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Discriminatory auction design for renewable energy

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Discriminatory Auction Design for Renewable Energy

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Discriminatory auction design for renewable energy

Mats Kröger* Karsten Neuhoff* Jörn C. Richstein†

July 25, 2022

Abstract

Designing auctions that favor low resource quality installations allows countries to geographically diversify their renewable energy production, while lowering payments to low-cost producers. In this paper, we develop a stylized model showing that a discriminatory auction design favoring low-wind-yield locations leads to a trade-off between production costs and producer rent and that the scheme can lower consumer costs even without considering the positive externalities of distributed generation. We explore the influence of the heterogeneity of production costs, the strength of the adjustment, and the regulator's knowledge about cost structures. Through a numerical analysis of the German reference yield model, we estimate that at current auction levels intra-technology discrimination through the reference yield model leads to a reduction of consumer costs of around 24.8 billion Euro or 13% between 2023 and 2030.

Keywords: climate policy, auctions, renewable energy, onshore wind power, reference yield model

JEL Codes: D44, Q42, Q48, Q54

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1 Introduction

Designing auctions that cost-effectively award support for renewable energy is crucial for achieving decarbonization goals at a minimal burden on consumers. Minimizing consumer cost is an important objective for governments since support schemes for renewable energy have a regressive distributional effect if they raise electricity prices (Neuhoff et al., 2013, Grösche and Schröder, 2014, Frondel et al., 2015) and since studies indicate that poorly designed renewable support schemes and market power can lead to excess profits for producers (Helm, 2010, Espinosa et al., 2021). At the same time the ambitious targets for renewable energy production, that have been announced by European governments, raise the question of where the additional production capacity will be located. Existing support schemes often lead to an inefficient concentration of renewable energy installations since, for instance, the low-cost potential for onshore wind power is often concentrated geographically (Newbery, 2021). The concentration creates the need for additional transmission lines or frequent, costly interventions to counteract the congestion of transmission infrastructure (Eicke et al., 2020). Additionally, the negative externalities of wind power are local while the positive externalities of wind power such as reduced fossil fuel import dependency are national, or in the case of reduced pollution even global. These local externalities, for example, the visual impact of wind turbines, can lead to resistance against additional installations and slow down or even prevent their construction (Zerrahn, 2017).

This paper analyzes the potential of intra-technology discrimination in auctions for renewable energy to induce a more even spatial distribution of installations while minimizing consumer costs. We define intra-technology discrimination as a bonus-and-penalty system that distinguishes between bidders of high and low resource quality, which is a characteristic observable to the regulator. This discriminatory auction design has two opposing effects on consumer costs. On the one hand, increased price competitiveness shifts the result in favor of bidders with lower resource quality that have higher production costs. On the other hand, the disclosure of resource quality allows for price discrimination, thereby reducing the producer rent of installations with higher resource quality. We develop a stylized model that captures this trade-off in a continuous setting thereby extending on existing analysis in a discrete setting (Fabra and Montero, 2020, Kreiss et al., 2021). We show that an increased heterogeneity of the observed cost component (i.e., the resource quality) and larger auction volumes increase the benefit of intra-technology discrimination, while a larger influence of the non-observed cost component reduces the benefit. Subsequently, we conduct a numerical analysis of the German auctions for renewable energy to test and quantify our hypotheses under real-world parameters.

The policy considered in the numerical analysis is the so-called *reference yield model*

(in German: *Referenzertragsmodell*) which introduces a bonus for bids from low wind speed regions and penalties for high wind speed regions in the German auctions for onshore wind energy. Germany is a relevant case study for the implementation of intra-technology discrimination since the German government stated the dual objective to rapidly grow its production capacity of onshore wind and to expand wind generation in areas with lower wind speeds in its 2021 coalition agreement. In our numerical analysis, we find that the reference yield model leads to a reduction in consumer costs even when the positive externalities of a more distributed generation of renewable energy are not considered. We estimate that the reference yield model leads to a reduction of consumer costs in the range of 24.8 billion Euro between 2023 and 2030, which is equivalent to a 13% reduction compared to the counterfactual in which the auctions are conducted without intra-technology discrimination.

The analysis presented in this paper relates to two strands of the literature. First, it relates to the literature on the application of auction theory to the allocation of support for renewable energy. Fabra and Montero (2020) analyze the difference between technology-neutral and technology-specific auctions. They identify the trade-off that technology-specific auctions lead to the support of less-efficient installations, while technology-neutral auctions allow the low-cost technology to capture producer rents. They find in a two technology model that a larger cost difference between technologies and a higher cost of public funds favor technology-separation while an increase in uncertainty regarding technology costs favors technology neutrality. They show that technology banding, which is an approach similar to the policy discussed in this paper, and technology specificity are welfare equivalent and dominate technology neutrality in the absence of uncertainty. However, when uncertainty concerning the technology costs is included, the choice between technology-specific auctions and technology-banding depends on the correlation between the costs of the two technologies. Kreiss et al. (2021) consider the difference between technology-neutral and technology-specific auctions focusing on how the allocation between two technologies changes with discriminatory pricing elements under a fixed quantity. They show that a discriminatory auction design can improve the auction outcome by preventing windfall profits for low-cost producers. The authors argue that discriminating between technologies can lead to a reduction in overall costs and that the performance of quality-based discrimination depends on the regulator's level of information about the technologies' cost structures. The trade-off between efficiency and producer rent is also reflected in the general academic discussion of support for renewable energy and the difference between technology-neutral and specific support schemes, such as Del Río and Cerdá (2014), Del Río (2017), and Lehmann and Söderholm (2018).

Second, the numerical analysis of our paper relates to the literature discussing the

effect of the German reference yield model. Engelhorn and Müsgens (2021) analyze the reference yield model based on a numerical simulation of counterfactual auction designs that they compare to the historic development. The authors find that the costs of the German energy transition would have been reduced by 30% for a cost-minimizing benchmark scenario.¹ Hitaj and Löschel (2019) analyze the effect of the German feed-in tariff on renewable deployment between 1996 to 2010 and, as part of their econometric analysis, consider a counterfactual scenario in which the reference yield model is replaced with a uniform support scheme. They find that the location-specific feed-in-tariff slightly reduces support costs compared to a uniform incentive due to the price-discrimination effect which outweighs the reduction in production. Bichler et al. (2020) use a numerical simulation to compare different regulatory options for renewable auctions in Germany. As the analysis focuses on regional specific auctions, it assumes that market participants bid at marginal costs in a pay-as-bid auction. Under this assumption they find that the reference yield model leads to higher allocational efficiency, measured in the allocation of capacity to states with a capacity below the system-optimal value, but increases costs by 5.4 - 7.2% compared to a nation-wide auction design without location-specific incentives. In addition, there are a number of policy reports that discuss the potential effects of the reference yield model (Agora Energiewende, 2014, Bundesministerium für Wirtschaft und Energie, 2015, Deutsche Windguard, 2019, Bundesministerium für Wirtschaft und Energie, 2020).

Our paper contributes to this literature in a number of ways. First, we capture the trade-off between efficiency and rent extraction in a stylized, continuous setting. We show that the effect observed in papers on discrimination between two technologies exists for the continuous setting of intra-technology discrimination as well. Second, the existing numerical analyses of the reference yield model obtained mixed results. By being the first paper to combine a theoretical and numerical analysis of the policy, we quantify the effects on producer rent and production cost, while also deriving conditions under which either effect might prevail. Thereby, we can show how differing assumptions in the existing literature lead to the converging results.

The rest of the paper is structured as follows. In Section 2, we introduce the institutional setting of our analysis. In Section 3, we present a theoretical model analyzing the effects of intra-technology discrimination via a continuous bid bonus in auctions for renewable energy. Section 4 presents a Monte-Carlo simulation of the German wind energy auctions to test the hypotheses derived from the theoretical model and to estimate the reduction or increase in consumer costs that is caused by the reference yield model.

¹For a second scenario considering land-use, building capacity, and acceptance constraints they find a cost reduction of 23%.

Section 5 concludes.

2 Institutional Setting

Table 1: Results from past auctions (Bundesnetzagentur, 2021b)

| Date | Auction Volume (MW) | Offered Volume (MW) | Minimum Bid (ct/KWh) | Maximum Bid (ct/KWh) | Strike Price (ct/KWh) |
|----------|---------------------|---------------------|----------------------|----------------------|-----------------------|
| 01.05.17 | 800 | 2,137 | 4.2 | 7.0 | 5.8 |
| 01.08.17 | 1,000 | 2,927 | 3.5 | 6.5 | 4.4 |
| 01.11.17 | 1,000 | 2,591 | 2.2 | 6.7 | 3.9 |
| 01.02.18 | 700 | 989 | 3.8 | 6.3 | 5.3 |
| 01.05.18 | 670 | 604 | 4.3 | 6.3 | 6.3 |
| 01.08.18 | 670 | 709 | 4.0 | 6.3 | 6.3 |
| 01.10.18 | 670 | 388 | 5.0 | 6.3 | 6.3 |
| 01.02.19 | 700 | 499 | 5.2 | 6.2 | 6.2 |
| 01.05.19 | 650 | 295 | 5.4 | 6.2 | 6.2 |
| 01.08.19 | 650 | 239 | 6.2 | 6.2 | 6.2 |
| 02.09.19 | 500 | 188 | 6.2 | 6.2 | 6.2 |
| 01.10.19 | 675 | 204 | 6.2 | 6.2 | 6.2 |
| 01.12.19 | 500 | 686 | 5.7 | 6.2 | 6.2 |
| 01.02.20 | 900 | 527 | 5.8 | 6.2 | 6.2 |
| 01.03.20 | 300 | 194 | 5.7 | 6.2 | 6.2 |
| 01.06.20 | 826 | 468 | 5.9 | 6.2 | 6.2 |
| 01.07.20 | 275 | 191 | 5.5 | 6.2 | 6.2 |
| 01.09.20 | 367 | 310 | 6.0 | 6.2 | 6.2 |
| 01.10.20 | 826 | 769 | 5.6 | 6.2 | 6.2 |
| 01.12.20 | 367 | 657 | 5.6 | 6.2 | 6.1 |
| 01.02.21 | 1,500 | 719 | 5.2 | 6.0 | 6.0 |
| 01.05.21 | 1,243 | 1,161 | 4.5 | 6.0 | 6.0 |
| 01.09.21 | 1,492 | 1,824 | 5.2 | 6.0 | 5.9 |
| 01.02.22 | 1,328 | 1,356 | 4.8 | 5.9 | 5.9 |

The setting for our study of intra-technology discrimination are the auctions for the support of onshore wind power in Germany. Scenario calculations for the German power system place the production of onshore wind power in 2050 at up to 413 TWh/year, which would require to quadruple the production compared to 2021 (Sensfuß et al., 2021). Germany’s support system for renewable energy has developed over many years, with support regulated by the renewable energy act (in German: *Erneuerbare Energien Gesetz*). While the renewable energy act initially supported onshore wind power through an administratively set feed-in tariff, this changed with the 2017 reform. The reform introduced tendering through auctions to incentivize cost-efficiency and introduced market elements to the support of renewable energy sources. The auctions are conducted as technology-specific, pay-as-bid auctions and include a price-cap that is dynamically adjusted based on the previous auctions’ results (Deutsche Windguard, 2019).²

²In addition to the technology-specific auctions, joint multi-technology auctions for onshore wind and solar power were conducted as a pilot from 2018-2020.

Between 2017 and 2022, Germany has conducted more than 20 technology-specific auctions for onshore wind energy in which the reference yield model was applied. Table 1 summarizes the auction results for the technology-specific auctions. The auction system struggled with undersubscription starting in 2018, which led to bids converging at the price cap of 6.20 cents per kWh and, subsequently, only moving when the price cap was adjusted downwards. Since 2021, some auctions have seen slightly increased competition. During the competitive auctions at the beginning of the auction period, prices had conversely fallen to a level under 4 ct/kWh.

Onshore wind power in Germany is an appropriate setting for studying intra-technology discrimination due to the difference in production costs between different locations. Figure 1 shows the average full load hours for all German municipalities. The figure illustrates that the high-quality potential (i.e., those areas with high wind speeds and full load hours) is concentrated along the coasts and that the site-quality decreases toward southeastern Germany. A similar pattern is visible for the existing production of onshore wind power in which the southeastern states have significantly lower capacity of wind power per square meter (Deutsche Windguard, 2019). The uneven geographic distribution of renewable production in combination with the intermittent nature of the production induces a significant externality for renewable energy. On the one hand, the concentration of capacity in areas far away from load centers can require curtailment of the renewable production due to network constraints. This introduces costs due to the need for re-dispatch in the short-term. On the other hand, the concentration requires investment in network capacity in the long-term, which leads to costs for society (Eicke et al., 2020). For the case of Germany, the cost of re-dispatch is estimated to be 220 million Euro in 2020 (Bundesnetzagentur, 2021a).

By incentivizing cost-efficiency without considering congestion costs, auctions have the potential to reinforce this pattern, leading to an even greater concentration of renewable energy production. To avoid this, Germany uses three instruments meant to introduce a more-equal distribution of installations that are debated in Eicke et al. (2020) and Deutsche Windguard (2019). The quota for bids from municipalities in Southern Germany ("Südregion") is meant to increase the number of accepted bids from the areas in the south that have historically seen limited wind power development. It states that at least 15% (from 2024: 20%) of supported projects must be located in these southern municipalities.³ The distribution grid component (German: "Vetelernetzkompete") is

³Before the 2021 revision of the Renewable Energy Act, the predecessor of the quota for southern bids were the so-called grid extension areas (German: "Netzausbaugebiete") that limited the addition of onshore wind power in certain northern municipalities to 902 MW per year. This posed a quantity cap on bids from these areas and was meant to reduce the strain on the North-South transmission lines until further

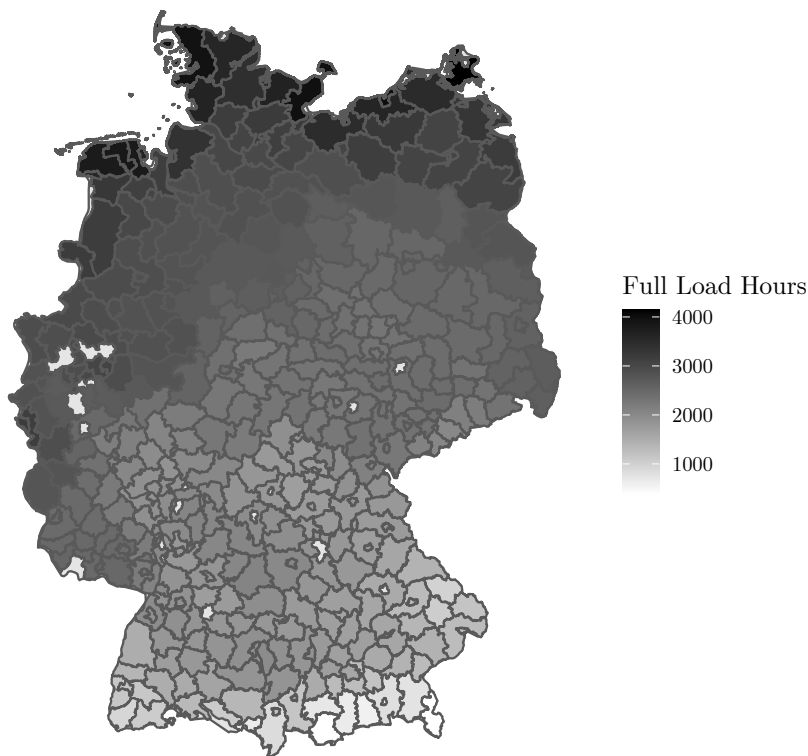


Figure 1: Distribution of resource quality for onshore wind (measured in full load hours) in Germany, own calculations

only considered in the multi-technology tenders for wind and solar power. It consists in a bid penalty to bids from municipalities in which the installed capacity for renewable energy already exceeds the maximum load. Finally, the reference yield model (German: “Referenzertragsmodell”) consists of a combination of a bid bonus for low-quality locations and a bid penalty for high-quality wind locations. The reference yield model is only applied in the technology-specific tenders for onshore-wind and is the focus of the subsequent analysis.

The reference yield model has formed part of Germany’s support scheme for renewable energy since the introduction of the renewable energy act in 2000 and was adapted for use in auctions in 2017. It intends to partially reduce the disadvantages of low-quality wind locations by introducing the concepts of reference yields and their corresponding correction factors. The reference yield model compares the full load hours that a turbine would produce over the course of five years at its intended location to the full load hours that the same turbine would achieve at the so-called reference location. The reference location is defined based on a number of characteristics such as an average annual wind speed of 6.45 meter per second at a height of 100 meters. The full load hours that a capacity was added.

turbine is expected to produce at its intended location is then divided by the reference yield of that turbine and the project is assigned a correction factor according to the mapping in Table 2. To avoid fraudulent behavior, the revenue at the specific location is controlled after five, ten, and fifteen years. If it deviates from the estimated yield at the time of the bid, the correction factor and the payments made to the installation are adjusted accordingly.

Table 2: Reference yields and correction factors

| % of reference yield | 60% | 70% | 80% | 90% | 100% | 110% | 120% | 130% | 140% | 150% |
|--------------------------|------|------|------|------|------|------|------|------|------|------|
| Correction factor | 1.35 | 1.29 | 1.16 | 1.07 | 1 | 0.94 | 0.89 | 0.85 | 0.81 | 0.79 |

Once generators have placed their bids, these are divided by the correction factor and the winners are selected based on the adjusted bids. However, the subsequent support payments are based on the actual bids rather than the adjusted ones. This implies that installations at worse locations are able to receive higher support payments than installations with a high wind yield, which introduces price discrimination among the projects. At the same time, the policy leads to the selection of projects at low wind-speed locations, thus leading to higher production costs. This introduces a trade-off that we analyze in the following section.

For revenues below 60 and above 150% of the reference location, the maximum and minimum factors of 1.35 and 0.79 are applied. Therefore, the reference yield model has no effect on very high and very low-quality wind locations. This introduces a discontinuity for the lowest and highest performing installations. In our subsequent analysis, we disregard this discontinuity, thereby assuming that such projects with very high yields are either always accepted while projects at the lower end of the yield curve are never accepted at all. This assumption is supported by data showing that 85% of wind installations in Germany have a reference yield exceeding 70% (Fachagentur Wind, 2016).

3 Stylized Model

To analyze the effect of an intra-technology discriminatory auction design, such as the reference yield model, we propose a stylized model of a regulator awarding support to renewable energy installations through a uniform price auction. Thereby, we illustrate that the trade-off between ensuring efficiency and limiting producer rents that has been described by Fabra and Montero (2020) and Kreiss et al. (2021) for a discrete case of discrimination between two technologies holds for a simplified, continuous case where bid bonuses are used to increase intra-technology competition. Using this stylized model, we

Table 3: Parameters of the theoretical model

| Parameter | Definition | Interpretation | Unit |
|--------------------------|---|--|--------------|
| PC | Production costs | Costs of all projects accepted for production. Calculated as the interval of individual costs $c_i(w_i, \theta_i)$. See Appendix A.1 for a detailed derivation. | Euro |
| PR | Producer rent | Difference between the remuneration and costs of all instalations. See Appendix A.2 for a detailed derivation. | Euro |
| CC | Consumer Costs | Sum of producer rent and production costs | Euro |
| a | Intercept, $=C(0,0)$ | The point where $w = 0$ and $\theta = 0$, i.e. the cost of the reference plant. | Euro |
| b | Slope, $b = \frac{\delta c(\theta, w)}{\delta w}$ | The slope of the cost curve with respect to the resource quality | Euro/ MWh |
| w | Resource quality | The resource quality at a particular location defined as the production in MWh over a five-year period. $w \in (\underline{w}, \bar{w})$. | MWh |
| θ | Other costs | Costs that are not dependent on the site quality (e.g., financing costs) and that are not considered by intra-technology discrimination, $\theta \in (0, \bar{\theta})$. | Euro |
| g | Adjustment Factor | Indicates how strong the costs are adjusted by the intra-technology discrimination, $g = 1$ implies that there is no adjustment, $g = 0$ implies that all locations have the same price. | - |
| Q^* | Auctioned quantity | Q^* indicates the maximum capacity that is awarded in an auction. | MWh |
| $\bar{c}(Q^*)$ | Cost of last unit | Cost of the last unit that is still awarded in an auction, depending on the total awarded capacity Q^* . | EUR |
| \hat{w}, \hat{w}^{RYM} | Resource quality of last unit | Resource quality of the last unit that is still awarded support in the base case (\hat{w}) or under technology discrimination (\hat{w}^{RYM}). | MWh |
| $\tilde{w}(\theta)$ | - | Resource quality of the last unit that is still awarded depending on the value of the unknown cost component θ . | MWh |

compare how consumer costs change with and without the policy and examine the trade-off between efficiency and rent extraction described in previous papers. Subsequently, we analyze how the effect size and direction changes based on the parameters of the model listed in Table 3.

3.1 Setting and Expected Effects

We are interested in comparing the change in consumer cost Δ_{CC} that arises after the introduction of intra-technology discrimination via a continuous bid bonus, like the reference yield model. Therefore, we consider the procurement decision of a regulator that

aims to minimize cost to consumers in two cases: A base case and a case of intra-technology discrimination (referred to as RYM). From the view of the regulator, project costs depend on a verifiable parameter w and an unobservable parameter θ . The model parameters and their interpretation are listed in detail in in Table 3.

$$\begin{aligned} \Delta_{CC} = CC_{RYM} - CC_{BaseCase} = & \underbrace{(PC_{RYM} - PC_{BaseCase})}_{\text{Effect 1: Inefficient selection of sites, } \Delta_{PC}} \\ & + \underbrace{(PR_{RYM} - PR_{BaseCase})}_{\text{Effect 2: Reduced producer rent, } \Delta_{PR}} \end{aligned}$$

The relevant outcome of the stylized model, the **difference in consumer cost** Δ_{CC} , can be decomposed into two separate effects. First, we are capturing the **increase in production cost** Δ_{PC} that arises due to a less efficient choice of supported installations. This inefficiency is caused by the unobservable cost component θ since the bid bonus is solely based on cost component w . Hence, it leads to a shift of the bid curve around the reference point and increases the competitiveness of projects at low wind-speed locations. This leads to a higher production costs of selected projects when the continuous bid bonus is applied in the auction. The effect is shown schematically in Figure 2 for a reference point of $w = 0$.

Second, we capture the **effect of decreased producer rent** Δ_{PR} due to the introduction of price discrimination. The bid bonus requires the auction's participants to disclose their resource quality w_i , thus allowing for price discrimination based on this cost component. This leads to lower payments being made to the installations, thereby reducing consumer costs. Since the resource quality is verifiable, there is no incentive to misreport w_i . The difference between these two effects determines whether the introduction of a bid bonus leads to a reduction in consumer costs.

Thus, the stylized model aims to capture the trade-off between the upwards effect on producer costs (i.e., the introduction of an inefficient selection of sites) and the downwards effect on producer rent, that has previously been described for the case of discrimination between two different technologies, for a simplified, continuous case of intra-technology discrimination between projects of different resource qualities.

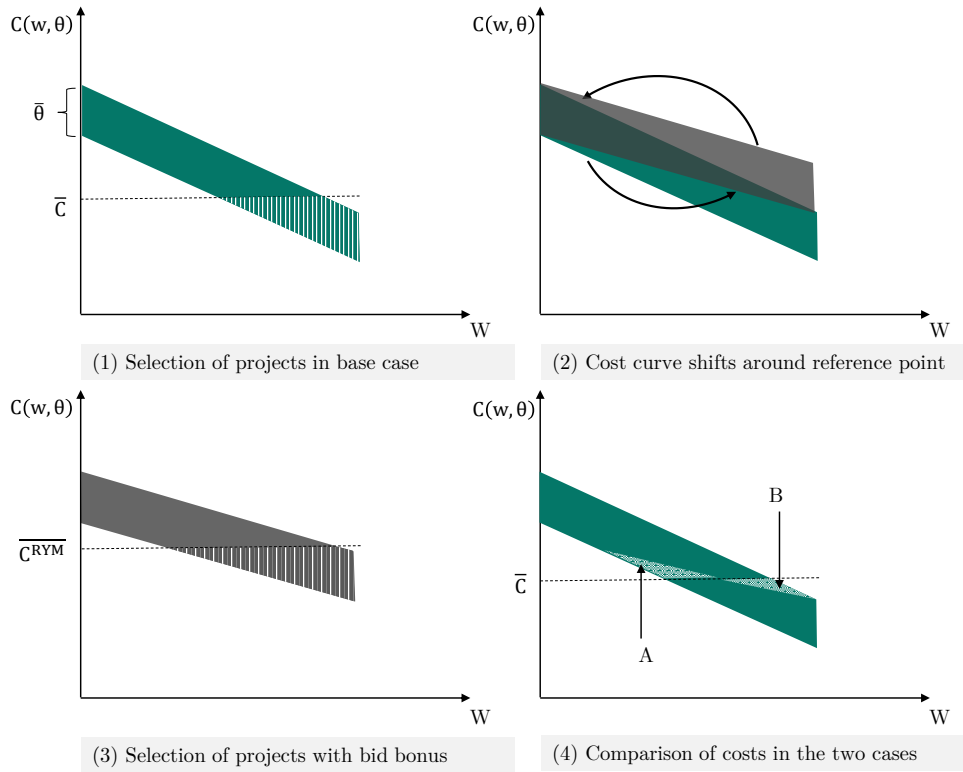


Illustration of the increase in production costs that arises due to the changing set of selected projects with and without intra-technology discrimination. In Panel (1), all projects below the strike price \bar{C} are chosen in the auction and represented by the shaded area. Panel (2) shows how the bid bonus shifts the cost curve (green) around the reference point $w = 0$, leading to an adjusted cost curve (grey) that has a lower slope. This leads to increase competitiveness of projects with a low resource quality. As Panel (3) shows, this shift leads to a different set of projects chosen under the new, adjusted strike price (\bar{C}^{RYM}). In fact, the bid bonus leads to a number of projects with a lower resource quality w_i being chosen due to their low unobserved cost component θ_i . Panel (4) compares the true costs of projects chosen with and without the bid bonus. While Area A indicates the projects that are only chosen when the bid bonus is applied, Area B indicates projects that are chosen only in the standard auction.

Figure 2: Simplified example of the increase in production cost

3.2 Model Description

We analyze the stylized case of a regulator that procures the fixed quantity Q^* through the auction of a commodity such as electricity.⁴ We assume that the auction is conducted as a uniform price auction (i.e., all projects are being paid the cost of the last unit chosen for support). However, in accordance to the revenue equivalence theorem, we can assume that the results extend to other auction types (e.g., pay-as-bid auctions). The regulator procures the quantity via an auction in which we differentiate between a standard auction and an auction with intra-technology discrimination through a continuous bid bonus g that is applied to all bids. The regulator aims to minimize consumer costs.⁵ Thus, the

⁴In a simplification of the auction design, we define Q^* as the production of the installations (in MWh) rather than their capacity (in MW).

⁵Kreiss et al. (2021) define support costs as the combination of the production costs and producer rent. We follow their approach. They argue that their results hold generally for different types of remuneration schemes (e.g., feed-in-tariffs or sliding premiums). Since we assume remuneration to be according to a contract for difference, the support cost are equal to the cost incurred by consumers if the difference

auction awards support either to the projects with minimum production costs $c_i(w_i, \theta_i)$ in the base case or minimum adjusted production costs $c_i(w_i, \theta_i, g)$ in the discriminatory case.

We assume that project costs $c_i(w_i, \theta_i)$ are equal to $a - bw_i + \theta_i$, i.e. that cost can be divided into the two additive components $c_i(w_i) = a - bw_i$ and $c_i(\theta_i) = \theta_i$. While w_i is a verifiable parameter (i.e., wind speed at location i) that must be disclosed when the bid bonus is applied and that is verifiable by the regulator, θ_i is not observable to the regulator. $c_i(w_i)$ represents the common cost factors between all projects (e.g., investment costs for the installations of the turbine) that are decreasing in the resource quality through economies of scale. Meanwhile, $c_i(\theta_i)$ can be thought of as any other project-specific cost factors that are not observable for the auctioneer and that are independent of the wind quality of location i , such as financing costs, development costs or grid-connection costs.⁶ Thus, the size of θ represents the regulator's *ex-ante* knowledge about a given project's cost and is a measure of both *ex-ante* uncertainty for the auctioneer and asymmetric information between the regulator and the auction's participants. We restrict the cost parameter θ to the domain $[0, \bar{\theta}]$ and the parameter w to $[\underline{w}, \bar{w}]$ where $\underline{w} < 0$ and $\bar{w} > 0$.

The bid bonus is defined relative to $w = 0$ (i.e., $w = 0$ is the point around which the cost curve is turned). For projects to the left of $w = 0$, there is a bonus reducing their bids, while all projects to the right of $w = 0$ receive a penalty making them less likely to be selected. Hence, the adjusted cost function after the bid bonus is applied is defined as $c_i^{RYM}(w_i, \theta_i, g) = a - gbw_i + \theta_i$ where $g \in [0, 1]$. Finally, we define the quantity function as $Q(w, \theta) = \int_0^{\bar{\theta}} \int_{\bar{w}(\theta)}^{\bar{w}} 1$. Thus, projects are uniformly distributed over resource quality and observable cost parameters, offering the identical quantity $q_i = 1$.

In summary, the two cases considered for our analysis are as follows:

1. *Base Case*

The regulator conducts a uniform price auction for the desired quantity Q^* . The auction leads to the selection of the projects with minimum production costs. Thus, the sum of production costs of all projects chosen in the auction are determined by:

payments are rebated to the public. Hence, we refer to these costs as consumer costs.

⁶The analysis of German onshore wind project's costs by Deutsche Windguard (2015) estimates that such additional investment costs are relatively high at 374 EUR/kW and have a high variation with a standard deviation of 40%. These costs include site specific construction costs (e.g., for the foundation and preparation of the site), firm-specific planning costs and costs for (environmental) compensation measures. Additionally, we would expect financing costs to deviate between project developers

$$PC_{min}(\theta, w) = \min \int_0^{\bar{\theta}} \int_{\tilde{w}(\theta)}^{\bar{w}} a - bw_i + \theta_i dw d\theta$$

$$s.t. Q(w, \theta) = Q^*$$

All projects selected in the auction are paid the cost of the last installation with the lowest accepted wind speed \hat{w} that is selected, such that the price p paid to all installations is equal to $c(\hat{w}, \theta)$.

2. Intra-technology discrimination

The regulator conducts an auction applying the bid bonus g . The procured quantity Q^* remains identical, but the set of projects chosen is different since the auction now selects the projects with the minimum *adjusted* costs. This changes the minimum resource quality that is selected for each value of θ (i.e., the border of the integral) from $\tilde{w}(\theta)$ to $\tilde{w}^{adj}(\theta, g)$.

Thus, the sum of production costs of all projects chosen in the auction applying the bid bonus is now:

$$PC_{min}^{RYM}(\theta, w, g) = \min \int_0^{\bar{\theta}} \int_{\tilde{w}^{adj}(\theta, g)}^{\bar{w}} a - bw_i + \theta_i dw d\theta$$

$$s.t. Q(w, \theta) = Q^*$$

In the case of intra-technology discrimination, projects must disclose their type w_i to the regulator, who is able to make their payment contingent on the resource quality. Thus, each installation is paid $p(w_i, g) = c(\hat{w}, \theta, g) - (1 - g)b(w_i - \hat{w})$. The price is dependent on the resource quality of an installation and the bid bonus.

We base our stylized analysis on a number of assumptions that allow us to solve the model and reduce complexity in the terms we derive. First, we limit the analysis to linear cost functions. However, in the numerical analysis, we show that the results also apply under more general functional forms. Second, we assume that the full range of the unobserved cost parameter θ is demanded in the auction since the range of θ is small compared to the range of wind speeds w . This implies that all offers from the highest resource quality location \bar{w} are accepted in the auction. Third, we do not consider the effect of bid shading and assume that the auction is conducted as a uniform price auction instead of a pay-as-bid scheme. However, as Kreiss et al. (2021) argue, pay-as-bid rules do not prevent windfall profits and the narrow range of bids in Table 1 indicate that

the participants in the German auction for wind energy can anticipate the strike price well. By assuming a uniform price auction, we can assume that the auction is incentive compatible and firms bid their true costs in equilibrium. Finally, we abstract from reality by assuming that the projects are remunerated according to a contract for difference rather than a sliding premium and that difference payments in times of high prices are rebated to the customers. This allows us to divide the consumer cost into producer rent and production costs without considering the uncertain revenues that firms could achieve under a sliding premium.⁷

3.3 Analytical Results

We analyze the procurement decision of the regulator in three steps using our stylized setup. First, we calculate the effect of intra-technology discrimination for the case of perfect knowledge of the regulator, i.e., when $\bar{\theta} = 0$. Second, we show how the result changes depending on the influence of the unobservable cost component. Third, we consider how the result changes when the parameters of the model are varied. A detailed derivation of the results presented in this section is found in Appendix A.1 and Appendix A.2. The results allow us to derive propositions that we further explore in the following section.

Case 1: No unobservable cost component

In the absence of the unobservable cost component, the difference of consumer costs can be calculated as:

$$\Delta_{CC} = CC_{RYM} - CC_{BaseCase} = \frac{Q^{*2}b(g-1)}{2} < 0. \quad (1)$$

The difference is negative since $g < 1$. Thus, when there is no unknown cost component, the introduction of intra-technology discrimination leads to a reduction in consumer costs. This can be divided into the two previously described effects:

$$\Delta_{PC} = 0 \quad (2)$$

$$\Delta_{PR} = \frac{Q^{*2}b(g-1)}{2} \quad (3)$$

In the absence of an uncertain cost component, the bid bonus does not lead to an inefficient selection of projects. However, disclosing part of the project's cost curves leads to a decreased producer surplus due to the introduction of price discrimination. The reduction in producer rent increases with the heterogeneity of the projects b , the strength

⁷See Neuhoff et al. (2018) for an extended debate of the effects of sliding premium and contracts for difference.

of the adjustment $(1-g)$, and the quantity auctioned Q^* .

Case 2: With unobservable cost component

When we add the unobservable cost component to the model, the difference in consumer costs becomes:

$$\Delta_{CC} = CC_{RYM} - CC_{BaseCase} = \frac{(g-1)(12(Q^*)^2 b^2 g^2 - \bar{\theta}^4)}{24bg^2\bar{\theta}} \quad (4)$$

The aggregate result is comprised by:

$$\Delta_{PC} = \frac{\bar{\theta}^3(g-1)^2}{24bg^2} \quad (5)$$

$$\Delta_{PR} = \frac{(g-1)(12(Q^*)^2 b^2 g - \bar{\theta}^4)}{24bg\bar{\theta}} \quad (6)$$

The difference in production costs is positive since we defined that $g < 1$. This illustrates the fact that the intra-technology discriminatory auction design leads to an inefficient selection of sites. Meanwhile, whether the overall difference and the difference in producer rent are positive or negative, depends on the relationships between the parameters of the model.

Thus, whether the effect of intra-technology discrimination on consumer costs is positive or negative depends on the heterogeneity of costs (b), the unobservable cost factor θ , the strength of the adjustment $(1-g)$, and the total volume auctioned (Q^*). To further investigate the effect of these parameters, we investigate the comparative statics with respect to these parameters. The comparative statics allow us to determine a number of propositions that we test in our numerical model.

Proposition 1: There exists an optimal adjustment g

$$\frac{\delta\Delta_{CC}}{\delta g} = \frac{12(Q^*)^2 b^2 g^3 + (g-2)\bar{\theta}^4}{24bg^3\bar{\theta}} > / < 0 \quad (7)$$

First, we find that the first derivative of Δ_{CC} with respect to g has an undetermined sign. The expression is negative when the adjustment factor g approaches zero (i.e., when the adjustment is strong), but it is positive when g is large. At the same time, the second derivative with respect to g is positive. Thus, there exists at least one positive g at which consumer costs are minimized.⁸ Since we defined Δ_{CC} as the difference between consumer costs with and without intra-technology discrimination, this indicates that there exists

⁸To be precise, the expression is positive when g approaches infinity. However, we define $g \in [0, 1]$. Thus, the minimal consumer costs might be local and a corner solution at $g=1$.

an optimal choice of the adjustment that minimizes consumer costs.

Proposition 2: A larger uncertainty reduces the benefits of intra-technology discrimination

$$\frac{\delta\Delta_{CC}}{\delta\bar{\theta}} = \frac{(1-g)(4Q^*b^2g^2 + \bar{\theta}^4)}{8bg^2\bar{\theta}^2} > 0 \quad (8)$$

Second, we find that the first derivative with respect to $\bar{\theta}$ (i.e., larger *ex-ante* uncertainty for the regulator) is positive. Thus, the larger the influence of the unobserved cost factor, the more the consumer costs increase when a continuous bid bonus is introduced.

Proposition 3: A larger auction quantity increases the benefits of intra-technology discrimination

$$\frac{\delta\Delta_{CC}}{\delta Q^*} = \frac{Q^*b(g-1)}{\bar{\theta}} < 0 \quad (9)$$

Third, we find that the first derivative with respect to Q^* is negative. This implies that a larger auction quantity improves the performance of intra-technology discrimination, since it increases the number of projects over which the regulator is able to price discriminate, while the inefficiency does not change with higher auction volumes.

Proposition 4: A larger difference in observable costs increases the benefits of intra-technology discrimination

$$\frac{\delta\Delta_{CC}}{\delta b} = \frac{(g-1)(12(Q^*)^2b^2g^2 + \bar{\theta}^4)}{24b^2g^2\bar{\theta}} < 0 \quad (10)$$

Finally, we find that the first derivative with respect to b is smaller than zero. Thus, the steeper the cost curve (i.e., the larger the heterogeneity in the project costs) the more the consumer costs decrease with the introduction of intra-technology discrimination.

4 Numerical Model

We develop a numerical model that allows us to compare the results from an auction with and without the reference yield model. The numerical analysis has two parts. First, we quantify the effects of the reference yield model based on a data set of German onshore wind potential. Second, we test the theoretical observations by conducting sensitivity analyses of the model through the adjustment of the model's parameters.

4.1 Numerical Model Description

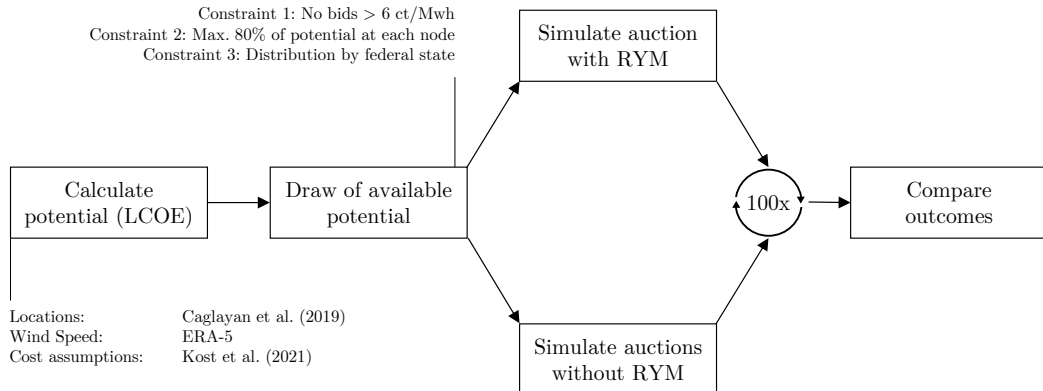


Figure 3: Structure of the numerical model

To analyze the effect of intra-technology discrimination through, we develop a numerical model to simulate auctions for renewable energy support with and without the reference yield model. As input, the model takes a cost potential for potential onshore wind locations that contains the levelized cost of energy measured in Euro per MWh and the wind quality measured in full load hours. This potential is transformed into the bids for the auction based on a selection mechanism. This selection mechanism is calibrated under a number of constraints to represent the distribution of bids observed in past auctions for wind energy in Germany. The selection mechanism and calibration are discussed in Appendix A.3.⁹ The auction mechanism is then applied to this set of bids. We simulate the auction once without intra-technology discrimination and once with the reference yield model. Subsequently, we evaluate the auction results from both scenarios by calculating the outcome variables of our theoretical model: The change in consumer cost Δ_{CC} , the change in production costs Δ_{PC} , and the change in producer rent Δ_{PR} . Appendix A.3 and Appendix A.4 contain a more in-depth description of the auction and selection mechanism. For each scenario, we simulate the auction based on a number of 100 draws of the selection mechanism to reduce the effect of outliers in our selection procedure on the results.

The parameters of the numerical analysis are modified slightly to conduct two connected analyses. First, we conduct a forward-looking analysis of a set of auctions from 2023-2030 in order to calculate the savings or losses incurred by the reference yield model. We assume that in accordance with recent government announcements, there is a yearly extension of wind energy by 6,500 MW that is allocated in four separate auctions (i.e.,

⁹In Appendix A.8 we drop the calibration by federal states and the limitation on the maximum bid quantity to test the robustness of our results.

each auction has a volume of 1,625 MW and the total volume auctioned over the eight years is equal to 52,000 MW). When simulating the forward-looking auction over multiple years, separate random draws are considered with and without the reference yield model to account for the unequal use of potential in both cases. Second, we conduct several sensitivity analyses meant to test the propositions derived in the theoretical model. For this, we consider a static setting analyzing a single auction from the previous analyses. The sensitivity analyses are:

1. A change in the slope of adjustment factors of the reference yield model (i.e., the adjustment parameter g) to test Proposition 1. To do so, we increase and decrease the slope of the adjustment curve by 10, 20, and 30%.
2. An increase the variance of costs (i.e., the unknown cost parameter $\bar{\theta}$) to test Proposition 2. Therefore, we increase and decrease the unobservable cost component by 5, 10, and 15% of total costs.
3. An increase and decrease in the auctioned quantity (i.e., the parameter Q^*) to test Proposition 3. For this, we increase and decrease the auctioned quantity by 10, 20, and 30%.

We design the numerical model to represent the current German auctions for renewable energy. However, some simplifications have been made that do not affect our results. Like in the previous analysis we abstract from the German auctions in calculating the cost to consumers as a CfD rather than a sliding premium. This will not change results if wholesale power prices are sufficiently low. We again assume a uniform rather than a pay-as-bid auction as we did in the theoretical analysis. Additionally, we do not include the second instrument aimed at increasing geographic diversity of wind installations (i.e., the current Southern quota) in order to avoid interactions between the two policies that might bias our results.

4.2 Data Description

Table 4: Assumptions of cost parameters

| CAPEX Euro/MW | OPEX Fix Euro/MW | OPEX Var. Euro/MWh | WACC % | Theta Euro/MWh | Lifetime Years |
|-------------------------|----------------------------|------------------------------|------------------|---------------------------|--------------------------|
| 1700 | 20 | 0.008 | 0.025 | $N(0, \frac{0.06}{1.96})$ | 20 |

We generate a dataset of German onshore potential detailing the location, costs, and full load hours of potential projects in order to use it as an input to our model. In this, we proceed as follows. We use the data provided by Caglayan et al. (2019) to compile a database of potential wind energy locations in Germany. The dataset describes

the technical potential of wind energy in Europe for a scenario of future turbine types in the year 2050 at 160,792 locations. The locations are derived applying a number of technical and socio-economic constraints including sociopolitical (e.g., distance to settlements, airports, or touristic sites), physical (e.g., slope, ground conditions), conservation (e.g., bird areas and natural monuments) and economic (e.g., access to roads, connection to electrical grids) constraints.¹⁰ We match these locations to the historic wind speed data provided in the ERA-5 dataset for the years 2019 to 2021 (Hersbach et al., 2020). By using three years of wind data we try to limit the effect of outliers. We calculate the potential output of a wind turbine at these locations using the power curve of the most frequently built turbine in Germany in the years 2016-2018, the Enercon E-115 (Fachagentur Wind, 2019). Thus, our full load hours should be comparable to recent installations in Germany. However, since the turbine is optimized for high wind locations, our results might underestimate production in locations with low wind speeds. Finally, we use the cost information provided by Kost et al. (2021) to calculate the levelized cost of electricity for each of the projects. Table 4 shows the assumptions made in the calculations of production costs. We deviate from their assumption in two ways. First, we assume a turbine lifetime of 20 years in accordance to the renewable energy act since investors will usually not cover the merchant risk of a wind project. Second, we include a random cost component that is normally distributed according to $\mu = 0$ and $\sigma = \frac{0.06}{1.96}$. Since in a normal distribution 95% of values are within 1.96σ of the mean, this implies the assumption that unobservable costs make up around 12% of the project's production costs.¹¹ We further assume a risk-free discount rate of 2% for the calculation of present values.

4.3 Results

Table 5: Results of the forward looking analysis

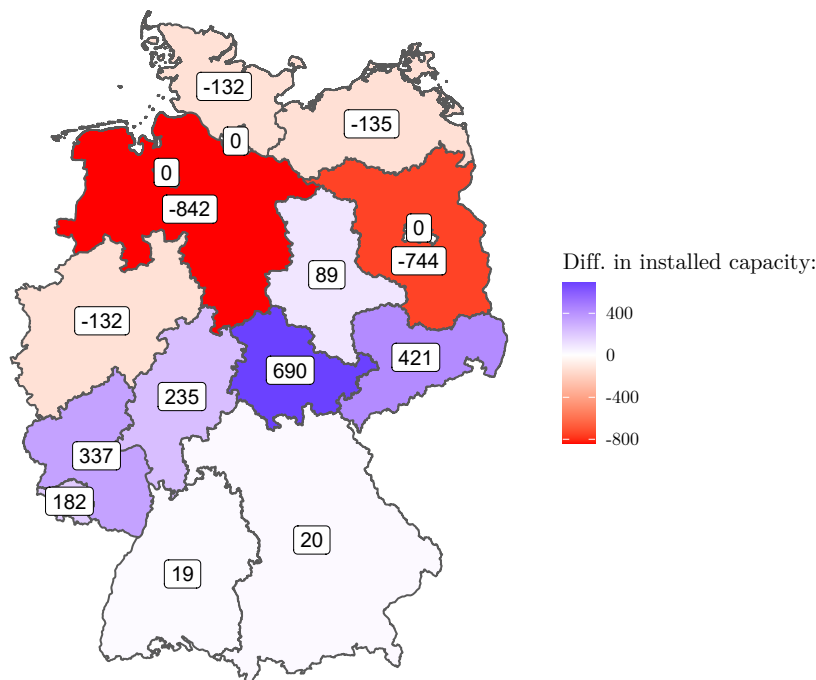
| Scenario | Δ_{CC} (in Euro/MWh) | Δ_{PR} (in Euro/MWh) | Δ_{PC} (in Euro/MWh) |
|-----------|--------------------------------|--------------------------------|--------------------------------|
| Base Case | -7.44 | -7.59 | 0.16 |

Results of the forward looking analysis for which we consider 32 auctions with a capacity of 1,500 MW each. We assume that auctions are conducted four times a year between 2023 and 2030. The results in the table represent the savings in EUR per MWh of production. Results in the text referring to absolute values are normalized to the production volume of the auction without the reference yield model since these auctions will have slightly larger production volumes due to higher full load hours. Results are in present values of production and expenditure, representing the average over 100 runs of the auction both with and without the reference yield model.

¹⁰For the full set of applied constraints see Ryberg et al. (2020). While Ryberg et al. (2019) calculated potential costs for these locations, their estimates are not applicable to our analysis since they assume future turbine configurations that lead to significantly lower production costs than those currently observed.

¹¹This is a similar magnitude to the findings by Deutsche Windguard (2015) that assume that around 12-15% of onshore wind energy costs are attributable to site-specific additional investment costs (e.g., planning, network connection or site preparations).

Overall, the forward looking analysis for the years of 2023-2030 reveals that the reference yield model leads to a significant reduction in consumer costs. Table 5 shows the results of the forward looking analysis. We find that the reference yield model leads to an increase in production costs of 0.16 Euro per MWh. This is due to the increased cost of selected projects after the application of the reference yield model. However, this is far outweighed by the effect on producer rent, which decreases by 7.59 Euro per MWh leading to an overall decrease in consumer costs of 7.44 Euro per MWh. Assuming a constant annual deployment volume of 6,500 MW per year between 2023 and 2030, these effects lead to an aggregated net present value decrease in consumer costs of 24.8 billion EUR. This is equivalent to a net present value of the reduction in consumer costs by 12.6% and an average saving of 606 Euro in net present value over the lifetime of the turbines per German household. Thus, even though the reference yield model introduces a small inefficiency in terms of production costs, the decrease in windfall profits of low-cost producers far outweigh these additional costs.



Map displays the difference in the additional installed capacity with and without the reference yield model summed over the 32 auctions and corrected for decommissioning of plants. Blue shaded areas indicate a positive difference when the reference yield model is applied; i.e. the blue shaded states receive additional installations in the scenario considering the reference yield model. Red shaded areas indicate a negative difference. Results based on 100 repetitions of the same simulation.

Figure 4: Change in added capacity with and without the reference yield model

The reference yield model also leads to a more even geographic distribution of additional wind power plants. Figure 4 shows how the distribution of additional turbines

changes when the reference yield model is applied. While the most northern and southern states are only marginally affected by the reference yield model, there is a shift of power plants toward the south in the middle of the country leading to an increased development of power plants especially in Thuringia, Saxony-Anhalt, and Rhineland-Palatinate. The finding that the reference yield model leads to a larger effect in the middle of the country is in accordance with our theoretical finding that the policy should not affect bidders at locations with very high or low resource quality.¹²

Overall, the results are similar to the findings of Hitaj and Löschel (2019) that looked at the predecessor of the policy before the introduction of auctions and found that it slightly reduced support costs. The difference to the findings of Bichler et al. (2020) is explained by our different assumptions on bidding behavior. The authors assume a pay-as-bid scheme and market participants bidding their costs rather than expected clearing prices because the primary focus of the paper is on a comparison of regional versus national auctions. Thus, the possible downward effect that the reference yield model would have on producer rent is outside the scope of their paper. While Engelhorn and Müsgens (2021) do consider the same trade-off between price discrimination and efficiency as is analysed in this paper, the difference in results is driven by differing assumptions on the size of the inefficiency in the geographical distribution of turbines that is introduced by the policy. Their counterfactual analysis finds a stronger concentration of wind deployment in northern Germany than the results from our numerical simulation, which only finds a local effect of the reference yield model.¹³

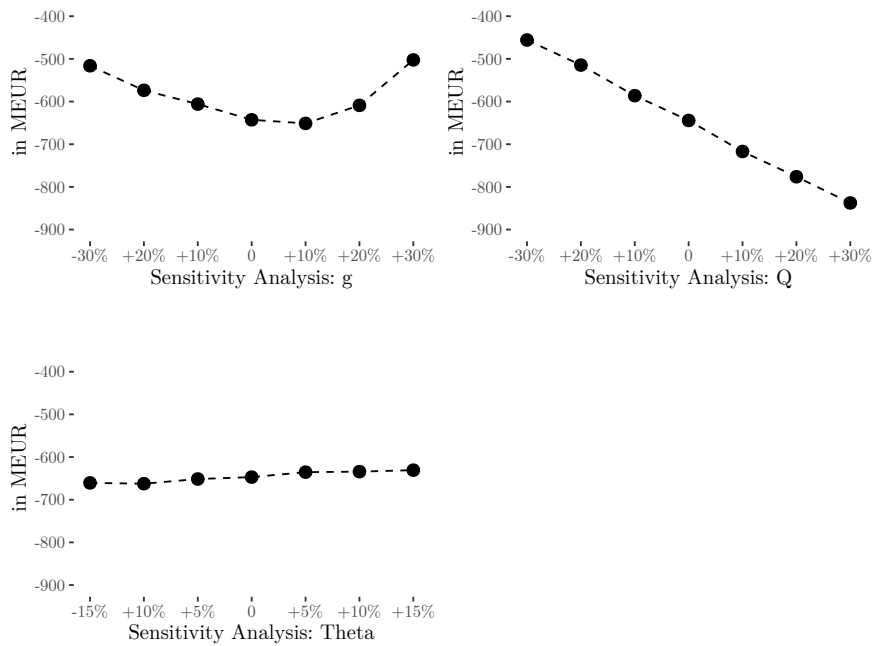
4.4 Sensitivity analysis

The subsequent sensitivity analyses illustrate a number of observations from the stylized theoretical analysis. Figure 5 shows the effect of the three sensitivity analyses with respect to the adjustment parameter (g), the quantity auctioned (Q), and the cost parameter (θ). Appendix A.9 contains further graphs from the sensitivity analysis.

First, we see that the graph of the change in consumer cost with respect to the change of adjustment parameter g is U-shaped. This illustrates Proposition 1 which claimed that there should be an optimal adjustment factor g and that an increase in the strength of the adjustment can have both positive and negative effects on consumer costs. The reason for this is a large increase of production costs at very strong adjustments due to an increasing

¹²Figure 11 in the Appendix shows the results of a single auction and illustrates the effect of the reference yield model on selected projects.

¹³In the cost minimizing scenario, the authors find that more than 82% of wind turbines are located in Lower Saxony and Schleswig-Holstein. For the second, more restrictive, scenario, they find a 60% concentration, while we find that only 43% of additional capacity is located in these states.



Results of the sensitivity analyses in million Euros of present values normalized to the production in the auction without the reference yield model. Negative results indicate savings from the reference yield model. An in-depth description of sensitivity analyses performed can be found in Section 4.1. Results based on 100 repetitions of the same simulation.

Figure 5: Change in consumer costs for the three sensitivity analysis

inefficiency, while very weak adjustments do not sufficiently lower producer rent. Second, we vary the unobservable cost parameter θ . As the stylized model indicated, we see that a larger unobserved cost component leads to both an increase in the producer rent and production costs. Thus, it illustrates the intuition from the stylized model that the reference yield model performs worse under larger uncertainty. However, the overall scale of the cost increases remains small. Third, we see that a higher auctioned quantity increases the savings. In the stylized model, this effect was caused by the fact that the inefficiency introduced by the reference yield model occurs locally around the reference point while the benefits of price discrimination can be realized over a larger number of installations. In the numerical model we do find that the increase in production costs increase slightly with higher auction volumes, thus indicating that the inefficiency is not entirely local but we do see that the change in producer rent far outweighs this increase.

4.5 Understanding the effect of the reference yield model

In addition to estimating consumer costs and illustrating the propositions derived from the theoretical model, the numerical analysis allows us to examine some general mechanisms of the reference yield model. First, Figure 6 illustrates the shift in bidding curves that result from the application of the reference yield model. As indicated in the stylized

analysis, the reference yield model flattens the bidding curve, thereby making bids in resource-poor locations seem more attractive. However, even after the application of the reference yield model, the bid curve continues to be downward sloping, such that the auction continues to provide a certain degree of cost efficiency.

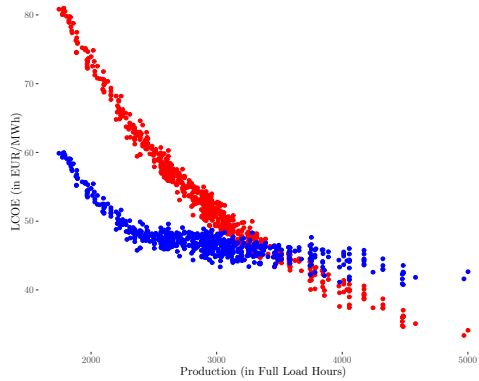


Figure 6: Shift in the bid curve before (red) and after (blue) the application of the reference yield model

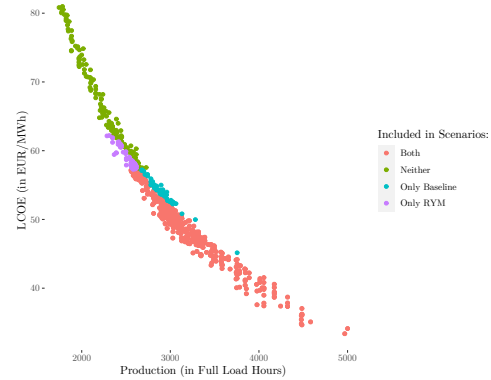


Figure 7: Projects selected with and without the reference yield model

Second, Figure 7 shows a comparison of the projects chosen with and without the reference yield model. It is apparent that the difference in projects follows the intuition of the stylized model. When the reference yield model is applied some projects with low wind quality but a low unobservable cost component are chosen, while some projects at good locations but with high unobservable costs are no longer awarded support. The figure further illustrates that the assumption that the projects with the best resource quality are always chosen regardless of their unobservable cost component θ holds for the numerical case.

Third, Figure 8 shows the difference in the resource quality of projects that are awarded support with and without the reference yield model. It is apparent that the reference yield model mostly affects project around the cut-off while projects with a very high resource quality are always chosen for support. This illustrates the previously discussed result that the reference yield model leads to a substitution of projects from northern Germany to the center of the country. However, it does not lead to a large scale substitution toward southern Germany, which is partially due to the low auction participation in these states.

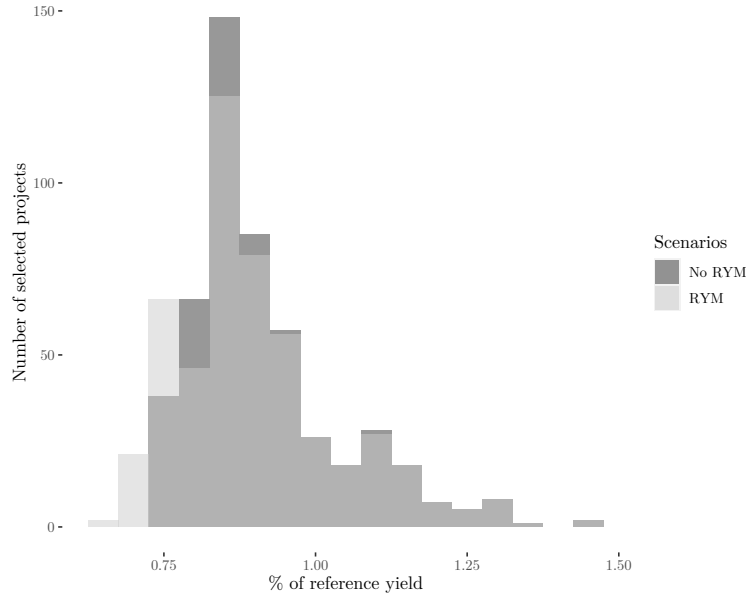


Figure 8: Projects selected with and without the reference yield model

5 Conclusion

In this paper we analyze the effect of an intra-technology discriminatory auction design for renewable energy that introduces a bonus-and-penalty system based on observable characteristics (i.e., the wind speed at different locations). Specifically, we focus on the trade-off between a less efficient selection of installations and the introduction of price discrimination. We develop a stylized model to improve the understanding of how different variables affect this trade-off. We find that an increase in non-observable costs leads to relatively higher consumer costs of intra-technology discrimination, but that higher spread in observable costs and an increase in the auction volume reduce the relative consumer costs of intra-technology discrimination. The results confirm the work of previous theoretical papers by Fabra and Montero (2020) and Kreiss et al. (2021) that consider the discrete case of competition between two technologies. We illustrate that their results hold in a continuous case and disentangle the effect on consumer cost into the effects on production costs and producer rent.

In a subsequent numerical analysis, we confirm these findings for the example of the German reference yield model. We conclude that the reference yield model leads to cost savings by introducing price discrimination even when firms can anticipate the strike price. For a case with competition, we estimate that the reference yield model leads to savings of 24.8 billion Euro (-12.6%) between 2023 and 2030. This is equivalent to a decrease in consumer cost of 606 Euro per household in Germany over the same time period.¹⁴

¹⁴In Appendix A.7 we show that these results are even clearer for the case of no competition in Germany

Our findings support the suggestion of location-specific pricing for renewable energy by authors such as Newbery (2021). They support the notion that the reduction in producer rent might outweigh the increase in production costs, thereby also informing the debate on technology-specific versus technology-neutral support schemes for renewable energy. This is an important finding, especially for countries like Germany that plan to rapidly expand their renewable energy capacities and that seek to diversify their production portfolio geographically. When expanding the reference yield model to further technologies, such as solar power, our findings suggest that the regulator should consider the influence of unobserved cost components as well as the cost difference between high and low yield areas. Importantly, our analysis does not consider the additional benefits that the reference yield model would have on the acceptance of wind power and the functioning of the electricity system. In particular, the reduction in congestion costs provide a further strong economic argument for the introduction of location-specific incentives for the expansion of renewable energy.

Our paper contributes to the literature by expanding the analysis of discriminatory auction design to a continuous case of intra-technology discrimination and by combining a theoretical analysis and a numerical model of the German reference yield model. Some caveats remain that present avenues for further research on the topic. First, our analysis omits a number of factors outside of our model that may lead to an increase in efficiency after the introduction of intra-technology discrimination. For instance, a larger geographic diversity of renewable energy installations will reduce congestion related costs and decrease the need for the extension of transmission lines. Additionally, if we assume that there is an inefficiency in government spending (as in Fabra and Montero (2020)), the reduced payments under the reference yield model lead to an increase in efficiency. Future research could consider and quantify these effects. Second, further research could theoretically and empirically analyze how intra-technology discrimination affects bidding behavior as this is an area that is excluded from our analysis. It can be speculated that the introduction of such a discriminatory auction design should increase the incentive for truthful bidding by increasing competition around the cut-off but leaves projects at very high resource quality locations unaffected. Third, combining the numerical analysis with a turbine-selection approach as presented in May (2017), would allow for determining if the reference yield model influences technology choice and to consider the effect that different turbine types have on the results of our analysis. Finally, our analysis abstracts from the real-life setting by assuming a remuneration through contracts for differences

during the 2010s since the absence of competition eliminates the possibility for an inefficient selection of projects. Thus, only the price discriminating function of the reference yield model is relevant in such a scenario.

instead of a sliding premium for the sake of simplicity. Future analysis could analyze the interaction between the reference yield model and a sliding premium.

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A Appendix

A.1 Calculating the production costs

In our first step, we analyze the increase in consumer costs that arises from selecting projects based on the adjusted rather than the “real” costs of a project. Thus, we are comparing the two integrals:

$$PC(\theta, w) = \int_0^{\bar{\theta}} \int_{\tilde{w}(\theta)}^{\bar{w}} a - bw + \theta \, dw \, d\theta$$

$$PC_{RYM}(\theta, w, g) = \int_0^{\bar{\theta}} \int_{\tilde{w}^{adj}(\theta, g)}^{\bar{w}} a - bw + \theta \, dw \, d\theta$$

Under the condition that

$$Q^* = \int_0^{\bar{\theta}} \int_{\tilde{w}(\theta)}^{\bar{w}} 1 \, dw \, d\theta$$

In solving the integrals, it is important to keep in mind that the area of selected combinations of (w, θ) is bounded by three constants $(0, \bar{\theta}, \bar{w})$, which are defined by the borders of our parameters, and a function $\tilde{w}(\theta)$ that fulfills the condition that $c(w, \theta) = \bar{c}$. This function describes the intersection of the cost function and the maximum support awarded in the auction by indicating the combinations of (w, θ) that lead to costs \bar{c} . The borders of the area over which we integrate are depicted in Figure 9.

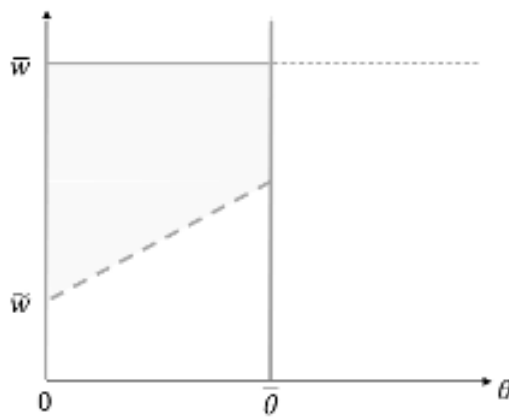


Figure 9: Borders of the integral

In solving the model, we conduct the following steps:

1. **Finding expression for the border $\tilde{w}(\theta)$**

First, we calculate the consumer cost in a standard auction. As discussed, the

intersection is defined by the combinations of (w, θ) whose costs are equal to \bar{c} . Thus, we can solve for $\tilde{w}(\theta)$ as:

$$\begin{aligned} a - b\tilde{w} + \theta &= \bar{c} \\ \Leftrightarrow \tilde{w}(\theta) &= \frac{a - \bar{c} + \theta}{b} \end{aligned}$$

2. Finding the maximum consumer costs

Second, we use the borders of the integral to solve our restriction on the maximum quantity to yield an expression for the maximum price awarded in the auction, i.e., \bar{c} . We can solve and rearrange the function to find an expression for \bar{c} under the assumption that the cost of the cheapest unit is zero, i.e. $a = b\bar{w}$:

$$\begin{aligned} Q^* &= \int_0^{\bar{\theta}} \int_{\tilde{w}(\theta)}^{\bar{w}} 1 \, dw \, d\theta \\ \Leftrightarrow Q^* &= \frac{\theta(2\bar{c} - \bar{\theta})}{2b} \\ \Leftrightarrow \bar{c} &= \frac{Q^*b}{\bar{\theta}} + \frac{\bar{\theta}}{2} \end{aligned}$$

The expression indicates the value of \bar{c} that result from a quantity Q^* being demanded.

3. Finding the production costs of Q^*

Plugging in our formula for \bar{c} into our integral, we can solve our expression for the production costs that result from auctioning the quantity Q^* :

$$\begin{aligned} PC(\theta, w) &= \int_0^{\bar{\theta}} \int_{\tilde{w}(\theta) = \frac{a - \bar{c} + \theta}{b}}^{\bar{w}} a - bw + \theta \, dw \, d\theta \\ \Leftrightarrow PC(Q^*) &= \frac{12(Q^*)^2 b^2 + 12Q^* b \bar{\theta}^2 - \bar{\theta}^4}{24b\bar{\theta}} \end{aligned}$$

Analogous to this, we can calculate the cost in the case where we use intra-technology discrimination via a continuous bid bonus depending again on the quantity Q^* and the chosen adjustment factor g :

$$\begin{aligned}
PC_{RYM}(\theta, w, g) &= \int_0^{\bar{\theta}} \int_{\tilde{w}(\theta)=\frac{a-\bar{c}+\theta}{bg}}^{\bar{w}} a - bw + \theta \, dw \, d\theta \\
\Leftrightarrow PC_{RYM}(Q^*, g) &= \frac{12(Q^*)^2 b^2 g^2 + 12Q^* b g^2 \bar{\theta}^2 + (1 - 2g)\bar{\theta}^4}{24b\bar{\theta}g^2}
\end{aligned}$$

Note that, while the borders of the integral differ, since a different set of projects is chosen in the adjusted case, the relevant cost function used to calculate the increase in production costs is the same in both cases since the bid bonus does not change the true production costs. Δ_{PC} is then calculated as the difference between these two cost expressions.

A.2 Calculating producer rent

In addition to the costs, we are interested in the producer rent that bidders can capture under the standard auction and the auction with the bid bonus.

1. Producer rent in the standard auction

Under the standard auction, the price paid to all installations is \bar{c} , the cost of the last unit procured in our auction. Thus, we can write the producer rent derived in the auction as:

$$PR(Q^*) = \int_0^{\bar{\theta}} \int_{\tilde{w}(\theta)=\frac{a-\bar{c}+\theta}{b}}^{\bar{w}} \bar{c} - a + bw - \theta \, dw \, d\theta$$

The rent can be solved as before to give:

$$PR(Q^*) = \frac{12Q^{*2}b^2 + \bar{\theta}^4}{24b\bar{\theta}}$$

2. Producer rent in the auction with bid bonus

In the auction with the bid bonus, the regulator receives additional information about the auctions quality that is then used to price discriminate between the auctions. We describe the price paid to all installations as $p(w_i, g) = c(\hat{w}, \theta, g) - (1 - g)b(w_i - \hat{w})$.

Therefore, we can calculate the aggregated producer rent over all projects as:

$$PR_{RYM}(Q^*) = \int_0^{\bar{\theta}} \int_{\bar{w}(\theta) = \frac{a - \bar{c} + \theta}{gb}}^{\bar{w}} p(w, g) - a + bw - \theta \, dw \, d\theta$$

This solves to:

$$PR_{RYM}(Q^*) = \frac{12Q^2b^2g^2 + \bar{\theta}^4}{24bg\bar{\theta}}$$

The difference in producer rent Δ_{PR} is then solved as the difference between the two expressions.

A.3 Selection mechanism applied in the numerical model

Table 6: Percentage of bids by federal state in past auctions (Bundesnetzagentur, 2021b)

| State | Percentage |
|-------------------------------|------------|
| Baden-Wuerttemberg | 3% |
| Bavaria | 2% |
| Berlin | 0% |
| Brandenburg | 17% |
| Bremen | 0% |
| Hamburg | 0% |
| Hesse | 6% |
| Mecklenburg-Western Pomerania | 7% |
| Lower Saxony | 17% |
| North Rhine-Westphalia | 19% |
| Rhineland-Palatinate | 5% |
| Saarland | 1% |
| Saxony | 1% |
| Saxony-Anhalt | 4% |
| Schleswig-Holstein | 15% |
| Thuringia | 4% |

When drawing the projects bidding in our auction, we impose a number of restrictions to achieve a distribution of bids that is similar to the bid-distribution observed in real-life. First, we restrict the bidding projects to those that would have a bid below 6 Euro per MWh after adjusting for the correction factor of the reference yield model, which has been the maximum bid allowed in recent years.

Second, we combine our potential dataset with the data in the official German registry of power plants to control for locations that have already been used for the construction of wind power (Bundesnetzagentur, 2022). We then limit bids to 80% of available capacity

at each node. Thereby, we want to exclude nodes where a large percentage of available locations are already occupied by existing wind parks. This restriction is necessary since Caglayan et al. (2019) do not consider whether a wind turbine has already been built at the location. For the forward looking analysis we assume that projects from the power plant registry have a lifetime of 20 years after which the sites become available for re-powering.

Third, we match the distribution of bids to the geographical distribution of bids that have been seen in the auctions from 2017 to 2021 and that are displayed in Table 6. Since most of these auctions saw little to no competition, we believe that matching the distribution of previous bids reflects underlying planning and availability constraints in the states rather than being an endogenous effect of the reference yield model. Matching the distribution at a more granular geographic differentiation is not possible due to a lack of available data. After imposing these restrictions, we randomly draw from our regional potential until we reach the maximum number of bids defined for the particular auction.

A.4 Auction mechanism applied in the numerical model

The auction mechanism applied in the model mimics the real German auctions for wind energy as they are employed in 2022. We assume that during the remainder of the decade (2023-2030) the government aims to built 6500 MW of wind power each year in accordance to recent announcements. Thus, we model 4 auctions per year with a capacity of 1,625 MW offered in each auction. We select projects based on their bid in the base case and according to their adjusted bid after applying the reference yield model in the reference yield model case. We set the bids of each location as $BidperMWh_i = ProductionCostperMWh_i$ in the base case and $AdjustedBidperMWh_i = \frac{ProductionCostperMWh_i}{CorrectionFactor_i}$ in the case of the reference yield model. After placing the bids for each installation, the auction mechanism selects the projects with the lowest bids in the base case and according to the lowest adjusted bids in the reference yield model. In our application of the reference yield model, we use the factors provided by the German Renewables Act in its 2021 version. The strike price is then calculated as the bid of the last unit that is chosen in the auction. While in the base case each project is paid the strike price, in the reference yield model case the strike price is multiplied by the correction factor of each location. This is equivalent to assuming that the winning installations can anticipate the adjusted strike price in each auction and bid just below it.

A.5 Verification of cost potential

The dataset used for this analysis was constructed according to the description in Section 4.2. We calculated summary statistics to verify the calculated values for full load

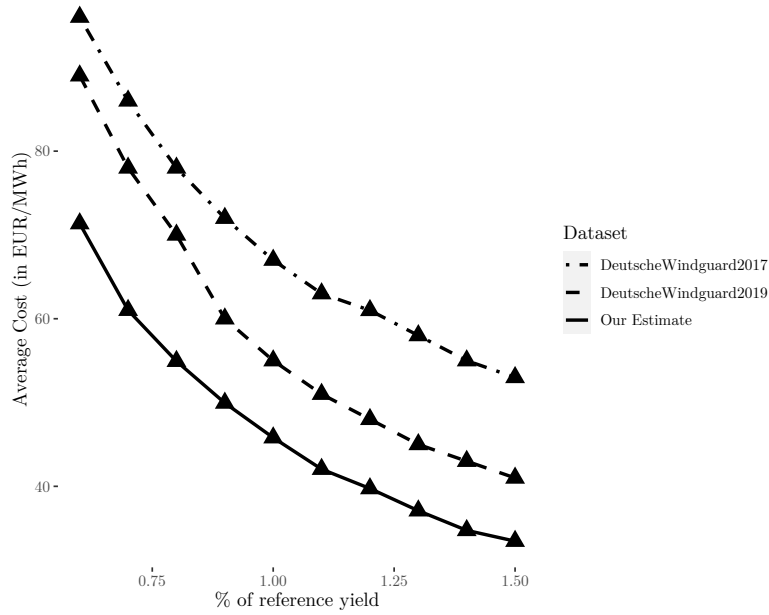


Figure 10: Cost estimate compared to literature values

hours and LCOE. Figure 10 shows the mean cost per MWh estimated for our dataset depending on the percentage of the reference yield. The estimates are compared to estimations from two technical reports from 2017 and 2019. We can see that our estimates for 2022 have a price decrease that is similar to the decrease that the reports estimated between 2017 and 2019. We would expect the levelized cost of electricity to decrease over time due to technological learning. Most importantly, we see that the slope of the cost curve is similar. This is very important for our application of the reference yield model, since the slope of the cost curve will determine how much of an effect the introduction of the reference yield model has.

A.6 Outcome of a particular auction

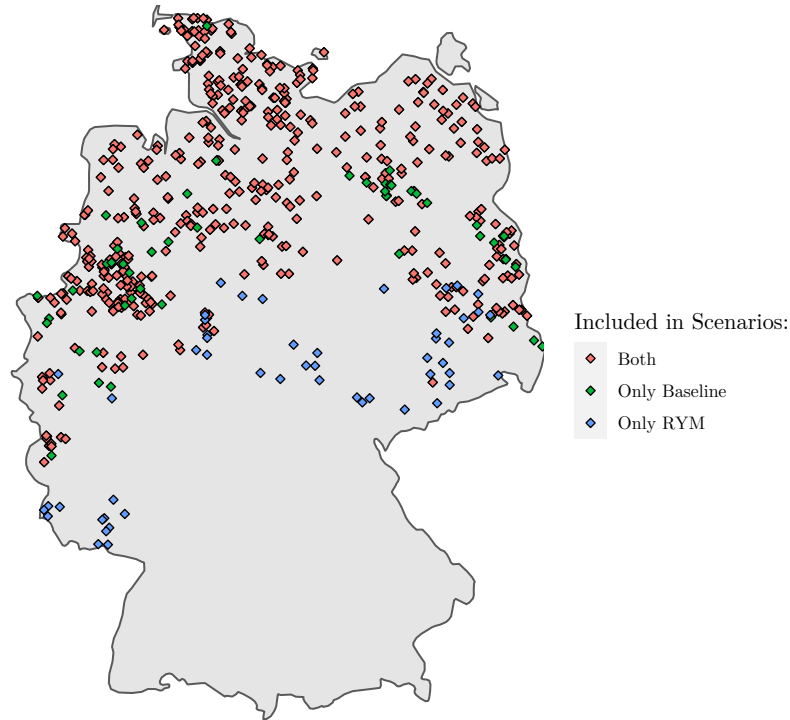


Figure 11: Projects selected with and without the reference yield model

A.7 Replication of auction without competition

Table 7: Results from the August 2018 auction

| Scenario | Δ_{CC} (in Euro/MWh) | Δ_{PR} (in Euro/MWh) | Δ_{PC} (in Euro/MWh) |
|--------------|-----------------------------------|-----------------------------------|-----------------------------------|
| Base Case | -10.18 | -10.18 | 0 |

Results of the numerical analysis of a single auction of 670 MW. Bids are calibrated to match the geographical distribution in the auction from August 2018 and for an excess capacity of only 39 MW. The results in the table represent the savings in EUR per MWh of production. Results based on 100 repetitions of the same simulation.

We aim to replicate the auction conducted in August 2018 to see the effect of low participation on the reference yield model. In order to do so, we adjust a number of model parameters. First, we assume that projects totaling 709 MW bid in the auction and that 670 MW are selected for support. Second, we adjust the regional calibration of projects to the observed distribution in the auction. We find that, without competition, there is no inefficiency in the bids since almost all projects are selected in both cases. The strike price of the simulated auction with the reference yield model is equal to 58.55 EUR/Mwh

and is thus similar to the replicated auction that had a strike price of 63 EUR/MWh.

A.8 Robustness check of geographical distribution

Table 8: Results from the robustness check

| Scenario | Δ_{CC} (in Euro/MWh) | Δ_{PR} (in Euro/MWh) | Δ_{PC} (in Euro/MWh) |
|-----------------|-----------------------------------|-----------------------------------|-----------------------------------|
| Base | 0.03 | -1.28 | 1.31 |
| Case | | | |

Results of the numerical analysis of a single auction of 1625 MW without any calibration of the bids by region. All available projects bid in the auction. The results in the table represent the savings in EUR per MWh of production.

To test how the restriction by federal state and the restrictions of the projects bidding affects our results, we drop the restrictions and simulate a single auction of 1625 MW without these restrictions. This leads to the selection of projects that are almost exclusively located at the most efficient locations along the costs. We find that under these extreme assumptions, the increase in production costs slightly outweighs the decrease in producer rent.

A.9 Additional graphs and tables from the sensitivity analysis

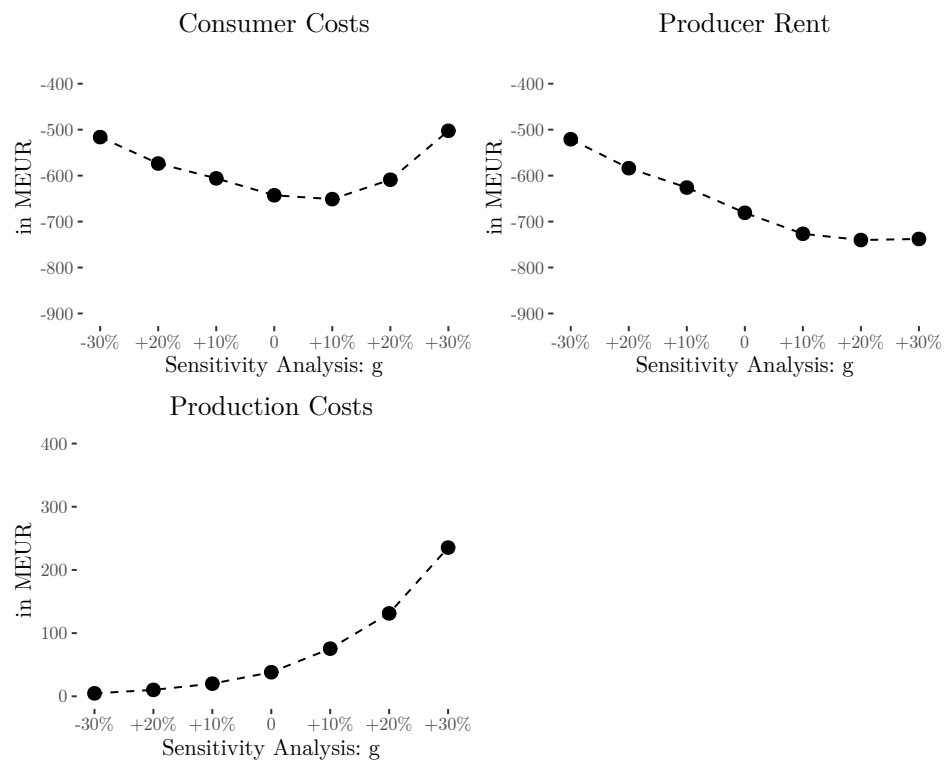


Figure 12: Change in consumer costs, producer rent and production costs from changes in the adjustment factor g

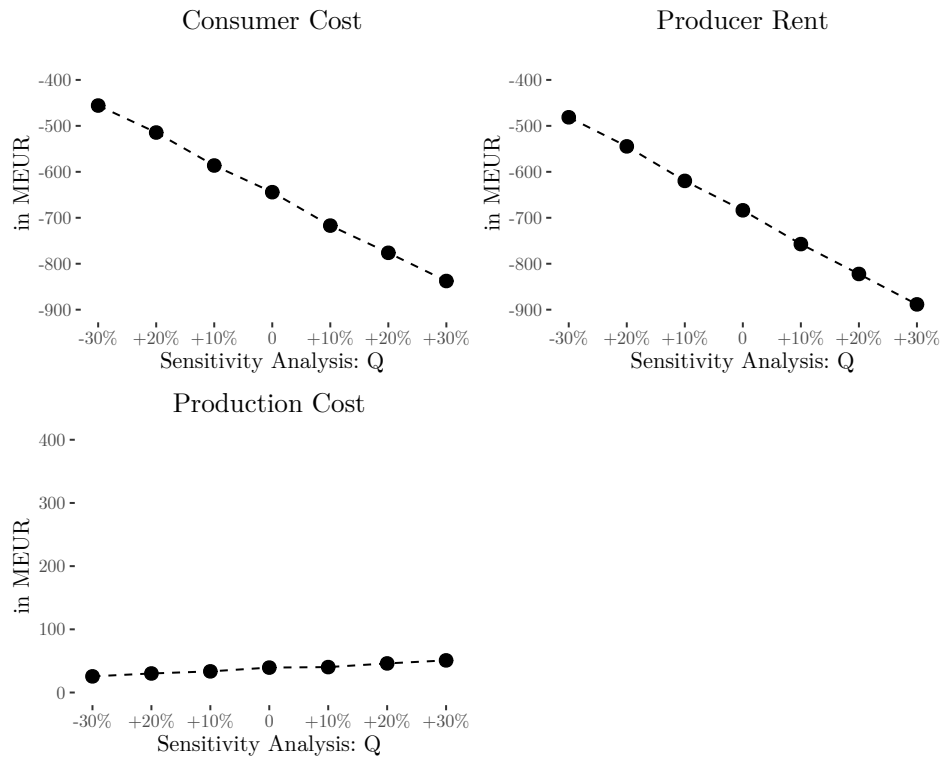


Figure 13: Change in consumer costs, producer rent and production costs from changes in the auction quantity Q

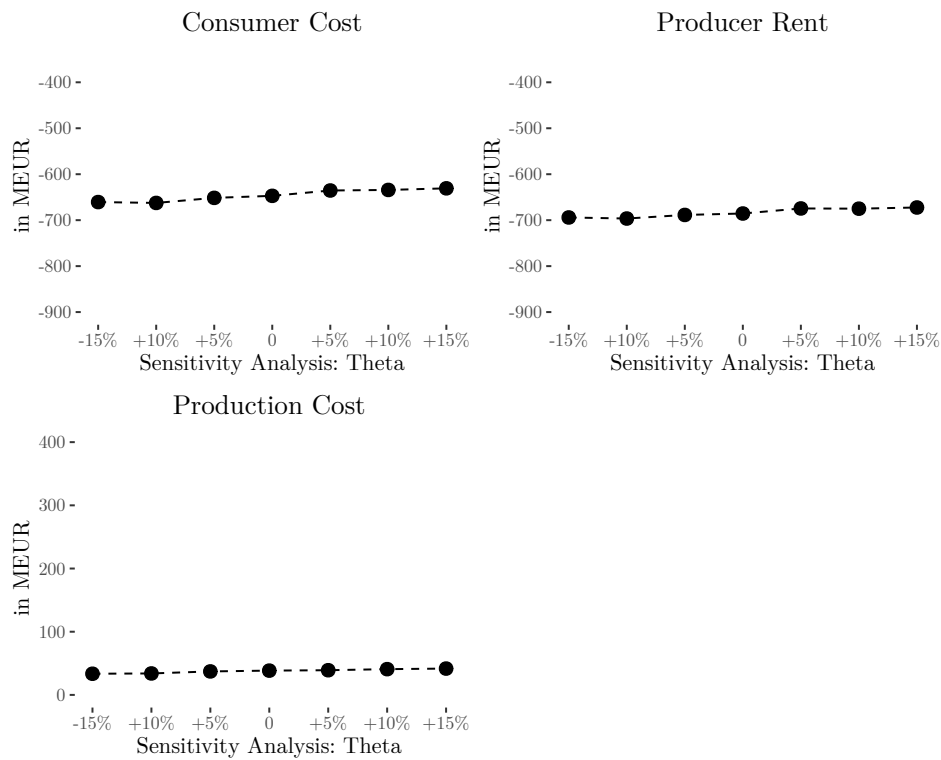


Figure 14: Change in consumer costs, producer rent and production costs from changes in the cost parameter θ

Table 9: Results from the sensitivity analysis

| Scenario | Diff. in Consumer Cost (in MEuro) | Diff. in Producer Rent (in MEuro) | Diff. in Production Cost (in MEuro) |
|------------------------------------|--------------------------------------|--------------------------------------|--|
| θ varied by -15% | -660.62 | -694.11 | 33.49 |
| θ varied by -10% | -662.49 | -696.44 | 33.95 |
| θ varied by -5% | -651.47 | -688.64 | 37.16 |
| θ not varied | -647.07 | -685.52 | 38.45 |
| θ varied by +5% | -635.44 | -674.51 | 39.07 |
| θ varied by +10% | -634.22 | -674.99 | 40.77 |
| θ varied by +15% | -630.74 | -672.42 | 41.68 |
| Q varied by -30% | -455.77 | -481.33 | 25.56 |
| Q varied by -20% | -514.49 | -544.63 | 30.15 |
| Q varied by -10% | -586.25 | -619.73 | 33.47 |
| Q not varied | -644.30 | -683.75 | 39.45 |
| Q varied by +10% | -717.01 | -757.26 | 40.25 |
| Q varied by +20% | -776.22 | -822.27 | 46.05 |
| Q varied by +30% | -837.60 | -888.46 | 50.85 |
| Slope of adjustment varied by -30% | -516.19 | -520.88 | 4.69 |
| Slope of adjustment varied by -20% | -573.66 | -583.83 | 10.17 |
| Slope of adjustment varied by -10% | -605.96 | -625.99 | 20.03 |
| Slope not varied | -642.78 | -680.88 | 38.10 |
| Slope of adjustment varied by +10% | -651.16 | -726.58 | 75.43 |
| Slope of adjustment varied by +20% | -608.95 | -740.17 | 131.22 |
| Slope of adjustment varied by +30% | -502.46 | -737.81 | 235.34 |