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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 [‡]

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Abstract

We assess the incorporation of wind or solar resource quality into renewable auction design as a means to geographically diversify renewable energy production and to reduce costs to consumers by reducing scarcity rents at sites with high resource quality. With a stylized auction model, we model the trade-off between production costs and consumer costs. After exploring the influence of the heterogeneity of production costs, the auction volume, and the regulator's knowledge about cost structures, we show that an optimal level of differentiation exists. Through a numerical analysis of the German reference yield model, we estimate that at current auction levels resource differentiation through the reference yield model leads to a reduction of consumer costs of around 21 billion Euro or 11% between 2025 and 2030, even without considering additional savings from increased regional diversification to reduce grid costs.

Keywords: auctions, renewable energy, price discrimination, resource differentiation, consumer costs

JEL Codes: D44, Q42, Q48, Q54

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1 Introduction

Affordable renewable energy is a cornerstone for the cost-effective decarbonization of economies around the world, both in the power system itself, as well as indirectly for the entire economy via sector-coupling (Brown et al., 2018, Hansen et al., 2019). While renewables have reached cost parity with fossil-fuel sources of electricity (Kost et al., 2021), they continue to require derisking against fossil-fuel market prices to maintain low financing costs and to increase the deployment volumes to meet the climate targets. This derisking of the investments is often done through long-term contracts that are auctioned by the regulators (Del Río and Kiefer, 2021). Such auctions are considered an efficient instrument for allocating public long-term contracts for renewable energy since they incentivize cost efficiency and market integration. In addition, they are supposed to reduce information asymmetries between the regulator and the bidders (Bruttel et al., 2016). In these auctions, minimizing costs to electricity consumers is an important objective for governments since consumer costs of electricity affect the transition cost in all sectors of the economy. This is especially true since energy costs are regressive (Haan and Simmler, 2018), the yearly costs from renewable energy support in Europe are substantive at more than 40 billion Euros (Busch et al., 2023), and the 2022 Energy crisis has shown the political controversy of high energy prices (Fabra, 2023).

At the same time, the ambitious targets for renewable energy production, as announced by European governments, raise the question of where the additional production capacity will be located geographically, especially in densely populated countries. Existing renewable support policies that focus on minimizing production costs often lead to an inefficient concentration of renewable energy installations since the low-cost potential is often concentrated geographically (Newbery, 2023) and the absence of locational price signals in European power markets does not incentivize regional diversification. The concentration creates the need for additional transmission lines or frequent, costly interventions to counteract grid congestion, such as re-dispatching power (Eicke et al., 2020). Investors in generation capacity are usually not fully exposed to these costs, which requires additional instruments to incentivize geographic diversification. Additionally, the negative externalities of wind power are local, while the positive externalities of wind power, such as reduced emissions or energy security, are national, if not even global. These local externalities, such as the visual impact of wind turbines, can lead to resistance against additional installations, particularly if highly concentrated, and such resistance slows down, or even prevents, their construction (Zerrahn, 2017).

This dual objective of cost minimization and geographical diversity constitutes a trade-off when auctions are used to allocate renewable energy support. The reason is

that geographical diversification leads to more expensive installations being built, which raises the cost that consumers pay for electricity (from here on: "consumer costs"). Additionally, the high-cost installations are price-setting in the auctions, which allows low-cost installations to capture higher producer rents, which further raises consumer costs. Regulators can try to circumvent this by considering the resource potential of each project in the auction design and employing resource differentiation, i.e., rules that make bids and payments dependent on qualities of the renewable energy source that the regulator can observe, such as the full load hours achieved or achievable at a site. Thereby, the government can increase the chance of success of installations from areas with lower resource quality (e.g., lower wind speeds leading to fewer full load hours of production) while simultaneously reducing the payments to bidders from high resource quality and, thus, low-cost installations. The design of such rules can build on the economic literature on government procurement through auctions (Klemperer, 2010, Fabra and Montero, 2023, Kreiss et al., 2021) and auction designs that distinguish between bidder types (Myerson, 1981, McAfee and McMillan, 1989, Marion, 2007, Krasnokutskaya and Seim, 2011). In Europe, such resource differentiation in renewable energy support auctions is implemented in the German, Austrian, and Dutch support schemes for renewable energy (Kröger and Newbery, 2024). Additionally, there are examples of resource differentiation in other areas of the energy and natural resource industry. For instance, in the offshore oil industry, royalty rates are regularly determined according to the water depth and field productivity, i.e. the accessibility and quality of the resource (EY, 2019). Likewise, mining royalties are often defined relative to the mineral content of the production, leading to higher taxation of mines with higher resource quality (Otto, 2006).

In this article, we analyze the effect of resource differentiation on consumer costs both analytically and numerically. First, we use a stylized microeconomic model to show the two effects of increased production costs through the inefficient selection of sites stemming from geographic diversification and reduced producer rent through the introduction of price discrimination. We find that resource differentiation is an effective policy for reducing consumer costs when the uncertainty about firms' cost structures is relatively small, the auction volumes are high, and the observable cost difference between high and low-quality installations is high. Second, in a numerical analysis based on a novel dataset of the levelized cost of electricity at 160,792 locations, we analyze the German case of the "Reference Yield Model". We find that this example of resource differentiation reduces consumer costs by 11%, which is equal to a reduction of 20.7 billion Euro for the planned onshore wind expansion from 2025 to 2030. The policy leads to a cost increase because it only leads to a small increase in production costs ($< 1\%$) since only a small number of additional high-cost installations are built when resource differentiation is introduced. Meanwhile, the benefits of producer rent reduction (-67%) accrue across all installations

and are substantial. Given the level of detail in the dataset we can further analyze the effect the rule has on geographical diversification. In our example, we find that the effect in areas with very low wind speeds is negligible but that the policy leads to an increased building of installations in locations of medium resource quality.

Our article relates to two strands of the economic literature. First, we relate to the literature on the design of auctions for renewable energy and the design of the support contracts allocated through these auctions. Specifically, the economics of resource differentiation relate to the debate about technology-neutral and technology-specific support for renewable energy (Fabra and Montero, 2023, Kreiss et al., 2021, Lehmann and Söderholm, 2018, Del Río and Cerdá, 2014, Del Río, 2017). While technology-neutral auctions for renewable energy support are considered to be efficient because they lead to the choice of the overall cheapest technologies, they leave high producer rents with low-cost technologies. Meanwhile, technology-specific auctions allow for separate strike prices for high- and low-cost technologies. A discriminatory auction mechanism can, for example, differentiate between high- and low-cost technologies by assigning them a bonus or penalty, respectively. Thus, it can reduce producer rents for the low-cost technologies but may, in the case of misspecification, also lead to additional expenses of building too many high-cost technologies (Fabra and Montero, 2023, Kreiss et al., 2021). The analysis of renewable energy support contracts relates to the very active body of recent research focusing on the design of contracts for differences (Newbery, 2023, Schlecht et al., 2024, Beiter et al., 2024, Neuhoff et al., 2022, 2023). Second, the numerical results add to the existing analyses of the German reference yield model that have found ambiguous effects on consumer costs. The previous papers have considered the reference yield model based on a numerical simulation (Engelhorn and Müsgens, 2021), an empirical evaluation (Hitaj and Löschel, 2019), and as part of a general analysis of the German auction system (Bichler et al., 2020). However, they found diverging results given the assumptions used in their papers. 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, it is the first paper to analyze the effect of resource differentiation in a microeconomic model. We capture the trade-off between efficiency and rent extraction in a stylized, continuous setting and present comparative statics showing in which settings it is most appropriate to employ resource differentiation. We thereby add to the microeconomic literature and can inform policy on the design of renewable energy auctions and support mechanisms. We extend the related economic literature by extending the microeconomic theory of a discrete dif-

ferentiation between technologies to a continuous case of intra-technology differentiation. Second, we add to the numerical and empirical evidence on the effect of the German reference yield model with a novel, numerical model of the German auctions for renewable energy. The model simulates the auctions for the years 2025-2030, drawing on the levelized cost of electricity at 160,792 potential wind energy locations in Germany. Finally, by being the first paper to combine a theoretical and numerical analysis of resource differentiation for renewable energy, we can 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 on the effectiveness of the reference yield model.

The rest of the paper is structured as follows. In Section 2, we present a theoretical model analyzing the effects of resource differentiation via a continuous adjustment factor in auctions for renewable energy. Section 3 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 are caused by the reference yield model. Section 4 concludes and discusses the policy implications of our work.

2 Microeconomic model

In order to understand the trade-off between efficiency (i.e., the selection of the most cost-competitive projects) and reduced scarcity rents (i.e., the reduction of producer rents from low-cost installations), we set up a stylized microeconomic model analyzing the effect of resource differentiation on consumer costs (Δ_{CC}). Thus, we consider the procurement decision of a regulator that aims to minimize costs to consumers in two cases: A base case (*BC*) and a case of resource differentiation (*RD*). The model builds on previous works by Fabra and Montero (2023) and Kreiss et al. (2021), who investigate technology-neutral and specific auctions for renewable energy. We extend the approach of these papers by considering a new question in a new setting. We investigate the introduction of continuous, intra-technology resource differentiation rather than considering the binary cost differences between two different technologies.

2.1 Model description

In the stylized microeconomic model, we analyze the case of a regulator that procures the fixed quantity Q^* through the auction of a commodity such as electricity.¹ The parame-

¹In a simplification of the auction design, we define Q^* as the production of the installations (in MWh) rather than their capacity (in MW).

Table 1: Parameters of the model

Parameter	Definition	Interpretation	Unit
Q^*	Auctioned quantity	Q^* indicates the maximum capacity that is awarded in an auction, $Q^* > 0$.	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
a	Intercept, $a = C(0,0)$	The point where $w = 0$ and $\theta = 0$, i.e. the cost of the reference plant, $a > 0$.	Euro
b	Slope, $b = \frac{\delta c(\theta, w)}{\delta w}$	The slope of the cost curve with respect to the resource quality, $b > 0$	Euro/ MWh
θ	Non-observable, project-specific costs	Costs that are not dependent on the resource quality and that are not considered by resource differentiation, $\theta \in [0, \bar{\theta}]$.	Euro
g	Adjustment Factor	Indicates how strong the costs are adjusted by resource differentiation, $g = 1$ implies that there is no adjustment, when g approaches 0 all locations have the same adjusted, observable costs, $g \in (0, 1]$.	-
\hat{w}	Resource quality of last unit	Resource quality of the last unit that is still awarded support in the base case.	MWh

ters of the model are summarized in Table 1. 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) and that the auction is incentive-compatible so that projects bid their true costs. However, in accordance with the revenue equivalence theorem, we can assume that the results extend to other auction types (e.g., pay-as-bid auctions), which is especially true for the auctions for onshore wind in Germany, which are investigated in the subsequent section of the paper, that have seen undersubscription and an anticipation of the strike prices. From Figure 10, which shows the auction volumes of the German auctions for onshore wind from 2019-2024, it can be seen that all but three auctions were undersubscribed. The undersubscription had the effect that most projects bid the strike price (Bundesnetzagentur, 2021).

The regulator procures the quantity via an auction for two-sided contracts for differences in which we differentiate between a standard auction and an auction with resource differentiation through a continuous adjustment factor g . Using the adjustment factor, the regulator adjusts the bids (i.e., the costs) from the projects, thereby increasing the chance of installations at locations with lower production to be selected for support. Graphically, the adjustment factor shifts the bid curve around the reference point as is shown in Figure 1. The regulator aims to minimize consumer costs. In accordance with previous works, we define support costs as the combination of the production costs and

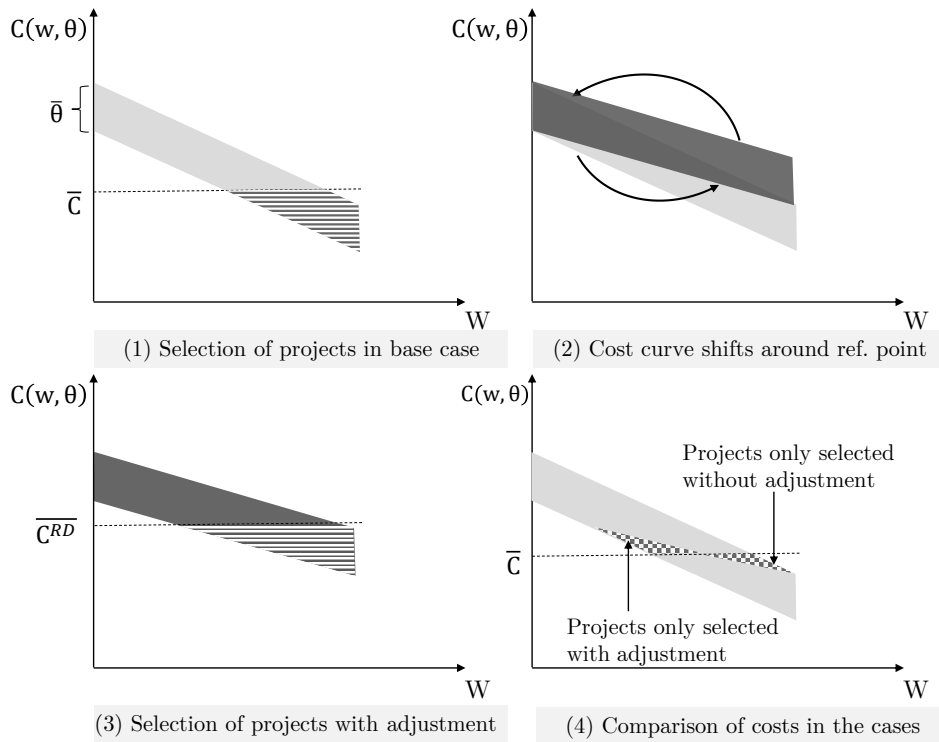


Figure 1: Illustration of how the adjustment factor affects the distribution of costs and choice of supported projects

producer rent (Kreiss et al., 2021).² The auction awards support either to the projects with minimum production costs $c_i(w_i, \theta_i)$ that depend on the cost components w_i and θ_i in the base case or minimum adjusted production costs $c_i(w_i, \theta_i, g)$ that depend on the cost components as well as the adjustment factor g in the case with resource differentiation. This effect is shown illustratively in Figure 1.

We assume that project costs $c_i(w_i, \theta_i)$ are equal to $a - bw_i + \theta_i$, i.e., that costs 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 quality at location i measured in full load hours) that must be disclosed when the adjustment factor is applied and that is verifiable by the regulator, θ_i is not observable to the regulator.³ Thus, $c_i(w_i)$ 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. Therefore, the size of θ represents

²Since we assume remuneration to be according to a two-sided contract for difference, the support costs are equal to the cost incurred by consumers if the difference payments are rebated to the public.

³In the example of the German reference yield model discussed in Section 3 the full load hours achieved at each location, which are an important determinant of a project's costs, are verified through measurements over five years.

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 $[0, \bar{w}]$.

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 is determined by:

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

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

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

2. *Resource differentiation*

The regulator conducts an auction applying the adjustment factor g , where $g \in (0, 1)$. 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 $c_i^{RD}(w_i, \theta_i, g) = a - gbw_i + \theta_i$. Selecting projects based on their adjusted costs changes the minimum resource quality that is selected for each value of θ (i.e., the border of the integral) from $\hat{w}(\theta)$ to $\hat{w}(\theta, g)$.

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

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

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

In the case of resource differentiation, projects must disclose their verifiable type w_i to the regulator, who is able to make their payment contingent on resource quality. Thus, each installation is paid $p(w_i, g) = c(\hat{w}, \theta, g) - (1 - g)b(w_i - \hat{w})$, i.e., the price

paid to the installation is dependent on its resource quality and the adjustment factor.

For both of these cases, we can calculate the production costs and production rent according to the step-by-step solution presented in Appendix A.2 and Appendix A.3.

2.2 Main result

We can then calculate the consumer costs that the price that consumers have to pay for the commodity, as the sum of producer rent and production costs. We can compare the difference in consumer costs as well as decompose the effect into the effect on production costs that stems from the inefficient selection of sites and the effect of reduced producer rents:

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

Using the solution steps presented in the Appendix, we find that the consumer costs in both cases are:

$$CC_{BC} = \frac{2bQ^{*2} + \bar{\theta}^2 Q^*}{2\bar{\theta}} \quad (2)$$

$$CC_{RD} = \frac{2bQ^{*2} + \bar{\theta}^2 Q^*}{2\bar{\theta}} + \frac{Q^{*2}bg}{2\bar{\theta}} + \frac{(1-g)\bar{\theta}^3}{24bg^2} \quad (3)$$

In the base case shown in Equation (2), the consumer costs depend on the slope of the curve b , the total quantity sold Q^* , and the uncertainty θ . In contrast, the consumer costs in the case of resource differentiation in Equation (3) further depend on two additional terms that are dependent on the resource differentiation that depends on g .

We can calculate and simplify the difference in consumer costs between the two cases as follows:

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

This aggregate result is comprised of the two effects on the production cost and the

producer rent:

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

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

The difference in production cost in Equation (5) is positive. This result is intuitive since resource differentiation leads to an inefficient selection of sites. Meanwhile, whether the overall difference (Equation (4)) and the difference in producer rents (Equation (6)) are positive or negative depends on the relationships between the parameters of the model. Thus, whether the effect of resource differentiation on consumer costs is positive or negative depends on the relative size of the heterogeneity of costs (b), the unobservable cost factor θ , the strength of the adjustment ($1-g$), and the total volume auctioned (Q^*).

2.3 Comparative statics

Table 2: Results of stylized microeconomic analysis

Effect on consumer costs	$\Delta_{CC} = \frac{(g-1)(12(Q^*)^2b^2g^2 - \bar{\theta}^4)}{24bg^2\bar{\theta}}$
Effect of increased unobs. costs	$\frac{\delta\Delta_{CC}}{\delta\bar{\theta}} = \frac{(1-g)(4Q^*b^2g^2 + \bar{\theta}^4)}{8bg^2\bar{\theta}^2} > 0$
Effect of increased obs. heterogeneity	$\frac{\delta\Delta_{CC}}{\delta b} = \frac{(g-1)(12(Q^*)^2b^2g^2 + \bar{\theta}^4)}{24b^2g^2\bar{\theta}} < 0$
Effect of increased quantity	$\frac{\delta\Delta_{CC}}{\delta Q^*} = \frac{Q^*b(g-1)}{\bar{\theta}} < 0$

While it is *ex-ante* unclear for a given g which of the two effects is larger – whether the policy leads to higher costs for consumers or not – the microeconomic model can help to understand how different factors affect the result. To further investigate the effect of these parameters, we calculate comparative statics with respect to these parameters θ , Q^* , and b by taking the first derivative. The results are displayed in Table 2. It shows that while an increase in the importance of non-observable costs (θ) leads to relatively higher consumer costs, a larger heterogeneity of observable costs (b) and an increase in the auction volume (Q) reduce the relative consumer costs under the policy of resource differentiation, as compared to the situation without such a policy. Thus, resource differentiation is most effective when the resource quality has a high effect on the overall costs compared to the unobservable cost factors.

In addition, we can take the first derivative with respect to the adjustment factor g , which is:

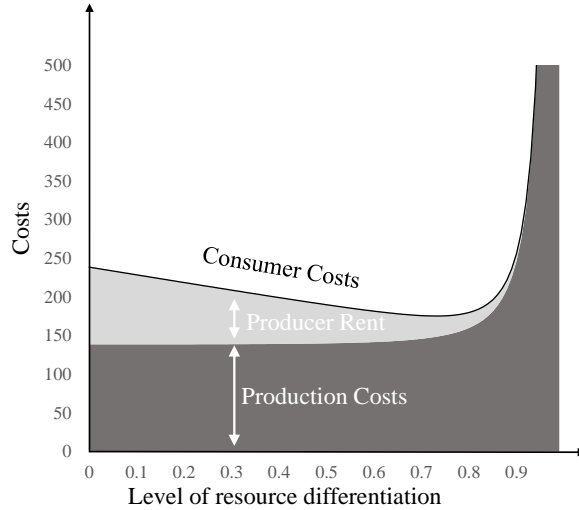


Figure 2: Illustrative effect of resource differentiation

Figure shows the theoretical effect of resource differentiation based on our calculations in the model for the parameters $a = 20$, $b = 2$, $Q = 20$, $\theta = 4$.

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

Since there exists a $\frac{\delta \Delta_{CC}}{\delta g} = 0$ and since the second derivative with respect to g is positive, there exists a positive g^* at which consumer costs are minimized. The effect is illustrated in Figure 2 for a specific calibration of the model. While resource differentiation initially leads to a reduction in overall consumer costs, the increase in production cost eventually outweighs the effect of reduced producer rent. Thus, for this parameter setting resource differentiation leads to an increase in overall costs at high levels of resource differentiation.

2.4 Discussion

The stylized microeconomic analysis supports the notion that resource differentiation can lead to a reduction in consumer costs if the effect on producer rent outweighs the rise in production costs. The analysis is based on several 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. The assumption of linear cost functions for electricity is often made in the literature (Acemoglu et al., 2017). 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 achieved full load hours w . This assumption 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, existing literature argues that pay-as-bid rules do not prevent producer rents (Kreiss et al., 2021) and the narrow range of bids in the previous bidding rounds indicate that the participants in the German auction for wind energy can anticipate the strike price well (Bundesnetzagentur, 2021).

3 Numerical model

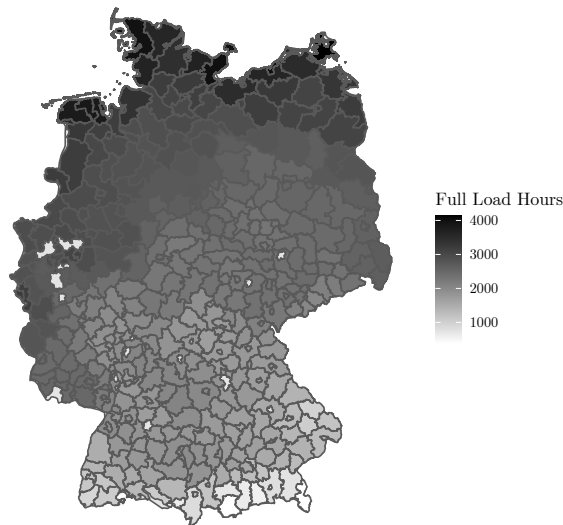


Figure 3: Distribution of resource quality for onshore wind (measured in full load hours) in Germany, own calculations

Figure 3 shows the average full load hours achieved in each German municipality. The numbers are based on our own calculations using the input data for the numerical model.

In the renewable energy space, an example of resource differentiation is the reference yield model, implemented in the German auctions for onshore wind since the introduction of the Renewable Energy Act ("Erneuerbare Energien Gesetz") in 2000. Other countries that differentiate payments based on the resource quality of wind energy installations are the Netherlands (Martin et al., 2019), and Austria (Government of Austria, 2023). Figure 3 shows why Germany is an interesting setting to study the effect of resource differentiation: The resource quality of wind differs strongly between regions, and the high-cost potential is concentrated along the coasts. The reference yield model partially reduces the disadvantages of low-quality wind locations by making payments dependent on the quality of the wind resource at its specific location. It requires participating onshore wind power projects to disclose the volume of electricity that the project would

produce over five years at its intended location. This volume is then compared to the production volume that the turbine would achieve at the so-called *reference location*. Depending on the ratio between the projected production at the project’s location and the projected production at the reference location, the project is assigned a correction factor according to the mapping in Table 3. To avoid fraudulent behavior, the wind yield at the specific location is controlled during operation. 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 (Fachagentur Wind, 2016). Once generators have placed their bids, these are divided by the correction factor, and the winners are selected based on the adjusted bids. Since the subsequent support payments are based on the actual bids rather than the adjusted ones, this implies that successful installations at locations with worse wind conditions are able to receive higher support payments than installations with a high wind yield.⁴

Table 3: 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

Table 3 shows the reference yields, calculated as the number of full load hours that can be achieved at the project’s location divided by the full load hours at the reference location and corresponding correction factors. Between two values in the table, the relevant values for the reference yields and correction factors are calculated as the linear interpolation of the upper and lower values.

Thus, the reference yield model introduces the two effects of price discrimination, which limits producer rents, and an inefficient selection of sites, which increases production costs, that we have discussed in the previous section. We use this setup to develop a numerical model of resource differentiation and to quantify the effect of the German reference yield model on support costs.

3.1 Model description

To analyze the case of the reference yield model, we conducted a numeric analysis of the German auctions for renewable energy by simulating the auctions for the years 2025-2030 based on a draw from 160,792 potential wind energy locations in Germany. Figure 4 describes the approach of the model.

⁴For 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 does not affect very high and very low-quality wind locations. This rule introduces a discontinuity for the lowest and highest-performing installations. In our analytical analysis, we disregarded this discontinuity, thereby assuming that such projects with very high yields are 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).

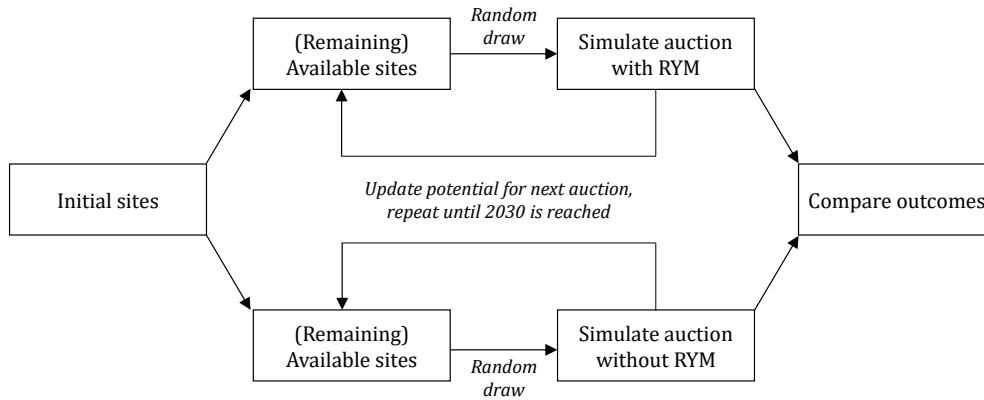


Figure 4: Structure of the numerical model

The model aims to capture the effect of resource differentiation in the case of the German reference yield model. As input, the model takes a cost potential for potential onshore wind locations that contain 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 auction mechanism is then applied to this set of bids. We simulate the auctions from 2025-2030, once without resource differentiation 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 costs Δ_{CC} , the change in production costs Δ_{PC} , and the change in producer rents Δ_{PR} . For each scenario, we repeat the simulation of the auctions 100 times in order to reduce the effect of outliers in our selection procedure on the results. Separate random draws are considered with and without the reference yield model to account for the unequal use of potential in both cases. Appendix A.4 and Appendix A.5 contain a more in-depth description of the auction and selection mechanism.⁵

The analysis is based on a number of assumptions. First, we assume the auctioning of two-sided contracts for differences (hereafter "CfDs"), i.e., a support scheme that guarantees a fixed remuneration (the "strike price") through a long-term hedging contract (Kröger et al., 2022). Second, given the 2022 update of the Renewable Energy Act, Germany plans to expand its renewable energy production by 6,500 MW each year until the end of the 2020s. We assume that there are four separate auctions per year (i.e.,

⁵In Appendix A.9, 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 six years is equal to 39,000 MW). Third, to focus on a competitive situation, which the German government is aiming for in future auctions, e.g., through regulation on zoning laws, we assume that in each auction, there is an excess supply of wind projects of 40%. We simulate four auctions per year for the period until 2030. Finally, we restrict the potential that can be built at each node of our model to 80% of the capacity and assume that each installation runs for 20 years until it is repowered and enters the auction again.

3.2 Data

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	$N(\mu, \frac{0.06}{1.96})$	20

We create 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. For this, we proceeded as follows. We combined publicly available data to compile a database of potential wind energy locations in Germany (Caglayan et al., 2019). The dataset describes the technical potential of wind energy in Europe for a scenario of future turbine types. The potential locations are derived by 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 (Ryberg et al., 2020). While the authors 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 (Ryberg et al., 2019). We match these locations to the historical 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 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 those of the present 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 from the literature to calculate the levelized cost of electricity for each of the projects (Kost et al., 2021). 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 with 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 and calculated as a share of the mean levelized cost of electricity so that the random cost component composes up to 12% of a project's costs.⁶ We further assume a risk-free discount rate of 2% for the calculation of present values. The existing power plants at each node of our dataset are taken from the official German registry of power plants (Bundesnetzagentur, 2022).

3.3 Results

a. Effect on consumer costs

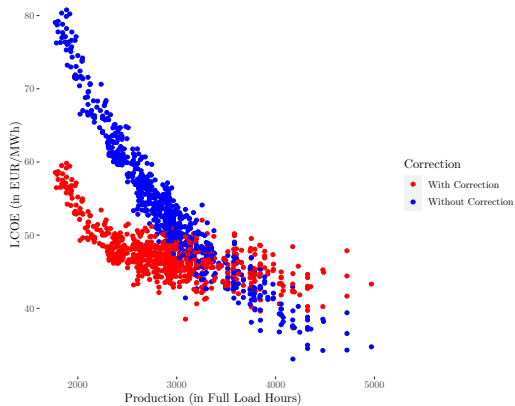


Figure 5: Shifting bid curve after resource differentiation

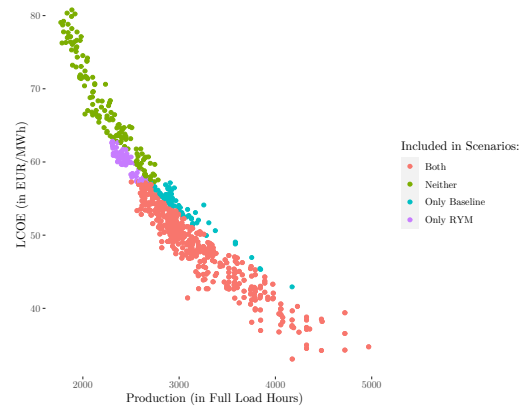


Figure 6: Projects selected depending on the scenarios

Figure 4 displays the shift in the application with and without the reference yield model. The case with the reference yield model is displayed in blue, while the case without resource differentiation is shown in red. Figure 5 shows which projects are chosen in the different scenarios. The green projects are never chosen, the red projects are always chosen, the violet projects are only chosen when resource differentiation (i.e., the reference yield model) is applied, and the turquoise projects are chosen only when resource differentiation is not applied.

First, we consider the effect that the reference yield model has on consumer costs. We find that it leads to a reduction in consumer costs of 5.15 Euro per MWh. This cost reduction is due to the fact that the increased production cost (+0.54 Euro per MWh) from choosing projects in less windy locations is far outweighed by the decreased producer rents (-5.69 Euro per MWh). Thus, the producer rent of projects is reduced by 67% while production costs only increase by 1%. For the entire period from 2025-2030,

⁶We assume that the variance of θ is $\frac{0.06}{1.96}$. Since, in a normal distribution, 95% of values are within 1.96 σ of the mean, this implies the assumption that unobservable costs constitute up to 12% of the project's production costs. This is a similar magnitude to the findings of previous research, which assumes 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, (Deutsche Windguard, 2015)).

the reference yield model leads to an aggregated net present value decrease in consumer costs of 20.7 billion Euro. This change is equivalent to a net present value decrease of 11% and an average present value saving of 505 Euro over the lifetime of the turbines per German household.

Figure 5 and Figure 6 illustrate the reason for the positive effect of resource differentiation on consumer costs by showing the projects selected with and without the reference yield model. Indeed, the reference yield model only leads to a substitution of projects in a small number of cases. This substitution reduces the average full load hours achieved by the turbines accepted for production, without counting for interruptions due to maintenance, from 3103 to 3056. Meanwhile, the effects on producer rents occur across the entire set of projects. As shown in the illustration, these producer rents are very unequally distributed, with the most productive producers gaining the highest scarcity rents.

b. Effect on geographical diversification

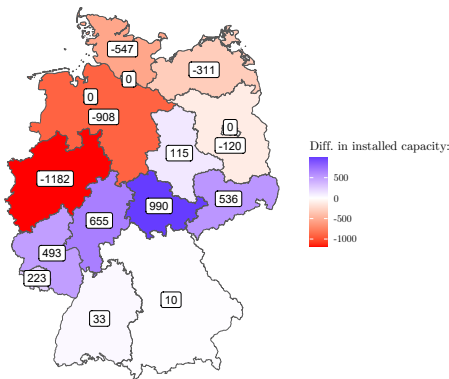


Figure 7: Change in awarded capacity per federal state in MW

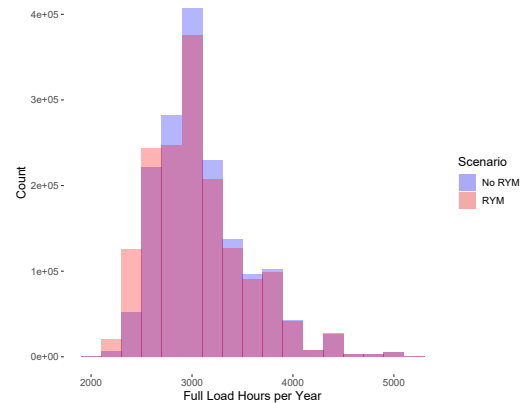


Figure 8: Projects selected depending on the scenarios

Figure 7 displays the difference in the additional installed capacity in MW with and without the reference yield model summed over the 24 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 simulation. Figure 8 shows the distribution of full load hours over the results from the numerical simulations for the case of the reference yield model (red) and without the reference yield model (blue).

Second, we consider the effect on the geographical diversification of onshore wind installations. Given the small number of substituted projects, it is not surprising that the reference yield model has a limited effect on the geographic distribution of projects. Figure 7 shows the difference in project capacity allocated to each federal state between 2025-2030. While there is a substantial shift of projects in the middle of the country, the Southern states of Baden-Württemberg and Bavaria receive only a small number of additional projects. This small shift is due to the fact that the reference yield model has

relatively moderate correction factors, such that the projects with the lowest resource potential are still not successful after the policy is applied. In relative terms, we find that the largest shift in projects is in Thuringia (+54%), Saarland (+37%), and Hesse (+21%). The largest decreases are in North Rhine-Westphalia (-7%) and Lower Saxony (-4%). The effect is further explored in Figure 8 showing the change in the distribution of full load hours between the two scenarios. It is clear that the change is mostly from medium wind speed areas towards the areas with lower wind speeds. However, there is again no effect on very high and low wind speed areas.

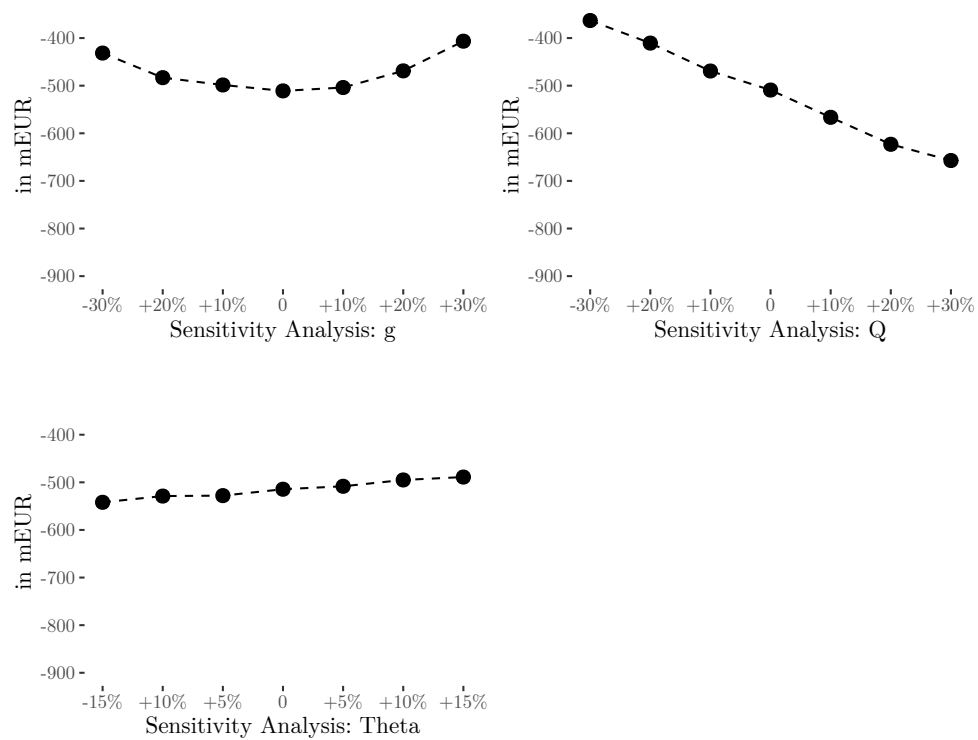
c. Effects in undersubscribed auctions

Finally, we can use the model to analyze the effect in undersubscribed auctions. The previous analysis deviates from the real-life auctions in Germany by assuming that there is an excess supply of wind projects in the auctions. In reality, between 2017 and 2023, auctions for onshore wind in Germany are suffering from undersubscription, i.e., there were fewer bids than the announced auction volume and auctions cleared at the bid ceiling (Bundesnetzagentur, 2021). In this case, only the producer-rent effect exists, while there cannot be a substitution toward lower-quality projects due to the lack of alternatives. We calculate that the reference yield model leads to a reduction of consumer costs of 13% in the case where there are fewer bids than the announced volume. Thus, the effect on consumer costs is indeed more substantial for undersubscribed auctions since there cannot be a negative effect on efficiency.

3.4 Sensitivity analysis

To check the robustness of our results, we conduct a number of sensitivity analyses by varying the parameters from our microeconomic analyses. Specifically, we vary the strength of the adjustment (i.e., the correction factors), the uncertain cost parameter, and the quantity auctioned. The results are displayed in Figure 9. We find that, in all cases, the result of a negative effect on consumer costs is robust and that the results further confirm the results of our microeconomic analyses. First, we find that there is indeed an optimal value of the adjustment factor g . When the adjustment becomes too big, the effect of the price discrimination starts to outweigh the additional savings through stronger price discrimination. Second, we find that an increased auction volume does indeed lead to stronger consumer cost savings since the benefits accrue over a larger set of projects. Third, we find that an increased *ex-ante* cost uncertainty θ reduces the benefits of resource differentiation.⁷ More detailed results from the sensitivity analysis can be found in Appendix A.10.

⁷Given the structure of the model, it is not possible to do a sensitivity analysis on the observable cost differences b without changing the structure of the input data.



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 the sensitivity analyses performed is found in the Appendix. Results based on 100 repetitions of the simulation.

Figure 9: Change in consumer costs for the three sensitivity analyses

3.5 Discussion

We design the numerical model to represent the current German auctions for renewable energy. While some simplifications have been made, these do not affect the ability to generalize our model results to the German case. As in the microeconomic analysis, we abstract from the German auction design in calculating the cost to consumers as a CfD rather than a sliding premium. This assumption is justified since the European Union demands that all auctions be changed to CfD auctions in the coming years (Busch et al., 2023). Even if the German regime were not to be changed, this would not change results if wholesale power prices were sufficiently low. Additionally, we assume a uniform rather than a pay-as-bid auction, as we did in the theoretical analysis. As argued before, this assumption should not change the results. Furthermore, we do not include the second instrument aimed at increasing the geographic diversity of wind installations (i.e., the Southern quota reserving part of the auctioned capacity to bids from the Southern states) in order to avoid interactions between the two policies that might bias our results.

Our results show that the reference yield model leads to a significant reduction in consumer costs. Previous academic literature has found ambiguous results that are explained by the assumptions made by the authors. Hitaj and Löschel (2019) analyze the effect of the German feed-in tariff on renewable deployment between 1996 and 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 volumes. Meanwhile, 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 nationwide auction design without location-specific incentives. However, given that the authors assume that firms bid at marginal costs and thus forgo resource and scarcity rents, the downward effect that the reference yield model would have on producer rent is outside the scope of their paper. Engelhorn and Müsgens (2021) analyze the reference yield model based on a numerical simulation of counterfactual auction designs that they compare to the historical development. The authors find that the costs of the German energy transition would have been reduced by 30% for a cost-minimizing benchmark scenario (i.e., for a scenario without the reference yield model).⁸ While the authors do consider the

⁸For a second scenario considering land-use, building capacity, and acceptance constraints they find a cost

same trade-off between price discrimination and efficiency, the difference in our results is driven by differing assumptions on the size of the inefficiency in the geographical diversification 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 small and local effect of the reference yield model.⁹

4 Conclusion and policy implications

For the economic success of the transition to a carbon-free economy, the costs of renewable electricity are a deciding factor. At the same time, there are strong reasons for diversifying the location of renewable energy projects including fairness and the functioning of the wholesale electricity market. This, would lead to the building of installations in areas with lower resource quality and, thus, higher production costs. This paper considers the possibility of *resource differentiation* in renewable energy auctions to solve this trade-off between efficiency and a larger geographic spread of installations. We do so by analyzing the effect of resource differentiation both in a stylized microeconomic model and a numerical analysis of the German reference yield model.

In our microeconomic analysis, we show for a continuous case of intra-technological resource differentiation that it can lead to a reduction in consumer costs. Furthermore, we disentangle the effect on consumer costs into the effects on production costs and producer rent. We find that an increase in the spread of non-observable costs, such as site-specific building costs, or firm-specific financing costs, leads to relatively higher consumer costs for a given level of resource differentiation. Meanwhile, a larger difference in observable costs in the auction, i.e., those affected by the quality of the renewable resource, and an increase in the auction volume reduce the relative consumer costs for a given level of resource differentiation. We find that an optimal level of resource differentiation exists to minimize consumer costs.

In the subsequent numerical analysis, we quantify 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 20.7 billion Euro (-11%) between 2025 and 2030. This change is equivalent to a decrease in cost to electricity consumers of 505 Euro per household in Germany over

reduction of 23%.

⁹In the cost-minimizing scenario, the authors find that more than 82% of wind turbines are located in Lower Saxony and Schleswig-Holstein.

the same time period. The results are even stronger if we consider a continuation of undersubscribed auctions that clear at bid capacity without the possibility of an inefficient selection of projects. Thus, only the price-discriminating function of the reference yield model is relevant in such a scenario.

The results presented in this paper strengthen the argument that resource differentiation is an adequate policy to reduce the cost of renewable energy expansion through reduced scarcity rents while only introducing a small externality. This is an important finding, especially for resource-constrained countries like Germany that plan to expand their renewable energy capacities rapidly and that seek to diversify their production portfolio geographically. When expanding resource differentiation to further technologies, such as solar power, our findings suggest that the regulator should consider the influence of unobserved cost components relative to the cost difference between high and low-yield areas. Importantly, our analysis does not consider the additional benefits that diversification of sites due to resource differentiation would have on the acceptance of wind power and the potential reduction in congestion costs. These provide a further strong economic argument for the introduction of location-specific incentives for the expansion of renewable energy. The results can further be extended to characteristics of renewable energy beyond the resource quality of installations, such as the production profile. Similar to resource quality, governments have an incentive to encourage the diversification of production profiles in order to reduce the volatility of renewable energy supply. Introducing an adjustment factor depending on such characteristics could offer further benefits to the electricity system and has been discussed in previous publications under the term "market-value-model".

Our paper contributes to the literature by expanding the analysis of discriminatory auction design to a continuous case of intra-technology resource differentiation 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 resource differentiation. Additionally, if we assume that there is an inefficiency in government spending, 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 differentiation 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. 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, it would be interesting to compare it to alternative approaches of limited excess profits at high resource locations, such as a limit of maximum full load hours covered by contracts for differences.

Data availability

All data and code used in this analysis can be made available online.

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A Appendix

A.1 Volumes from recent German auctions

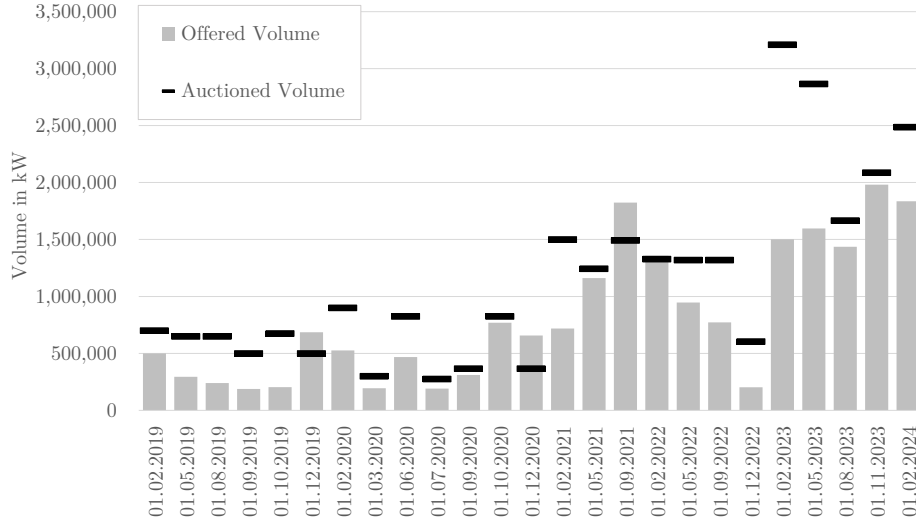


Figure 10: German auction volumes in 2019-2024 based on data from Bundesnetzagentur (2021)

A.2 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:

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

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

Under the condition that

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

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 $\hat{w}(\theta)$ 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 11.

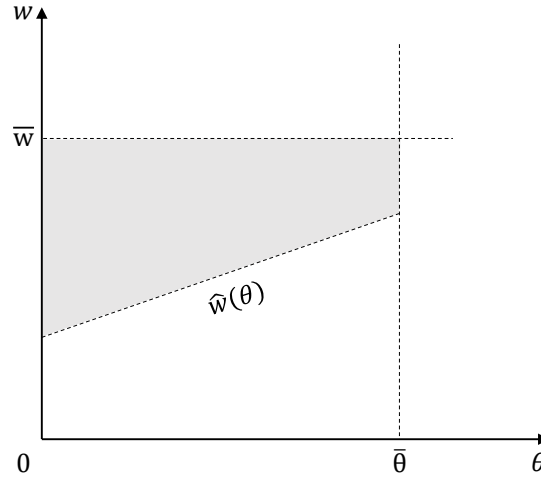


Figure 11: Borders of the integral

In solving the model, we conduct the following steps:

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

First, we calculate the consumer costs 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 $\hat{w}(\theta)$ as:

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

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 cost of the last project still chosen 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., $a = b\bar{w}$:

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

The expression indicates the value of \bar{c} that results 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 in the base case that result from auctioning the quantity Q^* :

$$PC_{BC}(\theta, w) = \int_0^{\bar{\theta}} \int_{\hat{w}(\theta) = \frac{a - \bar{c} + \theta}{b}}^{\bar{w}} a - bw + \theta \, dw \, d\theta$$

$$\Leftrightarrow PC_{BC}(Q^*) = \frac{12(Q^*)^2 b^2 + 12Q^* b \bar{\theta}^2 - \bar{\theta}^4}{24b\bar{\theta}}$$

Analogous to this, we can calculate the cost in the case where we use resource differentiation via a continuous adjustment factor depending again on the quantity Q^* and the chosen adjustment factor g :

$$PC_{RD}(\theta, w, g) = \int_0^{\bar{\theta}} \int_{\hat{w}(\theta) = \frac{a - \bar{c} + \theta}{bg}}^{\bar{w}} a - bw + \theta \, dw \, d\theta$$

$$\Leftrightarrow PC_{RD}(Q^*, g) = \frac{12(Q^*)^2 b^2 g^2 + 12Q^* b g^2 \bar{\theta}^2 + (1 - 2g)\bar{\theta}^4}{24b\bar{\theta}g^2}$$

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 adjustment factor does not change the true production costs. Δ_{PC} is then calculated as the difference between these two cost expressions.

A.3 Calculating producer rent

In addition to the costs, we are interested in the producer rents that bidders can capture under the standard auction and the auction with the adjustment factor.

1. Producer rents in the standard auction

Under the standard auction, the price paid to all installations is $\bar{c} = c(\bar{w}, \theta)$, the cost of the last unit procured in our auction. Thus, we can write the producer rents that are earned in the base case as follows:

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

The rent can be solved as the production costs before to give:

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

2. Producer rents in the auction with adjustment factor

In the auction with the adjustment factor, the regulator receives additional information about the project 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 rents over all projects as follows:

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

This solves to:

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

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

A.4 Selection mechanism applied in the numerical model

When drawing the project biddings 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 the 2021 auctions.

Second, we combine our potential dataset from Caglayan et al., 2019 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

Table 5: Percentage of bids by federal state in past auctions

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%

bids to 80% of available capacity at each node. Thereby, we want to exclude nodes where existing wind parks already occupy a large percentage of available locations. This restriction is necessary since the authors do not consider whether a wind turbine has already been built at the location (Caglayan et al., 2019). 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 repowering.

Third, we match the distribution of bids to the geographical distribution of bids as seen in auctions between 2017 and 2021, as displayed in Table 5 from Bundesnetzagentur (2021). 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.5 Auction mechanism applied in the numerical model

The auction mechanism applied in the model mimics the real German auctions for wind energy as employed in 2023. We assume that during the remainder of the decade (2025-2030), the government aims to build 6500 MW of wind power each year in accordance with its announcements. Thus, we model 4 auctions per year with a capacity of 1,625 MW of-

ferred 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 $Bid_{perMWh_i} = ProductionCost_{perMWh_i}$ in the base case and $AdjustedBid_{perMWh_i} = \frac{ProductionCost_{perMWh_i}}{CorrectionFactor_i}$ in the case of the reference yield model. After placing the bids for each installation, the auction mechanism selects those 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.6 Verification of cost potential

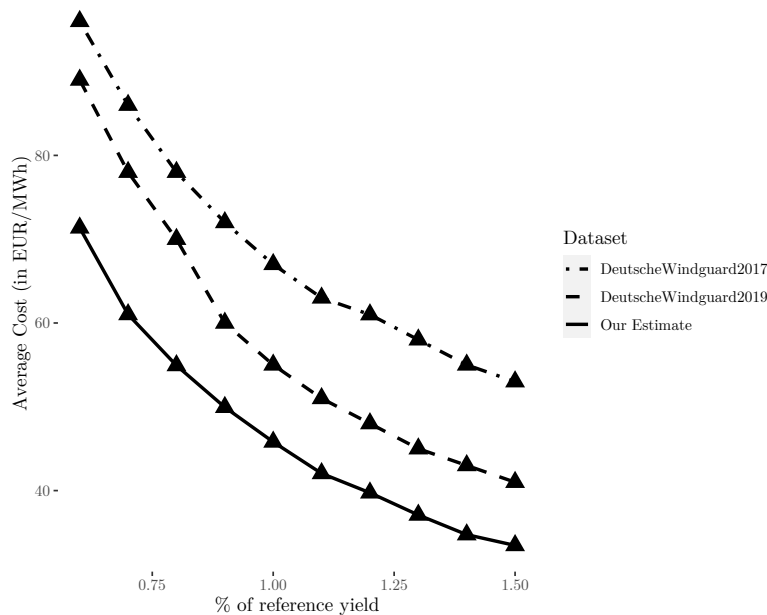


Figure 12: Cost estimate compared to literature values

The dataset used for this analysis was constructed according to the description in the main text. We calculated summary statistics to verify the calculated values for full load hours and LCOE. Figure 12 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. Our estimates for current costs show a decrease that is similar to the decrease that the reports estimated between 2017 and 2019. We expect the levelized cost of electricity to decrease over time due to techno-

logical learning. Most importantly, we see that the slope of the cost curve is similar. This observation is essential 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. We can further compare our cost estimates to estimates in the literature. We again find that the slope of the cost curve is very similar, even though a paper by Ruhnau et al. (2022) finds a lower average levelized cost of electricity due to the assumption of a longer lifetime of the turbines (30 instead of 20 years) (Ruhnau et al., 2022). Thus, while the level of our estimates might vary, the cost assumptions are robust with regard to the slope of our curves.

A.7 Outcome of a particular auction

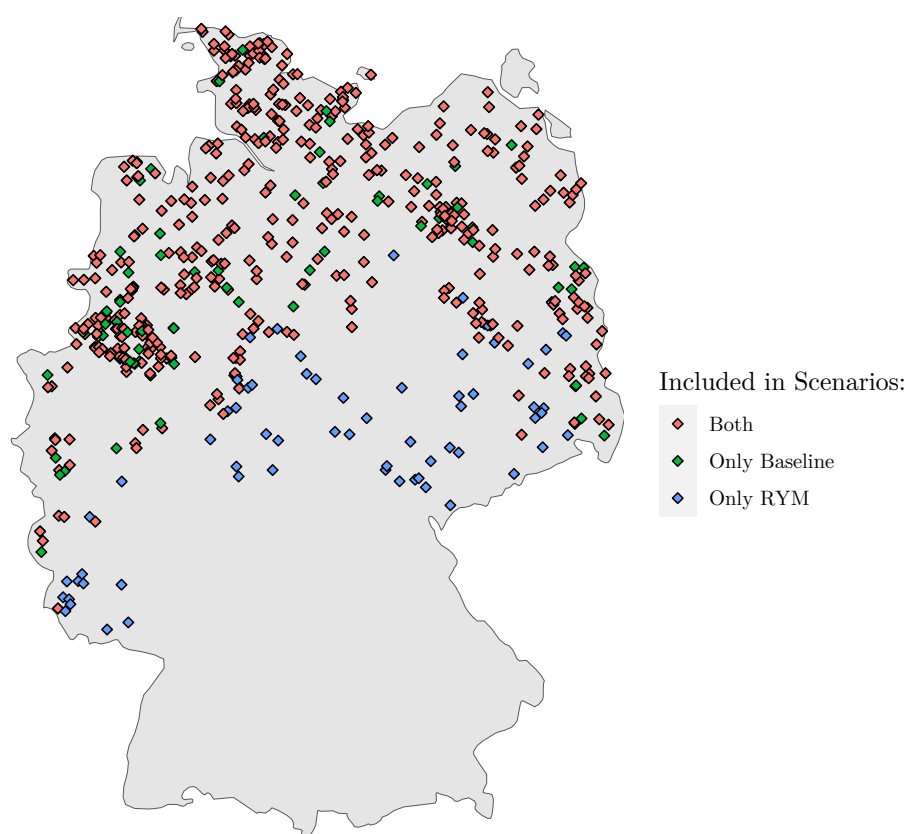


Figure 13: Geographic distribution of projects selected with and without the reference yield model

A.8 Replication of auction without competition

Table 6: Results from the August 2018 auction

Scenario	Δ_{CC} (in Euro/MWh)	Δ_{PR} (in Euro/MWh)	Δ_{PC} (in Euro/MWh)
Base Case	-10.15	-10.15	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 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.

A.9 Robustness check of geographical distribution

Table 7: Results from the robustness check

Scenario	Δ_{CC} (in Euro/MWh)	Δ_{PR} (in Euro/MWh)	Δ_{PC} (in Euro/MWh)
Base Case	0.86	-1.08	1.94

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

To test how the restriction by federal states and the restrictions of the projects bidding affect our results, we relax the constraints and simulate a single auction of 1625 MW without these restrictions. This change leads to the selection of projects that are almost exclusively located at the most efficient locations along the coasts. We find that under these extreme assumptions, the increase in production costs slightly outweighs the decrease in producer rents, leading to a two percent increase in consumer costs.

A.10 Additional graphs and tables from the sensitivity analysis

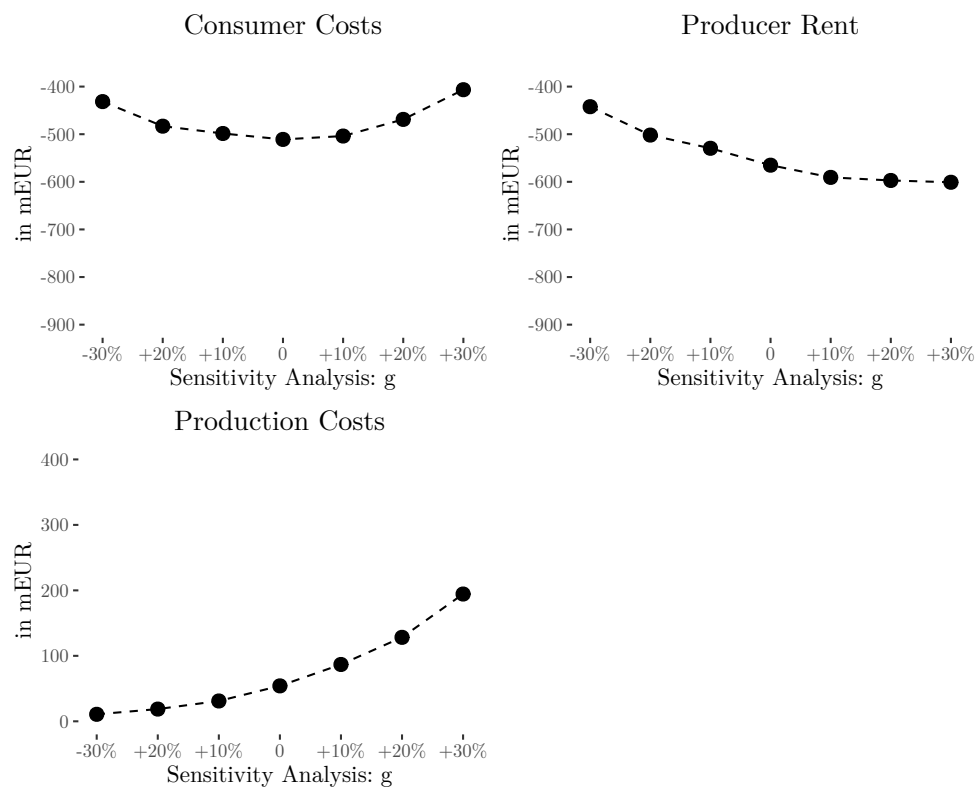


Figure 14: Change in consumer costs, producer rent, and production costs from changes in the adjustment factor g

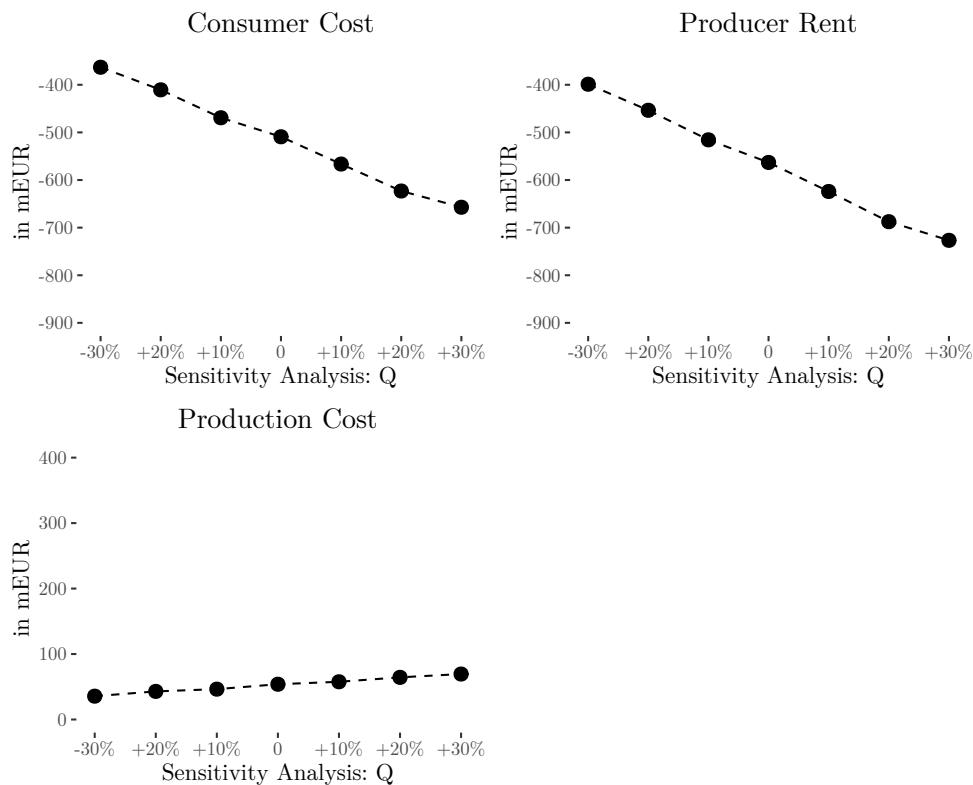


Figure 15: Change in consumer costs, producer rent, and production costs from changes in the auction quantity Q

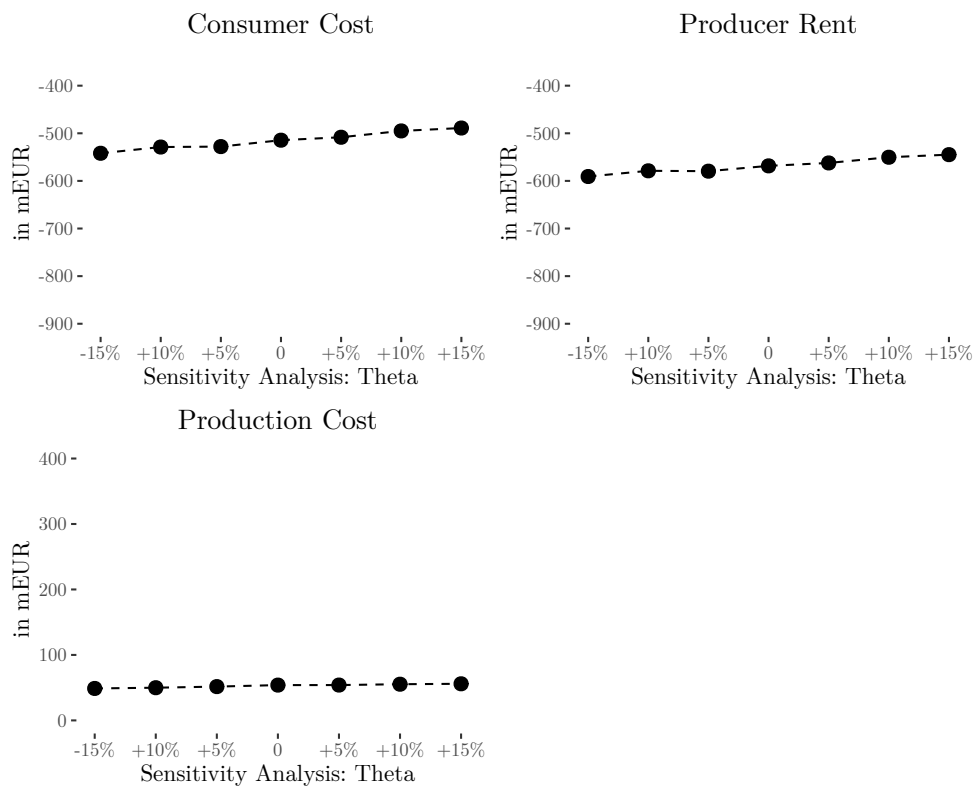


Figure 16: Change in consumer costs, producer rent, and production costs from changes in the cost parameter θ

Table 8: 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 -30%	-541.95	-590.77	48.82
θ varied by -20%	-528.86	-578.80	49.93
θ varied by -10%	-527.93	-579.56	51.63
θ not varied	-514.48	-568.41	53.92
θ varied by +10%	-508.31	-562.29	53.98
θ varied by +20%	-495.01	-550.29	55.28
θ varied by +30%	-488.93	-544.85	55.92
Q varied by -30%	-363.16	-398.82	35.66
Q varied by -20%	-410.58	-453.52	42.94
Q varied by -10%	-469.22	-515.61	46.39
Q not varied	-509.17	-563.07	53.89
Q varied by +10%	-566.45	-624.09	57.64
Q varied by +20%	-623.08	-687.49	64.40
Q varied by +30%	-657.18	-726.65	69.47
Slope of adjustment varied by -30%	-431.52	-442.23	10.71
Slope of adjustment varied by -20%	-483.15	-501.83	18.68
Slope of adjustment varied by -10%	-498.50	-529.56	31.06
Slope of adjustment not varied	-510.95	-565.07	54.12
Slope of adjustment varied by +10%	-503.86	-590.68	86.82
Slope of adjustment varied by +20%	-468.90	-597.16	128.26
Slope of adjustment varied by +30%	-406.55	-600.95	194.40