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A counterfactual analysis of renewable energy auctions taking the spatial dimension into account

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Abstract

Auctions have recently been introduced in many countries as a useful alternative to accomplish renewable energy supports. However, they are often accompanied by a high concentration of renewable energy power plants at productive sites, at the expense of other, less favorable sites. This paper studies the impact of alternative renewable energy auction designs on the promotion of renewable energy in Germany using a novel multi-level approach. To do so, we analyze auctions on three different spatial levels: the national auction, the regional auction-type I (federal states level) and the regional auction-type II (north/south auction). The initial step for modeling renewable energy auction schemes in Germany is to investigate the onshore wind potential with a high regional and temporal resolution, using the GIS-data-based tool REMix-ENDAT. The results of this analysis show a considerable as yet untapped onshore wind potential in the southern federal states of Germany. Second, an onshore wind auction model is developed using a system dynamics approach. Finally, the comparison of the support payment for different auction designs is evaluated using the electricity market simulation model (HECTOR). Findings indicate that more bidders from the southern federal states can win in the regional auctions. Detailed spatial analysis reveals a trade-off between balanced diversity of bidders and average auction price (the price difference varies from 0.5 €-ct/kWh to 1.5 €-ct/kWh in different scenarios). We conduct that, a noticeable potential support payment saving from regional auctions should be exploited in long-term renewable energy policy designs.

Keywords: Renewable auction design, System dynamics, Support payment

Nomenclature

α	Hellman exponent coefficient	FIT	Feed-in tariff
h_0	Reference height of the wind turbine	GIS	Geographic information system
AV	Applied value	h_1	Height of the wind turbine
CF	Correction factor	LCOE	Levelized cost of electricity
CLD	Casual loop diagram	MC	Marginal cost
CWE	Community wind energy	MP	Market premium
FIP	Feed-in premium	MV	Market value

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p_t	Price of time t	SD	System dynamics
PAB	Pay-as-bid auction	V_{h_0}	Reference wind speed
Q_t	Electr gen from onshore wind power plants		
QF	Quality factor	V_{h_1}	Average wind speed

1. Introduction

The reduction of CO_2 emissions is a common goal of both pan-European and national climate policies. The promotion of the use of renewable energies is an elementary part of the European Union's policy for reaching this goal. However, the European countries rely on a variety of mechanisms and approaches which are compatible with the character of their respective energy markets (Ferroukhi et al. 2015). Until 2014, the countries implemented various different instruments such as feed-in tariffs (FITs) and tradable green certificate (TGC) systems (Alvarez et al. 2017). In the last few years, European countries have changed their support schemes for renewable energies towards auction mechanisms for meeting the European regulations. After an initial testing phase, such auction-based renewable support schemes have been implemented in 19 European countries (AURES 2020). However, there is no homogeneous approach within Europe. The countries implement individual auction designs and provide different incentives within their respective support designs.

In line with the guidelines of the European Commission, Germany revised its own renewable energy support scheme in 2017 (EEG 2017). It implements capacity auctions for onshore wind, offshore wind, solar photovoltaics, and biomass. These auctions determine a sliding feed-in premium (FIP) for each successful bidder, which is a subsidy covering the difference between the electricity price and the auction clearing price and as such an important design element of modern renewable energy auction schemes. A general feature of auctions is allocative efficiency which results from the selection of the bidders with the lowest bids. To foster investments in northern regions close to the sea with high wind potentials and further inland in landlocked southern Germany, the EEG[1] 2017 implemented a location-specific auction mechanism (WindGuard 2018). A so-called correction factor[2] systematically increases the premium for generated electricity for wind sites with lower expected average wind speeds. The results of the wind auctions in Germany in 2017 and 2018 showed significant under-investment in southern Germany, and that the states in the south were failing to reach their local targets for wind power investments.

In this paper we analyze the impact of different auction designs on the expected auction results and on long-term investments in onshore wind peaks. To this end, we developed a novel system dynamics (SD) method to model and simulate renewable energy auctions. The geographic scope of the investigation is

[1]EEG: German Act on Granting Priority to Renewable Energy Sources (*Erneuerbare-Energien-Gesetz*).

[2]To enable fair competition among bidders in the auction and to increase comparability of bids from different regions, a one-leveled reference yield (*Referenzertrag*) is utilized. Accordingly, every bid is determined for an onshore wind installation situated at a reference benchmark location (the so-called "100 percent" location), where wind speed is 100 km/h at 100 m hub height. Then, all offers are compared within the auction mechanism and after the award decisions, the actual level of remuneration will be calculated on the basis of the specific correction factor of the individual location of each wind installation.

Germany, providing results for each of the federal states (NUTS-1 level)[3]. We use historic weather data as well as GIS analysis to determine bids for different wind classes and regions. The paper outlines alternative auction designs with different spatial formats including national and regional auctions in Germany. In contrast to previous studies, the analysis of the future market outcomes and the expected feed-in premia has been performed by linkage with a large-scale hourly European dispatch and investment model.

The proposed method and the results will help both renewable energy policy-makers and investors in their decision-making. Policy-makers, on the one hand, can learn how different policy designs impact long-term investments, and find out in which regions investments are likely to take place. On the other hand, investors can learn about the expected profitability of investments for each region as well as the expected revenues under the current and the new market designs. Additional other scenarios can also give insights on the risks that the investor faces: Changes in the energy policy as well as uncertainty about the speed of investment will lead to different market outcomes and will influence the expected long-term revenues.

The remainder of the paper is organized as follows. Section 2 provides an overview of the related literature. Section 3 outlines the methodology proposed for studying renewable energy auctions. The first part describes the GIS-based tool for analyzing regional wind power potentials. We then introduce our innovative approach for modeling renewable energy auctions. The last part of Section 3 presents an updated version of the SD model HECTOR, the market model used for the calculation of expected future market prices and FIPs. Section 4 provides an overview of the input data as well as the scenario building mechanism and assumptions. Section 5 comprises the simulation results of the analysis of the auction rounds until 2030, the resulting impact on regional investments, and the impact on the electricity markets. Section 6 concludes and suggests some ideas for further research.

2. Literature review

The higher the share of renewables in a power supply system is, the more accurate the representation of the electricity generated from renewable sources has to be. In addition to FITs and FIPs, well-designed auctions can reduce remuneration and support payments which are based on public funding (Del Rio 2017). Grashof (2019) identifies potential effects of a shift from guaranteed remuneration to auctions on incentives in order to start new (CWE) projects. These auctions have usually induced investment at very productive sites far from the main load centers (Ibrahim et al. 2011). Furthermore, the proximity of renewable power plants to consumers/the load can decrease transmission congestion in the network (Amado et al. 2017). Höfer and Madlener (2021) propose using price signals for renewables that consider the regional grid over-stress, in order to mitigate the renewable curtailment. Klie and Madlener (2020) develop a hybrid tool to calculate cost assumptions and market values of wind for all NUTS-2 areas in Germany using NUTS-2 aggregated wind data. Therefore, it can be seen that a growing body of literature has been considering the

[3]The NUTS classification (Nomenclature of territorial units for statistics) is a hierarchical system for dividing up the economic territory of the EU and the UK for the purpose of collection, development, and harmonization of European regional statistics. In this categorization, NUTS-1 denotes major socio-economic regions, such as federal states or provinces (European Union 2020).

location of wind power plants in order to assess the related energy policy implications (Aparico and Zucker 2015).

There is a considerable amount of literature on the impact of certain design elements on the success of renewable energy auctions (An overview can be found in (Cramton 2010)). The price ceiling is one of the important elements which can influence the level of competition among bidders (Del Rıo et al. 2015). Many other studies address the importance of predefined penalties and prequalification criteria of bidders (Del Rio and Linares 2014; De Jager et al. 2008). Maurer and Barroso (2011) propose two pre-qualification criteria in order to ensure the support cost efficiency and to obtain a high realization rate of the auction scheme. Del Rio (2017) discusses the trade-off between regional target expansions and allocative efficiency. Contrary to previous works, in this paper we explicitly focus on the spatial/regional dimension of renewable energy auctions.

A rich body of literature is based on experiences with RES in different countries and on the comparison of different auction designs. Lundberg (2019) studies the 2017 (onshore) wind power auctions in Germany, with a focus on the privilege for citizen energy cooperatives. This study examines how the auction design affects the diversity of actors in the auctions and the risk of winning projects not being realized. Toke (2015) analyzes the performance of two renewable energy auction/tender systems by comparing the Danish offshore wind power development with the renewable energy development in South Africa. The author concludes that cost reductions are not caused by the auction system *per se* but rather by a general decline in renewable energy technology costs. Furthermore, the effect of renewable energy auction systems tends to be the slow-down of the renewable energy development rather than a reduction in energy costs. Kreiss et al. (2017) show that discriminatory auctions are the preferred tools from an auctioneer's point of view who is aiming to achieve the expansion of renewable energies at the lowest total system cost as well as achieving a reduction of the public support payment. Previous works have been limited to address the expected revenue of investments under different market design taking spatial dimensions into account. This paper sheds new light on this research gap by means of various scenarios based on outcomes of previous auctions.

Current studies use different experimental and simulation approaches to scrutinize auction designs. Anatolitis and Welisch (2017) use an agent-based modeling approach for comparing auction pricing (uniform and pay-as-bid) for renewable energy in Germany, and provide first conclusions on the outcomes for future policy design. Their model shows that, over time, the successful bidders are different ones from before, since the number of smaller bidders (such as citizen energy companies) decreases. Whereas pay-as-bid auctions generate slightly lower prices in the German wind power auction, their pricing mechanisms do not differ substantially. Bichler et al. (2019) use numerical experiments to analyze different auction designs for Germany. They propose a combinatorial auction design which can ensure achievement of regional target capacities. Voss and Madlener (2017) scrutinize different auction schemes, bidding strategies, and the cost-optimal level of promoting renewable electricity in Germany and find that there is no unified strategy for winning, but that an optimal alignment of strategy in accordance with the auction modeling is needed. In this context, we take a new look at the future market outcomes by using a large-scale model. This coupling can substantially increase the accuracy of the calculation of market premia.

Scholars have been successfully using SD models for energy system modeling for many years and a good review can be found in (Teufel et al. 2013). The following literature illustrates past usages of SD for the electricity market. Eager et al. (2012) study conventional power plant investments in the energy market with a SD simulation model. Cepeda and Finon (2013) analyze the influence of the capacity forward market on investment decision making from a SD perspective in a market with a high share of large-scale wind power generation. They show that the capacity mechanism can decrease the social costs of large-scale wind power promotion. Petitet et al. (2017) compare scarcity pricing and a capacity mechanism with a SD tool. The results of their study indicate the merits of the capacity mechanism over scarcity pricing. None of the above-mentioned studies, however, has modeled a renewable energy capacity auction with SD. To the best of our knowledge, we are the first authors to model a renewable energy auction with a SD approach. Since bidders in this auction are assumed to show strategic behavior, a novel method for the modeling of this auction is being used. One of the crucial advantages of SD models over traditional modeling approaches using econometric or linear programming and agent-based models is that SD models do not require enormous amounts of empirical data for the simulation of the behavior of investors. In addition, it is quite flexible regarding the integration of strategic behavior and absence of complete information (Semertzidis 2015).

3. Methodology

We aim at forming an accurate model of the German onshore wind auctions for the year 2018 - the year when wind energy auctions started in Germany - until 2036. In this section, we outline model approaches that are used for conducting a counterfactual analysis[4] of the onshore wind energy auction in Germany. As can be seen in Fig. 1, we used three different models. First, a GIS- based tool analyzes the available wind energy potentials for all federal states of Germany. Second, based on the outcomes of the first model, a capacity auction with different regional dimensions is simulated from a SD perspective. The SD model was developed using the Vensim DSS 6.4E software. SD is a novel method for modeling and projecting the behavior of a complex system which has many factors, numerous interactions, and non-linearity (Jeon and Shin 2014). Finally, as the support payment (i.e. the FIP) is a vital indicator for evaluating auctions, HECTOR is used to simulate the electricity market for the calculation of this parameter. In the following sections, details of the above-mentioned model elements are provided.

3.1. GIS-data-based tool of analysis

The GIS-data-based tool (ENDAT)[5] is used here to determine the long-term potential for additional wind power plant capacities in different regions of Germany and the respective costs as well as estimated earnings for each wind farm. Land cover data provides information if an area is suitable for wind power

[4]Since we compare what actually happened in the auction with what might have happened in the absence of the intervention, we refer to as a ”counterfactual analysis”.

[5]This GIS-data-based model is a part of the REMix-EnDAT model developed at DLR (Scholz 2012; Stetter 2014). In this model renewable energy resources are investigated in high spatial and temporal resolution.

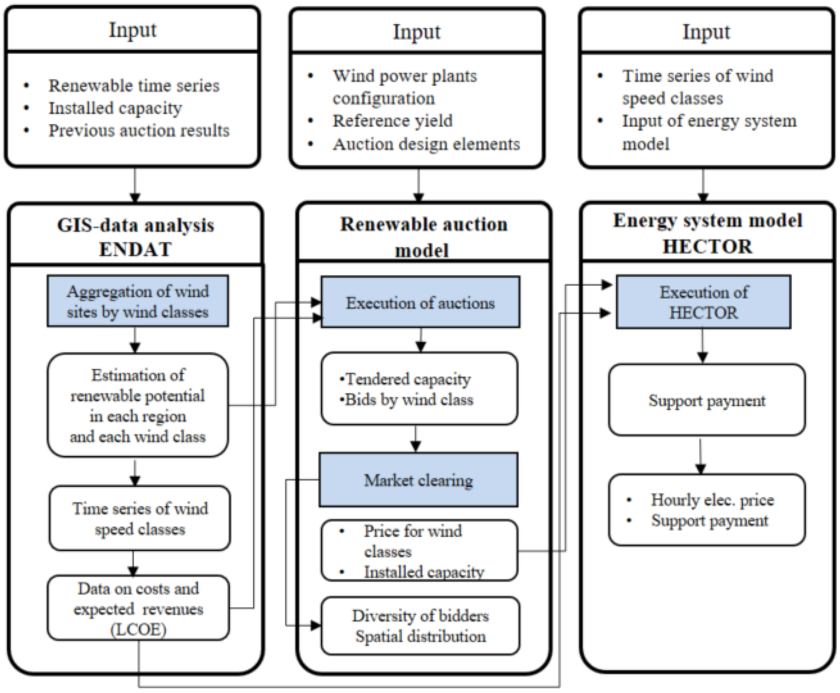


Figure 1: Overview of the modeling approach used

plants; further, it determines the expected density of wind power plants. Exclusion areas prevent the model to build wind turbines close to roads and other infrastructure or in environmental protection areas. ENDAT generates a range of input data for the subsequent auction and energy system models. A division into wind classes for the 16 federal states in Germany leads to 42 wind classes with regionally representative feed-in profiles. Based on this annual wind generation curves for existing and future wind power plants an economic evaluation can be conducted to estimate the expected bids in the capacity auction. The model allows the bids to be determined in different auction designs for different types of wind farms and for different federal states of Germany. ENDAT uses high-resolution geographical data and hourly historical wind data. Weather data and especially wind speed data for the year 2015 are used to estimate how much feed-in from future installed wind power plants will be generated. Based on the future feed-in and expected hourly electricity prices, estimates on the future earnings, under a given regulatory scheme, can be made. The aim of the GIS-data-based analysis is to determine the bid prices and quantities for each wind power capacity auction under a given set of assumptions. Data are aggregated for each federal state of Germany and for typical wind speed clusters. In this paper, ENDAT provides input data for the subsequent wind auction modeling. Further, it generates hourly profiles for the electricity generated by future wind power plants as an input for HECTOR.

3.2. Renewable energy auction model

Since we are performing a counterfactual analysis we do not calibrate the results of our model with previous auctions. This seems reasonable as the auction mechanism has been changed over the years and the available auction results only provide scarce data which could be used for the calibration. Moreover, the only available data are on the simple average or aggregated level and not on individual bids. Well-designed

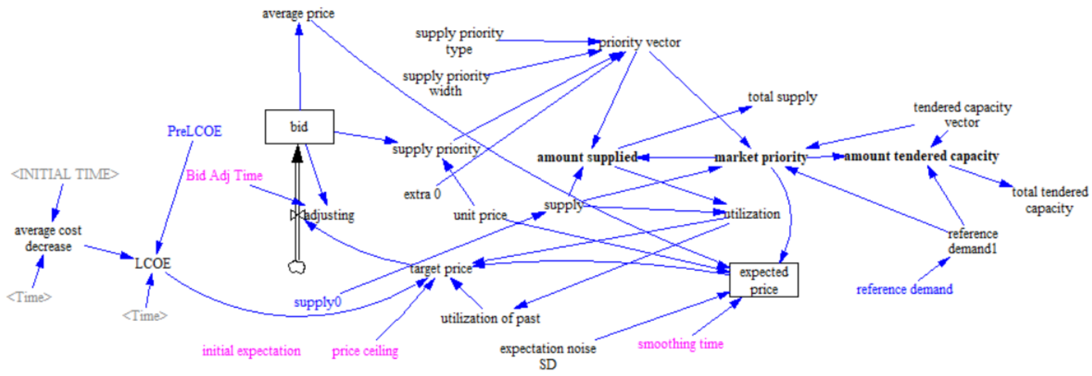


Figure 2: Casual loop diagram of the authors' own renewable energy auction design

and -implemented FIPs can decrease the required support payment. Hence, since the current auction design in Germany is conducted with FIPs, we focus on this kind of support scheme. To do so, the calculation of the market premium is based on Art. 36(h) of the German Renewable Energy Sources (RES) Act 2017 (EEG 2017). The market premium can be determined from the following equation:

$$MP = AV - MV, \tag{1}$$

where AV is the value to be applied, which can be assessed by the multiplication of a correction factor and the awarded price of bidders, and MP denotes the market value. This market value is calculated by transmission system operator (TSOs) in Germany on a monthly basis as follows:

$$MV = \frac{\sum_t Q_t . p_t}{\sum_t Q_t}, \tag{2}$$

where p_t and Q_t are the average spot market price and the total electricity generation from onshore wind power plants, respectively. The mechanism of how this correction factor works is shown in Table 1. The awarded price can also be determined according to the pricing mechanism of the auction. As an illustration, since energy citizens are paid in accordance with the uniform pricing rule, they are paid with the highest accepted bid in the auction. MV is the average monthly market value which is calculated in the HECTOR model.

A stock and flow structure involving a renewable energy auction is embedded into the casual loop diagram (CLD) presented in Fig. 2. Such a structure describes how the market is cleared in each auction round. Further, the relationship between bid and expected market clearing price can adjust the bids of bidders based on their previous utilization. Bidders bid close to the maximum of their marginal costs and to the expected price. However, they learn from the entire system's behavior, which is interpreted here as the average bidding market price. Then bidders are sorted in ascending order based on their offers and the market price is cleared accordingly.

The capacity auction is being modeled heuristically in a simulation model. In each auction round four parameters – the price ceiling, the marginal price, the expected price, and the utilization of installed capacity – impact the targeted price. Regarding the price ceiling, it is worth mentioning that according to the auction rules, bidders cannot bid more than 7 €-ct/kWh in these auctions. In discriminatory auctions, such as PAB or first-price sealed-bid auctions, bidders usually submit their bids with a safety margin. In auction theory, such behavior is called "bid-shading" (Menezes and Monteiro 2005). Since bidders submit their bids with regard to their Levelized Cost of Electricity (LCOE), each wind power plant operator bids by considering the plant-specific LCOE plus a mark-up considered to be appropriate. Since bidders behave strategically, this mark-up is chosen randomly in the first period modeled. However, bidders can learn from the system behavior in each auction round and can adjust their bids in further auction rounds. Furthermore, an expectation noise is used in order to make the bidding process more heuristic. On the one hand, bidders are price-takers, and hence they can make money by pushing utilization as high as possible at the clearing price. On the other hand, as bidders in the auction behave strategically, each bidder tries to bid close to the maximum of his/her marginal cost (MC) and expected price. As a simulation approach is used for the modeling of the capacity auction, we do not optimize costs/profits of bidders in each auction. According to this methodology, a priority function is used which matches the tendered capacity with supply of the bidders based on their priority. Since bidders are sorted in ascending order based on their price, the priority function is formed based on the price vector.

In this model, bidders are classified based on the wind speed class of the respective region. In other words, in each region we use the group of technologies as being representative for all bidders with that characteristic. Although project developers and energy citizens are paid differently (according to different pricing rules, i.e. PAB for the project developer and uniform-price bidding for the energy citizens).

3.2.1. The reference yield model

The reference yield method has been an indispensable and vital part of the support system for onshore wind energy since the introduction of the Renewable Energy Sources Act 2000 (EEG, 2000). The RES Act amendment 2017 updated this subsidy system by converting it to a single-level procedure that adjusts the compensation amount using correction and quality factors. To formulate the reference yield of a specific wind turbine, in a first step the average wind speed at hub height needs to be calculated based on eq. (3).

$$V_{h_1} = V_{h_0} \times (\frac{h_1}{h_0})^{\alpha}, \tag{3}$$

where V_{h_0} represents the average wind speed according to EEG 2017, h_1 denotes the rotor height of the wind turbine, h_0 indicates the reference height of the wind turbine, and α is the Hellman exponent coefficient. The reference site is defined with a Rayleigh distribution for which the details are listed in Table 1.

The main goal of the reference yield model is to promote the production of wind energy in less favorable locations in Germany. According to the results of the the previous auctions, the new installation of wind

Table 1: Reference site details

Quality factor	Unit	Definition	Value according to (RES) Act 2017
V_{h_0}	[m/s^2]	Reference wind speed	6.45
h_0	[m]	Reference hub height	100
α	[-]	Hellmann exponent	0.25

technologies is taking place in the northern part of Germany and fewer investors are tending to build wind farms in the southern part. The reason behind this issue is the heterogeneity of the wind power potential in Germany. On the one hand, this imbalance causes some major problems for the power system in Germany, such as transmission congestion; solving it is a time-consuming and expensive process. On the other hand, expanding wind power capacity in such a way that it is closer to the consumers is also a more profitable option for promoting wind energy in the power system because it can reduce transmission costs of the system (Ackermann et al. 2001). To do this, a reference yield model is introduced which allows all players to have a fair chance regarding their different site conditions. Hence, the amount of funding per kilowatt-hour is estimated for wind farms with regard to their location. As a result, they can compete in the auction more fairly.

After distributing funds to all selected plants, the system operator calculates the award value by means of corrective factors. In this paper, it is assumed that four onshore wind auctions take place each year. Considering the reference model, the winners can sell their energy for 20 years and receive wholesale electricity prices in addition to the market premium granted during this period.

3.2.2. *Calculation of quality and quantity factors*

To calculate the corrective factor which is needed for balancing the auction, the initial step is to determine the quality factor. This quality factor is related to the type of wind power plant. According to Art. 36(h) of the RES Act 2017, the quality factor is the proportion of the wind power plant yield to the reference yield (EEG 2017). Hence wind power plant yield and reference yield should be assessed for entire regions of Germany. The wind power plant's yield is the potential of wind power plants for generating electricity that can feed, or could have fed, into the grid. Subsequently, the corrective factor can be assessed by eq. (4):

$$Corrective factor_{[target]} = CF_{[left]} + \frac{CF_{[right]} - CF_{[left]}}{QF_{[right]} - QF_{[left]}} \times (QF_{[right]} - QF_{[left]}) \tag{4}$$

This formula interpolates corrective factors between the fixed value in Table 2 according to Art. 36(h) of the RES Act 2017. *QF* and *CF* denote the quality and the corrective factor which are calculated based on Appendix 2 of the RES Act 2017. In this paper, wind speed time series of 42 regions within Germany are used to estimate the corrective factor for each region separately.

Table 2: Correction factor in dependence of the quality factor (Source: EEG 2017)

Quality factor [%]	70	80	90	100	110	120	130	140	150
Corrective factor [-]	1.29	1.16	1.07	1	0.94	0.89	0.85	0.81	0.79

3.3. Renewable energy auction designs

In our analysis, considering the reaching of regional renewable energy (here: onshore wind) targets until 2030, we examine auctions from 2018 until 2036. Owing to the lack of transparency of results for past auctions and the changes in auction design and regulatory mechanisms, we do not calibrate our model to the results of previous auctions. Therefore, we perform a counterfactual analysis for three auction designs, whose auction mechanisms are defined in detail in the following.

3.3.1. National renewable energy auction

In the national auction design, which represents the prevailing current auction scheme in Germany, bidders from all regions in Germany take part in four auction rounds per year. The tendered capacity for each auction round is 700 MW. Each bidder submits a paired bid which encompasses ask price and capacity to be installed. After the submission of all bids, they are sorted based on the ask price. As long as the tendered capacity is not being reached by the cumulative capacity of bidders, bidders are considered to be winners of the auction. Finally, institutional bidders will be paid via the PAB mechanism. However, the pricing mechanism for citizen energy cooperatives is uniform, i.e. each bidder will be paid based on the price of the marginal producer. Bidders receive their remuneration in accordance with the reference yield model described in section 2.2.1 above.

3.3.2. Regional auction-type I renewable energy auction

Since with a national auction scheme some regions such as Bavaria or Baden-Wuerttemberg may fail to reach their regional targets[6], a regional auction is proposed and analyzed in this section. In a regional auction design, bidders submit their bids for regional target capacities (Grimm et al. 2017). The pricing and allocation mechanism and rules of these auctions are identical to the national auction. Since the cumulative capacity in regions would be very small, we assume that these auctions take place only once a year.

3.3.3. Regional auction-type II north/south auction

Concentrated expansion of onshore wind in the North sharpens the current network capacity constraints between the South and North of Germany. Hence, another, regional type of auction is proposed and analyzed in this section. In this auction, bidders can be categorized into two groups. All bidders above and below "mainline" (an arbitrary line of separation which is common in some political debate) take part in the northern or southern auctions, respectively. The pricing and allocation mechanism is akin to a national auction. Like the regional auction-type I, we assume that these auctions happen once a year.

[6] The regional targets are taken from German network development plan (ÜNP 2017).

3.4. The HECTOR model

We now turn from the renewable energy capacity auction to the energy market modeling. Simulating the electricity market for the whole of Germany, and considering the outcomes of these auctions, is the last modeling step required. To do so, outcomes of the auctions will be used in the large-scale model HECTOR. HECTOR is a simulation model that simulates generation, auctioning, dispatch and electricity exchange between regions of electricity markets (Sheykhha and Madlener 2019). The model is based on the SD architecture whose objective functions are solved for each hour (time step) separately. The objective function of this long-term model, which minimizes total system costs subject to a set of constraints, is being solved in the market clearance module. This function matches supply and residual demand considering regional constraints, such as import and export costs and transmission capacities, in order to find the lowest total system cost (Lohwasser and Madlener 2009).

In this paper, the calculation of the market premium is determined in HECTOR by means of a zooming approach for Germany. In other words, although HECTOR simulates the electricity market of the whole of Europe, and since we are modeling onshore wind power capacity auctioning in Germany, we focus on Germany only. Detailed information regarding the conceptual framework of the model can be found in (Sheykhha and Madlener 2019).

4. Input data and scenarios

For the analysis of auction designs, we use data from different sources. This includes data on onshore wind auctions and the electricity system. In this section, the data used for the model are briefly presented.

4.1. Input data

The first group of data relates to the bidders in onshore wind energy auctions. Accordingly, we use a combination of data from previous auction rounds, regional hourly data, wind onshore capacity potential, location of previous installed capacity, and techno-economic data of windmills.

The information of cumulative installed capacity, average hub height, specific power and investment costs of each region is extracted from (WindGuard 2018). We take 42 regions in Germany into account which are defined by wind speed classes (see section 3.1). This regionalization is thus based on the potential of different wind speed classes. As an illustration, Bavaria is divided into 5 subregions (4 m/s, 5 m/s, 6 m/s, 7 m/s, and 8 m/s). Each of these regions represents all windmills which can produce energy in areas with the mentioned average wind speeds. In order to create an amount of possible onshore wind capacity, we use data of MaxW (Grimm et al. 2017). This data set provides a capacity target for 2035. Since a part of our results (i.e. diversity of bidders and calculation of support payment) have been calculated based on outcomes of the auction in the first year, the yearly expansion with a linear expansion until 2035 has been taken into account. The corresponding regional distribution of capacity according to MaxW can be found in Table A1.

For the calculation of support payments for further years we have to use hourly electricity prices in German electricity market. Hence, we need to derive that hourly electricity price by means of a large-scale electricity market model (HECTOR). The second group of data is used from a data set obtained from the project 4NEMO[7]. This data encompasses all data needed for running European electricity market model which is coupled with an auction model. This includes demand data, commodity prices data, process data, process conversion data, transmissions data, and demand and renewable energy generation time series. More information regarding data requirements of HECTOR can be found in (Sheykhha and Madlener 2019).

4.2. Scenario building

When estimating the long-term investments in a country, four factors have a major influence on the technical expansion potentials for wind turbines determined by the model and further on the auction results and the expected long-term investments in each region.

- **Available areas:** Based on the used land cover data and the exclusion masks, potential available areas can be determined. Based on the underlying assumptions and the method of how to deduct existing wind sites, the availability may vary in each region.
- **Spatial density of wind installations:** This includes the distance between individual installations as well as groups of installations: The number within an accumulation of wind turbines and the distance between these wind farms have an influence on the overall spatial density.
- **Distance to settlements:** Regulatory requirements for minimum distances between wind turbines and residential areas also have a major impact in densely-populated countries like Germany. Previous studies have shown that increasing minimum distances from the populated areas by a few hundred meters significantly reduces the available land potential in Germany.
- **Available bids in each auction rounds:** A characteristic feature of repeating wind energy auctions is that in each auction round bids are submitted only for a small part of the technically possible areas available for the installation of wind turbines.

In this study, we want to focus in particular on the fourth point: the number of bids in each auction. Within the framework of three scenarios, different assumptions are made for the available bids in each auction.

Looking more closely at the past auctions for wind, it could be observed that the number of bids placed in the auctions fluctuated. In the 2017 auction rounds, the bids were around 2.5 times higher than the tendered capacity (Fig. 4). The competition was high so that prices in the auctions for long-term remuneration fell. This led to the result that prices fell well below the price cap set by the regulatory authority. In 2018 the requirements for participation in the auction changed. Due to the abolition of the exemption for citizen

[7]https://4nemo.de/

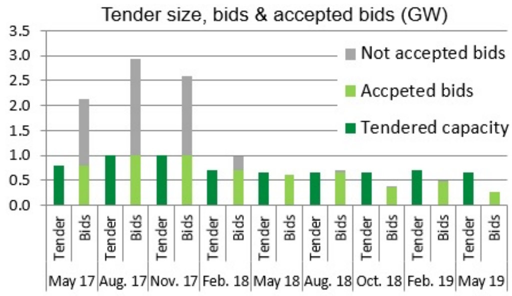


Figure 3: Tender size, bids and accepted bids of onshore wind auctions in Germany (Source: Federal Networks Agency, BNetzA)

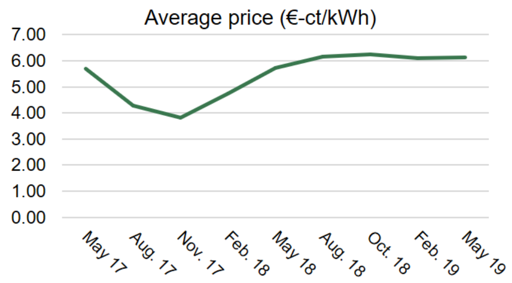


Figure 4: Average price of previous onshore wind auctions in Germany (Source: Federal Networks Agency, BNetzA)

wind turbines and increased requirements regarding citizen participation, the effort and thus the implicit costs for wind turbine operators to submit a bid increased. This led to a significant drop in bids in the following auction rounds, and hence the number of bids did not reach the tendered wind capacity. As a result, prices rose again to around 6 €-ct/kWh and they are thus only just below the regulated price cap.

Especially when considering the regional distribution of wind turbines, the number of available bids in each auction round plays a major role. While electricity in itself is a homogeneous good, the bids for wind turbines are not. Different locations result in different wind harvests and thus differences in the overall business case. The example of Germany makes it particularly clear: While locations near the coast have high average wind speeds and thus high capacity utilization, locations in southern Germany have significantly less wind on average. The bids available in the future depend on many factors. The following trend can be expected: The higher the actual costs of bidding are, including the costs for the acquisition and development of land and the costs for the participation procedures, the fewer bids will be submitted. The sunk costs for projects not carried out are simply too high.

The intuition behind the influence of bidding volumes on regional distribution is relatively simple: if there is a lot of competition and at the same time prices on the market are low, under the current regulatory regime, favorable locations with high wind utilization are preferred. As a result, more investments will take place in those regions in northern Germany with higher average wind speeds and thus higher wind power generation. With decreasing competition and fewer bidders in each auction round less efficient wind sites such as those in the south of Germany might be preferred; the overall installed capacity might shift to the south. How big this effect is and if it has an influence on the overall auction result is a key insight from the scenario run done in this paper.

In order to show the significance of the bid amounts on the energy system, we have formed three scenarios based on the observations in the historic number of bids. In the first scenario, we are at a similar level as in 2018, a total of 404 MW per year are added to the auctions. In the second scenario, the proportion is higher and a total of 1202 MW per year is considered as tendered capacity. The third scenario is characterized by a low level of competition. 3204 MW can be bid in each auction. Due to the low level of competition, plants in less favorable locations also receive sufficient investment incentives. While these

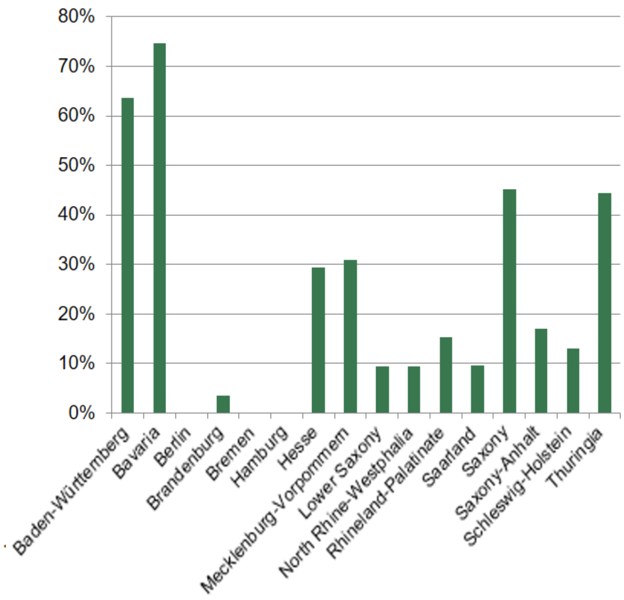


Figure 5: Share of technical wind farm potential that remains (Source: own calculations)

scenarios might be a little too artificial, they allow us to get a good understanding of the impact of the number of bids on the long-term auction results.

As previously described, regulations on minimum distance to settlements have a significant impact on the long-term wind potential. In recent years, it has also increasingly gained a political dimension. The national government and the individual state level governments used this to increase/to cope with increasing local problems of social acceptance. Especially Bavaria with a restrictive policy of a minimum distance to settlements of 10 times the heights (thus for an average wind turbine with a height of 180 m greater than 1.8 km) almost eliminated the states' long-term potential for further wind investments. In our assumptions, we assume a minimum distance of settlements of 700 m. In the case of states such as Bavaria and North Rhine-Westphalia, these assumptions might overestimate the long-term potentials based on the current regulation.

In our model assumption, we deal with the existing wind turbines by deducting the expected land consumption of the turbines installed in 2017 from the determined overall wind power potentials for each NUTS region. This simplified assumption offers a pragmatic approach to determine the remaining potentials in the more than 400 regions.

Fig. 5 shows the resulting overall technical potential for additional wind installations in each state in Germany in the coming decades. It can be seen that the states in the north have already a high density of wind turbines and tapped between 69% and 90% of their overall potential for wind turbine installations (based on the given regulatory scheme and given model assumptions), while the southern states Bavaria and Baden-Wuerttemberg so far only tapped 15% and 25% of their potential wind sights, respectively.

5. Model results and discussion

The results obtained from this study cover the following dimensions. First, since our scenarios are based on previous onshore wind energy auctions in Germany, a GIS-data-based analysis is presented. Second, the

Table 3: Total available onshore wind power potential in 13 federal states of Germany [MW]

States	Available capacity Scenario 1	Available capacity Scenario 2	Available capacity Scenario 3
Baden-Wuerttemberg	284	864	2309
Bavaria	716	2156	5747
Brandenburg	18	54	140
Hesse	77	225	594
Mecklenburg-Western Pomerania	162	491	1314
Lower Saxony	91	266	702
North Rhine-Westphalia	41	113	297
Rhineland-Palatinate	36	113	302
Saarland	0	5	18
Saxony	126	374	1013
Saxony-Anhalt	86	239	630
Schleswig-Holstein	50	131	356
Thuringia	131	383	999

auction results are compared in terms of diversity of awarded capacity, price development, and support payment. Finally, this section concludes with a discussion regarding the results obtained and the limitations of the study.

5.1. Results from GIS-data-based analysis

The latest results from the German onshore wind energy auction show that there is a future need to advance the auction design. The main goal of such adaptations should be to obtain efficient outcomes and still incentivize further cost reductions. That is, auctioneers should focus on reducing the possibility of inefficient outcomes and at the same time mitigate the risk of the ”winner’s curse” (Kreiss et al. 2017). The aim of using the GIS-data-based analysis tool is not only providing input for the auction model but also presenting realistic insights about the available potential of onshore wind in all federal states of Germany. Taken together, the results in terms of allocated capacity (Table 3) suggest building three scenarios based on the number of permissions in the previous years (2015-2017). Since the available potential of different states are dependent on the number of permissions in each state, the relation between the number of permissions and allocated capacity in each region is scrutinized in the following section. Accordingly, as was mentioned in section 3.1, the defined scenarios represent the potential for building new capacity in each year. Surprisingly, a noticeable remaining potential for the southern states of Germany was found (Table 3). Note that, as there is no available potential for building wind sites in the urban federal states of Berlin, Bremen, and Hamburg, an available potential of zero has been assumed for these regions (Fig. 5).

5.2. Diversity of bidders

This section evaluates the allocated capacity by federal state in different auction formats in 2018. Simulation results show a relationship between many permissions and investments in regions with lower conditions in the national auction. Since the southern states of Germany have higher investment costs for installing wind sites, increasing the number of permissions allows investors to build more profitable areas

Table 4: Diversity of bidders in different federal states [MW]

Region	Na1*	Na2	Na3	ReI1**	ReI2	ReI3	ReII1***	ReII2	ReII3
Baden-Wuerttemberg	352	318	53	72	209	209	88	249	394
Bavaria	880	672	0	220	885	885	220	660	1005
Berlin	0	0	0	0	0	0	0	0	0
Brandenburg	22	43	72	0	0	0	5.5	16.5	30
Bremen	0	0	0	0	0	0	0	0	0
Hamburg	0	0	0	0	0	0	0	0	0
Hesse	88	126	122	22	71.5	187	16.5	60.5	138
Mecklenburg-Western Pomerania	198	484	1008	49	261	49.5	148.5	400	0
Lower Saxony	132	249	414	0	0	0	33	82.5	191
North Rhine-Westphalia	44	98	139	11	38.5	93	11	38.5	69
Rhineland-Palatinate	44	54	63	11	33	93.5	11	27.5	44
Saxony	154	261	427	38	60	60	38.5	115.5	225
Saxony-Anhalt	110	144	249	0	0	0	37.5	71.5	120
Saarland	0	0	2.7	0	0	0	0	0	2.7
Thuringia	154	176	67	0	0	0	38.5	121	133
Schleswig-Holstein	66	144	288	0	0	0	16.5	44	0

* "Na" stands for national auction and the numbers are the scenario numbers.
** "ReI" stands for regional auction-type I.
*** "ReII" stands for regional auction-type II.

in the northern part. As an illustration, the lowest share of bidders is in the southern states in the third scenario for the national auction (Fig. 6). In contrast, results of the regional auctions imply that since there is no specific relation between the number of permissions and the allocated capacity, bidders in the southern states, and especially the two states with the highest available potential (i.e. Baden-Wuerttemberg and Bavaria) can install more capacity in their states (Fig. 6). So, in the regional auction, although the average cost level of bidders in Bavaria is higher than in other regions, investors tend to install their plants in this region much more frequently. Interestingly, a comparison of different auction designs illustrates that the available capacity of the southern states can be utilized in the regional auctions.

In the national auction, southern regions in Bavaria and Baden-Wuerttemberg lose 242 MW and 1179 MW auctioned of capacity in Scenarios 2 and 3, respectively. In contrast, the increased tendered capacity of these regions is 802 MW for both regional auction designs. Therefore, regional auctions can promote the participation of states regions with a higher LCOE. Another finding of this study is that regions such as North Rhine-Westphalia, Rhineland-Palatinate, Saxony, and Hesse featuring a middle range of LCOE (4-5 €-ct/kWh) can win in almost all auction formats. Furthermore, in some regions such as Brandenburg, Saxony, Saxony-Anhalt, Thuringia, and Schleswig-Holstein no further capacity expansion is essential to obtain regional targets. Consequently, they can be excluded from the regional auction which is in line with the aim of this auction design. It is worthwhile noting that since some federal states have exhausted onshore wind potentials, they have not been considered in these auctions.

5.3. Price development

This section presents the results of auction clearing prices in different auction formats. Although there are four auctions per year and one auction annually per national and regional auction design, respectively,

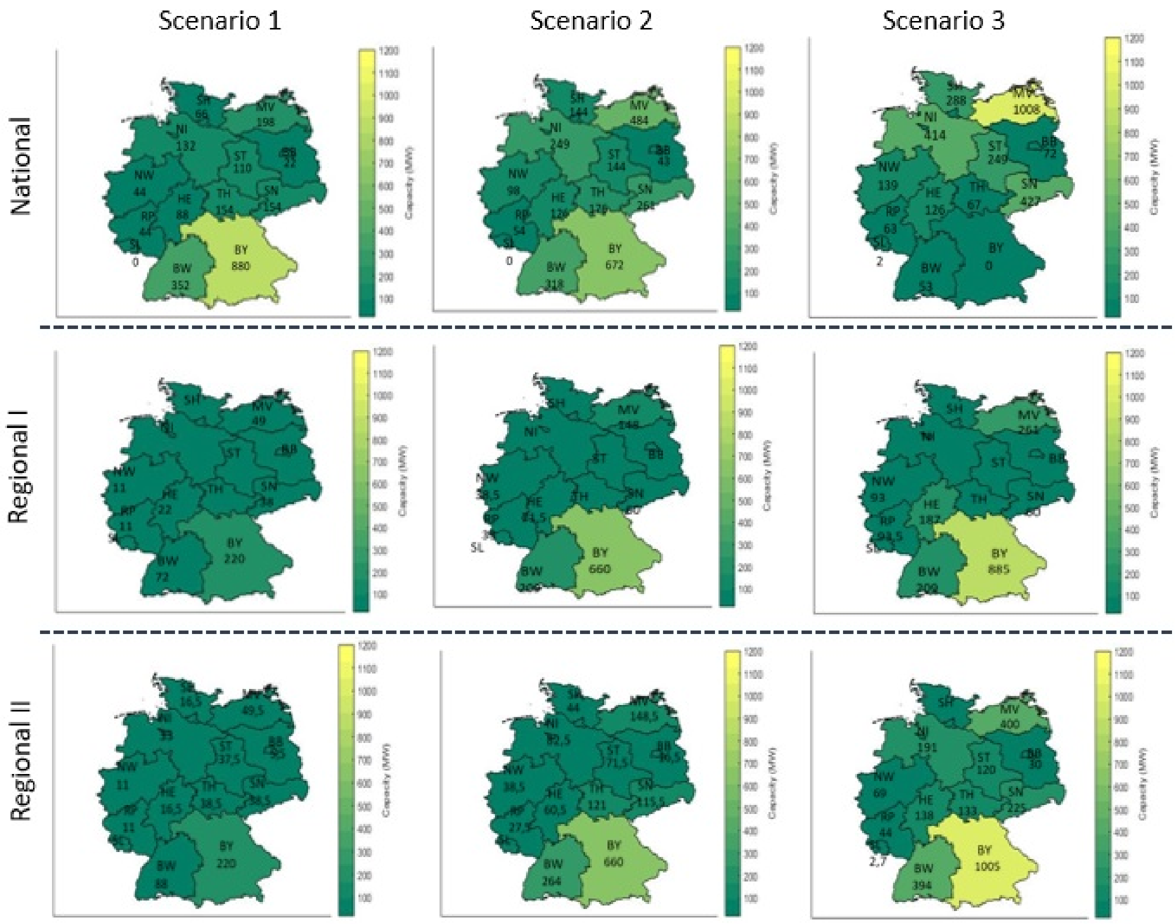


Figure 6: Diversity of bidders in all three regions and auction scheme scenarios (Source: Own calculations)

we compared the price development for 13 auction rounds. In other words, the impact of different time horizons has not been considered in this comparison. Fig. 7 shows the price development of 13 auction rounds for three scenarios. As can be seen in this figure, an increasing number of permissions leads to a lower average price. The reason behind this fact is that in Scenarios 2 and 3, more capacity is allocated to the northern states where lower LCOE prevail. Hence, the higher share of southern bidders causes an upward jump in the average price from the initial expectation of the market. Fig. 7 shows that the average price in Scenario 1 varies around 6 €-ct/kWh, which is 0.5 €-ct/kWh higher than Scenario 2. Excluding more bidders from locations with higher LCOE in the south of Germany can reduce the average price by at least 1.5 €-ct/kWh. On the one hand, when bidders are aware of the higher level of competition in the market, they bid lower in order to win in the market and, as a result, the average price of the last scenario shows the least change in the average price. On the other hand, since bidders with good locations (i.e. bidders with lower costs) are dominant in Scenario 3, and since their utilization ratio – which can be interpreted as the probability of losing in previous auctions being very low – the falling price pattern is unlike that of the other scenarios. However, these bidders decrease their bids slightly in the last auction rounds.

The simulation results of the second and third auction formats confirm that the general development of the three scenarios is akin to that of the national auction (Fig. 8a and Fig. 8b). Therefore, it can be concluded that an increasing number of permissions can decrease the average clearing price of an auction.

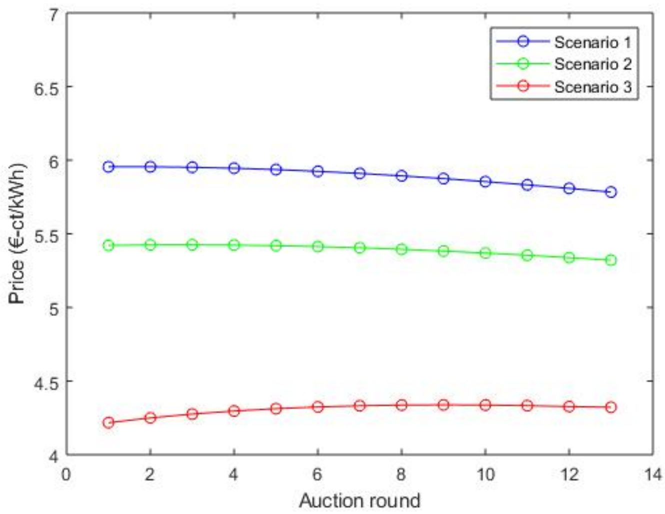
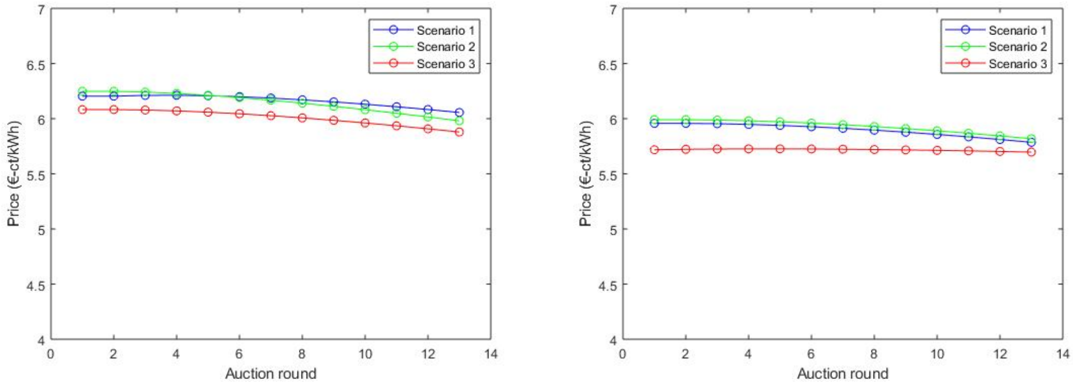


Figure 7: Average price in the national auction design, by scenario (Source: Own calculation)

Although differences between the different scenarios in the regional auctions are lower than those in the national auction, the relationship between the number of permissions and bidders' behavior is similar to that of the national auction. The average price in all scenarios of regional auction-type I varies between 6 €-ct/kWh and 6.5 €-ct/kWh. This trend reduces to a range between 5.5 €-ct/kWh and 6 €-ct/kWh for regional auction-type II. This 0.5 €-ct/kWh reduction stems from an increase in the participation of regions with a lower LCOE (see Table A2). On the one hand, one reason is that, in this auction format, more bidders with a higher LCOE can take part in the auction. On the other hand, the observed decrease in all scenarios could be attributed to learning effects and to a resulting decrease in the LCOE. Although a decrease of the LCOE is an exogenous parameter, the learning effect is simulated endogenously in the model. According to (Jeitschko 1998) there is a trade-off for bidders between increasing the probability of winning the early auction and being better informed and expecting an increased payoff in later auction rounds, so this trade-off induces bidders to bid lower. In this paper, since bidders learn from past events they bid lower in further auction rounds. The results of this analysis are in line with those of a strand of related literature (Jeitschko 1998; Engelbrecht-Wiggans et al. 1983; McAfee and Vincent 1993; Kannan 2010). Moreover, price trends of renewable energy auctions in many countries confirm this decreasing pattern (IRENA 2019).

5.4. Support payment

In this section, we assess the effect of the different auction designs studied here on the support payment. Although the profit maximization of wind power plant owners is a crucial determinant for motivating investors to build more wind power plants, auctions should also reduce the required total support payment. To do so, the support payment for all onshore wind power plants is simulated in HECTOR for the different auction formats. Hence, to analyze different auction designs, the time series for each region are used (full-load hours p.a. vary from 735 to 2732, depending on the region) and the sliding FIP is calculated in HECTOR for 20 years. The development of the average hourly electricity price in Germany from 2018



(a) (b)

Figure 8: Average price in the regional auctions, by scenario; (a): Regional auction-type I, (b): Regional auction-type II

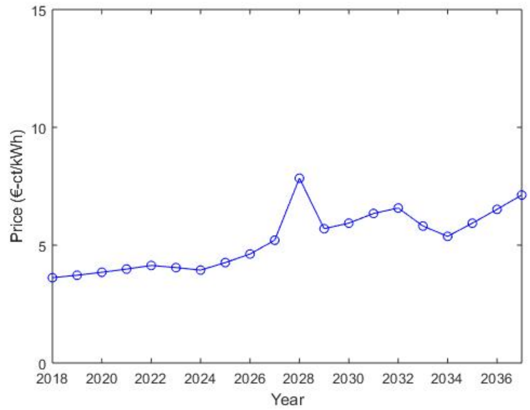


Figure 9: The average yearly electricity price over 20 years in Germany, 2018-2037 (Source: output of large-scale model HECTOR)

until 2037 is illustrated in Fig. 9. This coupling increases the accuracy of the model compared to other studies which have used simply a constant exogenous average price (Anatolitis and Welisch 2017). As described in section 3.2, if the difference between the onshore wind auction price and the average spot market falls below zero, wind installation will not receive any support payment in the market. Thus, the accuracy of spot price projection can influence the results substantially. This calculation is conducted using installed capacities in the first year of auction round. An analysis of the support payment reveals that increasing the number of permissions leads to different support payment trends in different auction formats.

In the national auction, by increasing the number of permissions, bidders with a lower LCOE dominate the market. Simulation results show a 2% and a 73% reduction in support payments in Scenario 2 and Scenario 3, respectively. The major decrease in the share of bidders from the south of Germany could be the reason for this downward jump in the support payment.

In the regional auction-type I, the support payment increases when permission numbers are higher. The support payment for this auction design soars from €5.85 million in Scenario 1 to €17.52 million and €24.09 million in Scenarios 2 and 3, respectively. An increased share of the southern states with higher LCOE is the primary cause of this increase. However, the regional auction-type I has the lowest support payment compared to other auction formats in Scenarios 1 and 2.

Table 5: Support payment over the 20 years's lifetime of a wind farms in all regions [million €]

Region	Na1	Na2	Na3	ReI1	ReI2	ReI3	ReII1	ReII2	ReII3
Baden-Wuerttemberg	6.13	5.37	0	1.29	3.76	3.75	1.58	4.74	7.31
Bavaria	16.28	13.43	0	4.08	12.24	16.42	4.08	12.24	18.41
Berlin	0	0	0	0	0	0	0	0	0
Brandenburg	0.08	0.15	0.25	0	0	0	0.02	0.06	0.12
Bremen	0	0	0	0	0	0	0	0	0
Hamburg	0	0	0	0	0	0	0	0	0
Hesse	1.09	1.34	0.56	0.27	0.84	2.19	0.04	0.64	0.87
Mecklenburg-Western Pomerania	0.002	0.005	0.01	0	0	0	0	0	0
Lower Saxony	0.22	0.41	0.69	0.04	0.14	0.34	0.05	0.15	0.31
North Rhine-Westfalia	0.17	0.36	0.53	0.04	0.14	0.19	0.04	0.14	0.26
Rhineland-Palatinate	0.40	0.47	0.55	0.10	0.37	0.98	0.10	0.25	0.41
Saxony	0.75	1.32	1.90	0.017	0.02	0.02	0.18	0.59	1.06
Saxony-Anhalt	0.66	0.94	1.31	0	0	0	0.16	0.43	0.75
Saarland	0	0	0.01	0	0	0	0	0	0
Thuringia	1.76	2.19	1.07	0	0	0	0.44	1.47	1.68
Schleswig-Holstein	0	0	0	0	0	0	0	0	0
Sum of regions	27.6	26.02	7.30	5.85	17.52	24.09	6.86	20.75	31.27

Analogously to the regional auction-type I, the support payment increases when more permissions are issued by the auctioneer in the regional auction-type II. The support payment in this auction design surges from €6.86 million (Scenario 1) to €20.75 million in Scenario 2 and €31.27 million in Scenario 3. Having allocated more FIPs for bidders from southern regions with a higher LCOE in this auction format causes rather high support payments for the third auction design compared to the second one.

Table 6 illustrates the support payment per unit of installed capacity in all federal states of Germany. In the national auction, the support payment per unit of installed capacity of all scenarios are approximately similar. We observe that this indicator does not change markedly for the three scenarios of the regional auctions niether. Interestingly, on combining different auction designs with different scenarios based on the level of competition, we deduce that regional auctions do not cause considerably higher support payments per unit of installed capacity in any region. However, since the installed capacity of the southern states in the national auction are zero they do not receive any support payment. Hence, as regional auctions do not need considerably higher support payment per unit of installed capacity, the authors recommend policy-makers to exploit them in their long-term renewable policies.

All in all, an analysis of the support payments implies that in a situation where the level of participation of bidders is low or medium both of the regional auction designs have superiority over the national auction design from the perspective of saving on the support payment. In addition, since these regional auction formats can improve participation of bidders from regions with a higher LCOE, policy-makers are recommended to implementing regional auctions that are compatible with the regional characteristics of energy systems.

Table 6: Support payment per unit of installed capacity [k€/MW]

Region	Na1	Na2	Na3	ReI1	ReI2	ReI3	ReII1	ReII2	ReII3
Baden-Wuerttemberg	17.41	16.88	0	17.91	17.99	17.94	17.95	19.03	18.55
Bavaria	18.50	19.98	0	18.54	13.83	18.55	18.52	18.54	18.31
Berlin	0	0	0	0	0	0	0	0	0
Brandenburg	3.63	3.48	3.47	0	0	0	3.88	3.63	4
Bremen	0	0	0	0	0	0	0	0	0
Hamburg	0	0	0	0	0	0	0	0	0
Hesse	12.38	10.63	4.59	12.27	11.74	11.71	10.74	10.57	6.30
Mecklenburg-Western Pomerania	0.01	0.01	0.009	0	0	0	0.003	0	0
Lower Saxony	1.66	1.64	1.66	0	0	0	1.73	1.81	1.62
North Rhine-Westphalia	3.86	3.67	3.81	3.63	3.63	2.04	3.97	3.63	3.76
Rhineland-Palatinate	9.09	8.70	8.73	9.09	11.21	10.48	9.26	9.09	9.31
Saxony	4.87	5.05	4.44	0.44	0.33	0.33	4.93	5.10	4.71
Saxony-Anhalt	6	6.52	5.26	0	0	0	4.43	6.01	6.250
Saarland	0	0	3.70	0	0	0	0	0	0
Thuringia	11.42	12.44	15.97	0	0	0	11.48	12.14	12.63
Schleswig-Holstein	0	0	0	0	0	0	0	0	0

5.5. Discussion

Previous RES auctions in Germany (ground-mounted PV pilot) show lower prices compared to the previous fixed level of support (Anatolitis and Welisch 2017). The simulation results of this paper stress that based on the selected scenario the support level of different auction designs can vary noticeably. Consequently, we recommend performing a counterfactual analysis for different auction formats by means of well-designed scenarios. We use three scenarios based on the number of permissions in previous auction rounds in Germany, although using more scenarios would represent probable auction outcomes more realistically.

The renewable energy auction model has several limitations. In this study, we considered 42 groups of wind power plants which are located in different regions of Germany based on their wind speed categories. The plant configurations for these wind power plants are based on the accepted wind farm of each region in the last version of German Wind Guard (2018) (WindGuard 2018). Although wind power plants have reached a mature status regarding their hub heights, rotor diameters, and specific power learning curves can impact these parameters slightly in the future. As a result, instead of defining many agents as investors, we assume that these groups of wind power plants can represent the behavior of investors of the respective regions in the market. Another reason could be that this simulation is conducted with SD and, since we model it from a macro perspective, the average behavior of the system is considered to be the main influencing factor for the decision making of wind power plant owners. Although SD is a suitable tool for modeling complex systems, it does have some limitations regarding the modeling of unquantifiable parameters. In the real world, wind farm decisions are made by humans. Hence, many soft factors – such as irrational behavior, complex psychological features, and regulatory issues – can influence bidders' behavior as well. Since it is challenging to model most of these parameters quantitatively (Bonabeau 2002), we have used a noise function in the auction model to include such uncertainties. In other words, companies have to consider the game-theoretic nature of auctions when bidding. Their behavior and bidding strategy will influence the other players' future behavior in the market and a favorable short-term result may not be beneficial in the long term. Therefore, the more market structures are defined quantitatively in the model, the more accurate the results can be expected to be.

On account of the fact that we use the simulation module for the renewable energy auction, we do not exactly optimize bidders' costs/benefits in these auctions. Instead, we use an allocation function that allocates a tendered capacity regarding bidders' priority. Having defined the priority function of bidders based on their LCOE, we simulate the clearing logic of the auction. Therefore, as long as the market is competitive and suppliers do a good job in forming expectations, the market outcome will be pretty close to what this allocation function yields without this behavioral detail.

Hourly electricity prices in further years is one of the significant factors in the calculation of the support payment. Unlike previous studies, which used approximation of hourly electricity prices and full-load hours (Anatolitis and Welisch 2017; Bichler et al. 2019), we used a large-scale model for this purpose. Hence, although this coupling enriches the accuracy of the research, it should be noted that the outcomes of auctions and support payments are related to the occurred prices in reality. By this end, using various well-designed scenarios can increase the robustness of the results and give a better outlook for both the future of the electricity market and that of renewable energy auctions.

Finally, another important limitation is related to the lack of transmission constraints among the German federal states in the model. Since one of the main drivers for proposing alternatives for the current auction design is that of transmission congestion, the inclusion of this significant parameter in the model can add value to the current research.

6. Conclusion and policy implications

The main purpose of the renewable energy auction is to support the expansion of renewable energy as an important element of the sustainable energy transition. This paper focuses specifically on the onshore wind auction. This auction not only targets the expansion goals and the controlling of new electricity production capacity but also the diversity of stakeholders. To this end, auctions should provide a fair opportunity for all stakeholders to take part in auctions, adequately considering their wind power potential in the areas where they have been installed. In this paper, we outline the impact of three different auction formats – the national auction, a regional auction-type I (federal state level) and a regional auction-type II (north/south auction) – on allocative efficiency and support payments using a novel multi-stage approach. Initially, we investigate the available onshore wind energy potentials with high temporal and spatial resolution in Germany. The results of the case study demonstrate that using a higher regional resolution model can lead to a higher share of the southern states of Germany, where the LCOE is higher. Then we propose a SD approach for modeling the capacity auction of renewable energy with a focus on the German onshore wind power market. The prerequisite for the implementation of a successful auction is the considerable qualitative difference between bidders. Our findings highlight that more bidders from the south of Germany can win in regional auctions, and regional targets of each federal state can be achieved. However, we find a trade-off between increasing shares of bidders from the southern states (a higher LCOE) and the average auction price because the average price of bidders in these auctions is slightly higher than that in the national auction (depending on the scenario, it varies from 0.5 €-ct/kWh to 1.5 €-ct/kWh). In the last stage, coupling renewable energy auctions with a large-scale model shows that regional auctions receive lower support payments when permission numbers are at the low and medium level. In the first scenario, the potential cost savings on the support payment are €21.75 million and €20.85 million for regional auction-type I and regional auction-type II, respectively. This saving is €8.5 million and €5.27 million for regional auction-type I and type II in Scenario 2. However, the national auction provides more saving compared to regional auctions in Scenario 3 (€17.9 million and €23.97 million). Regarding further applications of the proposed auction designs and proposed multi-stage analysis, they can be used in any other country where the electricity system faces an unbalanced distribution of renewable energy technologies. In countries where the use of renewable energy auctions is thriving, it might also be utilized by system planners in order for them to accurately identify the integration costs of renewable energies in the electricity system. The novel coupling of renewable energy auctions and large-scale energy systems can be beneficial for long-term studies with high shares of variable renewable energies. For future studies, simulating bidders' behavior towards fundamental changes (e.g. nuclear and coal phaseout in Germany) in the market can be conducted. Taking transmission constraints between regions into account, and performing a sensitivity analysis, can further enhance the robustness of support payment results.

7. Data availability

Data is used from the 4NEMO project data base, the REMix model, German government reports, and government websites. Please contact the corresponding author for details. A list of sources and the full dataset are available from the authors upon request.

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Appendix A. Model assumptions

Table A1: Distribution of capacity expansion by federal state (Grimm et al. 2017)

Region	MaxW
Baden-Wuerttemberg	13.7%
Bavaria	35.2%
Berlin	0.5%
Brandenburg	0
Bremen	0
Hamburg	0
Hesse	16.2%
Mecklenburg-Western Pomerania	7.8%
Lower Saxony	0
North Rhine-Westphalia	11.5%
Rhineland-Palatinate	6.7%
Saxony	4.9%
Saxony-Anhalt	0
Saarland	3.5%
Thuringia	0
Schleswig-Holstein	0

Table A2: Classification of regions based on wind speeds

Region	Wind speed classes
Baden-Wuerttemberg	4 m/s, 5 m/s, 6 m/s, 7 m/s
Bavaria	4 m/s, 5 m/s, 6 m/s, 7 m/s, 8 m/s
Berlin	NA
Brandenburg	6 m/s, 7 m/s
Bremen	NA
Hamburg	NA
Hesse	5 m/s, 6 m/s, 7 m/s, 8 m/s
Mecklenburg-Western Pomerania	6 m/s, 7 m/s, 8 m/s
Lower Saxony	6 m/s, 7 m/s , 8 m/s
North Rhine-Westphalia	6 m/s, 7 m/s , 8 m/s
Rhineland-Palatinate	5 m/s, 6 m/s, 7 m/s, 8 m/s
Saxony	6 m/s, 7 m/s, 8 m/s
Saxony-Anhalt	6 m/s, 7 m/s, 8 m/s
Saarland	6 m/s, 7 m/s
Thuringia	5 m/s, 6 m/s, 7 m/s, 8 m/s
Schleswig-Holstein	7 m/s, 8 m/s

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