support schemes in general, and auctions in particular. These questions will shed light on specific auction design elements and their impact on the auction outcome and will moreover provide insights into possibilities and limitations of auction based RES support. The questions are answered by combining methodologies to a novel research approach and will thus also expand the scientific literature on agent-based modelling and renewable energy auctions.

1.2 Core objectives

The overarching objective of this thesis is to provide insights into the relatively little studied field of RES auctions. This objective is addressed in three stand-alone modelling cases taking on three different markets - the UK, Germany and Denmark - and tackling one or several specific auction design questions related to these markets. Aside of the geographical and structural differences, these Member States also differ in their electricity market's participant structure and in the way their auctions for renewables support are designed. Furthermore, the insights and data available differ from case to case. Due to these reasons, the specific research question addressed in each case requires a variation of the methodological approach. While in all cases, the agent-based model which will be described in chapter 4 is applied, the preceding or complementary assessments differ. Also, for each case the model was calibrated to the respective market and extended to accommodate new design elements.

The three cases have been chosen specifically due to these differences to provide a wide array of auction design elements, electricity market configurations and policy goals. Three key hypotheses concerning auction design have been elaborated to be answered by these particular cases and several sub-questions are attached to each of these hypotheses. In the following, the research question(s) and key hypotheses attached to each modelling case are stated. Then, the core objective of each individual case is outlined by shortly drafting the approach how the key and sub-questions will be answered.

1) **How do penalties and pre-qualification criteria influence bidding behaviour?**

A lack of penalty and little or no pre-qualification criteria are likely to make a bidder less risk-averse: as non-delivery of an awarded project if the auction outcome is not favourable is a viable option for a bidder if she does not face a penalty or lose a substantial amount of (financial) pre-qualification when doing so. Sub-questions to be addressed under this core question are thus, how the overall realisation rate is influenced if there are no or low penalties in an auction. Furthermore, it will be investigated how average bid prices change and if there are any impacts that differ over technologies.

The first modelling case focuses on the technology neutral auctions of Contracts for Difference (CfDs) for renewables support in the UK. A special focus is put on risk aversion and bidding strategies and thus the auction outcomes in terms of prices and project implementation probability. The auctions are modelled to closely represent the auction design foreseen by the implementing agency, the Department for Business, Energy and Industrial Strategy (BEIS). Two alternative designs are presented: in the first one, bidders bid their true costs as a drop-out after being awarded would be penalized. The second one does not include a penalty. In that case, bidders are modelled with a cost function that includes a higher level of uncertainty.

2) **How does setting the schedule and volume influence auction outcomes?**

This is the main question being addressed in the second modelling case presented in this thesis. The main hypothesis concerning this question is that a higher frequency can help lower bid prices as technology cost decreases can be directly captured. At the same time, a too high frequency with too low volumes in each round could hinder participation in particular of multi-project or large-scale bidders. A directly related sub-question is how flexibility of the volume can improve auction schemes with relatively low volumes per round. It seems plausible that a flexible volume is a useful mechanism to adapt to a respective auction rounds' competition level and participant structure and allow for accommodation of larger projects in a round. This mechanism could help increase the overall deployment rate.

The second modelling case investigates different criteria for the design of multi-unit renewable energy (RES) auctions in small markets. The multi-technology RES auctions which are to be implemented in Denmark in 2018 serve as an exemplary case for the assessment. Focus of the assessment is how setting the auction schedule and the auctioned volume per round impacts the auction outcomes, accounting for the particular challenges of small markets. Agent-based modelling is again applied to answer these questions. A flexibility mechanism that allows up to 50 % of the auction volume to be shifted between auction rounds to accommodate potential large-scale or multi-project marginal bidders is also tested in the model.

3) **How much of the bidding behaviour in auctions can be explained by technology costs and other exogenous factors?**

Specifically, the third hypothesis is, that modelling bid prices assuming completely rational bidders and taking into account technology and other costs that bidders face, does not necessarily mirror empirically observed bidding behaviour. An additional question investigated is how discriminating a certain bidder type in an auction influences their respective bidding behaviour. This question is loosely connected to the key hypothesis. If the discriminated type is the most competitive bidder, not limiting their participation is likely to be beneficial for the auction outcome. However, in some cases discrimination between different bidder types can also be the most efficient solution in terms of bid prices.

The third modelling case analyses bidder behaviour in the German solar PV (photovoltaic) auction pilot. It combines insights from data analysis and game theory to optimize the agent based simulation model for analysing this specific question. A uniform pricing scheme, which serves as a benchmark case, and a pay-as-bid scheme, where agents adapt their bidding strategy is modelled. The findings are contrasted with empirical auction outcomes to test for potential differences in auction outcomes. Furthermore, sensitivities are tested to account for the exemption rule[5] implemented in the German solar PV pilot and how changing this rule would further influence bid prices.

Summarizing, a variety of insights are provided over a large geographical spread: different variations of the pricing rule, several exemption rules and designs of bidder participation and also various levels of technology neutrality. Furthermore, partly different policy goals have been envisaged by the auctioning entities in the different countries selected. In section 8, the respective country-specific results from the modelling cases will be contrasted to derive some more general conclusions to the overarching question on how to optimally design renewable energy auctions. The three key hypotheses are not least interesting as they touch on different stages of the auction process - covering pre-auctioning considerations as well as actual bidding behaviour influenced by different auction designs or constraints. Answering these particular questions with an agent-based model and carefully evaluating all given data and scientific literature at hand, answers some policy-relevant questions which address the overarching objective of gaining a better understanding of the

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[5] This exemption rule limits the participation of arable land bidders to a total of 10 per year, (see (Bundestag, 2017)) reasoning being that land use should be prioritized for food production.

implementation of renewables auctions. Future research ideas which can build on the assessments provided in this thesis will be discussed in section 8.

1.3 Structure

The structure of this thesis is as follows. Subsequent to this introductory chapter comes a section that provides background into multi-unit auctions as such - i.e. where they have been applied and what their implementation status quo is in the European Union.[6] Then, we go one step back and consider RES support as such, as well as its different designs. Specifically, the question why we are auctioning RES support and how exactly this support looks like - which support instrument is auctioned - is answered.

Then, chapter 2 gives a theoretical and methodological background to thoroughly understand the auction theoretical concepts underlying the thesis and its model. As the model is based on auction theory but implemented in an agent-based modelling framework, a next step is to cover all relevant literature on agent-based modelling (ABM), in energy research and in auctions and to present the gap in the literature - i.e. where these two fields actually intersect: agent-based modelling of auctions for renewable energy. This intersection still provides a large area that has not been covered by scientific research. The agent-based model originally developed in Anatolitis and Welisch, 2017 and extended and applied in this thesis, which is introduced in section 4, is an approach to combine auction theory and agent-based modelling to address this research gap. The methodology section contains insights on the two pricing rules, pay-as-bid and uniform pricing, that can be depicted with the ABM as well as technical implementation details.

In a next step, three modelling cases are presented, each being a stand-alone chapter in itself. They contain three applications of the model complemented with other methodology - thus making sense of the title of this thesis ("and beyond"). Each modelling case contains a country background, information on the respective auction design to be assessed, the relevant model extensions and then findings from the modelling and policy implications. All these findings will be integrated and generalized in the final chapter of this thesis, section 8. This section contains a summary of all modelling cases and a critical reflection on the work done in this thesis. Ideas for future research will be presented in the final concluding section.

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[6] Multi-unit auctions, which will be explained in section 2.1 are the main applied auction format when it comes to RES auctions. A theoretical background on this format is given in section 3.1.

Background

2

This section contains a short outline of the background necessary to understand the concept of RES auctions from a policy point of view. The following subsection sheds light on the overarching EU policy that led to the implementation of the different auction designs in these Member States and integrates all three cases into this framework.

2.1 Multi-unit auctions for RES support - the instrument

In this subsection, a short overview of the European Union's regulation on auctions for renewable energy is given: "the Guidelines on State aid for environmental protection and energy 2014-2020" (No. 2014/C 200/01) (European Commission, 2014) introduced a more market-based orientation towards renewable energy support, by redefining the cases in which subsidies can be granted for environmental protection and energy related objectives. Besides replacing feed in tariffs by a feed-in premium system, the guidelines foresee a gradual implementation of "competitive bidding processes" for allocating public support (European Commission, 2014) by 2017. An exemption from this rule can be granted if there are only limited projects or potential bidders and strategic bidding behaviour is likely. Furthermore, ideally a multi-technology tendering is foreseen by the European Commission, meaning that several technologies compete in the same auction scheme. Exemptions from the so-called "technology neutral" tendering can be granted if Member States want to protect actor diversity or foster new or innovative technologies.

These EU regulations have in consequence been transformed into auction-based support schemes at Member State level in a variety of EU Member States, as shown in Figure 2.1. While few Member States have pledged for an exemption rule from tendering, like Finland, some, e.g. Austria, are still in the implementation process.

Figure 2.1 shows which European Member States have already implemented auction-based renewables support schemes so far. Nine member states rely mainly on auction-based support to date. Among them are Denmark, the UK and Germany, three countries selected to investigate certain aspects of renewables auctions in the following case studies. Further member states have implemented auction-based support for renewable energy in combination with a feed-in-tariff (see Figure 2.1). The country-specific information needed as a background to understand the different model-based assessments is given in the respective modelling cases. Overall, it can be said that application of the guidelines and translation into state law has taken on quite different configurations.

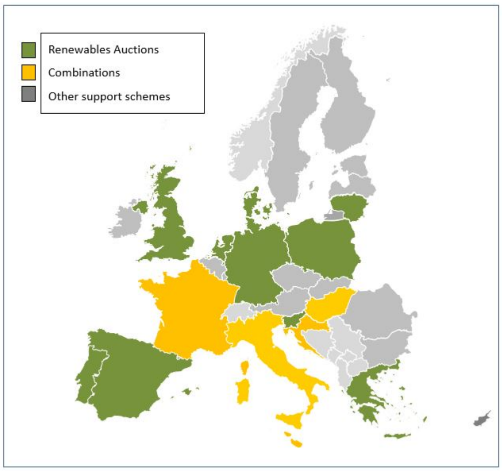


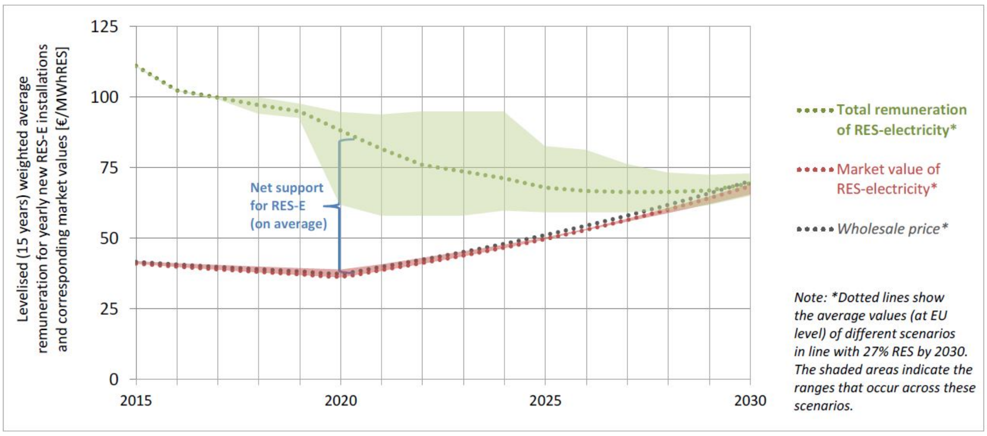
Fig. 2.1: Auction-based renewables support in Europe (2017), source: RES-legal

While this thesis focuses on multi-unit-auctions for RES in the European Union, it is important to emphasize that auctions for (renewable) energy have played a role for quite some time globally and have found successful application e.g. in Brazil or South Africa. Auctions for renewable energy have also been applied unsuccessfully in some countries worldwide. Whereas not all countries have disclosed the results of their auction schemes in a transparent manner, previous experiences do provide overall interesting insights into best practices and potential pitfalls of this support mechanism (see e.g. Del Río, 2017 or Winkler et al., 2018).

Giving some broader perspective, multi-unit auctions as such have also proven to be a valuable instrument for countries to assign licences, broadband etc. in the most market-based approach possible tackling the natural monopoly problem. Being able to draw on these experiences, the EU's guidelines on state aid and their regulations on auctions for RES support lay the groundwork for very efficient auction schemes, however leaving the member states with sufficient scope to design their respective schemes according to their market's properties and their policy goals. Research on multi-unit auctions is currently catching up on its empirical application, but there still remain many interesting policy relevant issues to be addressed, to which this thesis will add a small contribution. The variety of very recent pilot auctions and hence developed auction schemes in the European Union provide a variety of research opportunities. However, before answering the RES auction design questions selected for this thesis, some more background will be given on why these auctions are actually taking place - renewables support - and what is actually auctioned - different embodiments of a renewables feed-in-premium.

2.2 The case for future RES support

As outlined in work by Resch et al. (2017) there is still a substantial support gap to be filled, when it comes to deploying renewable energy and reaching the EU renewables targets. Figure 2.2 shows the dimensions of this gap in more detail. After giving the background on overall support needs, the different means of support are shortly described in subsection 2.3.



*Note: *Dotted lines show the average values (at EU level) of different scenarios in line with 27% RES by 2030. The shaded areas indicate the ranges that occur across these scenarios.*

Fig. 2.2: Support needs for renewable energy up to 2030, source: Resch et al., 2017

To which extent support for renewables will be needed in the upcoming decade mainly depends on the costs of renewable energy technologies, on future power and carbon prices and on risks associated with investments in power assets. Further cost reductions for renewable energy technologies can be expected in the upcoming decade, also due to the increasingly global deployment of renewables. This will lower the costs of supporting the deployment of renewables. Future power and carbon prices are, however, subject to higher uncertainty. The EU carbon market is currently confronted with an oversupply of CO2 emission allowances, while many EU power markets are struggling with overcapacity. Resolving these issues is also a matter of political intervention and therefore subject to high uncertainty (Resch et al., 2017).

A model-based assessment of future renewables deployment at national and EU level assuming achievement of the 27% target by 2030 confirms that the necessary remuneration for renewables is expected to decline over time (see Figure 2.2 (Resch et al., 2017)). On the one hand, the analysis indicates a strong decline in remuneration levels for renewables over the whole assessment period as a result of expected cost reductions for onshore and offshore wind as well as solar PV. On the other hand, the decrease in market values[1] of variable renewables partly diminishes these gains in later years. Market values for variable renewables are expected to more strongly decouple from average whole-sale electricity prices. Overall, the need for net support, i.e. the difference between necessary remuneration and market value, is shrinking for renewable electricity through to 2030: compared to the current situation a strong decline or even a phase-out of the need for net support may be achieved by 2030 – if energy and carbon prices will evolve as projected in recent EC forecasts (European Commission, 2016).

The discussion on how to continue support for mature renewable electricity technologies, such as onshore wind and PV, has intensified. A comprehensive argumentation why moderate support for renewable electricity generation will still be needed even beyond 2020 can be given as follows: strong market development of RES in recent years – triggered particularly by renewable support schemes – has been accompanied by considerable technology cost reductions, in particular of solar PV technologies. These cost developments have brought onshore wind and solar PV close to market maturity. However, while technology (and therefore investment) costs are a key element of RES competitiveness, there are several other aspects, which determine the market maturity of RES technologies (both from the revenue and the cost side) and therefore their potential for increased penetration in the future power markets (Resch et al., 2017).

Having shown the continued support needs and the uncertainty factors connected with the support need development, this builds the case to find a flexible support mechanism which can quickly accommodate not only technological cost developments but also changes in the market environment, as e.g. carbon price development or changes in RES technologies' market value. Seemingly, auctions for RES could be an instrument that covers all these needs. Before going into more detail as to how auctioning of RES support could be implemented beneficially, another important question has to be addressed: what kind of support should be auctioned? And how do different types of support align with different market situations? The following subsection will provide more insights on these questions.

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[1] The market value I refer to here is in relative terms and defined as the (generation weighted) average price a generator earns for her electricity generation in a certain period of time (see Ortner et al., 2016

2.3 Support for RES - what is auctioned?

A variety of support mechanisms for renewable energy exist, including investment aid, quotas, feed-in tariffs or green certificates among others. EU regulations, as stated earlier, envisage the implementation of a feed-in-premium to supersede feed-in tariffs as the former long-term means of choice to support renewables. A feed-in premium is support that is paid per unit of electricity generated and can be either fixed at a certain amount or can be attached to a reference value, i.e. a minimum market revenue expected from the electricity spot market. The latter is referred to as a sliding feed-in premium.

The discussion on whether to implement a fixed or sliding feed-in premium has started over a decade ago (see e.g. Ragwitz et al. (2007)). While a fixed premium is simpler from its design, the majority of EU member states have implemented a more flexible sliding premium. A fixed premium induces generators to take fluctuations in the price into account. A sliding premium guarantees a certain price and covers the difference between this price and the actual market price. Depending on how the reference price is determined, generators also account for fluctuations in the market price. A sliding premium can either be in the form of a contract for difference (CfD), where the generator always receives this price and all surplus goes to the regulator or it can cover everything below the agreed price and the generator can also retain a potential surplus.

The main difference between a sliding and a fixed premium is the distribution of the electricity market risks. In the case of a fixed premium, the renewable generators bear most of the market risk - only risks concerning long-term price developments, e.g. due to fuel prices remain with the regulator. The risk for generators can be reduced to a certain extent by implementing a corridor with cap and floor prices. In the case of a sliding premium or contract for difference (CfD), where the premium is a function of the average electricity price, the risk is put onto the regulator's side (Ragwitz et al., 2012).

According to Noothout et al. (2016), risk exposure is significantly higher under surplus capacities. Regarding a fixed feed-in-premium, the revenues fluctuate in line with the electricity price fluctuations as the premium paid on top of the market price is independent from the electricity market price. Therefore, revenues are less certain and stable, as extreme fluctuations of revenues might occur. Price risk exposure in the case of a sliding feed-in premium is low. However, the volume risk is large, since generators have to forecast and market their produced electricity (Noothout et al., 2016). A further determinant is how negative prices will be handled. If there is no sliding premium paid in hours of negative prices, this is an additional risk for generators.

Another important factor to take into consideration is that different technologies exhibit different levels of exposure to market risk. That is to say, when looking at for example onshore wind and solar PV, their generation patterns can imply a different vulnerability to hourly market price fluctuations. Depending on the market share of the respective technology and the load curve as well as the flexibility of the electricity system, the effect of changes in the market price can affect the technologies differently. The merit-order effect, as described beforehand, has quite a substantial impact on prices – and depending on the market share a technology already has in the system, this effect can be further increased - i.e. specifically a technology that is strongly represented in a market can suffer stronger losses in times of high generation.

A specific characteristic concerning wind power in particular, is that it is affected by (forced) curtailment in hours of excess supply (Giebel and Breitschopf, 2011). This can be absorbed by offering generators some kind of compensation, as the grid operator does for example in Germany. However, nowadays curtailment also is becoming more of an issue for solar PV as well, as for instance in China (Publicover, 2017). However, these findings show how price risks are perceived differently by generators with different predispositions. Furthermore, it has to be considered how the redistribution of the risk by implementing a fixed instead of a sliding market premium impacts financing conditions for renewable generators. This assessment is however beyond the scope of this analysis.

A fixed premium could thus for example lead to disadvantages for wind power generators in a certain electricity system, as they would have to carry more of the market risk and thus have to price it into their bids. If the expansion goal is supposed to be followed in a level-playing field way for multiple technologies, a more balanced way to support both technologies equally would be to implement a CfD or sliding premium, which would shift more market risk to the government.

In-depth information on the support auctioned in the respective countries analysed - namely, a market premium in different designs - is given in the respective modelling cases. Thereby, an understanding of the respective auction scheme and the market environment in which it takes place is enabled. Furthermore, a broader context is given on a) the overall support costs being faced and b) the respective support means, i.e. how the financing will take place after the auctioning procedure.

3

State of research and main research gaps

The following sections provide an overview on the current state of research in auction theory and agent-based modelling that touches upon the present analysis. The overview is comprehensive but non-exhaustive. Immediately it becomes clear that while both methodologies are suitable to assess the questions at hand, there has been little research thus far concerning the assessment of multi-unit auctions in general and even less concerning the specific field of renewable energy auctions. How the two main areas - auction theory and agent-based-modelling - come together is further outlined in the methodology section. Their application can then be seen in the three individual modelling cases.

3.1 Auction theory

The central aspects of auction theory necessary to understand RES auctions and of relevance for their implementation in the different cases assessed in this thesis are shown in this subsection. They are directly related to the application in cases later on, facilitating understanding and connecting the theoretical perspective with the modelling work. A main focus is laid on uniform pricing and pay-as-bid, as these are the pricing mechanisms applied in multi-unit auctions in the EU so far. These are static auction designs. A dynamic-static auction combination can be found, for instance in Brazil (Förster and Amazo, 2016). As this goes beyond the (geographical) scope of this thesis, however, this theoretical section focuses on static auctions only.

Although a great variety of different auction designs and hybrid formats exists (Dutra and Menezes, 2002), three basic principles should be met in every auction in order to guarantee a transparent procedure and thus a high acceptance among investors and the public as well (Ausubel et al., 2014; Haufe and Ehrhart, 2016): bids should be binding, the best bids are awarded and the winning bidders receive at least their bid price. In terms of single-unit auctions, the four most common formats are the English auction, the Dutch auction, the first-price and the second-price sealed-bid auction (Milgrom and Weber, 1982). For multi-unit auctions, the distinction can be derived from these formats. It is there differentiated between the descending and the ascending clock auctions (dynamic) and the uniform and pay-as-bid (PAB) auctions.

Variations and combinations of these formats have been applied in RES auctions globally. Single-unit auctions are used when a certain pre-developed project is tendered, as e.g. in the Danish offshore wind power auctions. In that particular case, participants bid for the permit and support payments to realise a specific offshore wind farm. Onshore wind power auctions as well as auctions for large-scale solar PV are currently taking place in several European member states. These auctions fall into the category of multi-unit auctions.[1] Since in the case of onshore wind and large-scale solar PV auctions, the auctioneer procures a specific electric capacity, the procured good is defined as homogeneous from the auctioneer's point of view.

Bidder's valuations can be captured with two different approaches in auction theory: the independent private value (IPV) and the interdependent value (IV) theorem. IPV has some simplifying properties in comparison to the interdependent model. It is assumed, that a bidder knows her exact valuation of the good she is bidding for. This valuation equals her individual signal. In comparison to the IV approach her valuation is not affected by the opponents' signals. In the IPV approach, the bidder has certain beliefs about her opponents' cost structure and the level of competition. These beliefs are approximated by using random variables.

The IV method is based on the assumption that the bidders' valuation depends not only on her own signal (e.g. her expected costs), but also on the unknown signals of her opponents. This is called the common value component. In the extreme case of a pure common value, the valuation is equal for all bidders, e.g. if the true valuation is the sum or average of all signals (expected costs) (Menezes and Monteiro, 2005). The textbook example of a pure common value is bidding for an oil field (Cramton, 2007). To summarize the most crucial features of this theorem, one can say that a certain amount of the valuation of the auctioned good is "common" for all bidders. Nevertheless every bidder receives a certain signal concerning her bid price, which provides imperfect information that differs among bidders to a certain extent. This concept will be elaborated in further detail in the UK CfD modelling case (chapter 5).

For RES auctions, an interdependent value approach should be considered, when a pre-developed project is auctioned. As stated earlier, this is the case for example in the Danish offshore wind power auctions. In these auctions, all bidders only

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[1] Since countries generally buy power in RES auctions, the overview will be based on the properties of procurement auctions. In this case, the auctioneer is the buyer, and the bidders are the suppliers. In contrast, an ordinary or "forward" auction as most commonly studied in auction theory, the auctioneer acts as the seller and the bidders as buyers. Nevertheless, the outcomes in both auction types are analogous (Klemperer, 1999).

have certain estimations about the electricity generation potential in the specified location. According to Haufe and Ehrhart, 2016, each bidder will realize the same electricity generation if awarded as the good they will be awarded is exactly the same - i.e. the pre-developed project. It can however be argued that the developer still has flexibility in the choice of turbines, which makes the IV property of this type of auction less tenable. In any case, all auctions assessed in this thesis are IPV auctions, of which the respective details will be elaborated in the three modelling cases.

In the auction simulations modelled in this thesis, I will start by looking at symmetric, risk-neutral and single-project bidders. This choice is motivated by two main reasons: firstly, the trade-off between model complexity and run-time compared to simplifying the setting is best met by this approximation. Secondly, symmetry and risk-neutrality allow to implement theoretical conceptualizations in the most accurate way. Thirdly and most importantly, even though this simplification rules out all forms of irrational and strategic behaviour which were (partly) observed empirically in RES auctions, for a model it is crucial to not predetermine the outcome by making too many preliminary assumptions concerning bidder's behaviour. To actually get to the impact of changing certain design elements of auctions, which is the main goal of the different modelling cases presented, it is crucial not to mix effects and to show how an auction design change affects a presumably rational, non-strategic and risk-neutral group of bidders. In the UK CfD auction case, the assumption of risk aversion is however relaxed. Multi-project bidders are furthermore allowed in the Danish auction case, adding to the model's complexity and introducing more strategic behaviour. It is nevertheless important to state, that even with these relaxed assumptions, the assumption of bidder's rationality is never dropped.

An interesting property of the standard auction formats described is outlined in the so-called revenue equivalence theorem. Revenue equivalence means that independent of the applied mechanism, the expected revenue generated in the English auction, the Dutch auction the first-price and the second-price sealed-bid auction is equal, under the following assumptions: it has to hold that, sellers are auctioning a single item, bidders have independent private values (IPV) and bidders are risk neutral. Furthermore, the number of bidders has to be independent of the type of auction used and except for their different valuations of the good they have to be identically distributed. (Klemperer, 1999). Lastly there should be no collusion or corruption (Cramton, 2007). According to Cramton (2007):

"In practice, none of these assumptions holds: many related items are for sale; bidder values depend at least in part on value estimates of other bidders and these estimates are correlated; bidder participation decisions are of paramount importance; bidders care about risk; there are ex ante differences among the bidders (e.g., some are large and some are small); and mitigating collusion and corruption are important."

Cramton (2007) further states that these different features all impact the performance of alternative auction designs. When choosing the best auction design for a specific setting, it should be checked beforehand, which of the aforementioned features are the most pertinent in the respective situation. The three modelling cases presented in this thesis furthermore account for Cramton's statement. They show different market settings and how certain auction design features are more or less important for reaching different policy goals in these environments. To summarize again which auction theoretic features are common to all three cases: the product auctioned is a homogeneous good and bidder's valuations are thus modelled as independent values (IPV approach). Bidder's are expected to be symmetric and risk-neutral, i.e. behave rationally in all cases.

Before getting into further details of auction design, it is important to present the two most common pricing rules in RES auctions for European member states: the following subsection (3.1.1) thus gives a theoretical background on pay-as-bid and uniform pricing. These pricing rules set the groundwork for all renewables auctions assessed in this thesis. This subsection is based on a paper by Anatolitis and Welisch (2017).

3.1.1 Pricing rules

In static auctions, all bidders submit sealed bids to the auctioneer simultaneously. The participants do not know their opponents' bids and are not able to adjust their offers accordingly. In static single-unit auctions the two most common formats are the first-price and the second-price sealed-bid auction. Since the modelling cases are limited to multi-unit auctions, I will outline the theory to understand their multi-unit counterparts, the pay-as-bid (PAB) and the uniform pricing auction (Menezes and Monteiro, 2005).

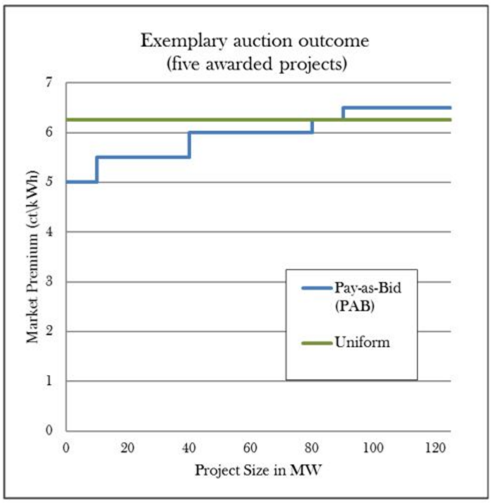

Fig. 3.1: Comparison of PAB and uniform pricing, source: own elaboration

Under the PAB pricing rule, successful bidders are awarded exactly their bid. When uniform pricing is applied, all successful bidders receive the same clearing price, which can be either the highest accepted or the lowest rejected bid. Figure 3.1 exemplifies this with a generic auction outcome. Basically, the area below the curves is the support that the awarded bidders will receive. While this support differs for all bidders in the PAB case, the bidders under uniform pricing will all receive the same amount for each kWh generated. In theory, both formats have the same expected revenue. How both pricing schemes behave in practice however, and which is more suitable for which market situation is not always straightforward.

To realize a profit in case of a winning bid, bidders under the PAB pricing mechanism have to put a mark-up on their cost. Due to this fact, a bidder will at least bid her individual cost, usually with a certain margin on top. In auction theory, this behaviour is known as "bid-shading" (Menezes and Monteiro, 2005). Under the PAB pricing mechanism, the agent maximizes her chance of winning and her expected profit by adjusting her bids accordingly and taking into account the possibility to win. In general, the higher her bid is, the lower her probability to win in the auction (Samuelson, 1986; McAfee and McMillan, 1987). A bidders' strategy is thus to maximize expected revenue.

As said beforehand, in uniform pricing the clearing price can be either determined by the highest accepted or the lowest rejected bid. In the case of the highest accepted bid, bidders have the incentive to exaggerate their costs, as their own bid might be the highest accepted one and thus determine the clearing price. Similar to PAB, bidders can only realise a profit > 0 by putting a mark-up on their cost. Bidders have no influence on the clearing price in case of winning in a lowest rejected bid auction, which is why bidding the true costs can be shown to be a weakly dominant strategy in that case (Krishna, 2010).

Thus, uniform pricing with a lowest rejected bid mechanism induces bidders to bid their true costs.[2] This property of the auction is called "incentive compatibility". In contrast to the different award prices under PAB, a single clearing price can be

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[2] Several studies have proven however, that due to irrational or strategic bidding behaviour, incentive compatibility doesn't necessarily hold in real-life settings (Cramton and Ausubel, 2006).

interpreted as more transparent and as sending a clear price signal to the public (Haufe and Ehrhart, 2016). Notwithstanding, proponents of PAB argue that uniform pricing can incentivize demand reduction and strategic bidding, leading to inefficient allocations (Morgan, 2001).

3.1.2 Learning

Learning is an important feature of auctions, as soon as they are sequential, i.e. held over several rounds and also when they are dynamic. Learning has been assessed substantially from the agent-based perspective, but there is also interesting auction and game theoretic literature which can contribute to the understanding of learning in auctions. Klemperer (2002), for instance states that "the opportunity for learning and strategizing can easily invalidate the predictions of one-shot auction theory." As this thesis investigates exclusively multi-round auctions, it is important to take this into consideration: as learning is one of the areas where classic auction theory reaches its limits, it provides a good bridge towards the explanatory possibilities of agent-based modelling, my methodology of choice.

Jeitschko (1998) describes learning in sequential auctions and stresses the trade-off of unveiling information and winning in the first round, as the outcome of the second round is usually more favourable for the winner. He explains this in a micro-economic model under strict assumptions, simplified to a setting where three bidders participate in two consecutive auction rounds. Jeitschko, 1998 states a theorem by Weber (1983), which explains that theoretically the outcome of two sequential auctions should be the same, as in the first round competition is higher - yielding a lower outcome for the winner and in the second round, while competition is lower, the probability of winning decreases (as it is the final round), which cancels out the effect of the lower competition. This should lead sequential (RES) auction outcomes to be constant, or to only reflect the development of technology costs but no further effects in terms of learning. However, being constrained to a very limited time horizon and having other strict assumptions, this theorem does not exactly reflect all circumstances that have to be considered when modelling a sequential, multi-unit RES auction. Further insights into learning in sequential auctions will thus be given from the ABM perspective in section 3.2.

3.1.3 Auction design

In this section, the design elements which were assessed in the different modelling cases are presented and put into context. More details can be found in the respective modelling cases. The overview is limited to the design elements of the standard multi-unit auction format which are analysed in this thesis[3]. There are several criteria by which an auction's outcome and thus also the impact of a certain design criterion can be evaluated (Haufe and Ehrhart, 2016). In this thesis, the focus is on price determination and expected auction revenue (the overall support costs). Furthermore, allocative efficiency is evaluated. An allocatively efficient auction mechanism maximizes welfare by allocating the auctioned good to the participant with the highest valuation. Applied to RES auctions, this leads the project developer with lowest support costs and/or highest scores in other relevant award criteria predetermined by the auctioning entity to be awarded (Haufe and Ehrhart, 2016). Finally bidders' risks - i.e. the award price risk and thereby the risk of winners' curse are evaluated to determine the success of an auction outcome. Winner's curse means that after being awarded the bidder realizes that her actual costs exceed the award price (Haufe and Ehrhart, 2016). This can lead to an increase in bidder default and lower realization rates. The number of potentially defaulting bidders as well as the share of non-realization serves to quantify the auction's outcome in respect to this evaluation criterion.

Penalties and pre-qualification criteria are the first design element assessed in this thesis. From a theoretical point of view, these features all aim to induce a higher expected realization probability (Kreiss et al., 2017a). Penalties for non-compliance or delays can take on different forms. These include the termination of contracts, lowering of support levels, shortening support periods by the time of the delay, confiscation of bid bond guarantees or penalty payments. Regarding the latter, they can be in the form of a fixed amount and modulated by the delay. They can be set per MW, per kWh or as a percentage of the investment made (see Del Río, 2015 for further details). Pre-qualification criteria can be described as follows: bidders have to provide certain certificates, assessments or pre-developments of their project at an early stage of the bidding procedure. These criteria can refer to specifications of the offered project, such as technical requirements, documentation requirements and preliminary licenses. They can also be connected to the bidder and require certifications, proving her technical or financial capability (Held et al., 2014).

Then, auction schedule and frequency are assessed, as well as the flexibility of the volume in each round. Setting the volume of an auction is an important decision in ensuring the effectiveness of the tendering scheme. Obviously, the volume targets should be set in relation to the capacity of the market is able to deliver. The auctioned amount should be in line with the RES-E targets, but induce a certain extent of competition. A too high volume can decrease the level of competition and increase bid prices. Unless auction schemes are linked to a fixed schedule of auctions at regular intervals, they may lead to a stop-and-go pattern of deployment. These

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[3] The concepts presented in the following are based on the overview in (Haufe and Ehrhart, 2016; Del Río, 2015)

conditions prevent investment in local manufacturing facilities and the development of a robust supply chain (IRENA, 2013). A certain level of frequency is thus important in RES auctions.

The final modelling case deals with participation in the auction, specifically with limits for certain bidder groups and how restricting participation impacts the distribution of bidders. Increasing diversity in auctions for RES usually leads to a certain amount of market segmentation (Del Río, 2015). This also holds for restrictions on participation. Participation restrictions can reduce the degree of competition and make collusive and strategic behaviour more likely, potentially resulting in higher bid prices. A greater technological differentiation is furthermore likely to result in higher system costs. Therefore, the advantages of promoting diversity in terms of minimisation of support costs (lower windfall profits) have to be weighed against the disadvantages. All cases will provide more background on each design element described here and present results on how its implementation can influence auction results.

3.2 Agent-based modelling (ABM)

Auction theory gives important inputs on the design of the optimal auction mechanism. Nevertheless, results usually only hold under restrictive assumptions concerning the bidder's rationale, the amount of rounds, the number of participants etc. Experimental results as e.g. by Erev and Roth (1998) show that learning models are sometimes more able to predict auction outcomes than classic Nash-Equilibrium predictions of economic theory (Hailu et al., 2011).

In this section, I explain agent-based modelling (ABM) and outline the advantages of this methodology for the present analysis. According to Bonabeau (2002), agent-based models have certain benefits over other modelling techniques: being able to capture emergent phenomena, providing a natural description of a system, and being flexible in regard to changes. Moreover, Axtell (1999) highlights that ABM has the property of establishing sufficiency theorems. As the main idea behind ABM consists of simulating the interactions between individual agents over time (Masad and Kazil, 2015), it is important to understand what exactly defines an agent. Wooldridge and Jennings (1995) describe agents as software-based computer systems located in a specific environment. These agents aim to reach their design objectives by autonomously taking actions. Furthermore, Wooldridge and Jennings (1995) define four major properties of agents: autonomy, social ability, reactivity, and pro-activeness.

Adaptation is an important feature of agent-based modelling (Dam et al., 2013). As this thesis focuses on the procurement auctions of renewable energies with a very clear time horizon and only a limited amount of rounds, the possibility of learning effects for the agents is limited. Nevertheless, a certain amount of learning is still implemented as shown in section 4.1. Selten et al. (2001) have studied the so called directional learning, which takes on a similar approach as the PAB learning algorithm, i.e. making use of previous rounds' results to adapt ones' own bid. According to Selten et al. (2001), ex-post rationality is a crucial feature of adaptive learning. They test their assumptions in a behavioural experiment on the winner's curse in auctions.

Erev and Roth (1998) present a meta-study of different games with a number of repetitions and compare outcomes of reinforcement learning and equilibrium modelling. Reinforcement learning means endorsing a predictive model with ex-post parameters from another experiment and is based on four main learning principles from psychology: the law of effect, the power law of practice, experimentation and recency. They show that including responsiveness to behaviour of other players further increases predictive ability of a model. In renewables auctions, players do not usually learn their competitors' behaviour in detail,[4] which is why no further responsiveness is implemented in the agent-based model applied in this thesis. Chen and Hsieh (2010) apply reinforcement learning to auction experiments and deliver further insights on heterogeneous personality traits to the individuals. A good summary of different learning models can be found in Camerer (2011).

Learning is usually implemented by a learning algorithm in agent-based modelling. Bower and Bunn (2001) have their agents adapt using a naive reinforcement learning algorithm in a comparison of pay-as-bid and uniform pricing auctions. Xiong et al. (2004) have implemented a multi-agent approach with adaptive agents developing bid prices according to the so-called Q-Learning algorithm. Q-Learning stems from the machine-learning field and is implemented to select an optimal action for any given (finite) Markov decision process. A good overview on learning algorithms is also provided by Weidlich and Veit (2008): a monotone learning algorithm is an algorithm where a bidder adapts her strategy each time after being rejected (e.g. slightly lowering the price). A phased algorithm on the other hand explores a number of rounds and then sets the future price to the one that generated the most revenue in previous rounds. In the case of RES auctions and taking into account the relatively constant decline in technology costs, the limited number of rounds and the strong competition, the contingency for developing advanced and strategic bidding strategies seems limited. A monotone algorithm thus seems to be the most adequate mechanism to apply in this thesis.

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[4] Usually, average awarded bid prices are published, as e.g. in Germany, but not a detailed account of all bids including project sizes and prices.

3.2.1 ABM in energy research

The following overview shows past applications of ABM in energy research. Several studies applying the ABM approach were published in energy research, whereas they often model an electricity (spot) market with a vast amount of agents in frequently occurring auctions, as e.g. power market simulations in Fraunhofer ISI's model PowerACE (Genoese and Fichtner, 2012) or the EMLab Generation Model by TU Delft (Chappin, 2013). Furthermore, a substantial amount of literature exists where ABM has been used to display and model complex interactions on the broader electricity market, i.e. modelling different agents' (TSOs, generators, regulatory institutions, consumers) behaviour and their respective interacting and sometimes contradictory objective functions and constraints, see e.g. Kiose and Voudouris (2015) and Widergren et al. (2006). Mizuta and Yamagata (2001) for example use agent-based modelling to represent greenhouse gas emissions trading. Concretely, they show how supply and demand form an equilibrium and that over several rounds.

ABM has also been used to assess different market design elements and policies for renewable subsidies, as shown in currently published research by Iychettira et al. (2017). To my best knowledge, Anatolitis and Welisch (2017) is the first paper to actually make use of agent-based modelling to assess auctions for renewable energy. Among the studies on agent-based electricity market models, comparing PAB and uniform pricing has been a popular research question in the past (Weidlich and Veit, 2008). Agent-based modelling is also suitable to assess micro-level energy system issues as optimizing grids (Kuznetsova et al., 2014). At the same time provides the possibility to assess very policy-oriented and large-scale research questions as the impacts of technological change (Ma and Nakamori, 2009) on energy markets. Further scientific energy-related auction literature applying an ABM approach can be found in Kiose and Voudouris (2015), Veit et al. (2009), Bunn and Oliveira (2001), or Li and Shi (2012) among others.

3.2.2 ABM in auctions

Agent-based modelling of non-electricity related auctions can also deliver interesting insights for the present analysis. Hailu et al. (2011) for example study how bidder agents learn. A combination of direction and reinforcement learning algorithms is thereby used to simulate performance. The authors look at auction scope effects, scale effects (budget and bidder size and their relationship) and auction pricing rules (uniform versus discriminatory, i.e. PAB pricing). Similar to this analysis, in Hailu et al., 2011 several auction rounds take place and bidders learn previous auction results. Bidders base their decision on these results as to whether they should continue to bid truthfully or add a mark-up on their opportunity costs. The paper differs to the extent that while bidders experience so-called directional learning (increasing their mark-up or leaving their bid unchanged) in the initial phase and later on, specifically after they have their first tender failure, are subject to reinforcement learning, meaning they optimize their strategy with a variety of alternative bid mark-ups. In this thesis, the learning process does not change - bidders are subject to technology cost induced price decreases and furthermore optimize their strategies according to competition levels and bid prices from the previous rounds (in the case of PAB pricing).

Hailu and Schilizzi (2004) apply ABM to compare the efficiency of auctions to a fixed support scheme for allocating conservation contracts to landowners. They want to establish whether bidding processes actually help to minimize information rents. An information rent is an economic concept, describing how an agent can benefit from retaining information not revealed to the principal.[5] For this particular setting, Hailu and Schilizzi (2004) find out that efficiency benefits of one-shot auctions do not necessarily apply to dynamic settings. They state that the auction mechanism is not superior to a fixed payment scheme, except when the latter involves the use of high prices. As the renewables sector is a setting with a constantly evolving cost development in technologies and a rapidly changing market environment, however, the situation for RES auctions is likely to be different: given the non-static situation and the different changing influences, a dynamic price-discovery mechanism as provided through RES auctions, could be more appropriate to determine support needs for renewable energy as an administratively set fixed scheme.

Hailu et al. (2011) furthermore model re-entry as an endogenous function of the competition level in the auction. In this thesis, a more simplistic approach is chosen. Bidders who are awarded are randomly assigned their re-entry from a distribution that matches their respective bidder category. Strong bidder categories are modelled to quickly re-enter, whereas weaker categories, as e.g. citizens energy companies in the German RES auctions continue participation earliest after one year. For the respective research questions being answered, this simplification is however sufficient, as I am interested in agent types rather than the specific agent herself. Furthermore in the study by Hailu et al. (2011), endogenous participation does not show significantly different results from the exogenous variant.

Mizuta et al. (2000) use agent-based modelling to better understand the dynamics in online auctions. They also model different bidder types, however as they look into a dynamic auction, they have more components to vary among the participants. Specifically, they model early bidders and late, more aggressive bidders who differ

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[5] For more information see the Spencer-Mirlees Theorem and further information economic theory, e.g. in Bergemann (2009).

in their objective function, i.e. early bidders score lower prices but with a lower probability of winning and vice versa. Later on, these bidders' behaviour is then modelled over several auction rounds by implementing a "motivation" parameter to include learning from previous rounds. A similar approach to model different objective functions can be found in the German modelling case (chapter 7, where the bidders for arable land face a more limited time horizon and thus have a different optimization strategy for their bids compared to the remaining bidders.

An agent-based modelling approach to depict several auction types (uniform, discriminatory and Vickrey) can be found in Hailu and Thoyer (2007). They assume participants to have only bounded rationality, i.e. that they exhibit cognitive limitations to evaluating the auction problem. Bids are constrained up and downwards but in a less restrictive manner than in the model used in this thesis, where rationality is assumed. In every round, the bidder in Hailu and Thoyer (2007) makes strategy choices. The bidder's award probabilities depend on her opportunity costs as well as on the history of choices she has made and the rewards obtained for those choices.

Fuentes-Fernández et al. (2010) present advantages and limitations of agent-based modelling in a meta-modelling approach. They exemplarily assess continuous double auctions and show how the meta-model can help improve other model's features. Learning from these past studies as well as empirical evidence on the development of RES auctions in a variety of (European) countries, helped develop and calibrate the agent-based model applied for the three modelling cases in this thesis. Potential pitfalls were accounted for and limitations are discussed and either ameliorated through additional analysis or stated in the respective modelling cases' conclusions to put the findings into perspective. Section 4 provides details on the agent-based model, whereas the three modelling cases describe its respective expansions and applications.

4

Methodology

To answer specific questions of relevance to policy makers, auction theoretic concepts have been implemented in an agent-based model, using all available data to model the respective market and their participants very close to reality. This combination of agent-based modelling and the computational learning and modelling of bidders with auction-theoretic conceptualization allows me to benefit from both methodologies' advantages.

This subsection describes the methodology underlying the model. After introducing the method, the model will be applied in three separate cases. More details on the different design features implemented in the model for the respective cases are shown directly in the three modelling chapters. For the reader interested in all technical details, the underlying Python infrastructure mesa which was used to build the model is available on github.

4.1 The agent-based framework

In auction theory, the bid function maps an agent's cost for realizing a project (or valuation of a good) to a bid price. Agents can receive b (their bid) in PAB, the highest accepted or lowest not awarded bid in uniform pricing, or 0 depending on the auction's outcome and try to maximize their profit (Krishna, 2010). Figure 4.1 shows a simplified approximation of how the agent-based model works and which factors are taken into account as model features.

It can be seen, that the bidder (or agent) is at the center of the modelling framework. She has some characteristics that determine her possibilities to submit bids, including the level of risk aversion, which is approximated by a discount factor for future rounds. More precisely, participants with an assumed higher risk aversion discount more heavily, as their preference to be awarded in an earlier round is higher as for participants who are less risk-averse.[1] Approximating risk aversion in this manner allows for a diversification of participants without implying too deterministic strategic

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[1] A good example for this is described in Anatolitis and Welisch, 2017: in German onshore wind auctions, citizens' energy companies are more risk averse as they have less overall funding and furthermore their composition is likely to not be of a long-term duration. Therefore, this type of actor is assumed more risk averse and more likely to prefer an award in an earlier round.

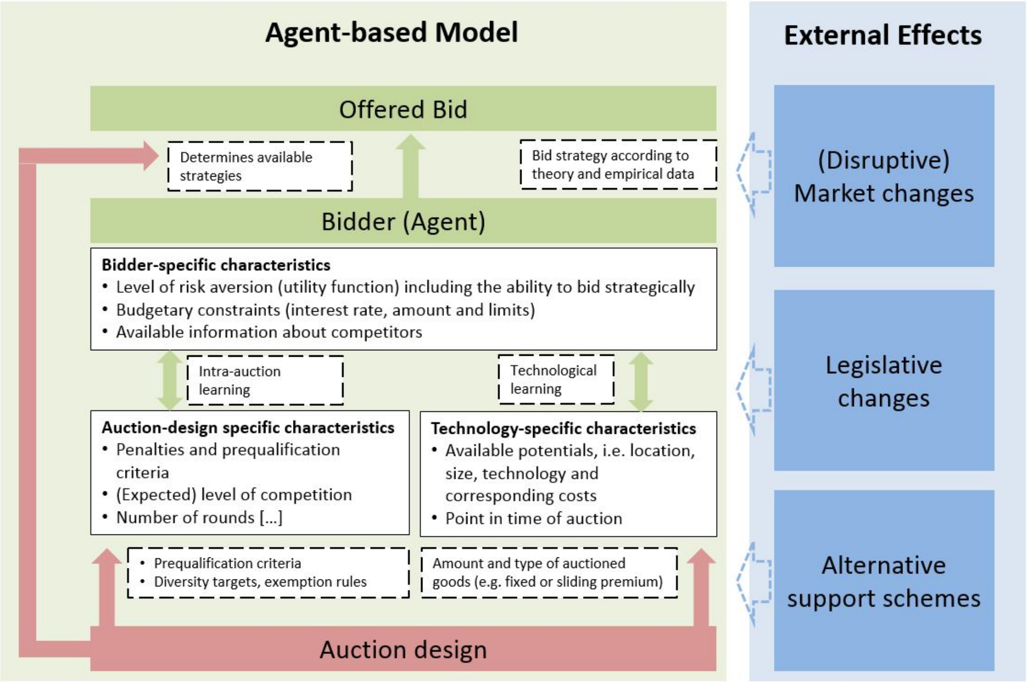

Fig. 4.1: Modelling framework, source: own elaboration

behaviour. Furthermore, the bidder is endorsed with the available information about competitors and certain budgetary constraints, i.e. the project size to be submitted and the associated costs and potential economies of scale influencing future bids. Furthermore, bidders have information about competitors available: they learn the overall mean bid price from previous auction rounds and the total number of competitors, as this information is commonly made available by most auctioning entities after a completed auction round. While the level of risk aversion is fixed in this model, the other two factors, budgetary constraints and information about competitors are adapted dynamically depending on the success in the previous rounds as well as on the overall auction outcome.

The auction outcome, i.e. the offered bid (bid price and volume) for one specific bidder as well as the overall result (total number of bids awarded and overall awarded bid price), furthermore depend on the auction design and the technology specific characteristics. These characteristics influence the distribution of the bidders, naturally, as they determine the participating technologies, limit project sizes, introduce entry barriers and exclude certain participants etc. The point in time of the auction refers to two factors: a) the stage of project development required for bidders, which is a crucial factor determining the planning horizon, financing and thus the bid price and b) the point in time in a sequential auction, i.e. whether or not the bidder is participating in the beginning or towards the end of a series of multiple rounds is crucial. This also influences a bidders' strategy. First of all, these framework conditions influence the selection of bidders, for example the participating technologies. Depending on the timing of the auction and the stage of development required, bidding strategies may vary among technologies or among different types of bidding entities (e.g. depending on their financing conditions). These factors are not directly included into the bidder's optimization functions, but influence their entry time, frequency of participation over several rounds and planning horizon. These features of agents are modelled as external factors - the framework of the agent-based model thus accounts for the limitations and possibilities of different auction designs towards different types of bidders.

This list is rather technical, but the respective features and their interactions become more clear in the different country modelling cases. Overarching across the factors influencing the bidder, is the auction design, which provides the framework in which the bidder acts, determines available strategies and predefines the criteria for participation and the awarded good. This concept will be filled with the necessary mathematical formulations in the following to understand how the bidder's behaviour is determined. It will be differentiated into uniform pricing, where bidders are assumed to bid only their true costs[2] and pay-as-bid pricing, where bidders adapt their belief function concerning their expected probability of winning in each auction round. The bidders optimize their bidding strategy in each round irrespective of the other participants as all auctions simulated are of a sealed-bid IPV format. They however learn outcomes from previous rounds and use them to adapt their bidding strategy. This will be explained in more detail in section 4.3, the description of the PAB bidding strategy. The following chapter thus provides the nuts and bolts for the understanding of the agent-based model. Anything still remaining unclear after this chapter will be made understood in the course of the modelling cases, fleshing out the theoretical concept with empirical data and actual auction design features.

Lastly, it has to be stressed, that there are further external (non-auction design) factors that also influence bidders' behaviour. These are sometimes unforeseeable - i.e. disruptive market changes or extreme declines in technology costs. These influences can furthermore appear in the form of legislative changes, ranging from balancing requirements for RES generators to opening up support schemes to other countries or changing other requirements. Market changes, i.e. falling spot prices, the exit of other technologies as for example a coal-phase out or a change in the ETS price can also change bidder's strategies. The same holds for alternative support schemes, as e.g. guaranteed feed-in-tariffs for small producers. All of these factors are extremely important for the development of bid prices and the corresponding support costs resulting from auctions. However, in terms of modelling, they are beyond the scope of this ABM and are thus not included, or only captured as model input parameters (e.g. minimum bid sizes, assumptions on cost declines

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[2] An exception to this assumption is made in the case of the UK auctions, where bidders adapt their bidding strategies under uniform pricing, when they are not faced with a penalty.

or the estimations of market price developments by bidders to know their support needs). After shedding light on the underlying agent-based framework, the following sections will now explain how the pricing rules were implemented in the agent-based model.

4.2 Uniform pricing

Uniform pricing means, that all successful bidders receive the same remuneration, which can be determined by the lowest rejected or highest accepted bid in this model.[3] The bid function is derived from auction theory. Several studies have shown, that bidding one's own cost in a multi-unit auction with uniform pricing (when the agent only places a bid for one unit) or in a second price auction – the single unit equivalent – is a weakly dominant strategy (Milgrom, 2004).

$$b_i = c_t \tag{4.1}$$

In the simulation, agents therefore bid truthfully (their exact costs c_t) in every round under uniform pricing. According to theory, the outcome of a functioning uniform pricing regime is incentive compatible (Klemperer, 2004). Uniform pricing usually serves as a benchmark case in the following analysis, as the bidding strategy is not influenced by parameters other than the agent's cost.

4.3 Pay-as-bid

Under discriminatory pricing rules (first-price sealed-bid and PAB), successful agents are paid exactly their bid b_t. Due to this fact, bidders will at least bid their individual cost, usually with a certain margin on top. In auction theory, this behaviour is known as “bid-shading" (Menezes and Monteiro, 2005). Under the PAB pricing mechanism, the agent maximizes her expected profit π over her chance of winning and the amount received in case of being successful by adjusting her bids accordingly and taking into account the possibility to win in the following rounds. In general, the higher her bid is, the lower her probability to win in the auction but the higher the profit in case of winning (e.g. Samuelson (1986) and McAfee and McMillan (1987)).

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[3] Potential problems of the latter will be discussed in the UK modelling case (chapter 5).

Since all cases assessed are designed as sequential multi-unit auctions, the bid vector b contains all the bids from the current round t until the last round in T. The discount factor is $0 < \delta < 1$, since winning in a future round is less favourable (Sugianto and Liao, 2014), and c_t is the agents' specific cost in round t. Assuming that the agents participate with only a single project in each round, they can only take part in the following rounds with their specific project if their current bid is unsuccessful. Consequently, the expected profit in one of the following rounds has to be adjusted by the probability of losing in the past auctions.

Thus, the current bid not only influences the current expected profit, but also the future ones, as the profit of the specific project is maximized taking into account a specific period of time and the expected probability of winning over all auction rounds. Adjusting the discount factor δ^t enables to account for the specific risk aversion of each agent type. The expected utility is calculated in each round, with T being the final round. This yields the following equation for t=0,1,2,...,T:

$$\begin{aligned}\max_{b} \mathbf{E}(\pi(\mathbf{b})) = \sum_{i=t}^{T} (b_i - c_t) \cdot Pr(\text{`successful bid in round i'}) \\ \cdot \prod_{x=1}^{i-t} Pr(\text{`unsuccessful bid in round i-x'})\end{aligned} \tag{4.2}$$

To summarize the simplified depiction in equation (4.2), one can state the following: the agent maximizes her expected profit $\mathbf{E}(\pi(\mathbf{b}))$ over all auction rounds T. She therefore weights the probability $Pr()$ of winning multiplied with the expected profit ($b_i - c_i$; bid price minus cost) in the current round against the probability $Pr()$ of losing in the remaining auction rounds. The nomenclature explaining all variables used in this thesis can be found in the appendix (section 9.2).

Agents include the level of competition into their expected profit. In this simulation, the concept of order statistics (Ahsanullah et al., 2013) has been used to model this: to determine the probability of submitting a successful bid, the agent assumes a number of n-1 participants (without her) with n_s (successful) bidders being able to win in the auction round. Therefore, at least the $n_s^t h$ lowest out of the n-1 other participants' bids has to be higher than her own one b_t. The agents assume the competition and the number of winners to be the same as in the preceding auction round. Due to a lack of information in the first round, the number of competitors and the number of possible winners in the first round is a best guess of agents, depending on their respective market environment. Further a cumulative distribution function (CDF) is introduced. This function $F()$ which captures an agent's belief on the other participants bid distribution and specifically, the probability that another bid b_j is lower, hence $Pr(b_j < b_i)$. Consequently, 1-$F(b_i)$ depicts the probability of her own bid being lower than her opponent's. Based on the approach in Ahsanullah et al. (2013), the probabilities are calculated in the following way:

$$\begin{aligned}\mathbf{E}(\pi_i(\mathbf{b_i})) = \sum_{j=t}^{T} \delta^{j-t} \left(b_i^j - c^j\right) \cdot \sum_{k=0}^{n_s^{t-1}-1} \binom{n^{t-1}-1}{k} F(b_i^j)^k \left(1 - F(b_i^j)\right)^{n^{t-1}-1-k} \\ \cdot \prod_{x=1}^{j-t} \sum_{l=n_S^{t-1}}^{n^{t-1}-1} \binom{n^{t-1}-1}{l} F(b_i^j)^l \left(1 - F(b_i^j)\right)^{n^{t-1}-1-l} . \qquad (4.3)\end{aligned}$$

The bidders maximize the expected profit given in (4.3) by optimizing their bid vector $\mathbf{b_i}$. After every auction round, the bidders adjust this bid vector given the additional information from the last round. Although the above equation is based on the auction-theoretic concept of first-price sealed bid auctions (McAfee and McMillan, 1987), the a bid function will not account for the other bidders' behaviour. In the following simulations, the above equation will be solved using maximization algorithms. How these were implemented is explained in the following section 4.4.

Agents, as autonomous entities, should be able to adapt their behaviour to changes in the system to simulate a realistic environment and learn from past occurrences. Information provided by the auctioneer flows into the learning algorithm implemented in the simulation for the PAB pricing rule. Each agent optimizes her expected pay-off over the entire time horizon. As shown previously, the expected profit depends on the CDF's parameters. The CDF is modelled as a normal distribution, similar to modelling the distribution of the market clearing price in electricity markets (Azadeh et al. (2012), Rahimiyan and Rajabi Mashhadi (2007), and Rahimiyan and Rajabi Mashhadi (2008)).

Therefore, the mean value (μ) can be seen as a central configuration parameter besides the standard deviation. The agents' learning algorithm consists of adapting μ to new information generated throughout the course of the auctions. In the first round, the assumptions on μ of $F()$ are based on each agent's own signal (her cost) which is the best approximation regarding the other agents' bids (Krishna, 2010). In the course of the auctions, new information becomes available, which is incorporated by the agents: they adjust the CDF by updating μ with the last round's overall mean bid. Figure 4.2 shows a simplified depiction of how the learning takes place in the agent-based auction model.

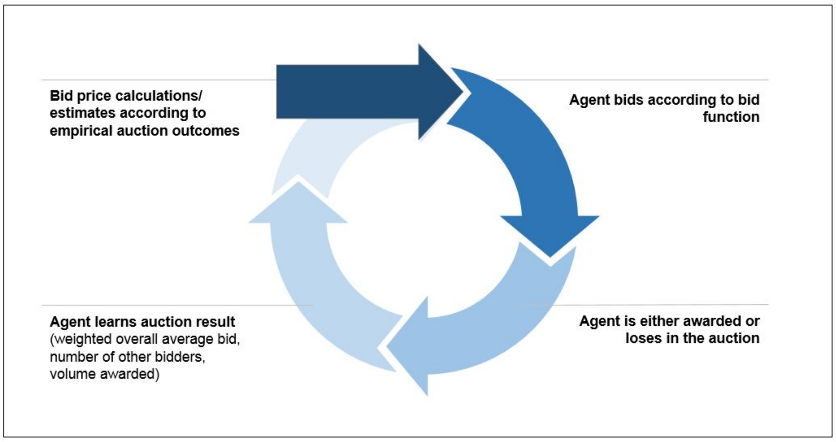

Fig. 4.2: Simplified learning algorithm, source: Anatolitis and Welisch, 2017, own elaboration

This definition of learning is one of the main properties of ABM (Wooldridge and Jennings, 1995): the environment, in this particular case the overall mean bid and the number of participants as well as the number of successful bidders in the previous round, influences the agents' behaviour. In return, the agents' individual bids have an impact on the overall average bid.

4.4 Technical implementation

To average over stochastic elements (Hailu et al., 2011) of the simulation, the mean of a minimum of 50 simulation rounds is used for each final result in the following modelling cases. In the PAB auction, each agent's bid vector is calculated before the auction round takes place by using a so-called "SLSQP algorithm" (Kraft, 1988). Using this specific algorithm has the advantage of defining boundaries for the optimization and thus not obtaining extreme values, which would be a possible result from applying a standard normal distribution. In certain applications and sensitivities nevertheless, normal distributions are also used to depict a certain bidder type. The agents' own cost is employed as an initial guess for the maximization algorithm. In all simulations executed, algorithm and model generate realistic values: within each bid vector, the corresponding bids decrease over all rounds, i.e. the later an auction takes place, the more aggressive the agents' bids become. This also leads the current bid (b_t) in each round, which determines the specific auction's outcome, to decrease (c.p.) over time.

As explained previously in section 3.1, a monotone learning algorithm is the most appropriate choice for modelling learning of bidders in this particular case. To be more specific, the learning modelled here is a form of directional learning.[4] Similar

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[4] For more detail see e.g. Selten et al. (2005).

to Hailu and Schilizzi, 2005, the agent-based model developed for this thesis takes into account the outcome of the previous round and the price is adapted accordingly. This holds for the overall outcome, as explained earlier. It can however also be changed to account for a previous win. This includes changes in future participation as well as changes in the bid price. Different examples of this implementation will be shown in the following modelling cases. As stated beforehand, exogenous assumptions on technology cost developments also influence the bid price, but are not determined by the bidder's learning algorithm.

5

Modelling case 1: Penalties and pre-qualifications in the UK CfD auction scheme

As stated earlier, the European Commission's guidelines on state aid for environmental protection and energy 2014-2020 (European Commission, 2014) foresee a gradual implementation of "competitive bidding processes" for allocating public support. A number of design elements exists, to create a tailor-made auction scheme, fit to a country's policy goals as well as its electricity market. Varying these design elements has crucial impacts on the auction outcome and, therefore, in the long term also on renewables deployment in the respective country. The following modelling case is based on my paper "**The importance of penalties and pre-qualifications: A model-based assessment of the UK renewables auction scheme**". It is currently under review at: Economics of Energy and Environmental Policy and has been submitted in September 2017.

An interesting question when it comes to auction design is how penalties and pre-qualifications affect bidding behaviour and how the project implementation rate is affected by setting these penalties and pre-qualification criteria. The United Kingdom's (UK) market is a particularly fit setting to assess this kind of question, due to the specific properties of its auction design. The bidding process is rather complex and there is not a clear time-line of auction rounds foreseen. Furthermore, bidding takes place into different commissioning years - increasing uncertainty of bidders in two respects: Firstly, as competition for the respective years is quite difficult to appraise beforehand, winners' curse from bidding into a year with a low number of participants can occur. Secondly, no effective non-delivery penalty was in place for the first auction round.

According to Kreiss et al. (2017a) cost uncertainties and potential negative consequences in case of of non-realisation have a large influence on the a realisation rate of projects awarded in an auction. Thus, both factors mentioned beforehand give participants in the UK renewable energy (RES) auctions an incentive to account for non-realisation in their bidding strategy: as the possibility of winners' curse is not unlikely and as dropping out of the auction in the case they do not break even with their submitted bid will not be penalised.

The following chapter will firstly give insights into the UK's RES support system and electricity market and then describe the auction design and how it is depicted in the model. Then the auction, different bidding strategies and potential outcomes are studied - by taking into account how potential changes in the design of penalties and pre-qualifications could influence lower bidders' uncertainties and impact project implementation rates.

5.1 Background to modelling case 1

This section briefly outlines the UK's electricity market and auction scheme as well as the auction-theoretic background necessary for understanding the analysis. Furthermore, agent-based modelling is explained and its suitability to assess the research question as well as potential limitations of the approach are shown.

5.1.1 UK electricity market and CfD scheme

The UK has a population of around 65 million people and in 2014, the year the CfD auction took place, its final energy consumption was 143 Mtoe (million tonnes oil equivalent) electricity that made up 18.5% of the UK's final energy consumption (26 Mtoe/339 TWh (Terrawatt hours)) according to Office for National Statistics (2017). Under the EU Directive 2009/28/EC (European Parliament and Council Directive, 2009), the UK is bound to meet 15% of energy consumption across all sectors from renewable sources by 2020 which translates to approximately 30% in the electricity sector. This is due to its favourable conditions for generating electricity from renewable sources (RES-E), especially from wind power (DECC, 2009). In 2014, the RES share of electricity generation was almost 20%, and overall renewable electricity supplied 7.8% of final energy consumption (DECC, 2015). The UK's target for the electricity sector is likely to be reached, whereas the country falls short in respect to the heating and transport targets (UK Parliament, 2016).

Interconnection currently exists with France, the Republic of Ireland, Northern Ireland and the Netherlands, amounting to a total capacity of 4 gigawatt (GW). More capacities are planned in the future, possibly to Belgium, Norway, France and Denmark, meaning that the UK could become increasingly integrated into the wider European electricity network (Fitch-Roy and Woodman, 2016). As the Brexit[1] is currently being rolled out, however, the future of this integration remains to be seen. Electricity generation and retail markets are liberalised. However, despite

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[1] Brexit is a shorthand way of saying the UK leaving the EU - merging the words Britain and exit to get Brexit. On Thursday 23 June, 2016, the voting age population voted in favour of Britain leaving the EU and the country is the UK is scheduled to leave on Friday, 29 March 2019 (BBC, 2017).

some recent trends towards independent electricity supply, electricity generation and supply in the UK remain dominated by six vertically integrated firms often referred to as the Big Six (Fitch-Roy and Woodman, 2016). Together, the Big Six account for more than 90% of domestic electricity supply and own approximately 70% of the UK's generation capacity (Ofgem, 2015).

Renewable electricity has been supported since 1990. The first scheme was the so-called Non Fossil Fuel Obligation (auction), which ran from 1990 to 1998. This was replaced by a quota, named the Renewables Obligation (RO) in 2002. Large scale solar PV (>5 MW) has been excluded from the RO in April 2015 and onshore wind in April 2016. The RO will expire for all other technologies in 2017. Its replacement - the Contracts for Difference (CfD) scheme - is an auction mechanism, and the first round of bidding took place in late 2014. In March 2016, the Government announced further auctions for contract allocation, with up to £730 M available for offshore wind and other less established technologies.[2]

The Contracts for Difference (CfDs) are part of a wider Electricity Market Reform package started by the UK Government in 2009. The aims of the reform were ensuring security of supply and decarbonization of the electricity system at least cost to consumers. The original policy objective of the CfD auctions was to increase competition within technology groups to bring down support costs and limit producer surplus. Technology neutrality is envisaged in the future (unspecified date) (DECC, 2011).

The CfD auctions are multi-unit, sealed-bid, uniform price auctions. Technology-specific ceiling prices known as "administrative strike prices" are intended to represent similar investor returns to the previous support mechanism, the Renewables Obligation (DECC, 2013). The auction scheme furthermore allows for technology capacity minima and maxima to be set. Auctioned volumes are determined by strict budgetary constraints. Budgets are capped year-by-year and thus not considering the total support period of the awarded projects. A winning bid has to lie below the highest awarded bid and must furthermore be comprised in the budget cap for any of the years in which a cap has been set. In terms of modelling auctions, this is challenging.

Budgets for the first auction were divided into two "pots", one for established and the other for less established technologies. This actually created two simultaneous auction processes (Fitch-Roy and Woodman, 2016). The first pot, for established

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[2] The first of these auction rounds is worth £290M. This round has been carried out in May 2017 and results have been published in early September 2017. However, only support for non-mature technologies has been auctioned in this second round, such that the results will only be partly of interest for the following analysis.

technologies, included onshore wind and solar PV, energy from waste with CHP, hydro (5 to 50 MW), landfill gas and sewage gas. It consisted of £50M (€64M) for projects commissioning from 2015/16, and an additional £15M (€19M) (i.e. £65M (€83M) in total) for projects commissioning from 2016/17 onwards. In the following, modelling will be focused on this pot. It has to be mentioned, however that larger amounts were set aside for the less established technologies (i.e. £260M in total), including offshore wind, biomass CHP, wave, tidal stream, advanced conversion technologies, anaerobic digestion and geothermal. In theory, a third pot for biomass conversion exists. However, no budget was allocated to this for the first auction (Fitch-Roy and Woodman, 2016). This specific distribution of funds shows that a policy objective of BEIS seems to be spurring innovation and achieving or maintaining technological diversity in the renewables sector.

5.1.2 Auction theory

In the auction simulations modelled in this chapter, symmetric, risk-neutral and single-project bidders are considered. As explained beforehand, the product auctioned is a homogeneous good. The following overview[3] of auction design elements will be limited to those relevant for this analysis. Bidder's valuations in this specific format are modelled as independent values (IPV approach), as each bidder draws independently from a given cost range. However, due to the fact that cost decreases take place simultaneously and equally for all bidders, a certain common value component also exists.

According to Kreiss et al., 2017a, one of the main reasons for non-realisation in auctions are bidders' uncertainties concerning their project costs. The non-realisation risk can be reduced by taking various measures. The most common measures are financial and physical pre-qualifications and penalties (Kreiss et al., 2017a). While these measures are already commonly used in practice, less theoretical literature exists on describing and understanding these measures, i.e. pre-qualification processes or penalisation of delay/non-delivery (Wan and Beil, 2009).

Implementing pre-qualification requirements can have ambiguous consequences. If pre-qualification costs are sunk costs, this may discourage the participation of actors (especially the smaller ones) by increasing the costs of participation (Del Río, 2015) and thus reduce competition in the auction. Financial pre-qualifications are very common in RES auctions, as e.g. in Germany, Denmark or Brazil. They help ensure that bidders are able to realise the project in case they are awarded (Held et al., 2014). This is due to the fact that the bidder's uncertainty of actually being able to finance a project is reduced by the administratively predetermined financial security.

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[3] For more details see the overview in e.g. (Haufe and Ehrhart, 2016; Del Río, 2015)

Physical pre-qualifications are e.g. a construction permit or further country specific permits (Kreiss et al., 2017a). These requirements are supposed to ensure serious bids and planning security (Del Río and Linares, 2014). They are also employed to avoid strategic bidding, i.e. outbidding to block others from realising their projects (Del Río, 2015). Outbidding means that bidders could submit several bids although planning to realise only one of the submitted projects. This way, they can influence the price and also hinder competitors. In general, pre-qualifications like securities prove to be effective for achieving higher realisation rates as shown e.g. by Calveras et al., 2004.

A penalty is a necessary condition, meaning that the bidder has to pay if she is awarded and does not comply with the expectations afterwards (Kreiss et al., 2017a). It is crucial, when setting penalties, to choose an appropriate level, as also shown e.g. for capacity markets (Mastropietro et al., 2016). A penalty set too high will discourage participation, whereas low levels or no penalties would lead to ineffectiveness in the realization process (Del Río, 2015). In terms of practical implementation it is crucial to see whether the project developer is actually responsible for a delay or non-delivery or if it occurred due to external causes (Held et al., 2014).

In general, larger bidders are better capable to pay a penalty, which makes them more risk averse and more desirable for loans, as bankruptcy (Chillemi and Mezzetti, 2009) is not a straightforward option (which could be the case for smaller, recently founded entities). They also have more resources to pre-qualify. Without a penalty or pre-qualification in place, bidders bid more aggressively: with a penalty system or a bid bond, the limit for losses changes to the maximum of security and assets or penalty (Kreiss et al., 2017a), meaning that bidders are willing to incur a certain loss in order to regain their pre-qualification.

5.1.3 Agent-based modelling

In this section, agent-based modelling (ABM) is explained and the benefits of this methodology for the following analysis outlined. Farmer and Foley (2009) stress that ABM is a crucial tool in economics to handle a range of nonlinear behaviour substantially larger than conventional equilibrium models. Furthermore, the methodology is able to incorporate a constantly changing environment.

There is a wide range of scientific energy-related ABM auction literature, which can be related to this particular chapter. Veit et al. (2009) for instance model strategic behaviour in the German electricity market to assess the implications of transmission constraints on power markets. Li and Shi (2012) show that agent-based simulation is a viable modelling tool which can provide realistic insights for the complex interactions among different market participants: they assess bidding behaviour of a wind generation company in the deregulated day-ahead electricity wholesale market. Further interesting research has been summarized in section 3.2.

Aside from that, agent based modelling of non-electricity related auctions has also delivered interesting insights for this assessment. Hailu and Thoyer (2007)'s study on how bidder agents learn, has provided valuable insights using a combination of direction and reinforcement learning algorithms to simulate performance. Thereby they look at auction scope effects, scale effects (budget and bidder size and their relationship) and auction pricing rules (uniform versus discriminatory pricing).

5.2 Model-based analysis of modelling case 1

The model-based analysis presented in the following chapter has its foundations in auction theory. Furthermore, a thorough analysis of data on technologies and the UK renewable energy market was carried out to model the respective market and its participants very close to reality. After introducing the methodology, its application will be shown and results discussed.

5.2.1 Agent-based model of the UK CfD auction

The agent-based model applied in and extended for this case has been described earlier in chapter 4. As stated earlier, in auction theory, the bid function maps an agent's cost for realising the project (or valuation of a good) to a bid price. Agents can receive b (their bid) in pay-as-bid (PAB), the highest accepted or lowest not awarded bid in uniform pricing, or 0 depending on the auction's outcome and try to maximize their profit (Krishna, 2010).

In the UK CfD auctions, pay-as-cleared (i.e uniform pricing) is implemented as a pricing mechanism. Uniform pricing means, that all successful bidders receive the same remuneration, which is determined by the highest awarded bid in this particular case. The bid function is derived from auction theory. Several studies have shown, that bidding one's own cost in a multi-unit auction with uniform pricing (when the agent only places a bid for one unit) or in a second price auction – the single unit equivalent – is a weakly dominant strategy (Milgrom, 2004). β is thus the bidding strategy applied:

$$\beta(c_i^t) = c_i^t \tag{5.1}$$

In the simulation, agents therefore bid truthfully (their exact costs c_t) in every round. According to theory, the outcome of a functioning uniform pricing regime is incentive compatible (Klemperer, 2004). However, a different strategy is modelled for the case where agents have an incentive to bid strategically instead of revealing their true costs. The auctions in the UK are not held sequentially. Instead one auction is held and participants can decide in which year they want to bid into. This requires participants to make an estimate on competition in that year and calculate their strategic bid at that point in time. The assumptions taken are outlined in the following sections. To average over stochastic elements of the simulation (Hailu et al., 2011), the mean of 100 simulation rounds per scheme is used as a final result.

To closely represent the UK auction scheme and its participants, several decisions on reducing complexity have been made to answer the research question, without sacrificing too much detail of the auction design. In this section, the model design and features of the agents are described and the specific choices explained: the auction design has been simplified in terms that agents translate the annually capped budget into a certain amount of capacity auctioned for each budget year. Participants in the UK renewables auctions estimate which amount of tendered capacity is represented by the annual budget. Thus, for the model, the same procedure was performed to translate the monetary budget cap into an amount of MW by using the official valuation formula depicted in the 2014 allocation framework (DECC, 2014).[4]

$$\begin{aligned}\text{Budget impact}_{s,yr,p} &= (\text{Strike Price}_{cy,t} - \text{Reference Price}_{yr}) \\ &\times \text{Load Factor}_{t,yr} \times YR1F_{s,c,p} \times \text{Capacity}_{s,p} \times (\text{Days}_{yr} \times 24) \\ &\times (1 - TLM_{yr}) \times RMQ_t \times CHPQM_s\end{aligned} \tag{5.2}$$

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[4] The official reference price assumed for the year 2015/16 is £ 51.06. The administratively set strike price for onshore wind was 95 and for solar PV it was £ 120 in 2015/16. The capacity included into the equation represents the capacity of the plant up to two decimal places. Load factors for onshore wind are 26.7% and for solar PV 11.1%. For the same year, the transmission loss multiplier (TLM_{yr}) is 0.0085 and the renewable qualifying multiplier (RMQ_t) is 1 for both technologies as is the CHP qualifying multiplier ($CHPQM_s$). The factor $YR1F_{s,c,p}$ is applied to account for phased projects and equals 1 otherwise. For simplification purposes, it is left at 1, assuming that all projects participate for the full year. The year 2015/16 has 365 days.

Specifically, the following procedure was applied, taking into account market shares of onshore wind and solar PV:[5] the amount of budget has to be divided by the annual amount of subsidy received for one MW of RES. As costs and load factor differ for solar PV and onshore wind, they will be included as to their respective market share into the calculation. This market share will be scaled up assuming the market for mature RES technologies would consist of onshore wind and solar PV only - thus ignoring the other participating technologies to facilitate the assessment of the auction outcomes:[6]

$$\text{Capacity} = \frac{\text{Budget}}{BI\,PV_{s,yr,p} \times 0.38 + BI\,\text{onshore}_{s,yr,p} \times 0.62} \tag{5.3}$$

BI is the budget impact of the respective technology calculated according to the official valuation formula. As mentioned, this assumption is simplifying. However, agents bidding in the auctions also scale the budget to their expectations of capacity tendered and potential competition. This calculation procedure thus yields an expected capacity that all agents can include into their respective bidding function to maximize their probability of winning and their profits. Furthermore, as seen in the outcome of the CfD auction that took place in 2014, only onshore wind and solar PV were awarded in the pot 1 for mature technologies. This shows that the modelled simplification actually matches the empirical evidence. The estimated capacity according to the calculations amounts to 565 MW in 2015/16 (£ 50M). For the remaining years the estimated capacity is derived from a budget of £ 65M per year (inflated by a factor of 1.0195). This translates to 734.5 MW for the following delivery years (2016/17, 2017/18, 2018/19, 2019/20, 2020/21) before being inflated. For simplification purposes and easier comparison, these capacities are taken left without factoring in an inflation rate.

The pricing rule, as described above, is pay-as-cleared (uniform pricing within each year). A separate price can be determined for technologies where a minimum volume has been set, unless the general clearing price for that year is higher than

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[5] Pot 1 (mature technologies) has been split among these two technologies and energy from waste with CHP, hydro, landfill gas and sewage gas. As, however, none of these technologies were awarded in the first auction round and due to simplification purposes, it will be assumed that only onshore wind and solar PV projects bid into the pot 1 technology auction. As in the first auction, no capacity minima or maxima were set for specific technologies in pot 1, both technologies compete for the whole pot in the modelled auction.

[6] Taking the installed capacity shares of onshore wind and solar PV from the October 2014, where the first allocation round took place, this yields the following: 5,028 MW of PV were installed according to UK government statistics (DECC) and 8,536 MW of onshore wind, also according to DECC. Deducting the small-scale installations below 5 MW which receive a FiT (2,802 MW for solar PV and 433 MW for onshore wind), this yields 8,130 MW for onshore wind and 2,226 MW for solar PV. Assuming that the two technologies make up 100 % of all auction participants for the mature technology pot, a share of around 78.5 % onshore wind and 21.5 % solar PV bidders was achieved.

Tab. 5.1: Agent distribution in the UK CfD auction model

Agent type	**Wind strong**	**Wind weak**	**PV strong**	**PV weak**
Average number of bidders first delivery year	10	10	15	15
New random draw of bidders per delivery year	0-2	0-2	0-2	0-2
Range of capacity bid [MW]	5-15	5-15	5-50	5-50
Cost distribution [p/kWh]	4.7-6.2	6.2-7.6	7.1 - 8	8 - 9.4
Cost degression	1.95% per year		7.5% first year, then 2.5%	

the clearing price for the protected technology (DECC, 2013). As this however was not the case for mature technologies in the UK auction, it was assumed instead that wind onshore and solar PV agents compete in one auction.

5.3 Simulation and validation of the UK CfD auctions

The distribution of the agents is as follows. The 2014 capacity shares for solar PV and onshore wind bidders as calculated beforehand are used to calculate the respective share of bidders: 21.5 % for solar PV and 78.5 % for wind onshore in 2014. In terms of the number of bidders, there was no information available, so an estimate on the wind and PV sector in the UK was made using the official statistics by BEIS (2016b). As the bidding volume was not reached in any of the delivery years, participation is assumed to be rather low in the auctions, with 1,025 MW participating for the first delivery year and a slight increase in each upcoming year.[7] To approximate the size of participating projects, it is resorted to the auction results as shown in the Appendix. All of the assumptions on the bidders are shown in Table 5.1.

Next, to introduce variation and depict a realistic range of participants, four types of bidders are modelled: a strong and a weak type for each technology who differ in their cost distribution. Long-term bidding behaviour cannot be differentiated, as a one-shot auction is considered. Table 5.1 describes the agent's characteristics (data on costs has been taken from BEIS (2016a)):

Aside of their different prerequisites, the two technologies compared also differ in the development of their respective costs. As so far only one auction round for pot I technologies has been executed in the UK, learning of agents and cost degression over

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[7] This increase is due to two facts. Firstly, the budget in the first year is lower. Secondly, later delivery years potentially attract more participants, as especially for wind power, longer lead times for construction are preferential.

several rounds can not be taken into account. However, assumptions on technology cost degression influence bidder's valuations of future delivery years - as there was a possibility to bid into several financial years. In the model this is implemented as four bidding rounds with a different cost degression for onshore wind and solar PV but without learning from previous auction rounds. Agents receive a signal on where their costs lie. This signal is a cost range, taking into account that there is always some form of uncertainty concerning the costs of a project. In the following, it is explained in more detail, how the agents deal with this form of uncertainty under the respective auction schemes.

According to IRENA (2014) estimates, costs for onshore wind could drop between 9 and 22% by 2020. Taking the average, yields around 1.95 % per delivery year starting 2015/16. For solar PV, a quite steep decrease has been observed in the past year, which is likely to have already been anticipated at the point in time of the auction. However, future expectations for module price developments are rather conservative and do not expect the extreme price decrease to continue, such that a piecewise linear degression for solar PV costs is implemented starting with a stronger decrease but then flattening until 2020. In total, DECC (2015) estimates that the decrease in the LCOE will be around 20% from 2015 to 2020 (KPMG, 2015). Taking into account their calculations, a 7.5% decline between 2015 and 2016 and then 2.5% for the following rounds is assumed.

Under the pay-as-cleared pricing mechanism, in theory the weakly dominant strategy is bidding one's true costs ($b_i = c_t$). However, as the UK auctions' outcome is based on the highest accepted bid, auction participants have the incentive to exaggerate their true costs, due to the fact that their own bid might be the highest accepted one and thus determine the clearing price (Ausubel, 2008). At the same time, uncertainty exists about the level of competition in the respective years that participants can bid into. This could also lead to strategic underbidding (depending on the expectations on the clearing price, the number of competitors, their costs and their bidding strategies) which in turn could lead to winner's curse for some bidders. Finally, a bid failing to break even can be easily withdrawn, because no actual penalty exists. Summarising, the UK CfD auction has some design features that incentivise strategic behaviour.

The type of strategic behaviour to be investigated is underbidding due to lack of penalties or pre-qualification criteria and its impacts on auction outcomes - prices, project implementation rates and agent distribution. As shown by Kreiss et al., 2017a similar considerations hold for the case of pre-qualifications, if they also count as a loss for the bidder in case of non-realisation. Due to simplification purposes it is only referred to penalties in the following, whereas from a theoretical point of view, these impacts can also be expected for the loss of pre-qualifications (see e.g. Waehrer, 1995).

As explained in the theoretical section, bidding behaviour changes, depending on whether the bidder factors in a penalty or not. Therefore, two cases are compared: in the first one, bidders bid their costs and a drop-out would be penalised. The second one does not include a penalty (or a financial pre-qualification that could be lost). This means, that if bidders refuse to accept the bid afterwards because of winners' curse as they strategically underbid and now cannot cover their costs, because the final strike price is too low, they will not be penalised. In this case, bidders are modelled with a different bidding function: the function in the system with a functioning penalty/pre-qualification lowers uncertainty concerning costs for the bidders.

In the model this is implemented as follows. Firstly, a default round is executed to show how a pay-as-cleared auction with a functioning penalty scheme would have performed. In this auction, agents bid their true costs according to the cost signal they receive. They have no incentive to deviate from this signal. Then a non-penalty case is modelled. In this case, the bidder's cost range contains more uncertainty, increasing the likelihood that they submit a bid below their true costs. If the final strike price however lies below their actual costs, the bidders default without consequence. In that case, the bidder thus receives a signal x with an uncertainty factor δ:

$$y = x + \delta \text{ where } \delta \in [-\epsilon, \epsilon] \tag{5.4}$$

The bidding function resulting is:

$$\beta(c_i^t) = x_i^t - \delta \tag{5.5}$$

Due to the fact that the bidder has the option to default,[8] she is able to submit a bid in the lower bound of the range of her signal, even though it might result in a loss. This means, these bidders act less risk averse than those confronted with a cost

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[8] According to Parlane (2003) in a second-price auction, which is the single unit equivalent to the uniform pricing auction, when bidders face limited liability (reduced or no loss) for defaulting, there is a strictly positive probability to do so. According to Waehrer (1995) a model of limited liability can be interpreted equivalently to a model of a lost deposit, making this applicable to the UK CfD auction model.

in case of defaulting. If the auction outcome is not favourable for the bidder (i.e. negative profit), she does not accept the bid. Equations (4) and (5) are adaptations of Board (2007). The distribution of the uncertainty factor is assumed to be common knowledge (see e.g. Parlane (2003)). Please note, that the factor is modelled to be either positive or negative, i.e. participants bid along a larger range and not only in the lower segment of the distribution of their received signal. This is a conservative assumption, still considering bidders as fully rational.

In theory, the expected revenue is on average the same for sequential or one-shot auctions, or at least its effect cannot be determined (see e.g. Hausch, 1986 among others). Another strand of literature, as e.g. Mezzetti et al., 2008 find that whether or not revenue for the seller is higher (i.e. in our case lower support costs for the auctioning body) in sequential or one-shot auctions, depends on whether the informational effect of executing several rounds outweighs the so called "low-balling" effect, which yields lower prices (in our case higher support costs) in the first round. Non-negligibly here is some uncertainty for bidders trying to estimate competition and the price level for several budget years due to the one-shot auction format. If they bid into a year with low competition and strategically underbid, this increases the likelihood of experiencing winners' curse (Fitch-Roy and Woodman, 2016). In Welisch (2017) the auction results are shown and a further explanation is given, why these results offer too little insight to actually "reverse engineer" bidder's expectations on competition in different delivery years, based solely on these results. Therefore only price development scenarios for RES technologies are taken into account and bidders' expectations on competition levels for the different delivery years are not varied.

The two simulations can be summarised as follows: a one-shot auction with a penalty and a one-shot, non-penalty auction, where the bidder can bid in the lower area of her received signal which increases the probability of incurring a loss and defaulting.

5.4 Results and discussion of modelling case 1

The modelled standard uniform pricing scheme provides results of an auction with a functioning penalty system that enforces bidders' compliance and thus induces them to bid truthfully. These results are then contrasted with the outcome of a uniform pricing scheme, where bidders are able to default without penalty after being awarded, given that the strike price is below their true costs.

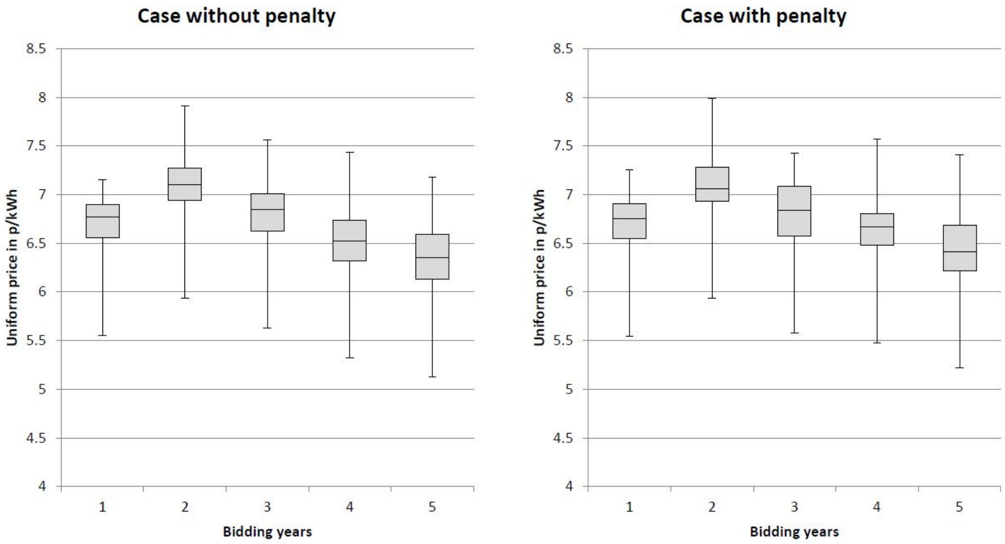

Fig. 5.1: Modelled bid prices for the UK CfD auctions (pot I technologies)

Figure 5.1 shows how the strike price changes in the auction scheme with and without penalty. The expected default rate in the non-penalty case is furthermore shown in Figure 5.2.

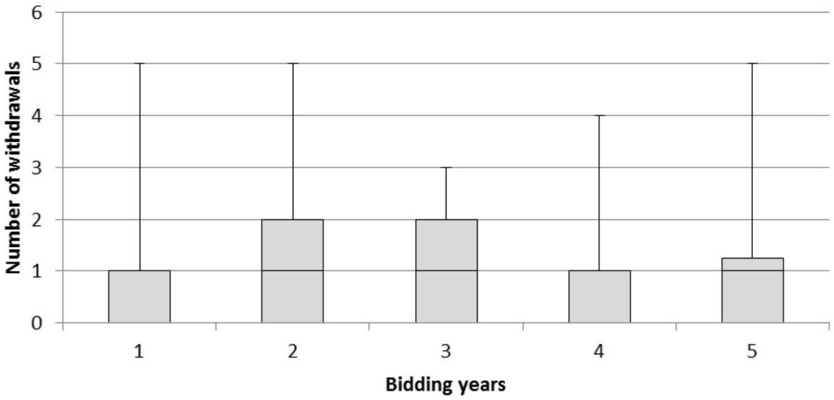

Fig. 5.2: Modelled dropout rate in the UK CfD auction (case without penalty)

The model results show that not factoring in a penalty can lead bidders to bid too low (the same holds for the lack of pre-qualification criteria). If they experience winners' curse as a result, they default. This leads to an increased drop-out of agents after being awarded. For the policy-maker this means a lower realisation rate from the auctions.

The most important findings from comparing the different modelling runs are the price differences and the differences in realisation probability. One can interestingly observe, that the strike price is slightly higher in the non-penalty case in the beginning, but then reaches slightly lower levels than the non-penalty case. Overall, there

Tab. 5.2: UK CfD auction model results (Uniform pricing with penalty)

Delivery year	2015/16	2016/17	2017/18	2018/19	2019/20
Capacity awarded [MW]	582.86	748.68	750.99	749.57	749.3
No. awarded bidders solar PV	0	1	1	1	1
No. awarded bidders onshore wind	20	25	24	24	25
Strike price [p/kWh]	6.73	7.1	6.83	6.64	6.48
Average profit [p/kWh]	0.97	1.19	1.10	1.08	1.05

Tab. 5.3: UK CfD auction model results (Uniform pricing without penalty)

Delivery year	2015/16	2016/17	2017/18	2018/19	2019/20
Capacity awarded [MW]	580.59	747.97	749.55	751.58	751.16
No. awarded bidders solar PV	0	1	1	1	0
No. awarded bidders onshore wind	19	24	24	24	24
Strike price [p/kWh]	6.7	7.08	6.82	6.54	6.38
Average profit [p/kWh]	0.96	1.21	1.12	1.03	1.0
Drop out [No. bidders]	1	1	1	1	1

is no significant difference to be seen. The capacity awarded is comparable for the penalty and the non-penalty case, however with roughly one bidder dropping out per delivery year in the non-penalty case, on average 23 MW will not be built per year and have to be deducted. Furthermore, comparing the average profit shows that in the non-penalty case, bidders achieve a larger profit than in the case where a functioning penalty is in place. This difference is, however, marginal as can be seen in tables 5.2 and 5.3 which show the complete simulation results (average values of 100 simulation rounds).

As the UK CfD auctions' outcome is based on the highest accepted bid, auction participants have the incentive to bid strategically, due to the fact that their own bid might be the highest accepted one and thus determine the clearing price (Ausubel, 2008). This could be a factor which influences the bidding behaviour, i.e. inducing the agent to bid above her costs. It is interesting to see, that the outcome of the non-penalty case does not show lower prices on average. Furthermore, a certain amount of participants underbid and then drop out in the model. As there is no information on project implementation rates of the UK auction thus far, it remains to be verified whether this will actually be the case. However, extremely low strike prices for the first delivery year (£ 50/MWh) were observed which are unlikely to allow bidders to cover their costs. In general, one can conclude from the theoretical literature, the empirical outcomes and the auction modelling, that the auction outcome is less predictable and capacity expansion goals are more likely to not be achieved when the auction design allows bidders to bid strategically without consequences.

In the empirical outcomes, it can be also observed, that the level of competition was quite fluctuating between the different auction rounds. This shows, that bidder's uncertainties rise, when they have little knowledge of competition that they can expect in a certain delivery year. Learning effects, i.e. technological but also from previous auction rounds are important and should be considered in designing an auction scheme. From a policy-maker perspective it thus has to be assessed, whether the administrative effort of holding annual auctions to increase stability outweighs the benefits of more balanced participation and more accurate and potentially lower costs in later auction rounds, compared to a one-shot auction. A further advantage of such a scheme is that it allows the auctioneer to adapt better to technological or market developments, by changing auctioned capacities or adapting the ceiling price. The second auction round in the UK only took place for non-mature (pot II) technologies, so the empirical results, unfortunately, do not provide further input data to refine the modelling of the mature technology auctions. However, the comparison shows extreme price decreases: strike prices for offshore wind farms from the second auction round in 2017 (for completion in 2022/23), i.e. are less than half the price which was attained in 2014 for completion the delivery year 2018/19 in the previous auctions (BEIS, 2017) and about one third lower for delivery in 2021/2022. This demonstrates that (technological) learning might be better captured in sequential auctions rather than having a one-shot auction for a large range of delivery years in place.

The aim of this chapter is to provide an understanding of auctions for RES and how design of penalties and pre-qualifications changes auction outcomes. Therefore, the choice of methodology needed to be one that allows deeper insights into the specific settings. In general, modelling is dependent on the model's input parameters. As auctions for renewable energy are a relatively new phenomenon especially in Europe and as the energy market as well as technological development are constantly changing in sometimes unforeseen ways, the model results cannot and are not aiming to provide accurate predictions of future auction outcomes. However, especially by combining agent based modelling, which allows quite precise depictions of human behaviour and quick reactions to a changing environment, with an auction theoretic background, insights are received which are valuable for policy makers looking into designing or improving an auction scheme. Notably, the result showing that the non-penalty case lead to drop-out and has no advantage in terms of lower prices, is quite useful for application of future policies. Overall, the analysis provides a novel approach of looking into renewables auctions and their specific design features and adds some interesting findings to the existing literature.

5.5 Conclusions of modelling case 1

This chapter presents an agent-based modelling approach to assess the impact of penalties and pre-qualifications in the UK CfD auction scheme for renewable energy. An auction theoretic framework is part of the model, as are specific characteristics of the UK electricity market and the market participants. Policy makers receive important insights from this analysis on how to design their auction policies according to their respective goals. While risking a reduced realisation rate, according to the model results, lower prices cannot be achieved in auctions with little or no pre-qualifications or no penalty for drop-out. If achieving a certain amount of installed capacity is important to the commissioning authority, higher pre-qualifications or an efficient penalty system could ensure this, as drop-out can be decreased and strategic underbidding avoided.

6

Modelling case 2: Designing multi-unit renewables auctions for the Danish market

This modelling case investigates different criteria for the design of multi-unit renewable energy (RES) auctions in small markets. It is based on my paper "**Multi-unit renewables auctions for small markets - Designing the Danish multi-technology auction scheme**", which is currently under review at the Renewable Energy Journal. It was submitted in December 2017. Small markets with a limited number of potential auction participants are quite frequent in the European Union. Implementing renewables auctions there can be challenging - due to potential lack of competition, relatively small auctioned capacities and other factors. The multi-technology RES auctions which are to be implemented in Denmark in 2018 serve as an exemplary case for the assessment. After calculating bidder's pre-auctioning cost assessments, the main research question is answered: how setting the auction schedule and the auctioned volume per round impacts the outcomes of the auction. Furthermore, a flexibility mechanism is tested, that allows budget shifts between rounds and can potentially increase deployment rates. Close cooperation with the Danish Energy Agency (ENS) provided relevant insights into this highly relevant topic.

The overall modelling case is structured as follows: the Danish electricity market and auction scheme are shortly outlined in this section. Section 6.1 then provides insights into the agent-based model simulating bidding behaviour in renewables auctions, which is applied to answer the research questions that concern auctioning. Next, chapter 6.2 shows the calculation procedure and theoretical implications for the expected bid price (pre-auctioning) as well as the auctioning procedure itself, by explaining the background to the model and its input parameters. Next, the results are presented and discussed in chapter 6.4. Conclusions and policy implications can be found in section 6.5.

To provide context to the following analysis, it is important to know that the Denmark ranks among the leading countries worldwide in terms of renewables deployment (non-hydro) as well as in wind-power technology. The RES share of annual gross electricity supply in Denmark has been on average 45% in 2016 (ENS, 2017b). Among Denmark's ambitious targets are 100% renewable energy consumption in

2050, (35% by 2020, including wind power as a provider of 50% of Denmark's electricity demand). Furthermore, the Danish electricity market is highly liberalised and split into two price zones (DK1 and DK2), which are part of the Nordpool area.

The Danish government plans to roll out a large-scale multi-unit multi-technology RES auction scheme beginning in 2018. While Denmark has significant experience with single-unit offshore auctions, the only multi-unit RES auction that took place in Denmark until now was a cross-border pilot scheme for 20 MW of PV together with Germany in 2016. This pilot auction provides some empirical evidence to draw upon, which is however limited (technology and volume-wise). The auction scheme planned to start in 2018 will be for a fixed premium on top of the market price (20 years support period), capped by a certain budget per round. The auction will be pay-as-bid and will apply to multiple technologies (including onshore wind and solar photovoltaics (PV)). Some of the design elements in this scheme could be subject to change in the long term. The following analysis will shed some light on impacts of their respective implementation.

6.1 Material and methods of modelling case 2

The methodology most suitable to address the given research question is modelling bidding behaviour in the Danish RES auctions by applying an agent-based model. This model has been previously described and applied in Anatolitis and Welisch (2017) as well as section 4.1 of this thesis. The interested reader is therefore referred to this paper for more details. A short summary account of the model's features can be given as follows: the agent-based model can depict a variety of auction schemes and their respective design elements as well as regulatory features as e.g. restrictions to participation. Pay-as-bid and uniform pricing auctions can be shown, either as a one-shot auction or a multi-round auction that allows participants and the auctioning entity to learn. It is furthermore possible to model the agents in a very detailed manner, to depict the respective auction participants in a country or to investigate a certain question concerning the auction outcome. In this research, aside of adapting the setting to accommodate the features of the Danish electricity market and auction scheme, the model has been expanded to allow for volume flexibility. A second model extension allowed for participation of multi-project bidders. This is an important feature for testing the feasibility of a non-flexible volume as well as the impacts of varying the schedule of the auction.

A high amount of detail was achieved in the representation of the Danish auction scheme, as the Danish Energy Agency (ENS) provided insights into all planned design features as well as into technology data and detailed outcomes of the joint Danish-

German PV pilot auction. Based on insights of the cooperation with ENS, two auction rounds with a budget that is equivalent to a total volume of 200 MW are assumed for the period 2018-2019. The ceiling price will be 15 DKK øre/kWh or 2.02 €ct/kWh. Furthermore, the auction will take place at a late stage in project development[1] with a retention penalty of 30 €/kW, making the prequalification requirements for bidders quite substantial. As stated beforehand, the pricing mechanism will be pay-as-bid and several technologies will be able to compete in a so called "open-door" common tender scheme for onshore wind, solar PV and offshore wind.[2]

The agents have been designed with the following parameters using data from different sources: the number of project developers participating in the auction was derived using ENS data. The number of solar PV bidders has been estimated by taking into account the outcome of the recent joint solar PV auction between Denmark and Germany. The number of onshore wind bidders stems from the most recent analysis on the Danish market (ENS, 2017a). The range of capacity bid per year is an estimate based on the solar PV auction results (for solar PV). For wind power, the numbers are based on the projects currently in the pipeline. The distribution for those projects is not uniform, but estimated as 30% of smaller projects (6-20 MW), 60% of medium-sized projects (20-60 MW) and 10% large-scale projects (60-135 MW). For solar power, a uniform distribution (2-50 MW) is assumed. The average cumulative capacity bid per year is based on the expected yearly deployment in Denmark. The time span takes into account the two upcoming years, although a longer period of time (up to 2025) is also modelled to show long-term developments of different variations of the scheme.

Bidders were furthermore subdivided into multi and single project bidders. This is due to insights from the solar PV pilot that took place in the end of 2016. In this pilot, the maximum allowed number of projects to be submitted per bidder was three. The nine winning bids of the auction came from three companies all owned by the same parent company (Danske Solparker/Better Energy). All bids had the same price i.e. 12.89 øre/kWh (1.73 €ct/kWh) for a 20 year fixed premium. Having the same price indicates that these bidders calculated that either all or no projects win: these three bidders therefore made use of economies of scale by offering several projects at once, thus being able to lower their costs and submit a lower bid compared to single project bidders.[3] For simplification purposes it was assumed in the modelling,

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[1] Projects already need approval, environmental impact assessment and a variety of pre-approvals to participate in the auction.

[2] Although participation of offshore wind, at least in the initial years is not likely to be expected, not least to alternative single-unit auction schemes are existing for this technology, offering a negotiated procedure with prequalification and a preliminary technical dialogue with the potential tenderers and investors, see Danish Wind Industry Association, 2017

[3] This bidding behaviour furthermore could indicate collusion. If limits are put on the submission of projects in future multi-unit auctions, it should be carefully checked for ownership of participating companies.

that multi-project bidders submit three bids each, as was the maximum amount allowed in the PV pilot auction. As they can make use of economies of scale, their cost distribution is assumed to be lower than that of the single project bidders.

The discount factor as well as new entry of agents in each round stems from a previous study on Germany (Anatolitis and Welisch, 2017), as Denmark has no long-term experiences with multi-unit auctions. The parameters are chosen to be rather conservative, i.e. not assuming a very strong change over the rounds. As explained beforehand, the period of time (2018-2019) is rather short-term, such that strong differences in award preference over time should not be expected. The expected probability of winning for participants over time is already accounted for in the bidder's respective optimization function, see Anatolitis and Welisch (2017). Specifically, bidding behaviour is adapted according to the remaining number of rounds and the therefore decreasing award probability over time. Figure 4.2 depicts the bidder behaviour in a simplified manner.

Furthermore, as the study assesses a completely novel auction scheme with limited previous auction outcomes to draw on, more focus was given on the bidder's calculus before the auction, also depicted in Figure 4.2. Specifically, a detailed analysis of the cost structure and expected market developments was performed to calculate the levelized cost of electricity (LCOE) of the participating technologies and to estimate the resulting fixed market premium that bidders would need to break even over the lifetime of their awarded project, given certain electricity market price expectations. The bidder's risk assessment in view of a fixed market premium and how it differs over the participating technologies is also accounted for. In combination with the cost assessment this gives realistic insights into the situation that bidders face before participating in the Danish multi-technology, multi-unit RES auctions.

6.2 Theory and calculation of modelling case 2

6.2.1 Pre-auctioning: bidder's calculus

As previously explained and indicated in Figure 4.2, bidders perform several financial calculations before entering in an auction, or deciding against it for that manner. The following two subsections give more insights into the parameters determining the bidder's decision.

6.2.2 Market risk based on the choice of premium

The Danish auction design foresees a fixed premium. As explained in section 2.3, a fixed premium is a more market-oriented instrument as it induces generators to take fluctuations in the price into account. With a fixed premium, renewable generators bear all the market risk. This risk exposure even becomes significantly higher under surplus capacities (Noothout et al., 2016). When holding a technology-diverse auction as the Danish one is laid out for, it should thus be considered, that different technologies exhibit different levels of exposure to market risk. Electricity generation patterns make them wind more and solar PV less vulnerable to market price fluctuations. The merit-order effect[4] has quite a substantial impact on prices – and especially as Denmark has a large share of wind power in its system, wind power plants would be likely to suffer large market losses in times of high generation. This does not affect solar PV as strongly, as its share in the system, up to now, is rather negligible.

A fixed premium thus leads to disadvantages for (especially) wind power generators, as they have to carry more of the market risk and thus have to price it into their bids. In the analysis, this is accounted for by multiplying the expected electricity spot price received by the different technologies by their respective market value factor[5] to account for differences in their generation pattern and the resulting market revenues. The market value factor taken for onshore wind is 0.85, based on a report by Hirth, 2016 and also found in Welisch et al., 2016. The market value of PV is assumed to be 1.1 according to estimations made by ENS.

6.2.3 Calculation of the necessary fixed premium

After accounting for the market risk that the respective technologies face, generation costs (LCOE) have to be calculated. From the LCOE and the expected market revenue, an average fixed premium can then be derived which the different technologies would need to cover their costs. Data on technology costs stems from the technology data catalogues published by the Danish Energy Agency (ENS, 2017a). This data was used to calculate the LCOE for each of the participating technologies. Specifically, expected full load hours (E_t), operation and maintenance costs (M_t), investment costs (I_t) and r, the weighted average cost of capital (WACC), calculated by Eclareon, making up 5 %, were taken into account (Brückmann, 2017). The support period in

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[4] The downward pressure on electricity prices in hours of high zero marginal cost variable RES infeed.

[5] The market value of a certain technology differs due to the aforementioned merit-order effect. Multiplying average electricity market revenues by a technology's market value factor accounts for its market value.

Denmark, 20 years, was taken as a write-off period, even though the actual life time of plants is potentially longer than this period.[6]

$$\frac{\sum_{t=1}^{n} \frac{I_t+M_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \tag{6.1}$$

Then, to assess support needs for generators, electricity market price projections by Energinet were used (Energinet, 2017). An average of the estimate for the two price zones was taken, as it is not known in which area the respective plants will be built. Taking the difference between the expected market price and the LCOE yields the gap needed for the generators to break even. Assuming differences in location, generator type and other factors, a cost range was assumed around this factor to introduce some bid price variation among the participants. Furthermore, it was assumed that the bid price range is in general lower for the multi-project bidders (irrespective of which technology), as they can make use of economies of scale. The calculations yield an LCOE for onshore wind at 37.99 €/MWh and for solar PV at 54.31 €/MWh. Taking into account ENS and other electricity price projections, this would lead to an average support need of 0.82 €ct/kWh for onshore wind and of 1.93 €ct/kWh for solar PV. As explained beforehand, bidder's cost ranges were set around these values to create a certain amount of variation.

6.2.4 Auctioning: implementation of design features

As stated beforehand, the pricing mechanism in the auction is pay-as-bid. Each bidder is awarded exactly her bid and adapts her respective bidding function with the new information received in each round. The bid is optimised based on the expected profit, which is already depicted and explained in section 4.3 as equation (4.3):

$$\begin{aligned}\mathbf{E}(\pi_i(\mathbf{b_i})) = \sum_{j=t}^{T} \delta^{j-t} \left(b_i^j - c^j\right) \cdot \sum_{k=0}^{n_s^{t-1}-1} \binom{n^{t-1}-1}{k} F(b_i^j)^k \left(1 - F(b_i^j)\right)^{n^{t-1}-1-k} \\ \cdot \prod_{x=1}^{j-t} \sum_{l=n_S^{t-1}}^{n^{t-1}-1} \binom{n^{t-1}-1}{l} F(b_i^j)^l \left(1 - F(b_i^j)\right)^{n^{t-1}-1-l} .\end{aligned} \tag{6.2}$$

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[6] It is expected that generators would want to recover their costs before they fall out of the subsidy scheme, which makes a 20 year write off a more realistic assumption than a write off over the actual lifetime of the plant.

The expected profit of the agent i given a specific bid vector $\mathbf{b_i}$ is shown in equation (6.2). The bid vector contains all of bidder i's bids b_i^t over all rounds (t to T). The discount factor $\delta \in (0, 1)$ represents the bidders' decreasing preference for being awarded in future rounds, c_i^t are the bidder's costs. This approach is based on Anatolitis and Welisch, 2017.

6.2.5 Setting schedule and volume

From a theoretical perspective, outcomes of an annual and a bi-annual auction scheme (with the same total volume) should be identical. Milgrom and Weber (1982) show that a bid is an increasing function of value. In each subsequent auction the bidder with the highest value among all active bidders wins. Nevertheless, the winner in the present auction has a lower value than the winner in the previous auction. This effect decreases the bids. In subsequent rounds, however bidders also bid more aggressively due their decreasing probability of winning: there are fewer rounds left in which they could still be awarded. In equilibrium, these two effects exactly offset each other. This means that the expected price in the current auction should be equal to the realized price in the previous auction (Trifunovic and Ristic, 2013). However, it has been seen in reality that sequential auctions are likely to differ in their outcome compared to one-shot auctions. According to Maurer and Barroso (2011) there are several benefits to sequential auctions: they allow price discovery in the case of uncertainty and are also more suitable for risk averse bidders. The authors also state, that on the other hand, if the transaction costs of holding several auctions are higher than the actual gains from price discovery, a single auction could be more suitable. Betz et al. (2010) also find that auctioning sequentially has positive impacts on revenues as fiercer competition can be induced.

As RES auctions in recent years have all exhibited a downward trend in bid prices achieved, the theoretical perspective assuming that a higher frequency of auctions leads to a price decrease through learning is adopted here. This learning is technological as well as intra-auction. Intra-auction means that agents adapt their bidding function taking into account previous auction outcomes (see Figure 4.2 and equation (6.2)).

Though sequential auctions may improve learning and decrease costs, there are two important factors to be considered: it might not make sense to split a very small volume into several rounds, especially taking into account that this could exclude larger projects from being awarded if the budget cap is met too quickly. As larger projects are often cheaper, this would potentially deter large bidders from participating, due to their lower award probability. Also, large bidders offering cheap bids could participate but not be awarded, because their bid exceeds the volume by a certain extent. Instead, they would either have to offer a smaller project size (probably increasing their costs as they cannot make use of economies of scale as planned) or pull out altogether. This would lead to either a lower amount of capacity being built or a bid to be offered to the next best (i.e. more expensive) bidder, increasing overall support levels. This depends on how the auction design is laid out for this kind of situation (see section 6.3). It has to be kept in mind, however, that the volume should also not be too large, as this would decrease competition and could potentially lead to undesirably high bid prices.

Second, as the Danish market is relatively small, competition levels could be too low to execute several rounds. For a pilot with a limited amount of rounds (two or four) and in an overseeable time period of two years, one could also assume perfect foresight of the participants – i.e. it would not make a difference in their estimation of expected revenues if the budget is split over several rounds or auctioned all at once. In the long run, however, looking into future auctioning of RES support in 2020 and beyond, decisions on frequency and volume become more important.

The budget size as well as how the budget is split, i.e. whether there are a few auctions with a large budget or several auctions of a smaller size, can impact the outcome. The more ambitious RES expansion goal for Denmark would foresee tendering 200 MW annually beginning in 2018. The current policy however foresees lower targets, of on average only 100 MW to be auctioned. As this volume is too low to be varied and split further, however, the scenario comparison modelled will assume the more ambitious expansion goal: a comparison of a 200 MW annual and a 100 MW bi-annual auction. Scenarios for a auction rounds up to 2025 are shown (8 annual rounds compared to 16 bi-annual rounds), to model long-term effects on bidder behaviour and realisation rates. The fixed budget, as foreseen in the current scheme is assumed to be continually implemented until 2025 for these auctions. A sensitivity with a flexible budget is then also performed in the following.

6.3 Budget flexibility

The auction rounds planned for 2018-2019 are analysed further, modelling two different approaches concerning volume or budget flexibility.[7] It is particularly interesting to see, if an increased budget flexibility over the auction rounds will be able to decrease the default of a certain amount of projects. For the simulation, the

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[7] In the following, for simplification purposes, it is only referred to budget flexibility. This flexibility refers, as mentioned earlier, to the auction scheme allowing for a budget increase up to 50 % in one round, decreasing the budget by the excess amount in the subsequent auction to balance out the overall support costs (see figure 6.1). For the modelling, however, the budget auctioned in each round was translated into a certain volume, so bidders can better estimate their award probability. The modelling results therefore always result in a certain capacity in MW.

volume auctioned in each round is fixed, as beforehand. The marginal bidder, i.e. the one whose bid exceeds the planned volume (translated from the budget, using ENS cost and technology data) in each round is offered to a) construct a smaller version of her project to be inside the bounds of the auctioned volume or to b) not receive an award, i.e. not build at all. Depending on the size of the marginal bidder's project and the point where the volume cap is reached, this could lead to a substantial decrease in project size, making the construction of the project unprofitable or unattractive for the project developer. Figure 6.1 visualizes how these two schemes compare:

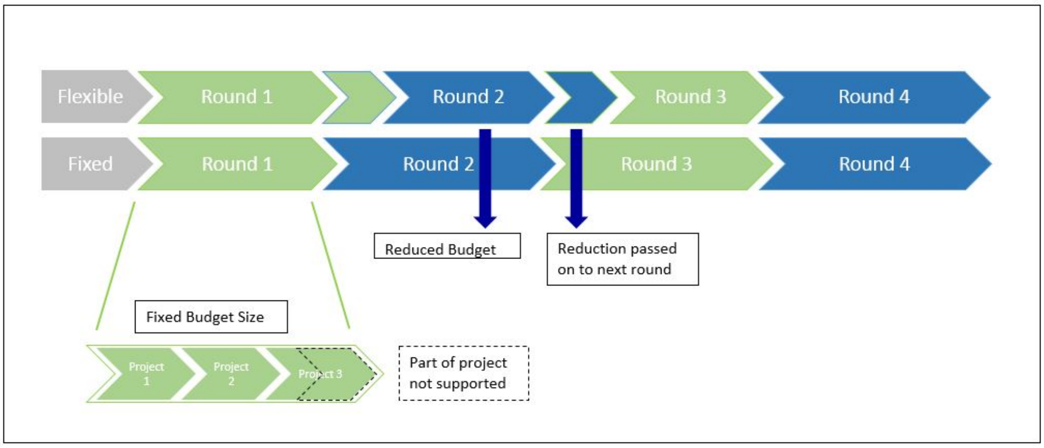

Fig. 6.1: Comparison of flexible and fixed budget options

Specifically, in the lower part of Figure 6.1 one can see a fixed budget which is either awarded completely or cut off at the marginal bidder, depending on whether the marginal project is constructed (partly) or not. Above, one can see the flexible budget mechanism, where budget can be exceeded and thus changes the budget auctioned in future rounds.

Jeitschko (1999) argues that an uncertain supply can decrease prices in a classic multi-unit auction. This could implicate for the Danish case, a procurement auction, that the uncertainty about the budget to be auctioned could yield bidders to submit higher bids. However, the insecurity in this case could also go the other way, depending on bidders' expectations: a marginal large-scale bidder in the first auction round could lead to a budget decrease of up to 50% in the second round. This in turn, could increase competition and induce more aggressive bidding in the first round.

An argument in favour of the flexible budget can be found in Held et al. (2014): the authors argue that flexibility can increase cost control. A further argument in favour of implementing a certain amount of budget flexibility is inherent to the nature of the Danish market and auction design. Firstly, the market is relatively small and the to-be auctioned budget is limited. Secondly, however, project sizes are the same as in other European countries (e.g. Germany), meaning that they can size-wise easily amount to half the auctioned volume. This leads to problems when the marginal bidder exceeds the budget by a large share of her project. With an inflexible budget, this would yield the bidder either having to realise a project with a reduced size, see Figure 6.1, which could lead to problems concerning the viability (economies of scale). If the bidder does not construct the project, this means she will have to participate again in a future round or, depending on the timing, might even lose her permit, even though the project would have been economically competitive in the auction round she was awarded in.

The model to further investigate this is set up as follows. A fixed mechanism is modelled, where the marginal project rejects their bid as soon as a reduction of one third or more of the project size would be necessary – assuming, due to simplification purposes and the aforementioned reasons, the marginal bidder will not be viable with reduction of this size. This also holds for multiple project bidders - for these bidders, all projects are counted as one and if more than one third of the total amount of the project volume is cut off due to the budget cap, it is assumed that all projects are pulls out.

Then, a second mechanism is simulated, where the marginal project is awarded in full, as long as it does not exceed 150% of the originally planned budget. If the budget is exceeded, this leads to the following rounds' budget being decreased by exactly that amount. Both cases are simulated for the auctions planned in 2018-2019. Outcomes in terms of constructed capacities and average awarded bid prices are then compared for both schemes.

6.4 Results and discussion of modelling case 2

6.4.1 Setting schedule and volume

As a starting point, the auctions planned for 2018 and 2019 were assessed. Specifically, a comparison of changing the auction volume from 100 to 200 MW per year was made. This gives insights into how the auction outcome varies in terms of deployment, prices and agent distribution. In Table 6.1 below, one can see the differences in auction outcomes between a more and a less ambitious deployment target. Auctioning 100 MW annually in 2018 and 2019, the bid price is on average 1.13 €ct/kWh in the first round and 1.1 €ct/kWh in the second. A slight decrease can thus be observed. In the two auction rounds, there is also a certain extent of non-realisation to be expected. This will be described in more detail in the following. All of the awarded bidders are onshore-wind bidders, as they are more cost-competitive.

Tab. 6.1: Impacts of varying the auction volume in the Danish auction scheme

100 MW Auction volume

Auction year	Mean awarded bid [€ct/kWh]	Wind bidders total	Wind bidders multi-project	PV bidders	Average Profit [€ct/kWh]
2018	1.13	2.67	0.93	0	0.08
2019	1.1	2.74	0.72	0	0.09

200 MW Auction volume

Auction year	Mean awarded bid [€ct/kWh]	Wind bidders total	Wind bidders multi-project	PV bidders	Average Profit [€ct/kWh]
2018	1.16	4.77	1.78	0	0.08
2019	1.15	4.72	1.29	0	0.12

In the two rounds of 200 MW, the bid price stays roughly the same, i.e. drops from 1.16 €ct/kWh to 1.15 €ct/kWh. The higher average bid price is due to the fact that more projects are awarded on average and thus not only the very cheapest receive support for their projects. The bid price is marginally higher than the one in the case of auctioning only half the capacity. Non-realisation due to cut-off is not as severe as in the previous case. One main take-away from this simulation is that a joint technology auction with onshore wind and solar PV will yield only wind onshore bidders to be awarded. Furthermore, it can be seen that increasing the volume leads to merely slightly higher average awarded bid prices in the short run. Therefore, competition seems to be sufficient to auction larger amounts of capacity.

The impact of varying auction frequency, i.e. auctioning the same volume in one round or spreading it over several rounds, is shown in for the long-term. Annual and bi-annual auction rounds of 200 or 100 MW per round were simulated for the time period up to 2025. The more ambitious volume target of 200 MW/year was chosen, as splitting 100 MW into several rounds is not a feasible solution, given the substantial amount of large-scale bidders in the Danish market. The analysis yields the following results: the two main criteria for comparison, costs (bid prices per auction round and as well as overall support costs) and deployment, i.e. the initial realisation rate develop quite differently.

As seen in Figure 6.2, the bi-annual scheme performs better in terms of bid prices, whereas the annual scheme is able to ensure a much higher realisation rate. Agent distribution is not depicted here specifically, as due to the large price differences and the relatively low auction volumes, only onshore wind bidders were awarded in the multi-technology auction scheme. Specifically, bid prices decrease from 1.16 to 0.91 €ct/kWh between 2018 and 2025 in the bi-annual case. They are constantly

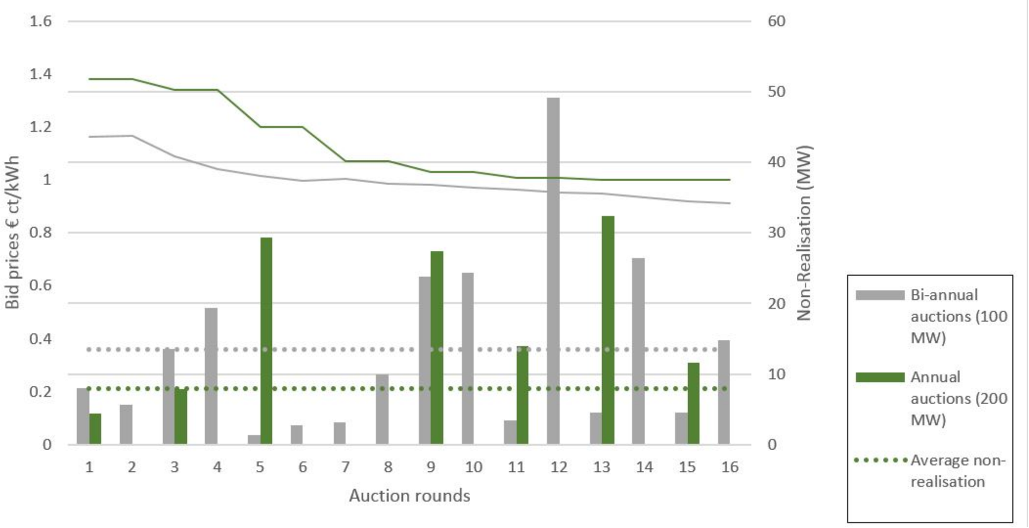

Fig. 6.2: Comparison of prices and non-realisation in annual and bi-annual DK auction schemes (from 2018 to 2025)

below the values of the annual case which exhibits a price decrease from 1.38 to 1.0 €ct/kWh. Average prices over all auctions are thus 0.12 €ct/kWh lower in the bi-annual compared to the annual case, translating roughly into 78,000 €less overall support costs per MW over the support period of 20 years.

Average non-realisation in the form of rejected marginal projects is however almost double the amount in the bi-annual case. We can observe an average of 7.94 % in the annual case compared to 13.45 % in the bi-annual auction rounds. In terms of capacity, this translates to a total deficit of 127 MW in the annual compared to 215 MW in the bi-annual auction case - i.e. 88 MW more capacity would be achieved with the annual auctions.[8]

Discussing these findings, one needs to account for goals of the auctioning entity. The current strategy is set on least cost. At the same time, ambitious targets for renewables deployment and climate protection are envisaged. An option to achieve a good trade-off between those two goals, could be implementing budget flexibility over the respective auction rounds and is shown in the following.

6.4.2 The impacts of budget flexibility

Under the assumption of multi-project bidders being the most cost competitive due to economies of scale, most awarded projects are provided by this type of bidder. This means that relatively few bidders with relatively large projects are awarded.

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[8] This number is assuming, as stated earlier, that there is no offer to the second-best bidder after the rejection by the marginal bidder.

These are exclusively wind onshore projects, due to their lower cost distribution. It can be seen that due to the large projects, the budget is often surpassed by a substantial amount. This leads to different simulation outcomes depending on the flexibility set screw in place, as seen in Table 6.2.

Tab. 6.2: Impacts of budget flexibility in the Danish auction scheme

Non-flexible budget

Auction round	Volume auctioned [MW]	Volume awarded [MW]	Mean awarded bid [€ct/kWh]	No. Wind bidders	No. PV bidders	Average Profit [€ct/kWh]
2018 [1/2]	100	92	1.14	2.82	0	0.09
2018 [2/2]	100	94.4	1.12	3.03	0	0.12
2019 [1/2]	100	86.4	1.06	2.94	0	0.05
2019 [2/2]	100	80.6	1.02	3.16	0	0.03

Flexible budget

Auction round	Volume auctioned [MW]	Volume awarded [MW]	Mean awarded bid [€ct/kWh]	No. Wind bidders	No. PV bidders	Average Profit [€ct/kWh]
2018 [1/2]	100	115.3	1.13	2.83	0	0.09
2018 [2/2]	84.28	104.43	1.12	2.41	0	0.11
2019 [1/2]	79.85	100.71	1.05	2.5	0	0.05
2019 [2/2]	82.14	79.14	1.02	3.01	0	0.03

The modelling was performed for the planned auctions in 2018 to 2019, assuming an ambitious target of 200 MW split into four auction rounds, to see the mechanism's impact over time. In a non-flexible case, less than the demanded 100 MW is actually awarded on average per round, as it is assumed that bidders do not build their project if more than one third will not receive a subsidy due to the budgetary cap being reached, and then withdraw altogether. This leads to lower support costs overall, due to the fact that less projects are awarded in total. As shown beforehand, the capacity falls short by 13.45 % on average. Depending on the goals pursued by the auctioning entity, the strict budget serves to lower the costs, however at the expense of not reaching the capacity goals.

When allowing the flexible budget option, it was put to use in all modelled rounds, as seen in Table 6.2. This means, that the original budget (here shown as expected volume in MW) was surpassed in the first round and in the following rounds, the adapted budget was (at least slightly) surpassed again. This leads to a slightly reduced demand in each round following the first one. Bid prices are nevertheless not affected by the flexibility mechanism - i.e. achieving the envisaged capacity can be ensured without increasing the level of bid prices by introducing a flexible budget. This comparison shows, that a flexibility mechanism can help achieve capacity targets in situations where small volumes are auctioned and large scale bidders participate in the auctioning, that are likely to exceed the volume in one round.

6.5 Conclusions of modelling case 2

The agent-based modelling of variations of the Danish auction scheme and the complementary financial assessments, show that the Danish RES market provides sufficient competition to auction higher volumes and follow more ambitious expansion goals with renewables auctions (i.e. 200 as compared to 100 MW): increasing the volume yields only slightly higher bid prices. Generalizing this result shows, that more ambitious expansion goals can also achieved through auctioning in smaller Member States and that auctioning too little volume in one round can furthermore deter large-scale bidders and lead to problems with realisation of marginal projects, especially when a fixed budget is in place. Moreover it was shown that at current cost levels, only onshore bidders would be awarded in the envisaged multi-technology scheme. Also, large-scale and multi-project bidders are likely to be the most cost competitive - indicating that further measures to maintain diversity could be useful.

A flexibility mechanism that allows the auction budget to be increased by up to 50 %, to accommodate potential (large-scale) marginal bidders, proves to be a useful tool to increase deployment rates, without negatively affecting bid prices. This holds for the Danish case but could also be a useful option to be applied in other countries with similar preconditions. With the help of this flexibility mechanism, an increased frequency of auctions with a lower volume each, could also be executed. It has to be taken into account, however, that more planning security in terms of capacity will be achieved with fewer auctions of a larger size. Furthermore, a larger variety of bidders can be awarded that way. The desired outcome thus depends on the envisaged policy goals of the auctioning entity.

Summarizing, the auction design in small markets should account carefully for the volume auctioned in each round and should ideally be flexible in allowing for the marginal bidder to exceed the auctioned volume. Furthermore, low auction volumes could lead to a concentration of onshore wind and large-scale bidders. There is thus a trade-off in achieving the lowest-cost option and in maintaining actor diversity and achieving the capacity expansion goals envisaged.

7

Modelling case 3: Uncovering bidder behaviour in the German PV auction pilot

This modelling case enables a deeper understanding of the ground-mounted solar PV auctions in Germany. It is based on the paper "**Uncovering bidder behaviour in the German PV auction pilot - Insights from data analysis, game theory and agent-based modelling**" which I wrote in collaboration with my co-author Jan Kreiss. It is currently under review at The Energy Journal and has been submitted in September 2017. The German PV pilot took place in six rounds in 2015 and 2016, testing both pay-as-bid (PAB) and uniform pricing schemes. Granted the opportunity to make use of detailed data on the pilot provided by the German Federal Ministry of Economic Affairs and Energy (BMWi), empirical outcomes of these auctions were statistically analysed. The findings from this analysis have been used as input parameters for the agent-based model. The model is further endorsed and contrasted by game theory. Practical experience thus improves the model and in turn learn modelling results can show how varying design parameters changes auction results. This two-sided learning offers new insights regarding the bidder behaviour in auctions for renewable energy support.

The findings are especially relevant in the eye of a current legislatory change: the Bundesländerklausel/Freiflächen-Öffnungsverordnung. This new law allows the German federal states (Bundesländer) to come up with their own restrictions or open their disadvantaged arable land for tendering of ground-mounted solar PV. Bavaria and Baden-Württemberg have already made use of this law and opened up tendering on arable land for up to 30 projects for the next auction in 2017 (Bavaria) and up to 100 MW annually (Baden-Württemberg). For more details see the legal publications by the federal states of Bavaria (Bayerische Staatsregierung, 2017) and Baden-Württemberg (Land Baden-Württemberg, 2017). This change in legislation will likely lead to an opening of these formerly restricted areas for upcoming auctions. It is shown through modelling how this will influence future auction outcomes.

The structure of this modelling case is as follows: first, a game-theoretic background of the underlying agent behaviour is given. Then the agent-based model is described, which incorporates the implications of the theoretical analysis and simulates the auction pilot with the given parameters on design and my knowledge on agent distribution in the German electricity market as well as on the price development of PV modules and generation of electricity from large-scale solar PV. Empirical auction outcomes are used to improve the modelling, however without pre-empting model results. They instead allow for an optimal depiction of the distribution of participants in terms of e.g. costs and project sizes in the German large-scale PV sector.

In the results section, the bid prices and bidder distribution are described and evaluate how bidding evolved over the respective rounds. Specifically the price development as compared to the actual prices is shown as well as the distribution of bids over the three rounds concerned and special insights into the behaviour of those bidders who submit bids for the restricted arable land areas.

7.1 Auction-theoretical foundations of modelling case 3

From an auction-theoretic viewpoint, the system that determines the support payments for ground-mounted photovoltaic plants in Germany beginning in 2015, consists of repeated, static multi-unit auctions. This section adds auction theoretic details to section 3 to enable a better understanding of this particular modelling case. Therefore, first of all, the individual elements of the auction well be explained and then brought together.

The multi-unit characteristic is common to most auctions for renewable energy support. That is, more than one project is awarded to supply the auction demand. In the analysed case of large-scale ground-mounted solar PV auctions in Germany, the auction volume in the first round was 150 MW of installed capacity, the maximum bid volume was 10 MW and thus at least 15 projects had to be awarded to supply the complete demand. As there were also smaller bid volumes, in total 25 projects were awarded in the first auction. The demand of installed capacity is considered homogeneous as there is no further differentiation and thus from a auctioneer's perspective the total demand is identical.

Vickrey, 1961 was the first to study multi-unit auctions and the different pricing rules that correspond to first- and second-price auctions in the case of single-unit demand. However, with multi-unit demand more diverse pricing rules are possible for static auctions with identical goods. The two most well-known options are the so called PAB or discriminatory auction and the uniform pricing auction. The latter one can be further distinguished regarding which bidder sets the uniform price all awarded bidders receive, either the highest accepted or the lowest rejected bidder. One problem of those pricing rules is, that they are potentially inefficient in the case where bidders can supply multiple units (Ausubel et al., 2014). That is, a bidder with the potential to supply more than one unit of the good has an incentive to over-exaggerate the bid for the second best and the following goods or even to reduce supply. This strategy enables them to increase the profit for the first or better bids and thus maximise profit.

Apart from this, both PAB and uniform pricing auctions have the same expected revenue given only bidders with single unit supply participate (Engelbrecht-Wiggans, 1988). This result is in line with the revenue equivalence theorem of single unit auctions (Riley and Samuelson, 1981). In contrast to the often heard belief that the outcomes of both auction formats, PAB and uniform pricing, can be quite different and thus yield different support costs, in theory the expected result is identical. Nevertheless, the bidding behaviour is quite divergent for the different pricing rules (Weber, 1983). Essentially, a uniform pricing auction where the lowest rejected bid determines the uniform price is incentive compatible: it is the optimal strategy for a participating bidder to bid her true costs independent of the bidding strategy of every other bidder. The bidder cannot improve her expected profit by deviating from this strategy. Therefore, the uniform pricing auction is considered the multi-unit equivalent of the second-price auction. However, incentive compatibility is not given if the highest accepted bid determines the price. Then, there is a positive probability for each bidder that her bid determines the price she receives and thus each bidder has an incentive to exaggerate her costs. In case of a PAB pricing rule this is true for every bidder. In case of winning, her bid always determines the price she receives. Hence, the PAB auction is considered the multi-unit equivalent of the first-price auction.

In the context of auctions for renewable energy support, the conditions deviate from this simplified theoretical basis. Firstly, as already discussed, the bidders might have multi-unit supply. Secondly, this is not a one-shot auction, but a repeated auction with several rounds each year over a multi-annual time frame. Even a bidder with only a single project has the possibility to participate in several auction rounds. Therefore, the strategic considerations from the one-shot auction have to be adapted (Milgrom and Weber, 2000). For the sequential PAB auction the adaptation is rather straightforward. In a one-shot auction the bidder has to consider the possibility to be awarded and the profit in case of award. In a sequential auction, the bidder considers the additional positive expected profit from being awarded in a future round. Thus, the more auction rounds remain, the more the bidder exaggerates her costs. If the bidder has not been awarded before the last round, she then applies the same bidding strategy as in the one-shot auction.

It is less intuitive to understand why there is also a deviation in the bidding strategy for uniform pricing if there is a sequential (repeated) auction. If a bidder submits a bid that is higher than her costs, the award price may be above her costs and she could still not be awarded. However, if all bidders would bid their costs, the award price would rise in every auction round as the lowest cost bidders are always awarded and thus do not participate in the forthcoming rounds. Thus, a bidder would prefer an award in a later round as this would yield more profit. To compensate for this effect, bidders exaggerate their costs and submit higher bids the more auction rounds are left. In the last round they behave like in a one-shot auction and bid their costs. As a result, the expected costs of a repeated uniform pricing auction are the same in each round and also the same as in a repeated PAB auction.

The additional difficulty of auctions for renewable energy support is that the set of participating bidders changes over time and the number of rounds each bidder can participate in may be different. Furthermore, the bidders could differ in other ways. For example their cost structure could be substantially different and it could also be possible to distinguish the bidders regarding the available information. Auction-theoretically such bidders are considered asymmetric (Maskin and Riley, 2000). The implication on the auction outcome and the bidding behaviour are manifold, depending on the context and the characteristics of the asymmetry. However, in most cases it is hard to calculate the bidding strategies and in some cases there might even be several bidding equilibria. A simple example will illustrate the concept of asymmetric bidders. Consider a case with only two bidders where the one with the lowest bid is awarded. The costs of bidder 1 are from a uniform distribution on $[5, 7]$ and the costs of bidder 2 are uniformly distributed on $[5, 9]$. Then those bidders are considered asymmetric as the respective cost distributions are unequal. As a further assumption, bidder 1 is considered a strong bidder and thus bidder 2 as a weak bidder. This is due to the fact that bidder 1 has a higher probability to have lower costs than bidder 2. If both bidders know the respective cost distribution, they also have asymmetric bidding strategies. The bidding strategy of bidder 2 is more aggressive (i.e. she exaggerates less) than the one of bidder 1 and also more aggressive than the strategy if she assumed bidder 1 to have the same cost distribution. For bidder 1 this holds vice versa. So a strong bidder will bid less aggressively if she knows that she is strong.

It becomes even more complex if one considers that the costs for a renewable energy source are not a purely independent private value.[1] In fact, many cost components for renewable energy sources are the same for most or all participants. The wind turbines and PV modules are major cost components and, except for large customer framework contracts, those costs are the same for all participants: they

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[1] If the costs of a bidder are independent of the costs of the other bidders but from the same distribution and are private information of the bidder then they are referred to as independent private values.

are referred to as common values (Wilson, 1969). Thus, the overall project costs of the bidders are interdependent, which consequently complicates the derivation of an auction-theoretic solution. Not only from a theoretical point of view, but also from the bidders' perspective, common values complicate the auction. Bidders may underestimate their costs or be too optimistic so that the award price is lower than the project costs which results in non-realisation (Kreiss et al., 2017a).

In addition to interdependent values, auctions for renewable energy support may also have other special characteristics as bids may be non-binding (Belica et al., 2017) or because certain bidder groups are discriminated in the auction (Kreiss et al., 2017b). As a result, auction theory reaches it limits when it comes to optimal bidding strategies and expected outcomes in such complex environments and if more than a qualitative analysis is required. For this reason, the theoretical analysis is complemented with an agent-based modelling approach to provide more quantitative insights on the results of the first auction rounds for PV installations in Germany.

7.2 Agent-based model for the German PV pilot

This chapter documents how the agent-based model was calibrated to assess the German ground-mounted PV auctions - its set-up and input parameters. The German PV pilot consisted of six rounds, three in 2015 and 2016 respectively. In each round quantities between 125 and 200 MW were auctioned, using PAB or uniform pricing. The ceiling price started at 11.29 ct/kWh then decreased to 11.19 and then 11.09 €ct/kWh [2] for the remaining four rounds (Bundestag, 2017). The model builds on work by Anatolitis and Welisch (2017) and makes use of the agent-based modelling infrastructure mesa which is Python-based.

7.2.1 System

In Germany, RES auctions are executed as follows: Participants submit their (sealed) bid in each round. Specifically, the bid contains a price in ct/kWh and a corresponding capacity in kW of their individual projects. The auctioneer sorts the bids in ascending order. If two agents bid an equal price, the one with the lower capacity is awarded. The location of the project is also submitted (Bundestag, 2017, § 30), such that the auctioneer is immediately able to differentiate between disadvantaged arable land which is per definition not suitable for farming in its current state (in the following just referred to as arable land for simplification purposes) and other areas, namely the area adjacent to a highway or railway or a converted area which was previously used for military, business purposes, infrastructure or housing (named

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[2] €ct are in the future only referred to as ct for simplification purposes.

converted areas in the following). The difference between these two areas is a crucial feature of the German PV auction scheme, as the former is restricted due to reservations by the German farmer's association (Bauernverband), see e.g. AgE/agrarheute (2015).

The described procedure holds for PAB and uniform pricing. Bids are chosen while the cumulative amount of capacity is lower than the demand. Immediately after the procured quantity is reached or surpassed for the first time, the auction round is closed. This procedure is implemented into the model in all its specifications (Anatolitis and Welisch, 2017).

In the German ground-mounted solar PV auctions, the auctioneer is the German federal network agency (Bundesnetzagentur). The auctioneer publishes the successful capacity amounts in detail. The lowest and highest accepted bids together with the weighted average winning bid are also made public. The actual bid prices remain private information of the auctioneer. In the simulation, the participants learn the weighted average overall bid (Anatolitis and Welisch, 2017). For the pilot rounds, three in 2015 and 2016 respectively, the ceiling prices for each auction round have been administratively set at 11.29, 11.18 (twice) and 11.09 ct/kWh (last three rounds). This has been implemented in the model, as have the auctioned quantities of 150 (twice), 200, 125 (twice) and 150 MW respectively.[3]

To average over stochastic elements of the simulation (Hailu et al., 2011), the mean of a minimum of 100 simulation rounds is used for each final result in the following modelling cases.

7.2.2 Agents

Agents are assumed to behave rationally. This means their bid is based on their costs and they try to maximise their expected profit over time. An agent is further characterized by her attributes, namely the size of her PV project, and her bidding behaviour – the bid function and the implemented learning algorithm (Anatolitis and Welisch, 2017). We assume three different types of bidders that participate in the auctions: a strong and a weak type for the converted areas - which are the most commonly auctioned areas in Germany, where the strong type draws from a lower cost distribution than the weak type. The different cost distributions assigned to the bidder types have been derived from statistical analysis of the actual bids submitted in the German ground-mounted PV pilot auction and are thus evidence-based.

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[3] In the last round, actually 160 MW have been auctioned, which is due to the fact that in earlier rounds around 10 MW had been returned (Bundesnetzagentur, 2016). As in the model, agents do not have the possibility to return bids. The auctioned quantity is left at the originally planned 150 MW to achieve the planned total amount of 400 MW for the year of 2016.

Moreover a third category is assumed, bidders bidding for arable land - these are the strongest types in terms of costs, however, due to legal restrictions (Bundestag, 2017) only 10 of these areas are allowed to be awarded in 2016. Therefore, their participation is restricted in the model to the same extent.

In the first round, a certain amount of participants is predetermined. For this, the actual auction outcome is used and about 180 bidders participate. Thanks to access to the detailed German PV auction pilot data, it was possible to implement very concise and realistic assumptions into the model concerning the agent's behaviour and cost distribution. First of all, as the number of bidders decreases over time, a drop-out of participants is assumed. This drop-out is determined endogenously by restricting further participation to only those bidders, who bid a maximum of 15% above the awarded bid. This is thought to be rational behaviour concerning the decreasing award probability over rounds. If a bidder was awarded, she is assigned a 50% probability of participating in the next round. This is also a realistic assumption examining the data on repeated participation.

Concerning new entry of bidders, the auction results were also assessed, finding that the number of entering participants decreases over time. Therefore new entry was modelled to be endogenously dependent on the previous auction outcome. Specifically, it was assumed that more strong than weak bidders enter in each round, as they have a higher estimate of their chances of winning. The number of new entrants is thus made endogenously dependent on the previous amount of bidders, and assume, also drawing on insights from empirical data, that 10% weak and 20% strong bidders enter in each round. Also, one can argue that more strong than weak bidders enter, as weak bidders are more easily deterred by decreasing prices over time. New bidders for arable land only enter to that extent as there are still projects available, i.e. if not all 10 were awarded in the first round of 2016.

Agents' costs also drawn on the empirical auction data.[4] It is assumed that all agents draw from a uniform distribution, which differs for the respective agent types. This cost distribution adapts dynamically to the previous strike price for newly entering participants. Furthermore, there is external cost degression which affects both new and previous participants equally. Specifically, this cost degression is piecewise and builds upon module price data and observed bidding behaviour for the two years. An overall decrease of 2% per round in 2015 and 3% per round in 2016 is assumed.[5]

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[4] Specifically, the distribution of bids from the first auction rounds was statistically evaluated and bidders were assigned a distribution. The development of these costs however draws on module price developments in the two years, in order to not merely replicate the empirical findings but to rather show the extent of price development possible due to technical developments.

[5] The module price translates into about 50% cost decrease, and as a steeper decline in 2016 was observed (PVXChange, 2017), this change between the years was implemented.

For project sizes, it is also referred to the empirical data and a random draw between 1 and 10 MW capacity for the converted area bidders as well as for the arable land bidders is implemented, as there is no empirical evidence to model a difference between those types when it comes to size.

Tab. 7.1: Agent distribution in the German PV auction model

Agent type	**Converted areas (weak type)**	**Converted areas (strong type)**	**Arable land**
Number of bidders in first round	75	75	0
New draw of bidders per round	20%	10%	varied
Range of capacity bid [MW]	1-10 MW		
Cost distribution [ct/kWh]	7.5-8	8-10	6-8.5
Type of distribution	Uniform distribution		
Cost degression	2% per round in 2015, 3% per round in 2016		
Time span	t = 0,1...5 (equals 6 rounds)		

7.3 Model documentation for modelling case 3

The model is run with the following parameters. For each agent type $a_{\text{converted,w}}$, $a_{\text{converted,s}}$ and a_{arable} the number of bidders (per type) for the first round is predefined as follows: $|a_{\text{converted,w}}| = 75$, $|a_{\text{converted,s}}| = 75$ and $|a_{\text{arable}}| = 0$.

Then the demand d^t for each round $t \in \text{range}(T)$ in MW and the auction's price limit p^t_{lim} in ct/kWh are implemented. Furthermore, the auction rounds in which each agent can participate are limited. In this particular case, the reason for the limitation is not the expiration of a permission but the general limitation of the auction pilot range(T). Each agent takes these input factors into consideration in order to optimise her bidding strategy over the given time period.

The bidder initialisation process is as follows. For each type of agent, the bidders are drawn and each bidder i is randomly assigned her initial costs c_i^0 from the respective cost distribution from this type of agent in ct/kWh and a project size q_i in MW. Each agent i is therefore characterised as

$$a_i = (c_i^0, q_i) \tag{7.1}$$

After the bid submission, the bids are sorted in ascending order where $b_{(1)}$ corresponds to the lowest bid and the bidders are awarded until supply equals demand: $d^t = s^t$ where $s^t = (q_{(1)} + q_{(2)} + ... + q_{(n_s^t)})$. For the arable land bidders (a_{arable}), in

2016 there is a limit of 10 awarded projects per year. The strike price is determined depending on the applied pricing rule. Before a new round takes place, a certain amount of new bidders in each category is drawn.

Degression takes place in every round. First of all, bidders whose bid was more than 15% above the highest awarded bid (strike price) do not participate in the next round. All other bidders have a 50 % chance to either participate in the following round or the round after that. They participate with a new bid b_i^{t+1} considering their new cost c_i^{t+1} which were multiplied by the degression factor λ^t: $c_i^{t+1} = \lambda^t \cdot c_i^t$.

7.3.1 Uniform pricing

In the case of a uniform pricing auction, the agents simultaneously submit their sealed bids (b_i^t, q_i). Bids are rejected if they are above the ceiling price $(b_i^t > p_{lim}^t)$ or lower than zero $(b_i^t < 0)$. The uniform remuneration in the model is determined by the lowest rejected bid $b_{n_s^t+1}^t$. As already mentioned in Section 7.1, in a one-shot auction with this pricing rule it would be a (weakly) dominant strategy for each bidder to bid her own costs. If the uniform pricing auction is repeated the strategic considerations change and bidders exaggerate their costs.

However, this only holds if the exact same auction is repeated. This does not hold for the considered case of the German PV auctions as there are many parameters that change. Firstly, the auction volume is not constant and also other parameters like the ceiling price change. Second and more importantly, the set of participants varies. Some of the agents are awarded and do not participate in the next round, while others continue participating. The same holds for non-awarded bidders. Furthermore, there are new bidders entering in each round. In such a complex environment, it is hard to determine a bidding strategy for a uniform pricing auction where the bidder has no direct influence on her award price (Lykouris et al., 2015). Due to these uncertainties, the bidders are assumed to apply the symmetric bidding strategy

$$\beta(c_i^t) = c_i^t \tag{7.2}$$

which corresponds to the bidding strategy in the one-shot uniform pricing auction. This provides a benchmark case to compare both, the actual results and the results from the simulation using the PAB rule.

7.3.2 Pay-as-bid (PAB) pricing

The bidding process is the same under the PAB pricing mechanism as in a uniform pricing auction. However, the main difference is the price determination. In a PAB auction every awarded bidder receives her bid. Therefore, when a bidder wants to maximise her expected profit $E[\pi(\cdot)]$ she has to weigh the possibility of winning in this round with the profit in case of winning and also the possibility to be awarded in an upcoming auction round. The possibility to be awarded increases with a lower bid but then the profit in case of winning decreases. The expected profit for rounds t=0,1,2,...,T for a representative bidder i is derived by equation (4.2) in chapter 4: the bid vector $\mathbf{b_i}$ contains all bids b_i^t of bidder i from the current round t to the last round T. Furthermore, the discount factor $\delta \in (0, 1)$ represents the bidders' preference that the same profit is less favourable in a future round than in the current round. In combination with the bidders costs c_i^t in the specific round, the profit in case of winning can be calculated. As a bidder can (by assumption) only participate with one project in any given round, the bidder can only participate in a future round with the same project if it has not been awarded previously. Hence, for all rounds $t < T$, not being awarded in this round still leads to a positive expected profit as there is a positive probability of being awarded in a future round.

In (4.3), the probabilities to be awarded in a specific round and to be not awarded in all previous rounds are not elaborated. (7.3) sheds light on this issue and shows where learning comes into play. The bidders are assumed to have a rough estimation regarding their competitors in the first auction round and based on the results of the auctions, they adapt their beliefs. Therefore, a cumulative distribution function (CDF) is introduced. This function $F(\cdot)$ captures an agent's belief on the bid distribution of the other participants. This belief contains both the expected number of competitors and their strength.

The bidders model the CDF as a normal distribution where they adapt the distribution through adjustment of the mean μ to the results of the previous rounds. In the first round, the agents base μ on their own signal and in the forthcoming rounds, they use the newly generated information to adapt μ to the overall mean bid of the previous auction round. Furthermore, the number of participants in the last round n^{t-1} and the number of awarded bidders n_s^{t-1} is considered for the forthcoming rounds (also accounting for the varying auction volume). Given these assumptions, from an agent's perspective, the probability $F(b_i^t)$ equals the probability that b_i^t is higher than the bid of one other bidder from the CDF $F(\cdot)$ and respectively $1 - F(b_i)$ depicts the bidder's probability of her own bid being lower than her opponent's.

Applying the concept of order statistics, the agents can calculate the expected probability of having a lower bid than a predefined fraction of other bidders. More precisely, based on the agents assumption on the strength of their competitors, the number of competitors and the number of successful bidders, the agent can calculate the probability of being awarded given a specific bid.[6] In the first round, they make an initial assumption on competition: $comp$ and on the number of successful bidders: $succ$.

Based on the approach in Ahsanullah et al., 2013 and Anatolitis and Welisch, 2017, the expected profit of the agent i given a specific bid vector $\mathbf{b_i}$ can be calculated as seen previously in chapter 6:

$$\begin{aligned}\mathbf{E}(\pi_i(\mathbf{b_i})) = \sum_{j=t}^{T} \delta^{j-t} \left(b_i^j - c^j\right) \cdot \sum_{k=0}^{n_s^{t-1}-1} \binom{n^{t-1}-1}{k} F(b_i^j)^k \left(1 - F(b_i^j)\right)^{n^{t-1}-1-k} \\ \cdot \prod_{x=1}^{j-t} \sum_{l=n_S^{t-1}}^{n^{t-1}-1} \binom{n^{t-1}-1}{l} F(b_i^j)^l \left(1 - F(b_i^j)\right)^{n^{t-1}-1-l} .\end{aligned} \tag{7.3}$$

The bidders maximise the expected profit given in (7.3) by optimising their bid vector $\mathbf{b_i}$. After every auction round, the bidders adjust this bid vector given the additional information from this last round. It should be noted that this approach is based on auction-theoretic bidding functions, but does not consider the other bidders' behaviour, i.e. their best response. Therefore, this approach has to be considered as a decision-theoretic optimization.

The bidding process, selection of winning bids and drawing of new bidders in the respective rounds is the same as in the uniform pricing scheme.

7.3.3 Results and discussion of modelling case 3

In this section, findings from modelling the German ground-mounted PV pilot in the uniform pricing benchmark case and as a PAB auction are presented. To provide adequate insights into the different bidding strategies of arable land bidders, a distinct auction for 2016 was simulated, taking into account their limits concerning the time horizon and the average capacity available for the allowance of 10 projects (55 MW). For competition, all arable land competitors as well as the lower cost

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[6] Moreover, as it is a multi-unit auction, the agents have to consider that not only the lowest bid is awarded but that there are different possibilities depending on which position in the order of the bids the agent will be.

converted area bidders are considered, i.e. all direct competition in the low price range.

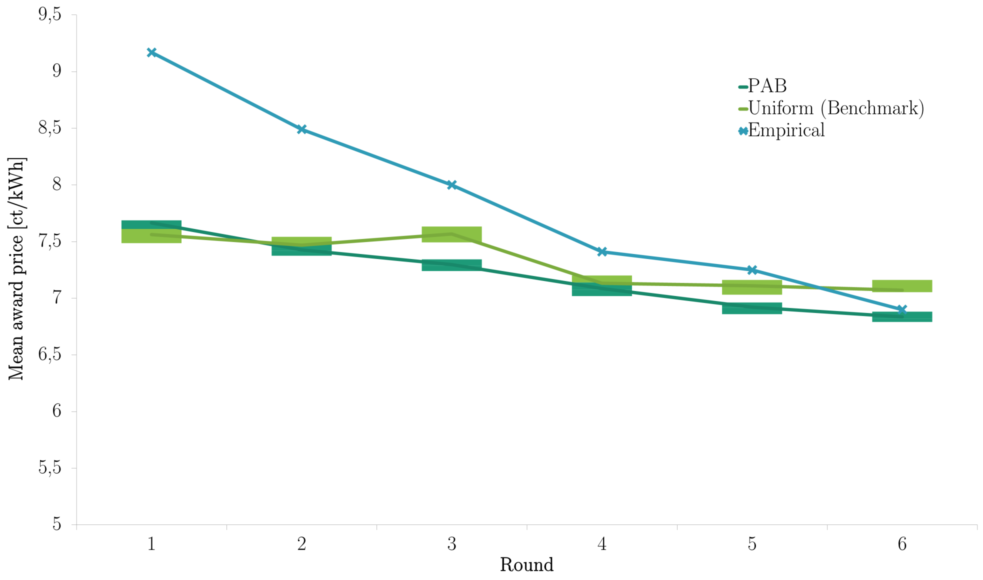

Fig. 7.1: Comparison of mean award price between empirical outcome and the model results in the German PV pilot

We then open up the auction to a range of scenarios where this limit on arable land bidding is lifted. Scenarios which are already taking place or are planned for the near future, due to the so-called FreiflächenÖffnungsverordnung/Bundesländerklausel are modelled. As explained earlier, this law enables German federal states (Bundesländer) to individually regulate the auctioning arable land (Ackerflächen) for large-scale ground-mounted solar PV.

Figure 7.1 shows a comparison of the auction outcome of the PV pilot auctions in Germany with the modelled PAB results as well as a uniform pricing benchmark case, where all modelled bidders bid their true costs. The dispersion shown for the modelled results is the distribution over 100 simulation rounds. It can be seen that the actual auction results of the PV pilot are substantially higher in the first three rounds compared to the modelled results. In the modelled PAB case, all bids lie (at least slightly) below the empirical auction outcomes, showing that with the competition present in the German solar PV auctions and accounting for technology cost developments, lower auction results would have been possible from the start of the auction. In the uniform pricing case - i.e. the case where all bidders reveal their true costs - all outcomes but the last one are below the empirical auction outcomes.

This shows that bidding in the German pilot became more and more aggressive over time, potentially even inducing bidders to put up with small losses to secure their

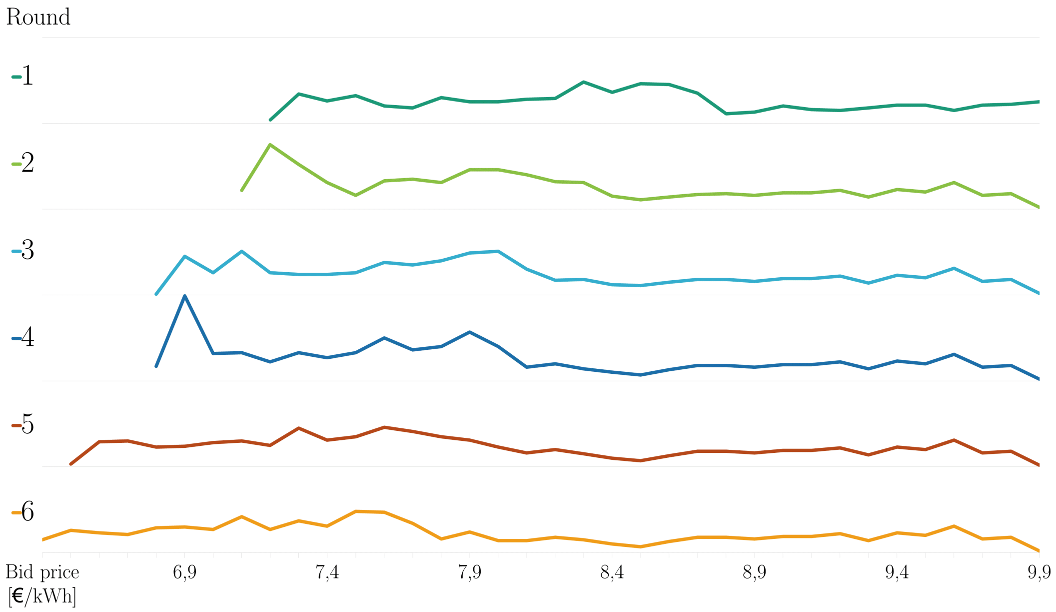

Fig. 7.2: Comparison of overall bid distribution for all three rounds in the PAB model of the German PV pilot

project realisation. This is in line with theory and empirical findings, showing that towards the end of a series of auctions, bidders become more aggressive as their probability to realise a successful bid decreases. To summarize, the sharp decline in award prices in the German PV pilot auctions cannot be explained by falling prices for PV modules and realisation pressure only. Comparing the empirical outcomes to the model results, it is highly plausible that the bidders reduced their costs through increasing the project efficiency and lower profit expectations throughout the value chain.

This finding is further substantiated by the PAB modelling results, which are very much in line with the final three rounds. The uniform prices vary more strongly with the respective capacity auctioned - this is a natural development, as bids are stacked and the final bid that determines the price is by default higher when a larger amount of participants is awarded. The reason for the monotonically decreasing prices in the PAB model lies in the expectation concerning the competition in the first draw of agents. They are modelled to expect a very low level of competition in the first round and then updating their knowledge about the actual competition over time and thus reducing their bids. In this, bidder behaviour was approximated in the pilot where the first rounds exhibited high(er) prices. Even making use of the earlier described two-way learning does not nearly provide the outcomes of the auction pilot as observed empirically.

Figure 7.2 shows the distribution of all bids for five exemplary simulation rounds. It distinguishes the distribution for the different rounds, starting with the distribution of all bids from the first down to the sixth round. Two general developments regarding the bidding behaviour are identifiable. First, the competitive bidders, i.e. those bidders with the lower costs and thus with bids on the left side of the figure, reduce their bid in the duration of the auctions. This can be seen by the shift to the left of the total curve from round to round in general and the shift to the left of the first peak in particular. The distribution of the bids of the weaker bidders, i.e. the bidders on the right hand side of the graph is different. From the second auction round onward, the bid distribution remains constant. The reasoning is, that those bidders learn their low probability of being awarded and thus have already bid really aggressively (close to their costs) at an early stage so that the timing only plays a minor role.

Tab. 7.2: Detailed results of the PAB model for the German PV pilot

Round	Average supply	Mean overall bid	Mean awarded bid	Mean highest awarded bid	Average profit
1	153.04	8.75	7.67	7.93	0.37
2	153.22	8.37	7.43	7.52	0.21
3	202.86	8.27	7.30	7.56	0.10
4	127.98	8.18	7.09	7.15	0.24
5	128.06	8.15	6.92	7.12	0.04
6	152.80	8.07	6.84	7.08	0.03

Table 7.2 further specifies the results of the PAB model. It shows that the mean overall bid follows the same trend as the mean awarded bid illustrated in Figure 7.1. So not only the awarded bidders reduce their bids throughout the auction rounds but also the bidders in general. However, this trend is not as strong as for the awarded bidders. The explanation therefore is already given by Figure 7.2. Furthermore, not only the average bid is decreasing but as a result also the average profit of the bidders decreases. Sole exception is Round 4 were the bidders on arable land participate for the first (and final) time.

While the modelled costs thus show that the agent-based model is suitable to reproduce the findings from the PV pilot auctions, insights on agent behaviour and composition are also of interest. Specifically, the impacts of allowing arable land bidders in 2016 and furthermore how auction results could change if the restrictions on these bidders' participation were lifted were analysed. This is shown in Table 7.3.

Tab. 7.3: Detailed results of the PAB model for arable land bidders in round 4 of the German PV pilot.

Round	Average supply	Mean overall bid	Mean awarded bid	Mean highest awarded bid	Average profit
4	58.17	7.54	6.90	6.94	0.21

The depicted results are from a scenario where only the arable land bidders compete, as well as a small partition of very low-priced converted area bidders. Specifically, a separate auction was implemented into the model, where all relevant model parameters were reduced: available size (an average of 55 MW), time horizon (one year, i.e. three rounds) and the number and characteristics of participants. This scenario represents the optimisation horizon of the arable land bidders, who basically compete amongst themselves and in the PV pilot only have a realistic award probability in the first round of 2016, due to the small amount of available land.

Model results from this scenario clearly illustrate that arable land bidders are amongst the most aggressive bidders. In all displayed criteria, the results are well below the original scenario in Table 7.2. Two main conclusions can be drawn from those model results. Firstly, the participation of arable land bidders reduces the award price and thus the support costs for renewable energy. Secondly, by discrimination against arable land bidders[7] who have a cost advantage the support costs may even be reduced further (Kreiss et al., 2017b). This is particularly visible when comparing the average profit of the bidders in the arable land auction to those of the overall auction scheme: in the discriminatory auction, the average profit is lower, showing a more aggressive bidding behaviour.

7.3.4 Conclusions of modelling case 3

This chapter analyses bidder behaviour in the German PV auction pilot which took place in six rounds in 2015 and 2016. For this, it uses a novel approach which combines insights from game theory and data analysis which were both used to optimise the agent-based auction simulation model. The first one to model the bidding behaviour of the agents more precisely, the latter one to calibrate the characteristics of the agents based on the actual auction outcome. A uniform pricing, incentive compatible auction round where all agents bid their costs as a benchmark case is modelled, as is a PAB scheme, where agents account for several auction and auction-round-specific parameters when optimising their bidding strategy over the course of six auction rounds.

The findings from both the uniform pricing and PAB scheme, are then contrasted with the empirical auction outcomes. Therefore, not only is the setting of the bidder characteristics oriented towards the actual auction outcome but also the setting of the model parameters. As a result, this chapter does not only offer insights into the model results but also how these results were derived. In particular, it is shown that the high bid prices in the first rounds and the monotonously decreasing price development can only be explained by high uncertainties and false expectations

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[7] Discrimination in that case is the restriction on a fixed number of awarded bidders.

regarding the competition. Furthermore, the sharp reduction in award prices cannot solely be explained by the reduction in PV module prices.

Moreover, the bidders who submit projects for the limited arable land areas and their specific behaviour are assessed. In addition to the overall auction simulation, their optimisation is modelled by taking them out of the auction and having them participate in a simulated separate environment - as the limitations on arable land actually caused a sort of discriminatory auction to take place. This simulation leads to two main conclusions. The participation of arable land bidders reduces the support costs significantly as those bidders are the most competitive types. Furthermore, the discrimination induces more aggressive bids of the arable land bidders due to the higher competition level amongst the strongest types of bidders. This could actually even lead to lower bid prices and thus overall reduced support costs.

Conclusions

8

8.1 Key findings

Overall findings from this thesis, resulting from the game-theoretic (agent-based) modelling of different EU countries' auction schemes and additional insights from auction theory and evaluation of empirical data, are as follows: depending on the goals of the policy maker, different auction design elements can play a crucial role for achieving the desired outcome of an auction. This can be least cost, agent diversity or reaching capacity expansion goals with a high realisation rate. The goal of presenting different case studies is to show policy makers and other interested parties what lessons they can learn from and for the respective auctions.

As modelling assumptions and the respective market design are clearly outlined, generalizable conclusions can also be drawn from each country-specific case. In the following, the results from each case are briefly summarized, by answering the questions asked in section 1.2. Then, the general conclusions deducted from these cases wrap up this section.

1) **How do penalties and pre-qualification criteria influence bidding behaviour?** How is the overall realisation rate influenced if there are no or low penalties in an auction? And how do average bid prices change? Do these changes differ over technologies?

In the context of the UK CfD auctions, it was tested to which extent bidder's behaviour would change if a credible penalty for non-realisation were implemented (which the first round of the scheme lacked). It was shown, that a certain amount of bidders will not realise their projects after being awarded under the current(non-penalty) scheme, due to the fact that they cannot cover their costs. This does not come at the benefit of lower prices, such that a penalty system would be a sensible choice to achieve envisaged capacity goals. The model results thus show that low pre-qualifications and low or no penalties lead to an increased drop-out of agents after being awarded. For the policy-maker this implies a lower realisation rate for the auctions. Furthermore, the non-penalty case does not yield lower prices compared to a case with a stricter penalty/pre-qualification system in place, i.e. it does not come with additional benefits from the support cost perspective.

2) **How does setting the schedule and volume influence auction outcomes?** How can flexibility of the volume improve auction schemes with relatively low volumes per round? How does this impact bid prices and realisation rates and to outcomes differ over technologies?

Agent-based modelling of the Danish auction scheme demonstrates that the Danish RES market provides sufficient competition to auction higher volumes and follow more ambitious expansion goals. Furthermore, with a fixed budget, it is more effective in terms of deployment achieved, to hold fewer auctions with a larger volume. A flexibility mechanism that allows up to 50 % of the auction volume to be shifted between auction rounds to accommodate potential large-scale marginal bidders, proves to be a useful tool to increase deployment rates, without negatively affecting bid prices. Furthermore it was shown that at current cost levels, only onshore bidders would be awarded in the envisaged multi-technology scheme. Also, large-scale and multi-project bidders are likely to be the most cost competitive - indicating that if actor diversity is a policy goal, then additional measures would need to be adopted.

3) **How much of the bidding behaviour in auctions can be explained by technology costs and other exogenous factors?** How does discriminating a certain bidder type in an auction influence their respective bidding behaviour?

For the German solar PV auctions, comparing empirical and modelling results shows that, especially in the early rounds, support costs could have been lower – possibly due to uncertainties and false expectations concerning competition. This is particularly visible in the first round. Adapting their expectations to a higher competition level, bidders in the pay-as-bid simulation subsequently decrease their bids. From simulating a separate auction for arable land bidders, it can be seen that arable land bidders reduce support costs substantially and that an implicitly discriminatory auction furthermore yields more aggressive bids and can induce further cost reductions.

The following general conclusions can be drawn from the results of the country and auction-design specific cases: the choice of uniform or PAB pricing does not have strong impacts on the support levels achieved by an auction. Having special regulations and exemptions in place however, can substantially change the results in terms of prices and/or agent distribution. Protecting a certain group of bidders or restricting the auction due to other concerned parties can lead to substantial distortions. On the other hand, having a price-only auction with little or no concern for e.g. small agents or third parties' interests could have other impacts as higher market concentration, a decrease in actor diversity and therefore lacking public acceptance etc. The same trade-off has to be considered when contemplating a multi-technology versus a technology specific auction.

Design of pre-qualifications and penalties is a crucial element for auctions to improve realisation rates and capacity expansion goals. Auctioned volume and frequency of auction rounds also matter. This is especially but not exclusively true for auctions in small markets. Again, setting a schedule and volume does not only impact bid prices and actor diversity but also realisation rates. Auctions for RES have been implemented in accord to the European Commission's guidelines on state aid for environmental protection and energy 2014-2020 (European Commission, 2014) to achieve the EU RES targets set by the European Commission and outlined by directive 2009/28/EC on the promotion of the use of energy from renewable sources (European Parliament and Council Directive, 2009). Therefore, when designing an auction it should be kept in mind to not only evaluate it in terms of cost(efficiency) but also effectiveness, i.e. the deployment rates actually achieved.

8.2 Limitations of the analysis

The aim of this thesis is to provide an understanding of auctions for RES and how different design elements change auction outcomes. Therefore, the choice of methodology needed to be one that allows deeper insights into the specific settings. While econometric or statistical analysis would also be a very interesting complementary tool to assess the nexus in auctions for renewable energy, there is currently a lack of empirical (long-term) time series data to make use of this methodology. By statistically evaluating empirical data wherever possible before calibrating the model, this methodology however found its way into the analysis in an indirect manner.

Theoretical analysis, from an auction or game theoretical perspective is a further interesting choice of methodology which allows for very detailed insights. The theoretical analysis however usually requires to limit the assessment by many factors, for example by restricting the number of bidders or rounds. This then lowers its empirical applicability and the direct derivation of policy implications. Multi-unit auctions, as discussed earlier in section 3.1, are not easily captured by theoretical models, as they include too many factors (participants, units to be auctioned etc.) that cannot be simplified. As far as possible, theoretical theorems were however implemented into the agent-based simulation model. So theory was accounted for to a certain extent.

Experimental economics are also a very insightful way to study behaviour in auctions. Auction experiments can provide insights into especially those characteristics of bidders that are not rational. This is a feature which can be only partly depicted by an agent-based model, as implementing irrational behaviour would lead to very deterministic outcomes. RES auctions however require bidders to be highly informed (due to pre-qualification criteria and several other requirements that have to be met before participating in an auction). RES auctions are connected to investment decisions which would be fairly difficult to explain to experiment participants. Furthermore, the ABM assesses long-term outcomes of auctions for periods up to 2025. Approximating this through an experiment would be quite difficult. Therefore, experimental economics can also be ruled out as a method to address the underlying research questions of this thesis.

ABM also has its limitations when it comes to certain auction designs. Research questions concerning e.g. the implementation of cross-border auctions and also single-unit or one-shot auctions do not benefit from being modelled by an agent-based model, as one of the main insights delivered by this methodology stems from the learning process. For the questions at hand, however ABM gave very insightful results and combined with further insights from theory and statistical analysis was able to give very clear depictions of the underlying mechanisms.

It also has to be stated that results found by modelling country cases do not necessarily provide a forecast for future auction results. This is an inherent flaw of all modelling exercises as certain future events, of disruptive nature or other, cannot always be accounted for. However, agent-based modelling is the most appropriate tool to provide policy relevant results on how varying certain auction design elements can impact an auction outcome. Therefore, the chosen methodological approach proves to be the most suitable to address the core objectives of this thesis.

A further limitation of the analysis that one can stress, is that the selection of countries is limited, i.e. the geographical coverage could be larger. This is correct, especially, as shown in Figure 2.1, several other European countries have implemented auctions for RES support. Nevertheless, the three Member States chosen for the analysis are quite different in their size as well as their electricity markets, their RES market composition and also their auctioning entities' policy goals. Therefore, a broad scope of application was still achieved. Furthermore, a trade-off between the amount of Member States assessed and the possible level of detail that can be achieved had to be made. For the objectives of this thesis, an in-depth assessment of a selection of markets seemed more adequate than a maximum coverage.

8.3 Outlook

This section briefly condenses the results from the different modelling cases into policy implications. Bringing together the results and limitations section, ideas for further research will also be developed.

Concluding on all the findings from this thesis, as well as the developments that have taken place connected to auctions for RES in Europe in the recent past, one can make the following statements. First of all, RES auctions have, empirically and confirmed by modelling, led to a decline in support costs, due to steadily decreasing bid prices on the respective means of support (fixed or sliding feed-in premium or CfD). Secondly, it is currently too early to evaluate realization rates that were achieved with RES auctions. This thesis gives specific insights into areas where non-realization could potentially be an issue and how this could be avoided.

Furthermore, findings on actor distribution and technology specific impacts of RES auctions were presented. Differentiating between groups of actors, by technology or in terms of cost-competitiveness, as shown for the German PV pilot in chapter 7 can be beneficial to achieve cost-efficiency and also actor diversity. Having exemption rules in place, as e.g. in the German wind onshore auctions, can benefit disadvantaged bidder groups but at the same time can also have unforeseen effects. The same holds for restrictions, as again seen in German auctions (for large-scale solar PV).

The approach(es) presented in this thesis are not suitable to address all kinds of issues concerning auction design. Modelling of single-unit auctions, as are held for offshore wind in Germany or Denmark, would require too many determinants for agents. As this type of auction usually takes place in a much narrower setting and with fewer participants, agent-based modelling would not provide many insights into potential auction outcomes. The same holds for cross-border auctions. An ABM approach to assess the impact of cross-border auctions would yield very deterministic results, due to the pre-definition of the participating bidders. As these bidders would be mainly differentiated by their cost distribution, an ABM approach would not provide any innovative insights aside of showing which of the participating Member States is more cost-competitive.

At the same time, not only the suitability of the approach but also the suitability of auctions to determine the level of RES support has its limits. One of these limits can also be mentioned in the cross-border situation. On the one hand, cross-border cooperation in electricity exchange can be very beneficial, see e.g. Welisch et al., 2016. On the other hand, especially cross-border auctions have to be implemented with great care - or they could induce competition on the demand side (auctioning entities) instead of on the supply side (RES generators). Furthermore, when RES auctions lead to too many problems and the auctioning entity includes a variety of elements that complicate the design and lead to undesirable outcomes, the trade-off between complexity and overregulation as compared to a simpler administrative setting of RES support has to be pondered.

In terms of future research, this opens up some interesting ideas. First of all, methodology-wise the ABM approach could be further complemented with other assessments to look into the questions discussed above. Secondly, research could deal with alternatives to auctions and could provide more insights into situations where RES auctions seem infeasible and why this is the case. An idea for future research which could again lead to an improvement of the agent-based model, is to include stakeholders and gain more insight into the bidder and investor perspective. This could concern financing, long-term planning as well as potential strategic behaviour. Gaining these insights could help improve the agents and their bidding strategies in the model and generate more realistic model results.

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Appendix

9.1 Abbreviations

ABM	Agent-based modelling
BEIS	Department of Business, Energy and Industrial Strategy
BMWi	German Federal Ministry of Economic Affairs and Energy
CDF	Cumulative distribution function
CfD	Contracts for Difference
CHP	Combined heat and power
DECC	Department for Energy and Climate Change
DK	Denmark
ENS	Danish Energy Agency
ETS	Emissions Trading System
EU	European Union
GW	Gigawatt
GWh	Gigawatt hours
IPV	Independent private value
IV	Interdependent value
LCOE	Levelized cost of electricity

Mtoe	Million tonnes of oil equivalent
MW	Megawatt
MWh	Megawatt hours
PAB	Pay-as-bid
PV	(Solar) photovoltaics
kW	Kilowatt
kWh	Kilowatt hours
RES	Renewable energy
RES-E	Renewable electricity
RO	Renewables obligations
TW	Terrawatt
TWh	Terrawatt hours
UK	United Kingdom

9.2 Nomenclature

Auction

$range(T)$	rounds per iteration	
t	auction round	
n^t	number of bidders in round t	
n_s^t	number of successful bidders in round t	
d^t	total demand in round t	MW
s^t	total supply in round t	MW
p_{lim}^t	price limit in round t	ct/kWh

Bidders

$\mathrm{a}_{converted,w}$	agents of type $Randflaeche$, weak	
$\mathrm{a}_{converted,s}$	agents of type $Randflaeche$, strong	
a_{arable}	agents of type $Ackerflaeche$	
c_i^0	bidder i's initial costs in the first round	ct/kWh
q_i	quantity offered by bidder i	MW
δ	discount factor	$\in$ (0,1)
$comp$	initial assumption on competition	
$succ$	initial assumption on successful bidders	
λ^t	degression factor in round t	
β	bidding function	
x	bidder's signal	
δ	uncertainty factor	

Colophon

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Hiermit erkläre ich, dass ich diese Arbeit selbständig verfasst habe, dass ich die verwendeten Quellen und Hilfsmittel vollständig angegeben habe und dass ich die Stellen der Arbeit einschliesslich Tabellen, Karten und Abbildungen, die anderen Werken oder dem Internet im Wortlaut oder dem Sinn nach entnommen sind, auf jeden Fall unter Angabe der Quelle als Entlehnung kenntlich gemacht habe.

Wien, 11. Januar 2018

Marijke Welisch