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Empfohlene Zitierung / Suggested Citation:
Lehmann, P., & Tafarte, P. (2023). *The opportunity costs of environmental exclusion zones for renewable energy deployment.* (UFZ Discussion Papers, 2/2023). Leipzig: Helmholtz-Zentrum für Umweltforschung - UFZ. https://nbn-resolving.org/urn:nbn:de:0168-ssoar-96256-2

HELMHOLTZ
Centre for Environmental Research

UFZ Discussion Papers

Department of Economics

2/2023

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April 2023

Publisher:
Helmholtz-Zentrum für Umweltforschung GmbH – UFZ
Permoserstr. 15
04318 Leipzig

ISSN 1436-140X

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Acknowledgements:

Research for this paper was funded by the German Federal Ministry of Education and Research (Bundesministerium für Bildung und Forschung – BMBF, grant no. 01UU1703) and the German Federal Environmental Foundation (DBU- Deutsche Bundesstiftung Umwelt, grant no. 34123/01-33/2). We received helpful comments for improving our paper during research seminars held at the Helmholtz Centre for Environmental Research – UFZ and the Land, Environment, Economics and Policy Institute (LEEP) of the University of Exeter.

The opportunity costs of environmental exclusion zones for renewable energy deployment

Abstract:

Exclusion zones, like protected areas or setback distances, are the most common policy instrument to mitigate environmental impacts of human land-use, including the deployment of renewable energy sources. While exclusion zones may provide environmental benefits, they may also bring about opportunity costs. This paper aims to understand and quantify the drivers determining the opportunity costs related to environmental exclusion zones. Using a simple analytical model, we propose that opportunity costs of exclusion zones can be decomposed into a substitution effect (because production is shifted to sites with higher or lower marginal production costs) and an output effect (because more sites may be needed to satisfy demand for produced goods). We provide a numerical illustration for the opportunity costs for two examples of environmental exclusion zones – setback distances to settlements and forest bans – which are implemented for wind power deployment in Germany. The numerical illustration builds on a spatially explicit optimization model using GIS data for more than 100,000 potential wind turbine sites in Germany. Our analysis reveals that opportunity costs may primarily arise in terms of higher local environmental impacts of wind power generation. Opportunity costs are mainly due to the output effect for setback distances, and the substitution effect for forest bans. We also show that the actual sign and size of opportunity costs depends a lot on the cost criteria under consideration as well as the type and stringency of the environmental exclusion zone. Our analysis emphasizes the importance to properly understand possible opportunity costs, and compare them carefully with possible benefits when implementing exclusion zones. Interestingly, our analysis also shows that very restrictive setback distances may not be recommendable at all: In our analysis they turn out to increase the total disamenity costs produced by wind power deployment – contrary to the policy objective pursued by this instrument. We believe that our analytical insights are also helpful when thinking about the impacts of environmental exclusion zones applied to other fields of environmental policy, such as urban development or agriculture.

Keywords: forest, Germany, land use, land-use restriction, setback distances, spatial modelling, wind power

JEL codes: Q23, Q24, Q28, Q42, R14, R32

1 Introduction

Exclusion zones are the most common policy instrument to address environmental impacts of human land-use. With the rising use of renewable energy sources (RES), such land-use restrictions have also been increasingly used to steer the deployment of wind parks and solar photovoltaic (PV) systems towards areas and sites with lower impacts on local residents and wildlife. A prominent example of environmental exclusion zones are setback distances for wind turbines which aim at reducing local disamenities for residents living nearby, such as noise emissions, shadowing, or losses in landscape aesthetic quality. They are in place in many European countries (Dalla Longa et al., 2018; Peri and Tal, 2021), the United States (Aidun et al., 2021; Oteri, 2008), and Canada (Watson et al., 2012). Other types of environmental exclusion zones ban RES deployment on sites which are considered as ecologically valuable and vulnerable, such as forests or peatlands, or as particularly scenic (Bunzel et al., 2019; Cowell, 2010; Cowell and de Laurentis, 2021; Hajto et al., 2017; Lauf et al., 2020; Lopez et al., 2021; Oteri, 2008). All these instruments have in common that they exclude deployment in legally defined zones, and allow for deployment elsewhere.

In terms of efficiency, environmental exclusion zones are ambiguous. On the one hand, they may generate benefits by reducing local externalities of RES deployment, e.g., on wildlife, or residents living next to installations. However, environmental exclusion zones also bring about opportunity costs. They may shift RES deployment to sites with higher market and non-market costs (other than the ones addressed by the exclusion zone). For example, implementing setback distances to settlements may help reduce disamenities for local residents. However, they may also imply that generation costs increase (if less windy sites have to be used), and that impacts on wildlife are aggravated (if the abundance of wildlife increases with the distance to settlements). This paper aims to understand and quantify the drivers determining the opportunity costs related to environmental exclusion zones for RES deployment more thoroughly.

We analyze a setting in which environmental exclusion zones are implemented on top of a tender scheme promoting RES deployment. Tender schemes are currently the most prominent RES policy worldwide (Grashof, 2021). They basically imply that sites for RES deployment are chosen to minimize generation costs for a politically set RES generation target. Using a simple analytical model, we suggest that opportunity costs of environmental exclusion zones can be decomposed into a substitution effect and an output effect. The substitution effect arises because adopting an exclusion zone shifts deployment from excluded to allowable sites. This substitution effect will be positive (increasing opportunity costs) if allowable sites chosen under a tender scheme have higher marginal costs, and negative otherwise. We show that a particularly strong positive substitution effect can be expected if marginal costs are very heterogeneous in space, and if they are negatively correlated in space with the exclusion zone and RES productivity. In addition, an output effect arises. If environmental exclusion zones exclude relatively productive RES sites, more sites will be required to attain the RES generation target. We show that the output effect is strictly positive and increases with spatial heterogeneity in RES productivity, spatial correlation between RES productivity and the exclusion zone, the stringency of the exclusion zone, and the ambition of the RES generation target.

We also provide a numerical illustration for the opportunity costs of environmental exclusion zones which are implemented for wind power deployment in Germany. The numerical illustration builds on a spatially explicit optimization model using GIS data for more than 100,000 potential wind turbine sites in Germany. Using this model, we analyze the opportunity costs of two types of environmental exclusion zones: setback distances to settlements and forest bans. Our model allows us to determine opportunity costs in terms of both market costs (generation costs) as well as a variety of non-market costs (local disamenities, impacts on landscape aesthetic quality, impacts on wind power-sensitive birds as well as impacts on general ecological conflict risks). Our analysis reveals that the opportunity costs in terms of higher generation costs are relatively small for most exclusion zone scenarios studied. This is primarily due to the fact that the output effect is small and the substitution effect is absent for this cost criterion. Our numerical simulation yields the most substantial opportunity cost effects for non-market costs. We find that the disamenity costs of attaining a wind power generation target are reduced (i.e., opportunity costs are negative) if moderate setback distances are adopted, as one may expect. In these cases, the positive output effect is more than offset by a negative substitution effect. Interestingly, though, very restrictive setbacks may produce overall positive opportunity costs, i.e. increase the disamenities of a attaining a generation target. This is because the output effect becomes extremely large, and sometimes even the substitution effect turns positive. This result thus stands in sharp contrast with the objective of mitigating disamenities which policy-makers usually pursue by implementing setback distances. Moreover, very restrictive setbacks also produce opportunity costs in terms of higher impacts on nature and landscape conservation. With respect to forest bans, our analysis highlights substantial opportunity costs in terms of higher disamenities. These are particularly high if wind power deployment is excluded from all forests. Finally, we find that both setback distances and forest bans may reduce the spatial generation potential for wind power deployment significantly. Overall, our analysis thus suggests that opportunity costs of environmental exclusion zones may be substantial and have to be balanced carefully with expected benefits from applying this policy instrument.

Opportunity costs of exclusion zones have already been studied in the economic literature. The focus has been on land-use restrictions applying to the development of residential and commercial areas (for reviews, see e.g. Kiel, 2005; White and Allmendinger, 2003) as well as agriculture and forestry (Adams et al., 2010; Börner et al., 2009; Naidoo and Adamowicz, 2006; Schröter et al., 2014).

More recently, the effects of exclusion zones have also been studied more intensively for RES deployment. Several studies use GIS analyses to show that the RES electricity generation potential may be reduced substantially if setback distances are applied (Lopez et al., 2021; Masurowski et al., 2016; Peri and Tal, 2021; Ruhnau et al., 2023; Sliz-Szkliniarz et al., 2019; Unnewehr et al., 2021), or if particularly scenic areas are excluded (McKenna et al., 2021). The significant effects of exclusion zones on RES deployment have also been confirmed by empirical ex-post assessments (Lauf et al., 2020; Meier et al., 2023; Stede et al., 2021). Yet, these studies do not provide an explicit assessment of opportunity costs.

In addition, there is a strand of energy system analyses which assess opportunity costs of environmental exclusion zones in terms of higher market costs. Such analyses have been carried out for several European countries (Price et al., 2018; Wang et al., 2020; Wehrle et al., 2021; Weinand et al., 2021) as well as the US (Mai et al., 2021; Palmer-Wilson et al., 2019; Wu et al., 2020). They find that implementing exclusion zones may increase energy system costs by up to around 20%. The actual size of opportunity costs depends strongly on the spatial context as well as the type and stringency of the exclusion zones considered. However, these assessments of opportunity costs are rather theoretical as they are based on endogenously determined, system-optimal deployment pathways for different energy technologies. Implementing an exclusion zone for wind power, for example, implies that less wind power is used and substituted by other energy sources. Hence, the basic approach of these studies is fundamentally different from the real-world policy scenario we analyze in our paper, where exogenously set deployment targets are implemented through tenders for different RES technologies. Moreover, the energy system analyses usually ignore non-market costs of RES deployment (a notable exclusion is Wu et al. (2020)). This is an important limitation as our analysis shows that exclusion zones may particularly produce opportunity costs in terms of non-market costs.

More closely related to our study are economic assessments of cost-potential curves. These usually determine how costs of RES deployment increase with a rising generation target to be attained. This assessment can be carried out with and without land-use constraints to determine opportunity costs of environmental exclusion zones. This approach is analytically identical to our policy scenario where a RES deployment target is to be attained at least generation costs through a tender scheme subject to an environmental exclusion zone. Using the cost-potential curve approach, studies have shown that setback distances increase generation costs only mildly by up to 5% in Germany and Poland (Ruhnau et al., 2023; Salomon et al., 2020; Sliz-Szkliniarz et al., 2019). McKenna et al. (2021) find a more substantial effect on generation costs if the most scenic areas are excluded from RES deployment in Great Britain. Some studies also include non-market costs, most notably local disamenities for households living next to RES plants as well as impacts on ecosystem services. Drechsler et al. (2011), Salomon et al. (2020) and Reutter et al. (2023) find that implementing setback distances to settlements and red kite nests in the German State of Saxony may decrease social costs of wind power deployment, i.e., produce negative opportunity costs. Yet, this only holds for moderate setbacks. They also show that if setbacks become too restrictive, the resulting increase in generation costs more than offsets the decrease in non-market costs. Ruhnau et al. (2023) also assess how setback distances affect the generation costs and local disamenities of attaining RES deployment targets in various EU countries. However, their reference scenario is the social optimum. Thus, they cannot provide insights on the performance of environmental exclusion zones in a real-world policy scenario where RES deployment is promoted through tenders. Delafield et al. (2023) analyse the impacts of implementing exclusion zones for nature protection and food security in Great Britain. They show that environmental exclusion zones may sometimes also increase the non-market costs of RES deployment – contrary to what is intended by their implementation.

While the aforementioned studies have already provided evidence that opportunity costs of implementing environmental exclusion zones may be substantial, they have not yet explored the underlying drivers of opportunity costs thoroughly. It remains largely unclear how exactly the findings are driven by the specific spatial context (e.g., the spatial heterogeneity and correlation of different cost criteria), and the policy scenario chosen (e.g., type and stringency of the exclusion zone, ambition of the RES deployment target). Thus, it is difficult to generalize insights from these studies which could be transferred to other spatial and political contexts. We believe that this limitation can be overcome by our approach which a) decomposes opportunity costs into a substitution and an output effect, and b) derives how either effect is driven by spatial and policy parameters.

The remainder of this paper is organized as follows: Section 2 introduces a simple analytical model to understand the opportunity costs of exclusion zones and the respective substitution and output effects. Section 3 provides a numerical illustration for Germany, shedding light particularly on the opportunity costs of setback distances and forest bans for wind power deployment. Section 4 discusses our results, and section 5 concludes.

2 Analytical model

We consider two types of sites which may be used for installing RES plants. Subscript a denotes sites where installations are allowed if the exclusion zone is implemented. Subscript e denotes sites where installations will be excluded. x_a and x_e are the numbers of sites used of each type. Electricity generation on either type of sites, $W_a(x_a)$ and $W_e(x_e)$, is assumed to be increasing and concave in the number of sites used, i.e., $W_a' > 0$ and $W_a'' < 0$ as well as $W_e' > 0$ and $W_e'' < 0$. Productivity in terms of electricity generation may vary between both types of sites if there is inter-type heterogeneity in generation conditions, such as wind speed or solar radiation. Concavity reflects the fact there is also intra-type heterogeneity in generation conditions. If more RES plants are to be installed, ever less productive sites need to be chosen. Total electricity generation is:

$$W = W_a(x_a) + W_e(x_e) \tag{1}$$

The costs of generating RES electricity on either type of sites, $C_a(x_a)$ and $C_e(x_e)$, are assumed to involve only fixed investment, operation and maintenance costs, represented by a cost parameter c. This is a reasonable approximation for wind turbines, solar PV, or hydropower (but not for bioenergy). We also assume that generation costs are identical for each site, i.e., that the same type of plant will be installed at all eventually chosen sites. Consequently, total generation costs $C(x_a, x_e)$ can be written as:

$$C(x_a, x_e) = C_a(x_a) + C_e(x_e) = c(x_a + x_e) \tag{2}$$

In addition, installing RES plants brings about external costs $K_a(x_a)$ and $K_e(x_e)$. We assume that external costs are identical for all sites of the same type but may vary across types. We also assume that external costs are linearly increasing in the number of sites used. Total external costs $K(x_a, x_e)$ are thus given:

$$K(x_a, x_e) = K_a(x_a) + K_e(x_e) = k_a x_a + k_e x_e \tag{3}$$

The simplification of linear external costs is necessary to keep the analytical model tractable. But as our numerical application will illustrate, this assumption also fits our empirical data fairly well for relevant generation levels. We will discuss the limitations resulting from this assumption later on.

We assume that the regulator aims to reach an exogenously set target $\bar{W}$ for RES electricity generation. RES targets exist in numerous countries worldwide (Spillias et al., 2020). In order to attain this target, the regulator implements a mechanism which minimizes generation costs of attaining the RES target. Thereby, we aim to represent a tender scheme, which is nowadays the dominant approach to promote RES deployment (Grashof, 2021). In the absence of any land-use restriction, the corresponding optimization problem is to minimize the following Lagrangian:

$$\Lambda = c(x_a + x_e) + \lambda\left(\bar{W} - W_e(x_e) - W_a(x_a)\right) \tag{4}$$

The corresponding first-order conditions are:

$$c = \lambda W_a' \tag{5}$$

$$c = \lambda W_e' \tag{6}$$

$$\bar{W} = W_a(x_a) + W_e(x_e) \tag{7}$$

From eqs. (5) and (6) directly follows that the optimal numbers of sites of either type, x_a^* and x_e^*, will be chosen such that marginal productivities are equal, i.e., $W_a'(x_a^*) = W_e'(x_e^*)$.

If an exclusion zone is applied to type-e sites, the RES target needs to be achieved by installing RES plants on type-a sites only. Since marginal productivity of type-a sites declines ($W_a'' < 0$), the increase in type-a sites necessary to meet the RES target will be larger than the number of type-e sites x_e^* that need to be replaced. Consequently, the optimal number of type-a sites in the presence of an exclusion zone, x_a^E, satisfies the following inequation:

$$x_a^E > x_a^* + x_e^* \tag{8}$$

Based on these assumptions, we can now derive opportunity costs of applying the exclusion zone, and explain how these can be decomposed into two effects: a substitution effect and an output effect. We will illustrate this for external costs in the following. But the analytical approach can be derived similarly for generation costs, as we will discuss. Opportunity costs OC can be simply given as the external costs of attaining the generation target with the exclusion zone applied net of the costs of attaining the target in the absence of any land-use restriction:

$$OC = K_a(x_a^E) - K(x_a^*, x_e^*) \tag{9}$$

This equation can be expanded to:

$$OC = \underbrace{K_a(x_a^E) - K_a(x_a = x_a^* + x_e^*)}_{\substack{Output\ effect\ (OE) \\ = k_a(x_a^E - x_a^* - x_e^*) > 0}} + \underbrace{K_a(x_a = x_a^* + x_e^*) - K(x_a^*, x_e^*)}_{\substack{Substitution\ effect\ (SE) \\ = (k_a - k_e)x_e^* \gtreqless 0}} \tag{10}$$

The *substitution effect (SE)* corresponds to the change in costs which would result if type-e sites were simply replaced by the same number of type-a sites. The substitution effect increases (decreases) opportunity costs if type-a sites have higher (lower) marginal costs than type-e sites. The absolute value of the substitution effect increases with the heterogeneity in marginal costs between both types of sites. Eq. (9) also shows that the substitution effect is zero if the marginal costs of both types of sites are identical – which applies to generation costs in our model. Moreover, the substitution effect also increases in x_e^*. This implies that an increase in the relative marginal productivity of type-e sites, $W_e'(x_e)$ – which would lead to more type-e sites to be used in the absence of an exclusion zone – will ceteris paribus increase the substitution effect.

The *output effect (OE)* corresponds to the additional change in costs due to the fact that the total number of sites needed to attain the RES target increases if the exclusion zone is applied. The output effect strictly increases opportunity costs. This follows directly from combining eq. (10) with eq. (8). This applies identically for generation costs. An increase in x_e^* (as produced for example by a higher marginal productivity of type-e sites) will also increase the output effect, everything else equal. This is because the increase in type-e sites x_e^* will come along with a proportionally larger reduction of type-a sites x_a^*, if the generation target is held constant.

In sum, this means that opportunity costs of an exclusion zone are strictly positive with respect to generation costs. With respect to this cost criterion, an exclusion zone implies a positive output effect and no substitution effect (see left chart in Figure 1). In contrast, the sign of opportunity costs in terms of external costs is ambiguous. Opportunity costs are positive if the output effect combines with a positive substitution effect (see middle chart in Figure 1) – or if is not fully offset by a negative substitution effect (see right chart in Figure 1). Yet, an exclusion zone may also produce negative opportunity costs, i.e., reduce external costs overall, if the positive output effect is more than offset by a negative substitution effect.

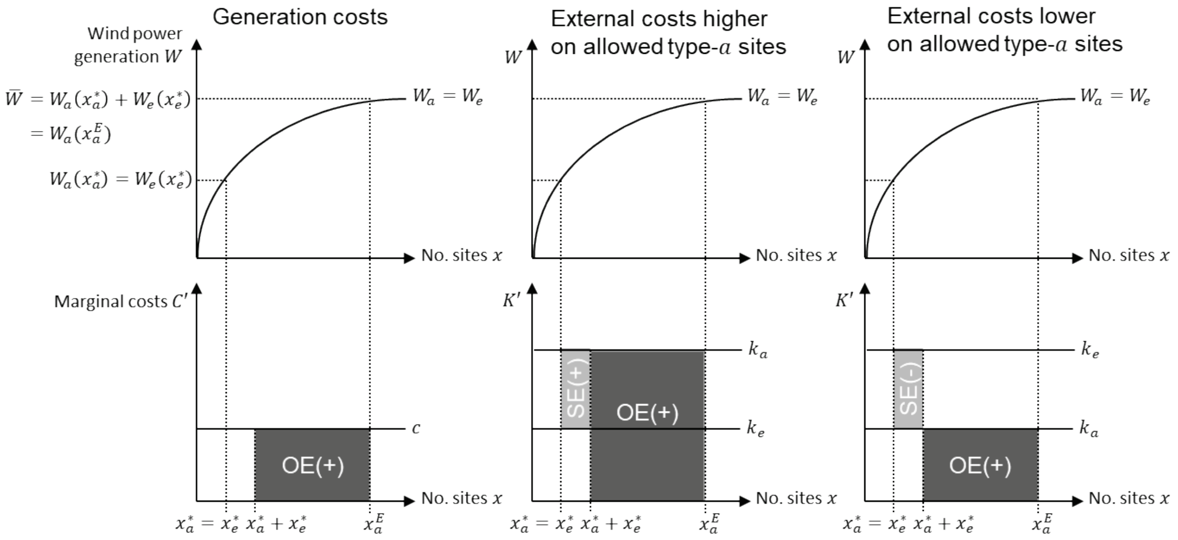


Figure 1: Graphical decomposition of opportunity costs of implementing an exclusion zone for three cases: a) generation costs (positive output effect, no substitution effect), b) external costs, which are higher on allowed type-a sites (positive output effect, positive substitution effect), and c) external costs, which are lower on allowed type-a sites (positive output effect, negative substitution effect). For the sake of illustration, productivity of type-a and type-e sites are assumed to be identical.

Increasing the *generation target* $\overline{W}$ implies both x_a^* and x_e^* will rise, ceteris paribus. Consequently, the substitution effect – which only depends on x_e^* in our model – will also increase. However, this only holds true in a model with linear external costs. If external costs are assumed to be non-linear, increasing the generation target may also result in a declining substitution effect – and the sign of the substitution effect may flip. In turn, the output effect strictly increases with the generation target because with declining marginal productivity of sites, $dx_a^E/d\overline{W} > dx_a^*/d\overline{W} + dx_e^*/d\overline{W}$.

Finally, it is also worthwhile to examine how changing the *stringency of the exclusion zone* may affect output and substitution effects. A more stringent exclusion zone implies that more sites will be excluded from production. This will happen for example, if a setback distances to human settlements is raised from 1,000 to 1,500 m. Increasing the stringency of the exclusion zone has two consequences. First, everything else equal, it will lead to a higher x_e^* and a lower x_a^*. Consequently, both substitution and output effect increase. However, there is also a second, ambiguous effect. Increasing the stringency of the exclusion zone will also alter the shape of the type-specific cost functions – which we assume to exist for external costs. If a more stringent exclusion zone results, for example, in a lower k_a and a higher k_e, the output and substitution effect will become smaller. Certainly, the opposite effects on k_a and k_e are also possible. In sum, raising the stringency of the exclusion zone strictly increases opportunity costs in terms of generation costs (because we assume identical marginal costs for both types of sites) and has an ambiguous impact on opportunity costs in terms of external costs.

3 Data and calibration for numerical application

We now provide a numerical illustration of our analytical insights. The numerical illustration applies the analysis to the specific case of setbacks distances and forest bans for wind power deployment in Germany. First, we will introduce the data this numerical illustration builds on.

3.1 Study region and potential sites

A GIS-based analysis is used to assesses potential sites for onshore wind energy in Germany in a green field approach. The analysis identifies a total of 106,497 spatially explicit potential sites (Figure 2a) on the basis of legal and technical restrictions (e.g., noise immission control standards, minimum distances to infrastructures, protected areas and areas technically unsuitable for the installation of wind turbines). These data is derived from Masurowski (2016). Minimum distances to settlements due to noise immission control standards have been updated and extended to 600-800 meters, depending on legal status of the settlement. Each of these identified sites fits a single wind turbine in the 3 MW class (Enercon E101 3MW). Using a geographical information system (GIS) data, we attribute a variety of characteristics to each potential site. We first assess the potential annual electricity generation for each site. This information is necessary to safeguard that a certain selection of sites meets an exogenously set generation target $\overline{W}$. In addition, we attribute information for five cost criteria for which we have been able to obtain high-resolution spatial data for the whole of Germany: We first look at generation costs (a monetary market cost of wind power deployment, C in our analytical model). Moreover, we examine four examples of non-market external costs related to wind power deployment (K in our analytical model): monetized disamenity costs as well as three non-monetary expressions for negative impacts on nature and landscapes (impacts on landscape aesthetic quality, avifauna, as well as general ecological conflict risks). Table 1 provides an overview of these cost criteria. We explain the calibration of all attributes in more detail in the subsequent sections. Obviously, these criteria only provide a partial assessment of costs (and benefits) related to wind power deployment. Additional energy system costs as well as environmental costs will usually arise.

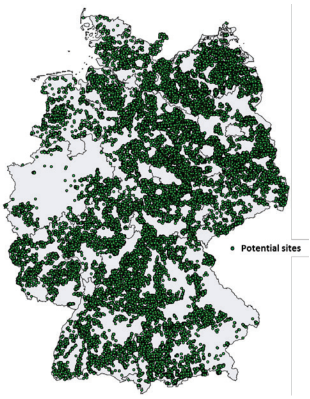
Generation costs	Market costs	Monetized
Disamenity costs	Non-market external costs	
Impacts on landscape aesthetic quality		Not monetized
Impacts on avifauna		
Ecological conflict risks		

Table 1: Cost criteria associated with wind power deployment and considered for the numerical application

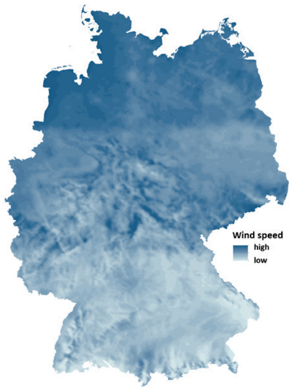
3.2 Annual electricity generation

In order to identify optimal sites to attain a certain level of electricity generation, assumptions need to be made how much electricity can be generated at each site. Based on the power curve of the Enercon E101 3.0 MW wind turbine (Enercon, 2015) and high-resolution wind climate data provided by DWD (2014) (see Figure 2b), we calculate the theoretical annual electricity generation for each potential site following the approach used by Eichhorn et al. (2017). Actual generation under realistic operation conditions is likely below this theoretical level. Inter alia, this may be due to generation losses at specific sites resulting from wake turbulences induced by the operation of other wind turbines in close proximity, as well as downtimes for maintenance and repairs. In our analysis, we account for these factors by reducing the annual electricity generation uniformly by 15% for each potential site and turbine (a similar approach is used, e.g., by McKenna et al., 2014; Sliz-Szkliniarz et al., 2019). The total annual electricity generation when wind turbines are installed at all potential 106,497 sites across Germany amounts to 778 TWh. This is more than seven times the production provided by onshore wind power in Germany in 2020 (Fraunhofer ISE, 2021).

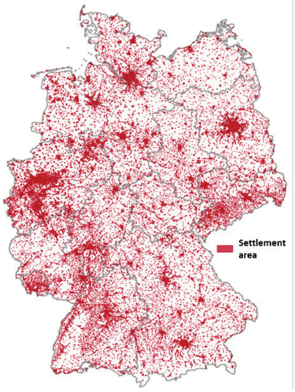
a) Potential sites for wind turbines in Germany without land-use restrictions (source: based on Masurowski, 2016)



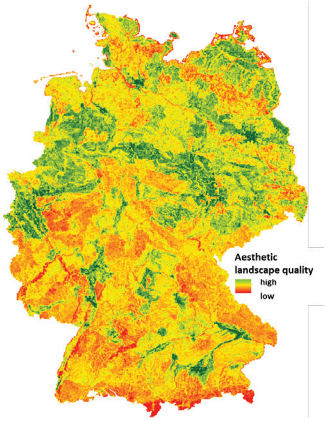
b) Wind speeds calculated for 135 m hub height (source: DWD, Eichhorn et al., 2017)



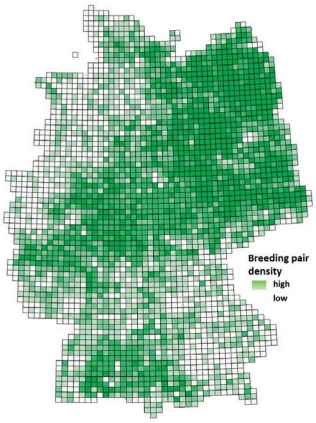
c) Settlement area (source: ATKIS geo data)



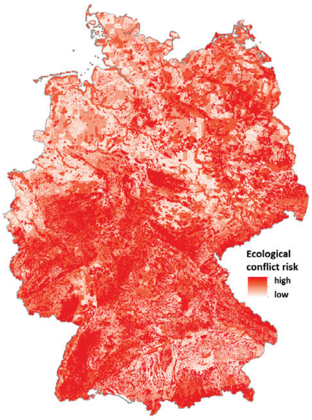
d) Landscape aesthetic quality (source: Hermes et al., 2018)



e) Number of breeding pairs of wind-power sensitive bird species (source: Tafarte and Lehmann, 2023)



f) Ecological conflict risks related to wind power deployment (source: Gauglitz et al., 2019)



g) Forest area (source: ATKIS geo data)

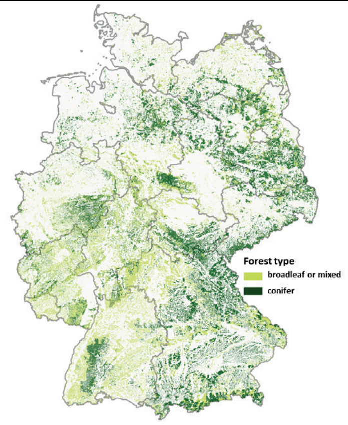


Figure 2: Geographical conditions for wind power deployment in Germany

3.3 Generation costs

Marginal generation costs of wind power deployment c are calculated for the representative wind turbine used (Enercon E101 3 MW). Generation costs are assumed to be identical for each site. They include the costs of investment, installation as well as operation and maintenance (Wallasch et al., 2015) of the wind turbine throughout the operational lifetime of 20 years:

$$\mathrm{c} = I_0 + \sum_{t=1}^{5} \frac{A_{1t}}{(1+r)^t} + \sum_{t=6}^{20} \frac{A_{2t}}{(1+r)^t} \tag{16}$$

where I_0 is the investment expenditure in the first year of operation (1,567 EUR/kW). A_{1t} is the annual total cost per year t for the first 5 years of operation (30 EUR/kW), A_{2t} the annual total cost per year t for the remaining 15 years of operation (50 EUR/kW), and r the discount rate at an annual rate of $r = 0.03$.

3.4 Disamenity costs

A detailed description of the calibration of disamenity costs applied in this paper can be found in Salomon et al. (2020). The disamenity cost function calibrated and described by Salomon et al. reflects increasing marginal disamenity costs with a decreasing distance between a household and a wind turbine (see Figure 3). The shape of the used hyperbolic cost function is determined by drawing on values from willingness-to-pay as well as life satisfaction studies (Gibbons, 2015; Krekel and Zerrahn, 2017; Meyerhoff et al., 2010). Disamenity costs per household are aggregated over a twenty-year time lifetime of a wind turbine using an annual discount rate of $r = 0.03$ (see, e.g., Drechsler et al., 2011). Finally, the overall disamenity costs arising if a wind turbine is installed at a specific site are calculated by adding up the disamenity costs across all households living within a 4,000 m radius around a potential wind turbine site. Thereby, the local disamenity cost estimate for each potential site considers the specific patterns of population density (see Figure 2c) in its vicinity.

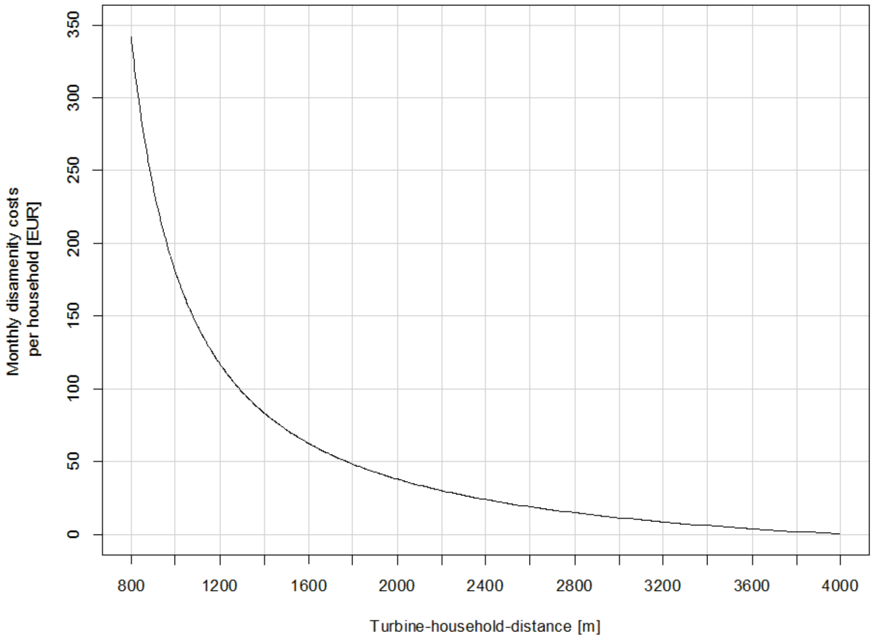


Figure 3: Assumed monthly disamenity costs (in EUR) accruing to a household from wind turbine depending on the turbine-household distance in meters [m] (Salomon et al., 2020)

3.5 Impacts on landscape aesthetic quality

Modern wind turbines can have a negative impact on the aesthetic quality of landscapes. This implies non-market costs associated with the spatial allocation of wind turbines (Kienast et al., 2017; McKenna et al., 2020). We use a spatially high-resolution and uniform non-monetary assessment of landscape aesthetic quality provided by Hermes et al. (2018) for Germany (see Figure 2d). Their approach ranks aesthetic landscape quality on a scale from 0 to 100 with a high resolution of 100 m x 100 m. The ranking is based on the attributes of diversity, naturalness and uniqueness of the landscape, as mandated by the German Federal Nature Conservation Act. We link these rankings to our potential wind turbines sites by computing the average ranking of landscape aesthetic quality within a 1000 m radius around each site. This modification was made to better aggregate the overall value of the surroundings of the wind turbine as well as to account for the fact that the effect of a modern wind turbine reaches much further than the original 100 m x 100 m radius. When minimizing the impact on landscape aesthetic quality, the optimization will give priority to potential wind turbine sites with a low average ranking. This basically assumes that the marginal costs produced by installing a wind turbine is lower at sites with a low aesthetic landscape quality.

3.6 Impacts on avifauna

A main conservation concern relates to possibly adverse impacts of wind power deployment on wind-power sensitive bird species (for a review, see, e.g., Zerrahn, 2017). Such impacts can be considered another non-market cost of wind power deployment. To provide a quantitative, non-monetary expression of this cost, we use an indicator based on the abundance of bird species considered sensitive to wind turbines as well as on the recommended minimum distances of wind turbines to nesting sites of the respective bird species. This approach is outlined in detail in Tafarte and Lehmann (2023). The indicator is based on the number of breeding pairs per bird species weighted by the species-specific normalized circular area of activity and aggregated for all species in a region of approximately 11 km x 11 km (see Figure 2e). The resulting indicator value is assigned to all potential wind turbines sites located in the respective region. When optimizing with respect to this nature conservation criterion, wind turbines will be first installed at sites with the lowest indicator value. Thus, we basically assume that the marginal impact produced by a wind turbine at site increases with the number of breeding pairs of wind-power sensitive bird species in the respective region.

3.7 Ecological conflict risks

Finally, we also include a more general assessment of ecological conflict risks related to wind power deployment. This criterion is also a non-monetary measure of non-market costs of wind power deployment. It is measured by an ordinal risk scale. The full procedure is provided in Gauglitz et al. (2019). The risk valuation is the result of an iterative expert discourse and describes the probability of conflicts between wind turbine development and nature conservation assets on the basis of available environmental information. A low risk level indicates an area where a wind power deployment is unlikely to produce significant conflicts, a high risk level indicates an unsuitable area with multiple possible conflicts. The risk level is the result of a nationwide comparative assessment. Mapping spatially differentiated risk levels on a 1 to 6-point scale for wind energy is achieved in a combined GIS-based and discursive process. Under consideration of the typical effects of wind turbines, potential risks are identified especially with respect to avifauna, bats or recreational functions. Altogether all objects of protection – flora and fauna, biodiversity, water, soil, air and climate, diversity, characteristic features and beauty as well as the recreational value of nature and the landscape – are operationalized. Nationwide available data, e.g., for Nature 2000 sites, are used for the operationalization. The potential risks represented by these datasets are rated considering impact and vulnerability of the objects of protection. Based on these ratings and additional information about their normative meaning and accuracy, a risk dataset is generated. To map a nationwide nature conservation risk rating concerning wind turbines, the datasets for each object of protection are aggregated rule-based. The result is a nationwide map rating sites according to the overall risk that is used as a criterion to allocate wind power plants (see Figure 2f). This criterion thus includes impacts measured by the previous criteria (disamenity costs, impacts on landscape aesthetic quality, impacts on avifauna) – but also goes beyond them. The total score for ecological conflict risks of a spatial allocation of wind turbines is derived by summing up the risk ratings of all selected sites.

Table 2 provides spatial correlation coefficients for the cost criteria introduced above:

	Generation costs	Disamenity costs	Landscape quality	Impacts on avifauna	Ecological conflict risks
Generation costs	1.000	0.526	0.297	-0.303	0.304
Disamenity costs		1.000	0.106	-0.223	0.024
Landscape quality			1.000	-0.233	0.412
Impacts on avifauna				1.000	-0.103
Ecological conflict risks					1.000

Table 2: Spatial correlation coefficients for the cost criteria across all potential sites

3.8 Policy scenarios and numerical solution approach

For our numerical analysis of opportunity costs of exclusion zones, we look at two prominent examples relevant for wind power deployment: setback distances to settlements and forest bans.

Setback distances are a very common policy applied in the US, Canada and many European countries to regulate wind power deployment spatially (Aidun et al., 2021; Dalla Longa et al., 2018; Ember, 2022; Lopez et al., 2021; Oteri, 2008; Peri and Tal, 2021; Salomon et al., 2020; Sliz-Szkliniarz et al., 2019; Stede et al., 2021; Watson et al., 2012). The intuition underlying this policy instrument is typically to reduce local disamenities resulting from noise emissions, shadowing, or changes in landscape aesthetics. Setback distances are typically applied uniformly, i.e., irrespectively of geographical conditions which may affect the level of disamenities (e.g., visibility). Two characteristics determine how many sites are excluded by setback distances: the distance itself and the reference point with respect to which the distance has to be respected. In Germany, an amendment to the Federal Building Code adopted in 2022 allows for a uniform setback distance of 1,000 m. However, the amendment also allows for tighter setback distances if these had already been implemented by Federal States before the amendment was adopted. The Federal State of Bavaria adopted the most restrictive rule requiring a setback distance of ten times the height of the wind turbine. For modern wind turbines this results in setback distances of 2,000 m and more. The Federal Building Code does not regulate the reference point with respect to which the setback distance applies. Consequently, Federal States define the reference point in very different ways. In some, the setback distances apply only to larger settlement areas (e.g., villages, towns, referred to as “inner area”). In other Federal States, the setback distance also has to be respected for scattered settlements or even individual buildings (referred to as “outer area”) (FA Wind, 2022). Figure 4 illustrates these different setback approaches. A setback applied only to the inner area would only exclude site A. A setback also applied to the outer area would exclude sites A and B. For the purpose of our analysis, we consider three possible setback distances of 1,000, 1,200, and 1,500 m. The two smaller setback distances are applied either to inner or outer areas. We apply the 1,500 m setback distance only the inner areas. Implementing this setback distance for outer areas would make attaining the generation target we consider later on (300 TWh/a, see below) impossible. Table 1 provides an overview of the resulting setback scenarios. It shows how the number of available sites declines with increasing setback distances and a more restrictive reference point (outer area instead of inner area). Figure 2c maps settlement areas to provide a first idea where in Germany setback distances are likely to exclude land for wind power deployment.

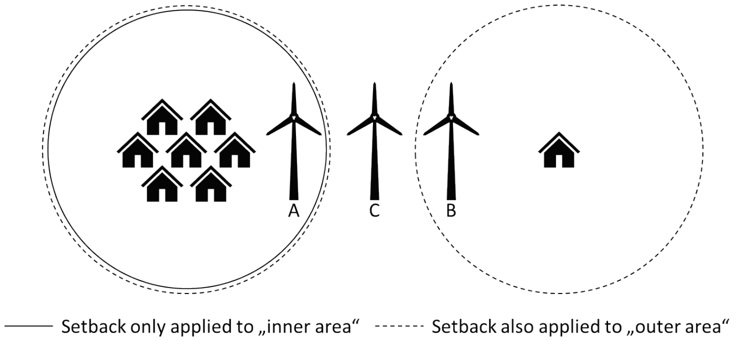


Figure 4: Schematic illustration of different setback approaches

Several European countries and US counties have also implemented forest bans for installing wind turbines (Bunzel et al., 2019; Hajto et al., 2017; Oteri, 2008). The intention of forest bans is usually to protect the diverse ecosystem services provided by forest from being deteriorated by wind turbines. In Germany, the actual design and implementation of forest bans varies a lot across Federal States (Bunzel et al., 2019). Some ban wind power deployment from forests generally. Others do not generally restrict wind power deployment in forest or at least allow for it in certain types of forest, such as conifer forests. For our analysis we consider two types of forest bans: a ban on mixed and broadleaf forests only and a ban on all forests (see Table 3). Figure 2g provides an idea how different types of forest are distributed across Germany.

		Sites available
No exclusion zone		106,497
Setback distance	1,000 m to inner area (1000mIA)	103,523
	1,200 m to inner area (1200mIA)	92,494
	1,500 m to inner area (1500mIA)	74,464
	1,000 m to outer area (1000mOA)	74,436
	1,200 m to outer area (1200mOA)	41,621
Forest ban	on broadleaf and mixed forests	87,461
	on all forests	60,478

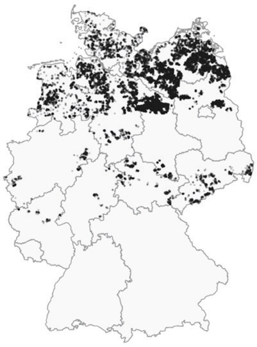
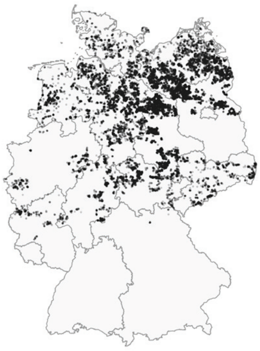
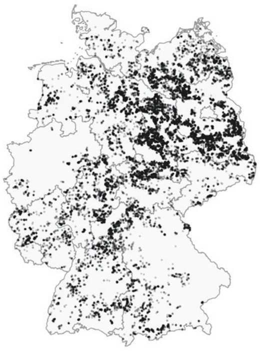
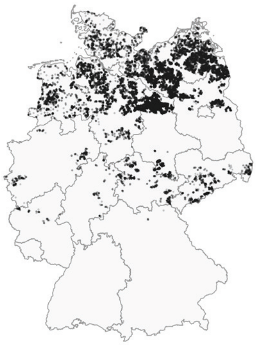
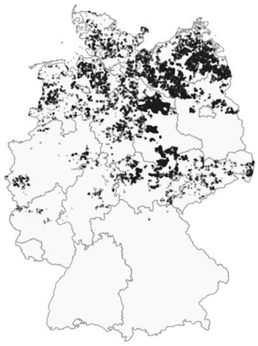
Table 3: Exclusion zone scenarios considered for the analysis

As outlined in the analytical model, we assume that sites are chosen to achieve a given annual electricity generation target $\overline{W}$ at least generation costs C (as under a tender scheme) subject to the different exclusion zones. In Appendix 1, we also analyze spatial allocation rules that could be considered instead of minimizing generation costs. We use the General Algebraic Modeling System (GAMS) to solve the optimization problem. Thereby, we derive the optimal spatial allocation and number of sites for the different exclusion zone scenarios ($x_a^* + x_e^*$ if no exclusion zone applies, and x_a^E if an exclusion zone applies) for a given generation target $\overline{W}$. In addition, we get the respective market and non-market costs of attaining the generation target under the different exclusion zone scenarios ($C(x_a^*, x_e^*)$, $K(x_a^*, x_e^*)$ and $C_a(x_a^E)$, $K_a(x_a^E)$). Repeating this approach for increasing levels of electricity generation (in 8 GWh steps), we are able to derive an explicit expression of market and non-market cost functions for each exclusion zone scenario ($C(x_a, x_e)$, $K(x_a, x_e)$ and $C_a(x_a)$, $K_a(x_a)$). This allows us to also compute $C_a(x_a = x_a^* + x_e^*)$ and $K_a(x_a = x_a^* + x_e^*)$. Thereby, we have all information necessary to compute the substitution and the output effect for a given generation target $\overline{W}$ and exclusion zone scenario – as provided in equations (9) and (10).

4 Results of the numerical application

4.1 Opportunity costs of exclusion zones for a generation target of 300 TWh/a

We will first shed light on the opportunity costs of exclusion zones which we find for an annual electricity generation target of 300 TWh/a. According to different scenario analyses, this target corresponds to the upper bound of electricity that has to be generated from onshore wind power in Germany in 2030 to be on track for climate neutrality by 2045 (Ariadne, 2022). It is also the lower bound of electricity generation from onshore wind power which these scenario analyses find necessary for 2045. Figure 5 illustrates the spatial allocation of wind power deployment resulting for the different exclusion zone scenarios for an annual electricity generation target of 300 TWh/a.

No exclusion zone  32,607 sites	Setback distance of 1,000 m to inner area (1000mIA)  32,701 sites	Setback distance of 1,200 m to inner area (1200mIA)  33,035 sites
Setback distance of 1,500 m to inner area (1500mIA)  33,758 sites	Setback distance of 1,000 m to outer area (1000mOA)  34,472 sites	Setback distance of 1,200 m to outer area (1200mOA)  41,386 sites
Ban on broadleaf and mixed forests  32,933 sites	Ban on all forests  33,862 sites	*Figure 5: Spatial allocation of wind power deployment and number of sites necessary to attain an annual electricity generation target of 300 TWh/a under different exclusion zone scenarios*

4.1 Setback distances

Figure 6 summarizes our numerical results for opportunity costs related to implementing setback distances. It illustrates output and substitution effects as well as net effects for the different cost criteria under consideration. As outlined above these results are derived based on the assumption that sites are chosen by a tender scheme which minimizes generation costs subject to the setback distance scenario. We shed light on alternative spatial allocation rules in Appendix 1.

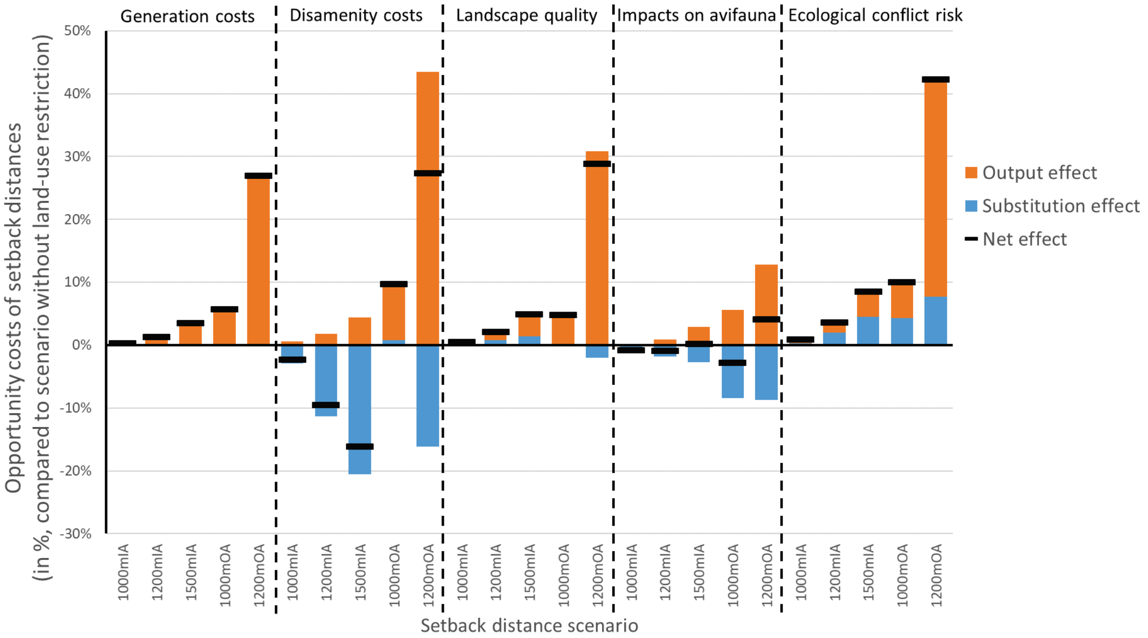


Figure 6: Opportunity costs of setback distances in terms of different cost criteria, decomposed into output and substitution effect

As suggested by the analytical model, the output effect is generally positive and increasing with the stringency of the setback distance for all cost criteria. It is fairly modest (up to 10% increase of costs) for the less restrictive setback scenarios. This is straightforward as these exclusion zone scenarios only lead to a relatively small increase in the number of sites needed to attain the annual electricity generation target of 300 TWh/a (see Figure 5). However, the output effect is very pronounced for the most restrictive setback scenario (1200mOA, up to 40% increase of costs and more). This scenario excludes a substantial number of sites in Germany's windy North. As a consequence, wind power deployment is shifted to the South, and substantially more sites are required to meet the electricity generation target (see Figure 5).

The net opportunity cost effect depends on how the output effect compares to the substitution effect. As we assume that generation costs are identical for all sites, implementing setback distances does not produce a substitution effect with respect to this cost criterion. Thus, in line with the analytical model, setback distances lead to a strictly positive net opportunity costs effect with respect to higher generation costs.

In contrast, the sign of the substitution effect – and therefore also the net opportunity cost effect – is ambiguous for the different external costs we consider. The most interesting case is the substitution effect for disamenity costs. For setback distances applied to inner areas only (core settlements), the substitution effect is negative. This can be expected: Setback distances exclude sites near populated areas. Consequently, the remaining allowable sites have lower disamenity costs (i.e., $k_a < k_e$). Overall, the substitution effect more than offsets the output effect for these setback scenarios, i.e., net opportunity costs are negative. Interestingly, though, the substitution effect turns positive if a setback distance of 1,000 m is also implemented for outer areas (1000mOA). This can be explained by the fact that excluding sites also in the vicinity of individual buildings may overall shift deployment closer to populated areas. For example, in Figure 4, replacing site B by site C may mean a site closer to an agglomeration with higher disamenity costs is chosen. In sum, this setback scenario thus increases overall disamenity costs as both the output and the substitution effect are positive. The substitution effect turns negative again if an even tighter setback distance is applied to outer areas (1200mOA). However, it is more than offset by the very high output effect. Thus, overall, opportunity costs in terms of disamenity costs are also positive for this scenario. These results are also confirmed if we assume a linear disamenity cost function (see Appendix 2). In fact, this modification even increases opportunity costs across all setback scenarios.

The substitution effect with respect to landscape aesthetic quality is also ambiguous but fairly small. Most likely this is due to effect that both generation costs and disamenity costs are positively correlated with landscape aesthetic quality at the macro level (see Table 2). Even with setbacks implemented, wind power deployment remains largely clustered in the windy and sparsely populated Northeast, which scores low in terms of landscape aesthetic quality. Overall, the net opportunity cost effect is positive for landscape aesthetic quality due to the output effect.

For impacts on avifauna, the substitution effect of setbacks becomes increasingly negative with more restrictive setback scenarios. This may be counterintuitive because setbacks shift deployment away from settlements – and wind-power sensitive birds could be assumed to be more abundant in sparsely populated areas. Yet, this effect cannot be captured properly by our model as the impacts on avifauna are assessed using relatively coarse raster data. Presumably, the negative substitution effect is therefore due to fact that setback distances slightly reduce the concentration of wind power deployment in the Northeast of Germany which exhibits a relatively high abundance of wind-power sensitive avifauna. Depending on the setback scenario, the substitution effect sometimes offsets the output effect, and sometimes does not. As a consequence, the overall opportunity costs of setbacks in terms of impacts on avifauna are ambiguous but small.

The substitution effect of setbacks is generally positive for ecological conflict risks. This captures the fact that moving sites away from settlements may mean that ecologically more vulnerable sites are used. Combined with the positive output effect, implementing setbacks thus produces strictly positive opportunity costs in terms of ecological conflict risks.

4.2 Forest bans

Figure 7 summarizes our numerical results for implementing a forest ban in addition to a tender scheme (again, results with alternative spatial allocation rules can be found in Appendix 1). Also in this case, the output effects are strictly positive for all criteria. Yet, they are relatively small, particularly if compared to those observed for setback distances. This reflects that fact that banning forests leads to an only modest increase in the number of wind turbines needed to attain the 300 TWh/a generation target. We can also see that the output effect increases with the stringency of the forest ban.

For disamenity costs, the substitution effect is positive. This is straightforward as a forest ban shifts wind power deployment to open areas where settlements are typically located. The substitution effect is particularly pronounced if not only mixed and broadleaf forests but also conifer forests are banned. This can be explained by the fact that with our exclusion zone scenarios, wind power deployment occurs in the North of Germany (see Figure 5) where most forests are coniferous (see Figure 2g). Combined with the output effect, banning wind turbines in forests therefore produces substantial opportunity costs in terms of disamenity costs, particularly if all forest is excluded.

The substitution effects are small for the other external cost criteria but mostly negative. For landscape quality and ecological conflict risks, this can be attributed to the fact that forest areas generally score high for these criteria. Excluding forests thus mitigates respective impacts. The substitution effects are ambiguous for impacts on avifauna. This can be explained that most of the wind-power sensitive bird species we consider occur at the edge between forested and open land. Combined with the coarse spatial resolution of our underlying data, this may explain the ambiguity of the substitution effect. Consequently, the net effects on nature and landscape resulting (sum of output and substitution effects) from banning wind power deployment are also mixed and small in our model.

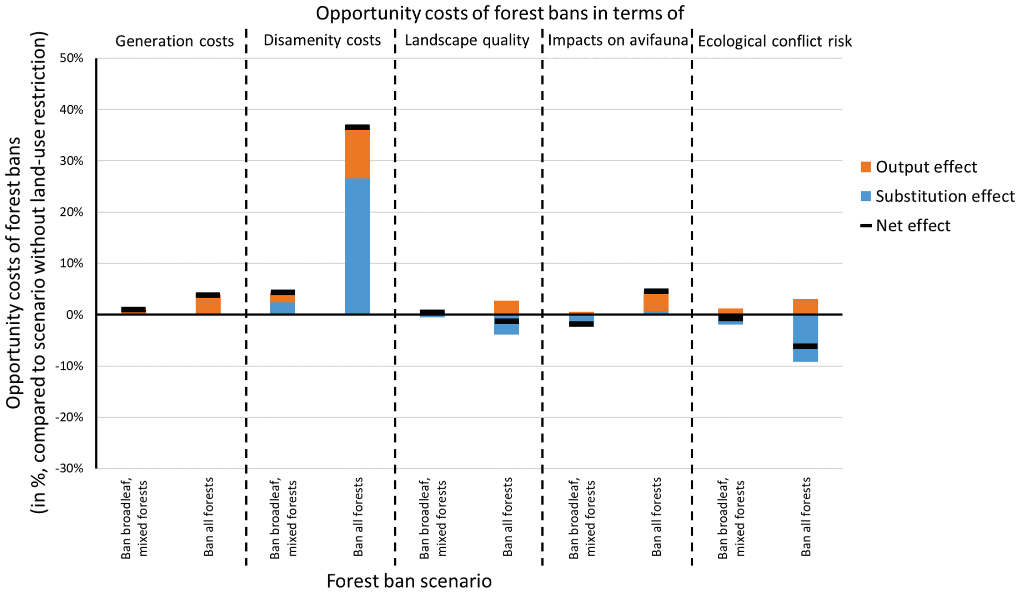


Figure 7: Opportunity costs of forest bans in terms of different cost criteria, decomposed into output and substitution effect

4.2 Opportunity costs of exclusion zones with increasing generation targets

In addition, it is also important to understand how opportunity costs – and output and substitution effects – may change with increasing electricity generation targets for wind power. Figure 8 illustrates this relationship for the exclusion zone scenarios and cost criteria under consideration. The first and third column represent costs as a function of the generation target. These functions thus depict the shadow price of achieving increasing levels of generation target $\overline{W}$ in terms of the respective cost criterion. The second and the fourth column illustrate costs as a function of the number of wind turbine sites used. Hence, these functions correspond to $C_e(x_e)$ and $K_e(x_e)$, respectively, from the analytical model. As above, these graphs are derived based on the assumption that sites are chosen to minimize generation costs for a given generation target. The red lines illustrate the cost functions if no exclusion applies. The dashed and dotted lines represent the cost functions for the different exclusion zone scenarios. The cost functions in Figure 8 have different end points. These represent the fact that the maximum annual electricity production potential (or the maximum number of wind turbine sites) declines from 778 TWh/a (106,497 sites) if no exclusion applies to 304 TWh/a (60,479 sites) if the most restrictive setback distances applies (1200mOA), and to 469 TWh/a (60,479 sites) if wind power deployment is banned from all forests. Looking at the graphs representing costs as a function of the generation target, the gap between the dashed/dotted lines for a given target represents the net opportunity costs of applying exclusion zones. Looking at the graphs representing costs as a function of wind turbine sites, the gap for a given number of sites represents the substitution effect only. The gaps observable for a generation target of 300 TWh/a correspond to the values reported in the previous section.

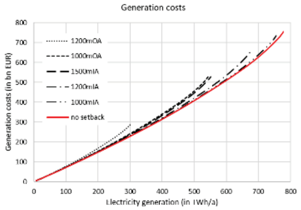
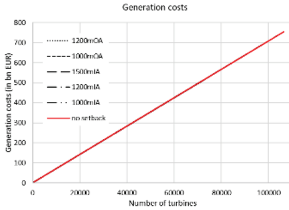
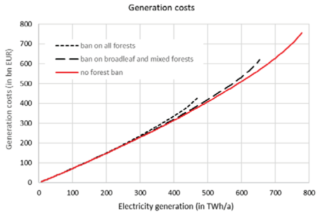
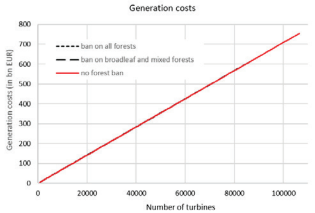
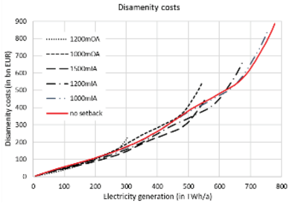
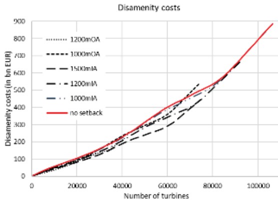
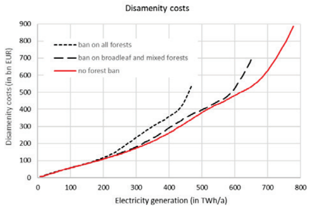
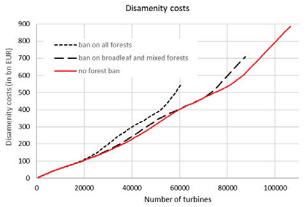
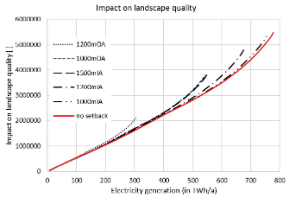
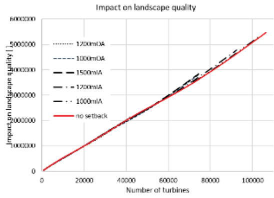
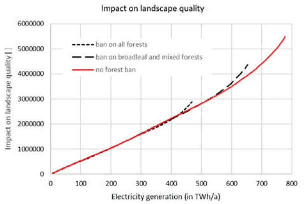
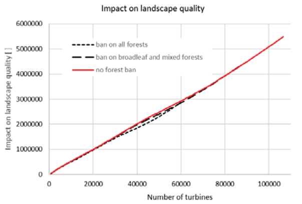
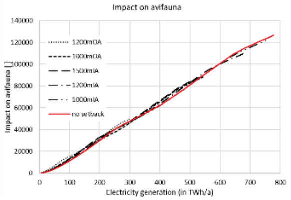
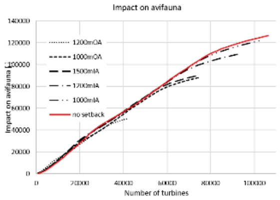
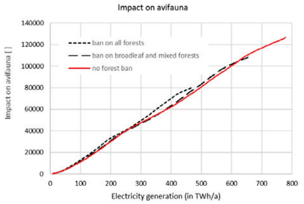
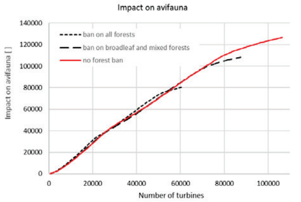
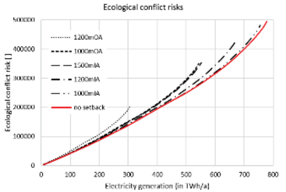
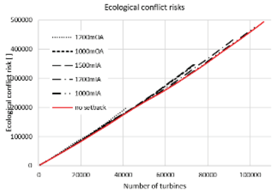
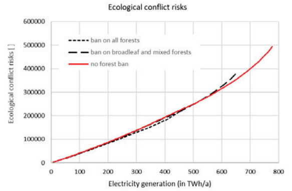
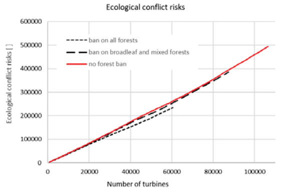
	Setback distances		Forest bans	
	Costs as a function of electricity generation	Costs as a function of no. of wind turbine sites, $C_e(x)$ and $K_e(x)$	Costs as a function of electricity generation	Costs as a function of no. of wind turbine sites, $C_e(x)$ and $K_e(x)$
Generation costs				
Disamenity costs				
Impacts on landscape quality				
Impacts on avifauna				
Ecological conflict risks				

Figure 8: Costs of wind power deployment for different exclusion zone scenarios and cost criteria, as a function of generation and number of turbines sites

For generation costs, net opportunity costs of exclusion zones rise with increasing generation targets – both for setback distances and forest bans. In this case, no substitution effect exists because costs are identical for each site (resulting in the linear cost function $C_e(x)$). Only the output effect matters. The output effect increases with increasing generation targets because the marginal productivity of additionally used sites declines – as we highlighted in the analytical model. Similar outcomes can be observed for impacts on landscape aesthetic quality and ecological conflict risks. For these cost criteria, substitution effects also hardly matter because spatial heterogeneity across potential sites is fairly small at larger spatial scales (illustrated by the quasi-linear cost functions $K_e(x)$). In fact, spatial heterogeneity with respect to landscape aesthetic quality and ecological conflict risks may be more pronounced if individual sites are compared. However, these small-scale differences cancel out when we compute cost functions in stepwise manner because high- and low-score sites are distributed fairly evenly across the potential sites in the different German regions (compare Figures 2a, 2d, and 2f). Consequently, net opportunity costs with respect to these cost criteria rise with increasing generation targets primarily because the output effect increases.

For disamenity costs, the effect of increasing the generation target on net opportunity costs is ambiguous, primarily because the size and sign of the substitution effect varies with generation targets. The substitution effect depends on the convex shape of the disamenity cost function $K_e(x)$. Convexity results from the fact that marginal wind productivity and marginal disamenity costs are negatively correlated in space in Germany (see Figures 2b and 2c, also mirrored by the fact that generation costs and disamenity costs are positively correlated, see Table 2): In order to reach higher levels of electricity generation, deployment has to expand from the sparsely populated but windy North further to the more densely populated but less wind south (see Figures 2b and 2c).

Let us first look at how this affects the net opportunity costs of setback distances. For these scenarios, the substitution effect becomes increasingly negative with initially rising targets. As deployment expands to more densely populated areas in the center of Germany, setback distances can then help to reduce disamenities substantially by moving deployment away from settlements. These negative substitution effects more than offset the output effect, resulting in negative net opportunity costs. For higher targets, however, the negative substitution effect shrinks. This is because the more the generation target approaches the maximum possible generation potential of the exclusion zone scenario under consideration, the smaller become the degrees of freedom for reallocating wind turbines spatially. For high generation targets, these negative but small substitution effects are then more than offset by the output effect, which is strictly positive and increasing in generation targets.

For forest bans, the net opportunity costs in terms of disamenity costs are strictly positive and by and large increase with increasing generation targets. In this case, not only the output effect but also the substitution effect is positive and increasing. The rising substitution effect is also due to the convex disamenity cost function. As outlined above, increasing generation targets expands deployment to the more densely populated center and South of Germany. Forest bans then shift deployment to even more populated non-forested areas.

Interestingly, for impacts on avifauna, the net opportunity costs remain fairly small with increasing generation targets for all exclusion scenarios. This because the output effect and the substitution effect cancel out. With increasing generation targets, the substitution effect of exclusion zone becomes ever larger because the cost function $K_e(x)$ is concave for impacts on avifauna. Concavity results from the fact that wind productivity and impacts on avifauna are positively correlated in space (also mirrored by the fact that generation costs and impacts on avifauna are negatively correlated, see Table 2). Increasing generation means that deployment expands further to Southern half of Germany where the abundance of wind-power sensitive birds is lower. Implementing exclusion zones accelerates this expansion, resulting in a negative substitution effect. However, this negative substitution effect is offset by a positive output effect which increases in generation targets.

5 Discussion

5.1 Drivers of opportunity costs of environmental exclusion zones

Our analysis has shown that it is useful to distinguish between an output effect and a substitution effect to understand what drives opportunity costs of environmental exclusion zones. In particular, this allows us to disentangle a set of drivers of opportunity costs which can be generalized beyond our case study.

The output effect strictly increases opportunity costs. A necessary condition for the output effect to occur is spatial heterogeneity in marginal wind productivity across available sites. In other words, the wind power production function has to be concave as the one we find for our German case study. In addition, the output effect depends on the spatial correlation between marginal wind productivity and the exclusion zone. The output effect will be particularly large if a substantial share of the excluded sites have good wind conditions. In our case study, this holds true for both setback distances and forest bans. Moreover, the ambition of the generation target and the stringency of the exclusion zone matter. As they increase, deployment approaches the flatter part of the wind power production function. Consequently, more sites with relatively low marginal productivity have to be used to replace excluded sites with good wind conditions. This is why the output effect is particularly high for our most restrictive exclusion zone scenarios (1200mOA, ban on all forests).

A substitution effect only arises with environmental exclusion zones if marginal costs are spatially heterogeneous. Only in this case, shifting deployment to other sites can increase or decrease the total cost of achieving a generation target. In our model, heterogeneity is absent by assumption for marginal generation costs, and small for marginal impacts on landscape aesthetic quality and ecological conflict risks. Hence, we find that exclusion zones produce relatively small substitution effects for these cost criteria. In contrast, substitution effects are more substantial for disamenity costs and impacts on avifauna, which exhibit more spatial heterogeneity. The ambition of the generation target and the stringency of the exclusion zone may have an ambiguous effect on the size of the substation effect – as we observe particularly for disamenity costs.

The substitution effect can be positive or negative, i.e., increase or decrease the opportunity costs of environmental exclusion zones. The sign of the substitution effect depends on two sub-effects. The sign of sub-effect one hinges on the spatial correlation between marginal costs and the exclusion zone. If this correlation is negative, i.e., if exluded sites have relatively high marginal costs, implementing the exclusion zone will lead to a negative sub-effect one. In our case study, this applies, for example, to setback distances and disamenity costs, or forest bans and ecological conflict risks. In contrast, a negative spatial correlation between marginal costs and the exclusion zone will lead to a positive sub-effect one. This holds true, for example, for forest bans and disamenity costs. The sign of sub-effect two depends on the spatial correlation between marginal costs and marginal wind power productivity. This correlation is important because we assume that the general spatial allocation rule promotes the use of the most productive sites available to attain a generation target. Implementing an environmental exclusion zone than necessarily shifts deployment to less productive sites. In Germany, for example, exclusion zones tend to shift deployment from the windy North to the less windy South. Now, if marginal wind power productivity is positively correlated in space with marginal costs – i.e., if more productive sites have higher marginal costs -, sub-effect two will be negative. In our example, this holds true for impacts on avifauna (see the concave cost function in Figure 8). In turn, sub-effect two will be negative if the spatial correlation between marginal wind power productivity and marginal costs is negative, i.e., if more productive sites have lower marginal costs. In Germany, this holds true to some extend for disamenity costs. The overall sign of the substitution effect consequently depends on how both sub-effects combine.

5.2 Lessons learnt for the German case

Our analysis also allows deriving some lessons for the specific regulatory context of our German case study. First of all, we confirm that environmental exclusion zones may reduce the potential for wind power deployment substantially. We find that the maximum possible generation level is reduced by up to 60% if the most restrictive setback scenario is implemented, and up to 40% deployment is completely banned from forests. This is in line with previous findings for setback distances in Germany (Masurowski et al., 2016; Ruhnau et al., 2023; Stede et al., 2021; Unnewehr et al., 2021), Israel (Peri and Tal, 2021), and the US (Lopez et al., 2021).

Opportunity costs in terms of generation costs are generally moderate (up to 5%) for most exclusion zone scenarios and relevant deployment levels. Only the most restrictive setback scenario 1200mOA produces more substantial increases in generation costs. The moderate effects we find for exclusion zones are again in line with previous analyses of setback distances in Germany (Ruhnau et al., 2023; Salomon et al., 2020; Stede et al., 2021). Analyzing different types of exclusion zones in the United Kingdom, Delafield et al. (2023) also find only minor effects in terms of generation costs. In contrast, Reutter et al. (2023) find more substantial generation cost effects of setback distances. This is because they analyze the implementation of a fairly ambitious generation target in a relatively small region of Germany. Generally, the increase in generation costs we find is solely due to the output effect – i.e., more wind turbines needed to reach the generation target with an exclusion zone in place – as we assume generation costs to be identical across sites.

We find that the more relevant effects of exclusion zones arise for the non-market costs we consider in our analysis. Setback distances produce negative opportunity costs (i.e., benefits) in terms of disamenities – but only when the setback is applied solely to the inner area of settlements. In these cases, a positive output effect is more than offset by a negative substitution effect. This finding is important because reducing disamenities may a main rationale behind implementing setback distances. However, the opportunity costs in terms of disamenity costs may become positive for very restrictive setback distances which are also applied to outer areas. In these cases, the output effect is extremely high, and even the substitution effect may turn positive and aggravate opportunity costs. Such surprising effects have not been found in previous studies for Germany – most likely because these only looked smaller regions (Drechsler et al., 2011; Reutter et al., 2023; Salomon et al., 2020). The opportunity costs of setbacks in terms of impacts on nature and landscape conservation are mostly very limited. The only exemption is the most restrictive setback scenario 1200mOA, particularly because it produces substantial output effects for other non-market costs. Negative impacts of setback distances on nature and landscape conservation have also been found by in previous analyses (Reutter et al., 2023; Wu et al., 2020), which however do not explore the underlying drivers of these opportunity costs. Overall our study thus suggests that if setback distances are implemented, they should not be too restrictive. Importantly, they should differentiate between inner areas (with more restrictive setbacks) and outer areas (with less restrictive setbacks). Similar policy recommendations are derived by Drechsler et al. (2011), Salomon et al. (2020), and Reutter et al. (2023). However, their conclusion primarily rests on the argument that for very restrictive setback distances higher generation costs more than offset lower disamenity costs. In contrast, our recommendation is based on the observation that also disamenities may increase with very restrictive setbacks.

Our analysis reveals that forest bans produce substantial trade-offs with respect to non-market costs if they exclude wind power deployment in all forests. On the one hand, a ban on all forests may produce negative opportunity costs (i.e., benefits) with respect to landscape aesthetic quality and ecological conflict risks. For these criteria the positive output effects are more than offset by negative substitution effects. This finding is important because nature and landscape conservation often motivate policy makers to implement forest bans. On the other hand, our analysis shows that a ban on all forests produces very substantial opportunity costs in terms of higher disamenities. Consequently, decisions on a possible ban on all forests have to be based on a very careful assessment of possible benefits and costs. In contrast, our study suggests that excluding wind power deployment solely from broafleaf and mixed forests may be less critical. The opportunity costs we find for this exclusion zone scenario are minor – and may be acceptable particularly there are substantial societally benefits of forest bans beyond those considered in our model.

5.3 Limitations

Several limitations of our analysis merit a closer consideration. First of all, we have analyzed environmental exclusion zones implemented in separation. In reality, however, they may overlap. For example, several German states and US counties have implemented both setback distances and forest bans (Bunzel et al., 2019; Ember, 2022; Oteri, 2008). Overlapping exclusion zones is analytically equivalent to an increase in the stringency of exclusion zones. More sites are excluded and, hence, the output effect can be expected to increase. The impact on the substitution effect can theoretically be positive as well as negative. It depends on how the different types of exclusion zones are correlated in space as well as on the criterion under consideration. Consequently, the overall effect of overlapping exclusion zones on their opportunity costs can be ambiguous and depend a lot on the spatial context. Looking at various environmental exclusion zones in the United Kingdom, Delafield et al. (2023) find that overlapping them does in fact increase the social costs of deploying wind power, solar photovoltaics and bioenergy.

A second limitation is related to our basic policy setup. Throughout our analysis, we assume that an exogenously set wind power generation target has to be reached at least generation costs without or with exclusion zones. Hence, we apply a cost-minimization approach that keeps total wind power generation fixed. Generally, this is a plausible assumption. It mimics a technology-specific tender scheme which is the dominant approach to promote wind power deployment in most countries nowadays (Grashof, 2021). This notwithstanding, it is also worthwhile to discuss possible implications in a setting where the level of wind power generation is allowed to vary and determined endogenously. This would be the case, for example, if wind power deployment was solely promoted indirectly through carbon pricing. In such a setting, the output and substitution effects induced by environmental exclusion zones would be smaller. This is because implementing an exclusion zone excludes productive sites and makes wind power deployment costlier overall. As a consequence, wind power generation will be replaced to some extent by other generation technologies that are cheaper at the margin. A lower generation level reduces both output and substitution effects of environmental exclusion zones, as we have shown in our analytical model. Hence, the opportunity costs of exclusion zones as we model them would be smaller. This intuition is somewhat confirmed by energy system analyses which determine the optimal wind power share endogenously. They frequently find that the optimal level of wind power generation declines when exclusion zones are applied, in some cases it even drops to zero (Mai et al., 2021; Palmer-Wilson et al., 2019; Price et al., 2018; Wang et al., 2020; Wu et al., 2020). Importantly, these studies also look at energy system costs beyond the generation costs of wind power plants considered in our model, most notably generation costs for other types of power plants needed as well as network costs. In these analyses additional opportunity costs of environmental exclusion zone arise because a) a spatial reallocation of wind power deployment may require more network extensions, and b) because more costly generation technologies have to be used to replace the productive wind power sites excluded. Overall, however, the increase in total energy system costs resulting from environmental exclusion zones lies within the ranges we find for wind power generation costs only.

A final limitation related to our basic policy setup concerns the assumption that the most productive sites are chosen first. We think that this assumption is useful to mimic a “market scenario” as it results under a tender scheme (and also under carbon pricing). And indeed, various empirical analyses show that existing wind turbines in Germany have been allocated primarily to sites with the best wind conditions (Goetzke and Rave, 2016; Hitaj and Löschel, 2019; Lauf et al., 2020). However, eventual siting decisions are usually not only determined by tender schemes and exclusion zones that we have considered so far. For example, individual wind turbine projects typically also to need to undergo a permitting process. In the context of this process, a variety of criteria are reviewed including also local disamenity costs as well as impacts on nature and landscape conservation. Consequently, real-world siting decisions may at least partly deviate from an allocation that minimizes solely generation costs. In Appendix 1, we show that opportunity costs of environmental exclusion zones may be both larger or smaller if we assume other spatial allocation rules than a “market scenario”.

5 Conclusion

Exclusion zones are frequently used to reduce environmental impacts of human land-uses, like urban development, agriculture, or the deployment of renewable energies. To assess the efficiency of land-use restrictions, the expected environmental benefits from implementing exclusion zones must be compared to their opportunity costs. Opportunity costs arise if excluding land use in some areas increases the market and non-market costs of production. Understanding the drivers of opportunity costs is thus crucial for policy evaluation. We propose that opportunity costs of exclusion zones can be decomposed into a substitution effect and an output effect. The substitution effect occurs because exclusion zones shift land-based production from excluded to allowable sites. The marginal market and non-market costs of production may be higher or lower on allowable sites than on excluded sites. Hence, the sign of the substitution effect is ambiguous. In addition, exclusion zones may exclude sites with relatively high productivity. This implies that more sites may be needed to satisfy demand for the produced goods. The output effect therefore strictly increases opportunity costs of exclusion zones.

To illustrate our analytical insights numerically, we use two examples of environmental exclusion zones implemented for wind power deployment in Germany: setback distances to settlements and forest bans. Our analysis reveals that opportunity costs may primarily arise in terms of higher non-market costs of wind power generation. Opportunity costs are mainly due to the output effect for setbacks and the substitution effect for forest bans. We also show that the actual sign and size of opportunity costs depends a lot on the cost criteria under consideration as well as the type and stringency of the environmental exclusion zone.

We believe that our analytical insights are also helpful when thinking about the impacts of environmental exclusion zones applied in other fields of environmental policy. For example, banning or restricting agricultural land-use in some areas, e.g., to protect local ecosystems or groundwater bodies, may mean that agricultural activities are intensified on other sites (the substitution effect). Moreover, overall more land may be used to satisfy demand for agricultural products (the output effect). If further development in urban agglomerations is excluded, e.g., to protect urban green spaces, developments may occur further away from urban centers (the substitution effect). This may also mean that overall more land is occupied by developments, e.g. for additional transportation infrastructure connecting outskirts with city centers (the output effect).

Our analysis does not mean to dismiss environmental exclusion zones in general. Instead, it emphasizes the importance to properly understand possible opportunity costs (e.g., higher disamenity costs due to forest bans), and compare them with possible benefits (e.g., protection of ecosystem services provided by forests) when implementing exclusion zones. Interestingly, however, our analysis also reveals a case where an environmental exclusion zone appears to be an inappropriate instrument of environmental policy. Very restrictive setback distances may in fact increase the total disamenity costs produced by wind power deployment – contrary to the policy objective pursued by this instrument. In addition, our analysis points towards using more differentiated exclusion zone approaches, – e.g., setback distances differentiating between the size of settlements, or forest bans differentiated by the type of forest. Differentiating exclusion zones may help to attain environmental policy objectives at lower opportunity costs. More generally, our analysis may also strengthen the case for using alternative policy instruments to exclusion zones to mitigate environmental impacts of human land-use. Alternatives may include permitting processes which carry out environmental impact assessments for each site individually – or market-based approaches which internalize non-market costs and benefits of siting decisions by respective pricing schemes. Analyzing how such policy instruments compare to environmental exclusion zones may be a promising avenue for further research. Certainly, such comparative assessment will also have factor in that such policy instruments may be much more cumbersome to implement administratively than simpler environmental exclusion zones.

Appendix 1

Throughout our main analysis, we assumed that sites for wind power deployment are chosen to minimize generation costs subject to a given generation target and the exclusion zone scenario ("market scenario"). Here, we additionally analyze opportunity costs of exclusion zones with other spatial allocation rules. More specifically, we also analyze four alternative spatial allocation rules that minimize a) disamenity costs, b) impacts on landscape aesthetic quality, c) impacts on avifauna, and d) ecological conflict risks. For each spatial allocation rule we determine the opportunity costs of implementing an exclusion zone compare to setting without any exclusion zone in place. Figures 9 und 10 illustrate the opportunity costs of our exclusion zone scenarios with respect to the different cost criteria for a generation target of 300 TWh/a, assuming varying spatial allocation rules. The black bar highlights the results when generation costs are minimized (the "market scenario") – and is thus identical to the black bars in Figures 6 and 7.

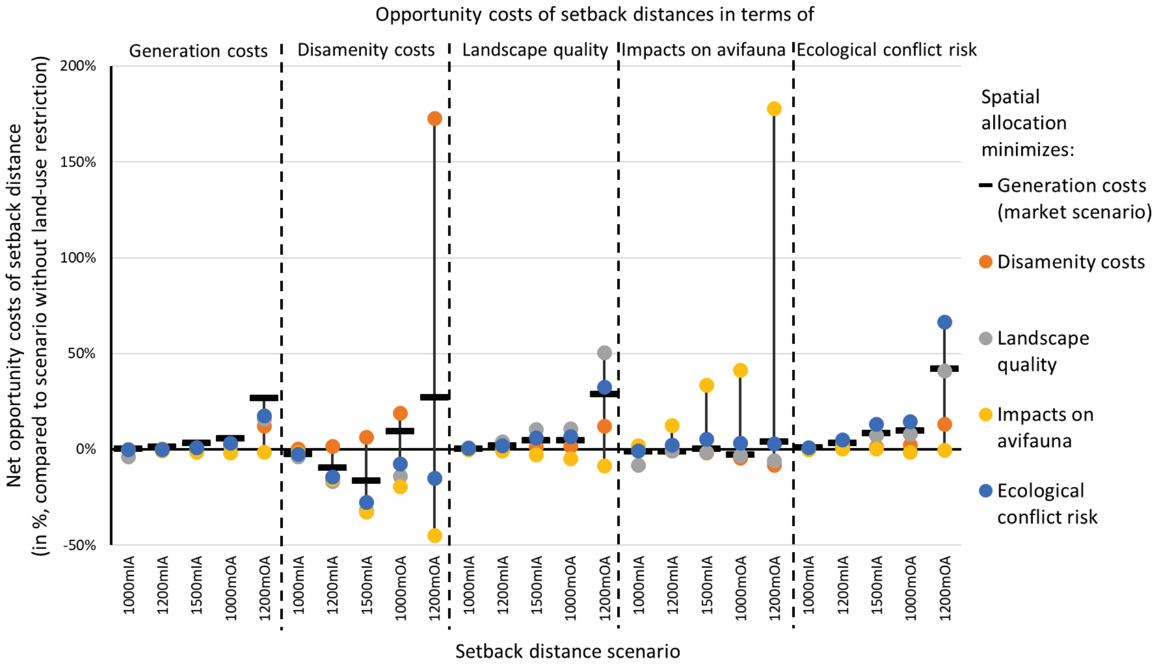


Figure 9: Opportunity costs of setback distances in terms of different cost criteria for a generation target of 300 TWh/a, with alternative spatial allocation rules

Generally, opportunity costs of exclusion zones with respect to a specific cost criterion are largest when this criterion is already addressed by the underlying spatial allocation rule. Consider, for example, the case where the spatial allocation rule aims to minimize impacts on avifauna. This could be the case, for example, if the protection of birds has a high priority in the permitting process for new wind turbine sites. In this case, implementing an exclusion zone produces the largest opportunity costs in terms of impacts on avifauna, compared to all other allocation rules. This is straightforward as in this case the impacts of the exclusion zone scenario are compared to the ideal case with minimum impacts on avifauna. Interestingly, this observation similarly applies to disamenity costs and setback distances. If minimizing disamenity costs is the leading spatial allocation rule, implementing setback distances produces particularly large opportunity costs in terms of disamenity costs. This is because uniformly applied setback distances may exclude sites with relatively low disamenity costs (those located close to small villages or even individual residential buildings, see Figure 4) and relatively high wind yield. Therefore, setback distances may substantially reduce the degrees of freedom to achieve a given generation target at least disamenity costs.

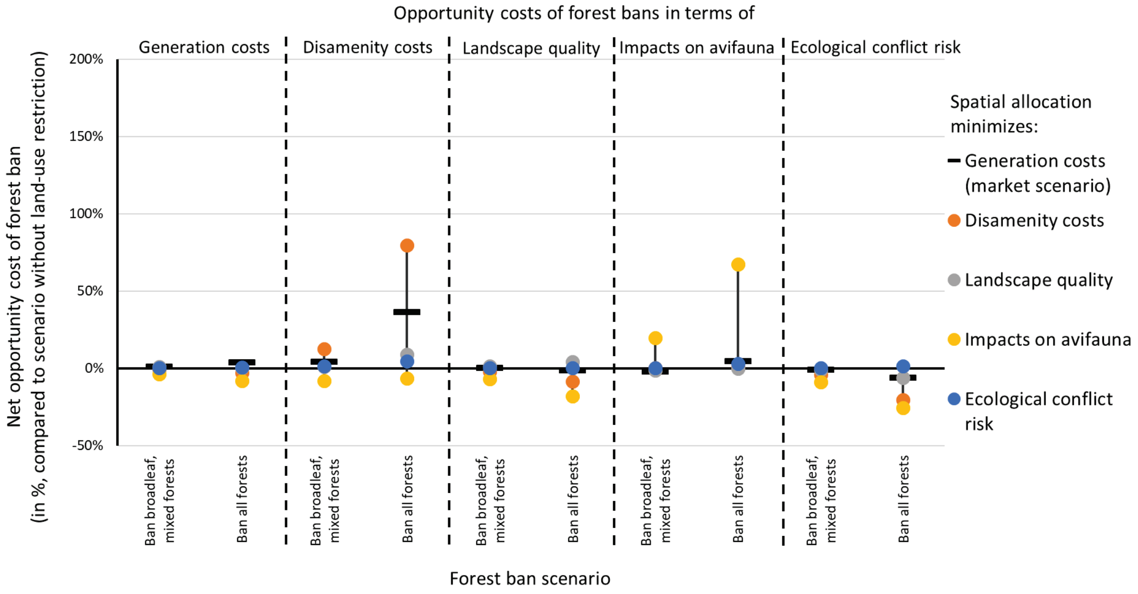


Figure 10: Opportunity costs of forest bans in terms of different cost criteria for a generation target of 300 TWh/a, with alternative spatial allocation rules

It is also worthwhile to look beyond the special cases where the spatial allocation rule and the cost criteria under consideration are identical. Figures 9 and 10 show that in all other cases the opportunity costs of exclusion zones under alternative spatial allocation rules are equal or lower than in the market scenario. A striking example is the outcome for the most restrictive setback distances (1000mOA and 1200mOA). They produce negative opportunity costs (i.e., benefits) with respect to disamenity costs if the spatial allocation rule aims to minimize impacts on landscape aesthetic quality, avifauna, or ecological conflict risks. This stands in contrast to the results under the market scenario. The result can be explained by the fact that landscape aesthetic quality, impacts on avifauna and ecological conflict risks are hardly or even negatively correlated in space with disamenity costs (see Table 2). Minimizing the costs with respect to the former criteria results in a spatial allocation which includes a considerable number of sites with high disamenity costs. Implementing setback distances mitigates this effect, and thus produces negative opportunity costs with respect to disamenity costs.

Appendix 2

To review the sensitivity of our results with regard to the assumed disamenity function, we have repeated our analysis with a linear household disamenity cost function which has the same value as the hyperbolic cost function depicted in Figure 3 at 800 m and a value of zero at 4,000 m. Thereby, we reduce the spatial heterogeneity of disamenity costs. Figure 12 compares the output and substitution effects of different setback scenarios with respect to disamenity costs for the hyperbolic and linear disamenity cost functions.

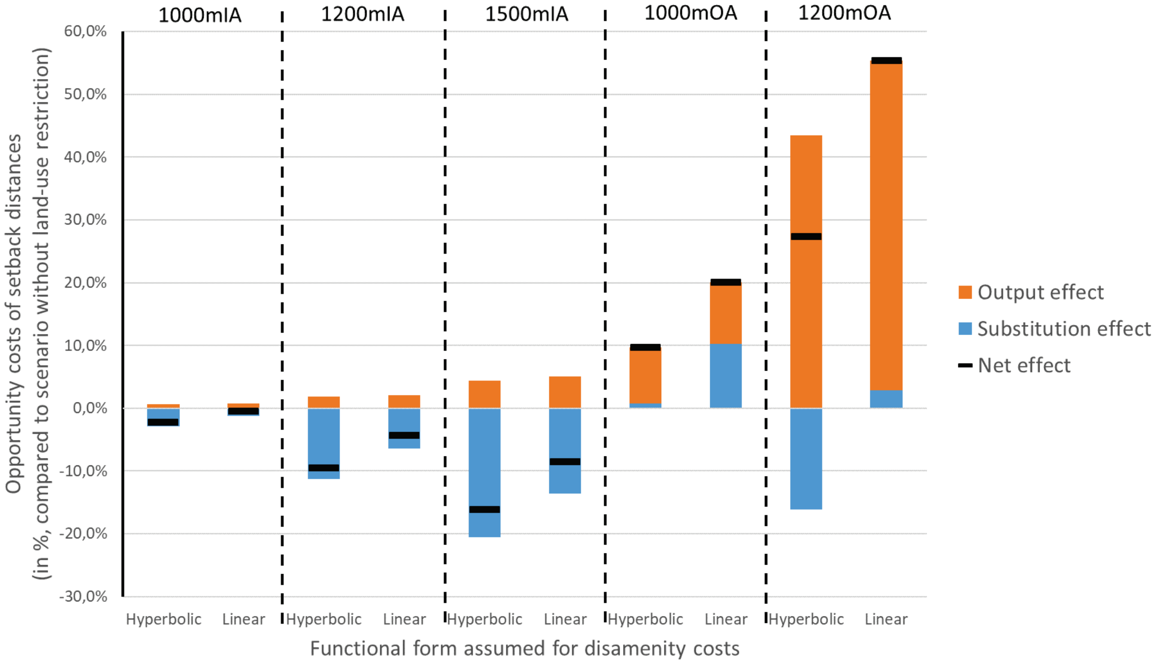


Figure 11: Output and substitution effects in terms of disamenity costs, for different setback distance scenarios and hyperbolic and linear disamenity cost functions

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