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# Social Costs of Setback Distances for Onshore Wind Turbines: A Model Analysis Applied to the German State of Saxony

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## Abstract

Wind power is a key for decarbonizing economies. Yet, wind turbines can produce negative environmental externalities. These include bird collisions and disamenities for residents. Setback distances for onshore wind turbines to settlements and bird nests are a common policy instrument to address these externalities. In this paper, we evaluate the cost-effectiveness of setback distances. We use a spatially-explicit model to investigate the social costs of different options for setbacks to settlements and red kite nests. In terms of social costs, we consider production costs and external costs associated with residents' disamenities and red kite impacts given an exogenously set wind energy production target. The model is applied using data for the German State of Saxony. Three key results are: (1) More restrictive setbacks may increase social costs. (2) Uniform red kite setbacks reduce social costs rather than uniform settlement setbacks. (3) Differentiated settlement setbacks for different settlement types lead to substantially lower social costs than uniform setbacks.

**Keywords** Wind turbines · Externalities · Setback distances · Social costs · Spatially-explicit modeling

## 1 Introduction

Wind power is a key technology for decarbonizing the energy sector. However, wind turbines themselves can have some negative environmental externalities. These effects include disamenities for humans caused by noise emissions and visual impressions as well as wildlife impacts, especially regarding birds that can collide with wind turbines (Dai et al. 2015; Mattmann et al. 2016; Zerrahn 2017).

A common policy instrument that is used worldwide for addressing such local externalities is setback distance requirements which define buffer zones around settlements

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and bird nests in which wind power is prohibited. With respect to residents, state-level or regional setback distance requirements are in place in many countries, for example, in Europe, North America or Australia (Watson et al. 2012; Hall et al. 2013; Sturge et al. 2014; Unnewehr et al. 2021; McKenna et al. 2022). With respect to birds, risks for vulnerable and endangered species are often mitigated by banning wind turbines within buffer areas around nesting locations (Vignali et al. 2021). Such setback distances may be specified either nationwide or regionally. For instance, Aydin et al. (2010) report on nationwide setback distance requirements for bird habitats in Turkey. At regional levels, exclusions around nests of sensitive bird species have been used by authorities, for example, in Norway, Spain, and South Africa (Janss et al. 2010; Murgatroyd et al. 2021; Gulbrandsen et al. 2021). Setback distances to breeding sites of certain bird species are also used in Germany for regional planning and local approval procedures for wind power projects (Köppel et al. 2014; Backes and Akerboom 2018).

However, it is politically a controversially discussed question what setback distance requirements should be prescribed. For years this question has been topical in many countries both with regard to birds as well as with regard to settlements (Masurowski et al. 2016; Hajto et al. 2017; Köck et al. 2018). From an economic perspective, different setback distance options can be assessed by the social costs that are associated with the wind turbine allocations which will occur with these options. As social costs of an allocation, we consider the sum of private energy production costs and external costs that arise from all deployed wind turbines. While more restrictive setbacks may reduce the addressed externalities, such land-use restrictions may at the same time increase production costs and other external costs.

Command-and-control instruments (beyond hazard control) are generally considered less cost-effective in the case of non-uniformly mixed pollutants, primarily because of typically uniform and binary control behavior without accounting for existing (cost) differences (Goulder and Parry 2008; Perman et al. 2011). If differentiations apply, performance gaps may be reduced (Cropper and Oates 1992). With respect to setback distances, two aspects seem particularly relevant. First, uniform setback distance regulations are blind to gradual differences concerning the addressed environmental impacts of the sites, which are within and outside the specified setback distances, respectively. Second, uniform setback distance regulations are also blind to production costs and other external costs. For both reasons, it can be suspected that setback distances do not lead to an optimal social planner's solution, but only to second-best outcomes.

Against this background, our overarching research question is: how cost-effective are different setback distances in regulating multiple externalities related to wind power deployment, and what are relevant variables influencing their cost-effectiveness when energy production costs and two different types of external costs are considered? We address this question by examining four sub-questions. (1) How close can a social planner case be achieved by different possible setback distance options? (2) Do social cost effects of setback distances depend on the externalities they address? (3) Do more restrictive setback distances imply lower social costs and what are relevant partial effects in this context? (4) Can the cost-effectiveness of setback distances be improved by spatial differentiation, e.g., between densely and sparsely populated areas?

To answer these research questions, we use a spatially-explicit modeling approach to model allocation decisions made by a social planner as well as profit maximizing investors. The model is applied with GIS data for the German State of Saxony. We focus on two externalities and associated setback distances: on disamenities for residents (Lehmann et al. 2021) and on negative impacts on the red kite, a protected wind turbine sensitive raptor bird species (Schaub 2012). We consider these two externalities

because they are particularly relevant for the wind power deployment in Germany where our study region is located. The high relevance of potential wind power impacts that are perceived as harmful by residents is reflected in the formation of a large number of citizens' initiatives in recent years, hindering local wind power projects in Germany (Weber et al. 2017; Wiehe et al. 2021). The relevance of potential wind power impacts on the red kite stems from the facts that Germany hosts about half of the world's red kite population (Nicolai et al. 2017) which implies a high national responsibility for the global conservation of this species and that many wind power projects in Germany are sued and impeded because of possible red kite conflicts (Lachmann 2019). Although collisions with wind turbines are only one life risk among several for red kites, additional anthropogenic mortality from wind turbines can threaten local red kite populations (Bellebaum et al. 2013). Katzenberger and Sudfeldt (2019) find that there is indeed a highly significant negative correlation between red kite population changes and wind turbine density at the county level in Germany.

Our paper builds upon a growing body of empirical studies indicating that externalities decline with increasing distances to wind turbines. Regarding impacts on birds, this applies to wind turbines' distances to bird nests (Rasran et al. 2017). Regarding local disamenities for residents, distance decays are observed in life-satisfaction approach studies (von Möllendorff and Welsch 2017; Krekel and Zerrahn 2017), revealed preferences studies like hedonic pricing studies (Gibbons 2015; Sunak and Madlener 2017; Dröes and Koster 2021), and stated preferences studies like choice experiment studies (Wen et al. 2018). However, while these studies suggest that externalities could be reduced by setbacks, they do not further analyze effects of setbacks.

There is also some literature that explicitly deals with setback distances for wind turbines. Several studies address the question of how different settlement setback distances affect the available wind power potential. For instance, Sliz-Szkliniarz et al. (2019) find for Poland that a settlement setback of 2 km reduces the technical wind onshore potential on Poland's land area by up to 63%, compared to a setback of 1 km. Examining Germany, Masurowski et al. (2016) analyze that the impacts of settlement setbacks on the wind energy potential is highly spatially heterogeneous across the country. Stede et al. (2021) conclude that the introduction of restrictive settlement setbacks in the German federal State of Bavaria reduced the deployment of wind power there by up to 90% and increased levelized costs of electricity (LCOE) by about 0.2 ct/kWh. Similarly, Meier et al. (2023) estimate based on a dataset for the whole of Germany that increasing a settlement setback by 100 m has lowered yearly wind power additions by 15.4%. An analysis by Peri and Tal (2021) for Israel suggests that increasing settlement setbacks to 1.5 km and above would severely reduce the available wind power potential, but would not result in major reductions in local disamenities. Considering a further possible trade-off of settlement setbacks, Eichhorn and Drechsler (2010) show for the German region of Western Saxony that increasing settlement setbacks is potentially detrimental to the protection of the red kite. However, all studies mentioned before do not analyze explicitly the social costs of setback distances in monetary terms.

Still, a few studies also address similar questions and use similar approaches as in the present paper considering social costs explicitly. Drechsler et al. (2011) study the following question for the German region of Western Saxony using a monetization approach for negative impacts of wind turbines on residents and red kites: what is the optimal (uniform) settlement setback distance that allows to bring social costs (as sum of production costs and external costs) of wind power generation to the lowest possible level if a certain given energy production target needs to be achieved? Looking at all of Germany, Drechsler et al. (2017)

perform a similar optimization for the allocation of wind turbines and ground-mounted PV systems on the basis of a cost-effectiveness criterion. During the optimization process, i.a., the level of a (uniform) settlement setback distance is optimized. For this purpose, in addition to electricity generation costs, external costs for residents are included in the optimization by a cost function for settlement setback distance requirements (whereas red kite impacts are not considered). Also taking a social cost perspective, Salomon et al. (2020) conduct a systematic robustness analysis to investigate which (uniform) setback distance requirements to settlements and red kite nests in the German State of Saxony are most robust when different modeling uncertainties are taken into account, i.e., which setbacks have a high probability of exhibiting comparatively low social costs given modeling uncertainties.

However, all previously cited studies do not provide second-best cost-effectiveness analyses how closely the social cost optimum can be attained with different setback requirements in a market setting with profit-seeking investors. We address this research gap. We also add to the literature on the social costs of setbacks by systematically examining causal effects of different setback options. Concretely, we disentangle the social cost effects of setbacks in the studied multiple externalities setting by tracing them down to the impacts on energy production costs and the two external costs considered. A further novelty of our study is that we consider not only uniform setbacks but also spatially differentiated setbacks in our analysis.

The remainder of the paper is structured as follows. Section 2 depicts the applied modeling approach and data used. Section 3 presents the modeling results for our basic assumptions as well as a sensitivity analysis. Section 4 discusses the results with respect to our research questions and points out uncertainties and limitations of our analysis. Section 5 concludes and suggests avenues for future research.

## 2 Modeling Approach

We next describe the used optimization approaches (Sect. 2.1, see also the nomenclature in Table 1). First, we depict in general terms how we model a social planner's allocation minimizing the social costs of wind energy production (Sect. 2.1.1). We then describe in general terms how we model market solutions given different policy scenarios for setback distances (Sect. 2.1.2). After that, we turn to the data and parameterization used for the application of our modeling approach (Sect. 2.2). We describe the used data for our study region and the production and revenue potentials there (Sect. 2.2.1) and depict the concrete assumptions that we make for the social cost modeling (Sect. 2.2.2). Finally, we describe the policy scenarios for setbacks that we consider (Sect. 2.3).

### 2.1 Optimizations

#### 2.1.1 Social Planner

As a reference scenario, we model a social planner case. This benchmark represents the allocation of wind turbines that minimizes social costs for a certain energy production target. We start from an empty landscape without any wind turbines (greenfield approach). In order to ensure the highest possible turbine allocation optimization

**Table 1** Nomenclature

| Symbol | Description |
| --- | --- |
| $AEP$ | Potential annual energy production |
| $AET$ | Annual energy production target |
| $AF$ | Annuity factor |
| $C$ | Total social costs |
| $C^{\text{prod}}$ | Total energy production costs |
| $c^{\text{prod}}$ | Wind turbine investment and O&M costs |
| $C^{\text{res}}$ | Total external costs for residents |
| $C^{\text{rk}}$ | Total external costs for red kite losses |
| $d$ | Distance |
| $h$ | Household |
| $i$ | Potential site |
| $I$ | Setback policy scenario |
| $j$ | Red kite nest |
| $k$ | Index for setback policy scenario |
| $K$ | Number of considered setback policy scenarios |
| $l$ | Subsidy level factor |
| L | Expected population loss |
| $p$ | Electricity market value |
| $R$ | Red kite setback |
| $s$ | Subsidy rate factor |
| $S$ | Settlement setback |
| $x$ | Binary decision variable for site selection |
| $\pi$ | Total profit |

potential for the social planner, we assume that no regulatory leeway with respect to setback requirements is exercised.

In our modeling framework, the social costs $C$ of a specific wind turbine allocation are the sum of the total energy production costs $C^{\text{prod}}$, external costs for residents $C^{\text{res}}$, and external costs for red kite losses $C^{\text{rk}}$ that stem from all installed wind turbines at sites $i$ (see later Sect. 2.2.2 on the assumptions for these costs). The minimization problem then is: select from all potential sites $i$ those that minimize social costs subject to the constraint that a given energy production target is achieved. Thus, the objective function and energy production constraint for the optimization are:

$$\min_{x_i} C := C^{\text{prod}} + C^{\text{res}} + C^{\text{rk}}$$
$$s.t. \quad AET = \sum_{i} \left( x_i \cdot AEP_i \right) \tag{1}$$

The total annual energy production target is denoted by $AET$, the potential annual energy production at site $i$ is denoted by $AEP_i$, and the deployment decision at site $i$ is denoted by $x_i$ (with $x_i = 1$ if site $i$ is selected and $x_i = 0$ if site $i$ is not selected).

## 2.1.2 Market Solution

Apart from the social planner case, we also model wind turbine allocations that result from a market driven wind power deployment given different policy scenarios for setback distances. We assume $K$ setback policy scenarios $I_k$ $(k = 1, \ldots, K)$ each of which defines the set of all potential sites $i$ per scenario where wind turbines can be deployed: $i \in I_k$ (see later Sect. 2.3 on the assumed setback policy scenarios). We model the market solution for each assumed setback policy scenario considering the rationalities of two actors: investors and the regulator setting a wind power subsidy. As for the social planner case, we use a greenfield approach, assuming an initially empty landscape without any wind turbines installed.

Regarding investors, we assume that they maximize their profits by installing wind turbines at the most profitable potential sites ignoring external costs for residents and red kite impacts. For the profit maximization, private costs and achievable revenues are relevant. In terms of private costs, we consider (total discounted) wind turbine investment, operation, and maintenance (O&M) costs $c_i^{\text{prod}}$ at the potential sites $i$. The quantity component of possible revenues is shaped by the potential site-specific annual energy yields $AEP_i$ (kWh). The price component of possible revenues is composed of the electricity market value $p_i$ (ct/kWh) and a subsidy rate (ct/kWh). We assume the subsidy rate to be dependent on a level factor $l$ (see below) and a site-specific factor $s_i$. The motivation for a site-specific factor $s_i$ may be a politically intended spatial discrimination in wind energy support per kWh. Such a discrimination may be pursued, e.g., between windier and less windy sites as it is laid out in the German wind power support scheme (EEG) through the so called reference yield model (Referenzertragsmodell). An annuity factor $AF$ is applied to sum up and discount the achievable yearly revenues over the same time horizon which is taken into account for the investment and O&M costs. Altogether, the profit maximization problem of investors for a given setback policy scenario $I_k$ can then be formulated as:

$$\max_{x_i} \pi := \sum_{i \in I_k} \left( x_i \cdot \left( AEP_i \cdot \left( p_i + s_i \cdot l \right) \cdot AF - c_i^{\text{prod}} \right) \right) \tag{2}$$

where $x_i = 1$ if site $i$ is selected and $x_i = 0$ if site $i$ is not selected.

The regulator determines a subsidy level factor $l$ which allows attaining a desired energy target $AET$ at the least production costs $C^{\text{prod}}$. This reflects the idea of an auctioning wind power support scheme. When determining $l$, the regulator considers the investors' reaction function $x_i(l)$ resulting from (2). Consequently, the regulator's optimization problem writes as follows:

$$\min_l C^{\text{prod}}$$

$$s.t.$$

$$C^{prod} = \sum_{i \in I_k} \left( x_i(l) \cdot c_i^{\text{prod}} \right) \tag{3}$$

$$AET = \sum_{i \in I_k} \left( x_i(l) \cdot AEP_i \right)$$

## 2.2 Data and Parameterization

### 2.2.1 Study Region, Energy Target, Energy Yields and Revenue Factors

As study region for our modeling, we consider the German federal State of Saxony with about 4 million inhabitants located in the eastern part of Germany. This study region is chosen because Saxony has a special responsibility for the worldwide protection of the red kite: more than half of the world's red kite population is located in Germany and Saxony hosts about 8% of the total German breeding population (Grüneberg and Karthäuser 2019).

We identify suitable areas in the study region where wind energy could be used potentially. This is achieved by using a GIS approach which excludes all areas in the study region that are not suitable for wind turbines due to physical and legal constraints. For this purpose, as in other studies (Masurowski et al. 2016; Permien and Enevoldsen 2019; Ryberg et al. 2020), various criteria are taken into account, such as terrain slopes, nature protection zones, and safety distances to infrastructure (see for more detail Reutter 2022). In terms of setback distance requirements for settlements and red kite nests, we consider 18 different policy scenarios (described in more detail in Sect. 2.3). The main data input for the GIS analysis is an official geo-database containing information on human settlements, land cover, traffic infrastructure, etc. in the study region (Bundesamt für Kartographie und Geodäsie 2016). The red kite nesting data used for the analysis were provided upon request by the Saxon State Office for Environment, Agriculture and Geology (LfULG).

In a second step, we then use the software MaxPlace to determine concrete potential wind turbine sites $i$ within the identified suitable areas (Masurowski 2016). MaxPlace applies different algorithms on the suitable areas aiming to maximize the number of potential sites within them. For the spacing between neighboring wind turbines, MaxPlace follows DWIA (2003) and presumes elliptical buffer spaces between neighboring wind turbines of five rotor diameters in mean wind direction and three rotor diameters perpendicular to that. As reference turbine we consider the Nordex N131 with a hub height of 134 m, a rotor diameter of 131 m and a nominal power of 3 MW. This turbine is chosen, as it is suitable for medium wind conditions that prevail at most sites in the study region and has been widely installed in Germany in recent years (Quentin and Cremer 2021).

Drawing on wind data (DWD Climate Data Center 2014) and the power curve of the N131 (Nordex Energy GmbH 2013) the possible annual energy production $AEP_i$ is calculated for all potential sites as described, for example, by Eichhorn et al. (2017). As in other studies (e.g., McKenna et al. 2014), typically occurring energy production losses are accounted for by a uniform reduction of all sites' potential energy yields by 15%. We assume an annual energy production target $AET$ of 4.5 TWh/a for the study region. This target refers to the wind power production necessary approximately in the year 2030 to attain long-term decarbonization targets (Reutter 2022).

We cover a total time span of 20 years for all considered revenues and costs as this is a typical lifetime of a wind turbine (Williams et al. 2017). Considering a private annual discount rate of 5%, we therefore assume that the annuity factor $AF$ for summing up the yearly discounted revenues is $AF = 12.5$. As electricity market value $p_i$, we assume uniformly 2.7 ct/kWh which is in the range of the average German onshore wind electricity market prices of the previous years (50Hz Transmission GmbH et al. 2020). With respect to the site-specific factor $s_i$ for the subsidy rate, we assume, according to Par. 36 h of the German Renewable Energies Act (EEG 2017), that it is up to 29% higher at low-wind sites and up to 21% lower at high-wind sites compared to a legally defined reference site. However, it

may be noted that despite the considered subsidy rate uplifting at low-wind sites and down valuing at high-wind sites, the modeled market solutions still primarily lead to the use of the windiest sites so that the assumed site-specific factor $s_i$ has hardly any effect on the modeled social costs.

### 2.2.2 Energy Production Costs and External Costs

The total production costs $C^{\mathrm{prod}}$ of a specific wind turbine allocation are the sum over the investment and discounted operation and maintenance (O&M) costs $c_i^{\mathrm{prod}}$ during the considered 20 years lifetime of all wind turbines that are deployed as part of the allocation. We assume for the modeling that the investment and O&M costs $c_i^{\mathrm{prod}}$ are identical at all sites $i$. For this, we consider total (at a private annual discount rate of 5%) discounted investment and O&M costs of $c_i^{\mathrm{prod}} = €6.31 \cdot 10^6$ per wind turbine (Salomon et al. 2020). To account for uncertainties regarding the future production costs (e.g., due to technical progress, changing commodity prices, and changing interest rates), we vary the assumed cost value by €1 million up and down (i.e., $\pm 16\%$) for a sensitivity analysis.

The external resident costs of a single wind turbine are modeled by a distance decay function considering all households in the study region. Concretely, we use the disamenity cost function described by Lehmann et al. (2021) and Salomon et al. (2020). Figure 1 shows the assumed function for the monthly external resident costs (measured in EUR) accruing to household $h$ from wind turbine $i$. The overall resident costs $C^{\mathrm{res}}$ of a particular allocation of wind turbines are then obtained in two steps. First, the distance function is applied to all wind turbines $i$ and households $h$ in the study region. Second, the obtained monthly costs of all wind turbines are aggregated, discounted (at an annual social discount rate of 3%) and summed up for the 20 years time span of the analysis. To account for uncertainties regarding the actual resident cost levels (e.g., concerning the appropriate monetary
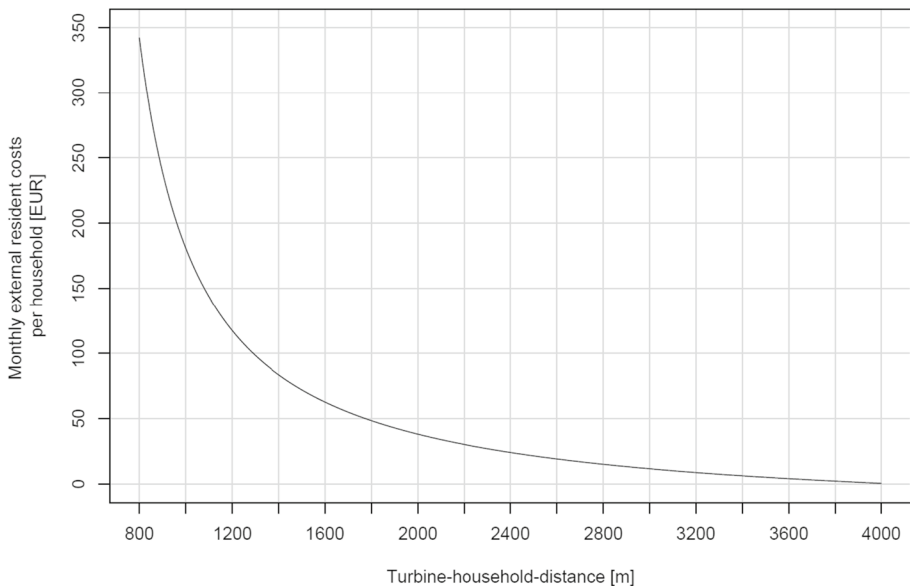


**Fig. 1** Distance function for the monthly external resident costs (in EUR) accruing to household $h$ from wind turbine $i$

valuation of local wind turbine disamenities and possible habituation effects, cf. Krekel and Zerrahn 2017), we multiply the function shown in Fig. 1 for the monthly external resident costs by factors of 0.3 ($-70\%$ compared to the baseline value), 0.8 ($-20\%$ compared to the baseline value), and 1.2 ($+20\%$ compared to the baseline value) for a sensitivity analysis.

For the calculation of external red kite costs associated with collision losses, we proceed in four steps (see for more detail Reutter 2022; Salomon et al. 2020). First, we assume that the impact of a wind turbine $i$ on a red kite $j$ declines exponentially with increasing distance $d$ between the wind turbine and the red kite's nest as shown in Fig. 2. Second, we translate the sum of all these impacts by a linear factor into an expected population loss $L$. Third, we calculate monthly external red kite costs (in EUR) per household depending on the population loss $L$ by applying a quadratic cost function (as shown in Fig. 3). Fourth, we multiply the monthly red kite costs per household with the number of households in our study region (Saxony), $2.17 \times 10^6$, discount the monthly values (at an annual social discount rate of 3%) and sum them up over the 20 years time frame of the analysis to finally obtain the overall red kite costs $C^{rk}$ for a given allocation of wind turbines.

To account for uncertainties regarding the red kite costs, we multiply the assumed function shown in Fig. 3 by factors of 0, 0.8, 1.2, and 2. By doing so we can address uncertainties concerning people's willingness to pay for red kite protection and indirectly also uncertainties concerning the population effect of the modeled impacts. For instance, a factor of 0 can be interpreted as a case where any population decline is not perceived as a loss by people at all and/or where the installed wind turbines do not harm the red kite population at all. In contrast, a factor of 2 can be interpreted as a case where people value a given loss of red kites higher (by 100% ceteris paribus) than assumed by the baseline function—and/or where the red kite population loss induced by a given wind turbine allocation is considerably larger than assumed by the baseline function.

The chosen lower-bound scaling factor for resident costs is only $-70\%$ (and not $-100\%$ as for red kite costs). This is because in contrast to the red kite externality (which might be
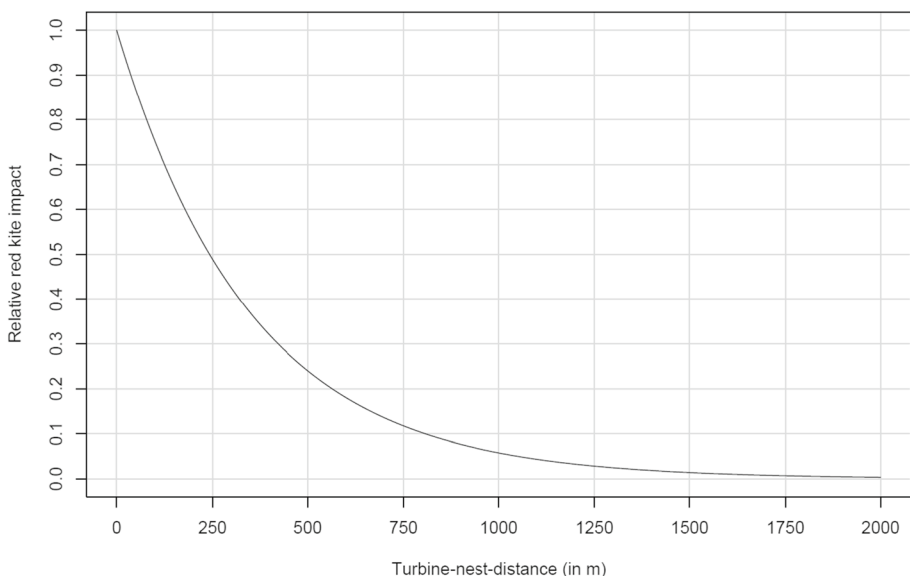


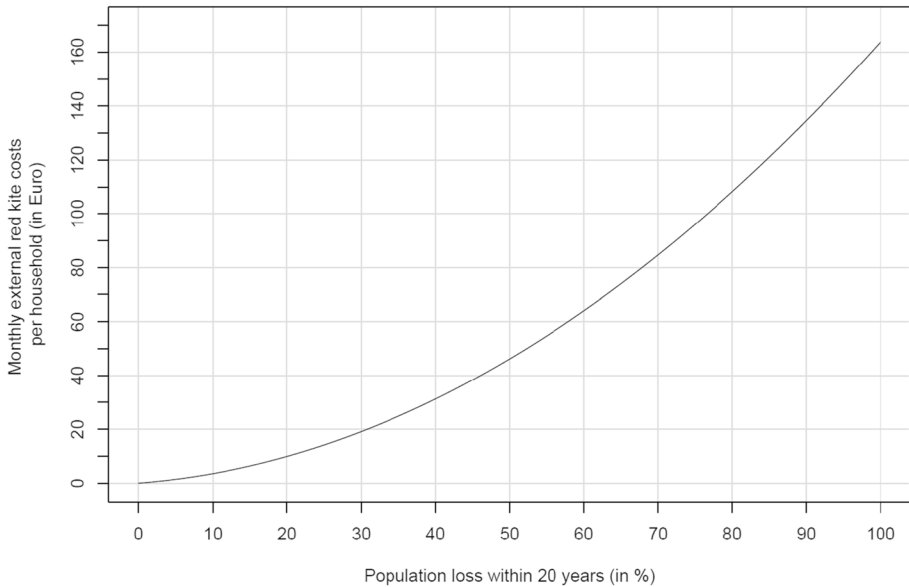**Fig. 2** Distance function for the impact of a wind turbine $i$ on a red kite $j$

**Fig. 3** Monthly external red kite costs per household (in EUR) depending on population loss *L*

resolved in future, for instance, by technological collision avoidance and species protection programs), the resident externality can hardly be zero for any given turbine allocation. The chosen upper-bound scaling factor is set higher for red kite costs (+ 100%) than for resident costs (+ 20%) because the absolute cost levels of both cost types differ in the assumed base case. This allows to analyze the impacts of substantially higher external costs also for the red kite externality, which has, in absolute terms, a much lower cost level than the resident externality in the modeled base case (see Sect. 3.2).

## 2.3 Setback Policy Scenarios

The policy scenarios $I_k$ that we examine are defined by combinations of setback distances for wind turbines to human settlements ('settlement setbacks') and red kite nests ('red kite setbacks'). These setbacks affect the areas which can be used for wind power and hence the potential sites $i$ for wind turbines.

On the national level in Germany the smallest legally possible settlement setback distance for our reference turbine (Nordex N131) is about 800 m, as laid down by the German Immissions Control Act (Eichhorn et al. 2017). Beyond that, the German States (Länder) and partly also regions below the State level can (and do) apply more restrictive settlement setback distances for wind turbines in spatial planning (FA Wind 2022). The most restrictive regulation is set in the South German State of Bavaria. Here, a distance of 10 times the wind turbine's total height is demanded, which for the assumed N131 with a total height of 199.5 m (134 m hub height plus 65.5 m rotor radius) corresponds to nearly 2000 m.

One crucial question in the context of settlement setback distances is how the term settlement is defined. The most far-reaching approach to this is that one settlement setback distance applies uniformly to each individual residential building. The underlying idea of

such a uniform settlement setback distance is to provide an equal level of protection to all residents, regardless of where they live.

In a pre-analysis we found that the energy target of 4.5 TWh/a which we assume for our study region (Saxony) cannot be met with uniform settlement setback distances above approximately 1400 m for all residential buildings. More restrictive uniform setback distances would exclude too many potential sites. Therefore, we consider in terms of uniform settlement setback distances 1400 m as most restrictive policy option. In addition, we consider 800 m as least restrictive possible option as well as two intermediate uniform settlement setback distances of 1000 m and 1200 m, respectively.

In contrast to uniform requirements, an alternative approach that is used in practice is to differentiate settlement setback distances according to whether many people or only a few are potentially affected by a wind turbine. The underlying (utilitarian) idea might be that a higher level of protection should apply when many people are affected by a wind turbine than when only a few people are affected. A possible distinction in this context can be made by differentiating between the outer area and the inner area. As defined in the German Federal Building Code (Par. 35 Baugesetzbuch), the outer area consists of land that is neither within the scope of a qualified development plan nor part of a contiguously built-up district. Thus, for instance, individual farmhouses in the countryside are typically settlement elements in the outer area, while residential buildings in a city are settlement elements in the inner area.

For our modeling, we consider two differentiated settlement setback distance options. First, we consider an extreme case, in which a setback distance of 800 m is assumed to settlement elements in the outer area and a setback distance of 1800 m to settlement areas in the inner area. Combined with a settlement setback distance of 800 m for the outer area, a settlement setback distance of 1800 m for the inner area is (approximately) the largest setback distance which still allows that the assumed energy production target can be met.

As a second differentiated settlement setback distance option, we also assume a combination of a settlement setback distance of 800 m for the outer area and a settlement setback distance of 1600 m for the inner area. This scenario is considered because it is—regarding the inner area—significantly less restrictive than the other differentiated settlement setback scenario considered (1600 m vs. 1800 m) while it is at the same time—regarding the inner area—still significantly more restrictive than the assumed scenario with the most restrictive uniform settlement setback distance (1600 m vs. 1400 m).

Currently, Saxony mandates a settlement setback of 1000 m, which applies not only to the inner area but also to the outer area, if at least five residential buildings are located in close proximity to each other (Par. 84 SächsBO). This implies that the current regulation broadly acts like a uniform minimum settlement setback.

In terms of red kite setback distances, we assume three different options. The first option is a 1500 m setback distance to red kite nests. This option corresponds to the current recommendation of bird conservationists in Germany (Working Group of German State Bird Conservancies 2014). The second option that we assume is a setback distance to red kite nests of 1000 m. This option corresponds to a prior recommendation of German bird conservationists (Working Group of German State Bird Conservancies 2007). As a third option, we assume a total absence of any red kite setback distance (0 m). This would imply that red kite protection is completely ignored in terms of setback distance regulations.

With a new regulation from 2022, potential wind turbine sites closer than 500 m to a red kite nest are strictly not allowed throughout Germany, sites within a radius of 500–1200 m are denied by default unless a habitat potential analysis proves them to be harmless or

protective measures (such as shutdown schedules) are implemented, and sites beyond the 1200 m threshold are permitted by default (Par. 45b BNatSchG). Thus, the uniform red kite setback of 1500 m, which is demanded by the bird conservationists and which we assume as the most restrictive red kite setback in our modeling, lies rather at the upper end of what might be politically imaginable in Germany. Moreover, setting an even more restrictive red kite setback above 1500 m would barely bring any further benefits in terms of species protection. This is because the collision probability decreases only minimally above a turbine-nest distance of 1500 m (cf. Fig. 2).

In combination of the six assumed settlement setback distances and three assumed red kite setback distances, we analyze a total of $K = 18$ different setback distance scenarios for market solutions (Table 2). Table 3 provides an overview on key properties of the scenarios considered. For the social planner case, we start from the potential sites of the scenario in which the potential wind power areas are restricted as little as possible to maximize the allocation optimization potential for the social planner. As mentioned above, the selected reference turbine has to be located at least approximately 800 m away from households due to binding nationwide noise control regulation in Germany. There was no such explicitly legally defined minimum distance for red kite nests in place when we prepared our study. Therefore, for the social planner's case, we assume a minimum distance of 800 m between households and turbines and no minimum distance between red kite nests and turbines (S800_R0 scenario).

## 3 Results

### 3.1 Results with Basic Assumptions

Given the same potential sites $i$ (resulting from a settlement setback of 800 m and 0 m red kite setback), the modeled investment decisions of a social planner and of the market solution differ considerably (Fig. 4). In the modeled market solution, the wind turbines are clustered almost entirely in the south-west of Saxony (Erzgebirge region) as the best wind conditions prevail there. In the social planner case, on the other hand, the wind turbines are more dispersed and cluster partially in the north-east of Saxony (Oberlausitz region), where medium wind conditions prevail, but population density is low and no red kite hotspot exists. Only 154 of the potential sites are used in both the social planner case and the market solution, while 346 potential sites are exclusively used in the social planner case

**Table 2** Policy scenarios $I_k$ considered in the analysis. Each policy is defined by a combination of a settlement setback distance option (S) and a red kite setback distance option (R)

| Settlement setback (S) | Red kite setback (R) | | |
|---|---|---|---|
| (uniform or differentiated for outer/inner area) | 0 m | 1000 m | 1500 m |
| 800 m | S800_R0 | S800_R1000 | S800_R1500 |
| 1000 m | S1000_R0 | S1000_R1000 | S1000_R1500 |
| 1200 m | S1200_R0 | S1200_R1000 | S1200_R1500 |
| 1400 m | S1400_R0 | S1400_R1000 | S1400_R1500 |
| 800 m/1600 m | S800/1600_R0 | S800/1600_R1000 | S800/1600_R1500 |
| 800 m/1800 m | S800/1800_R0 | S800/1800_R1000 | S800/1800_R1500 |

**Table 3** Key properties of the assumed policy scenarios $I_k$

| Policy scenario | Total suitable area (km$^2$) | Share of suitable area in the total land area (%) | Number of potential sites | Total annual energy production potential (TWh/a) |
|---|---|---|---|---|
| S800_R0 | 862 | 4.7 | 4117 | 33.1 |
| S800_R1000 | 740 | 4.0 | 3569 | 28.7 |
| S800_R1500 | 638 | 3.5 | 3081 | 24.8 |
| S1000_R0 | 482 | 2.6 | 2324 | 18.4 |
| S1000_R1000 | 427 | 2.3 | 2053 | 16.2 |
| S1000_R1500 | 380 | 2.1 | 1829 | 14.5 |
| S1200_R0 | 271 | 1.5 | 1283 | 10.0 |
| S1200_R1000 | 246 | 1.3 | 1171 | 9.1 |
| S1200_R1500 | 226 | 1.2 | 1073 | 8.4 |
| S1400_R0 | 155 | 0.8 | 748 | 5.7 |
| S1400_R1000 | 145 | 0.8 | 690 | 5.2 |
| S1400_R1500 | 136 | 0.7 | 652 | 5.0 |
| S800/1600_R0 | 203 | 1.1 | 923 | 7.2 |
| S800/1600_R1000 | 193 | 1.0 | 880 | 6.9 |
| S800/1600_R1500 | 182 | 1.0 | 823 | 6.4 |
| S800/1800_R0 | 148 | 0.8 | 670 | 6.2 |
| S800/1800_R1000 | 143 | 0.8 | 642 | 5.0 |
| S800/1800_R1500 | 137 | 0.7 | 616 | 4.8 |
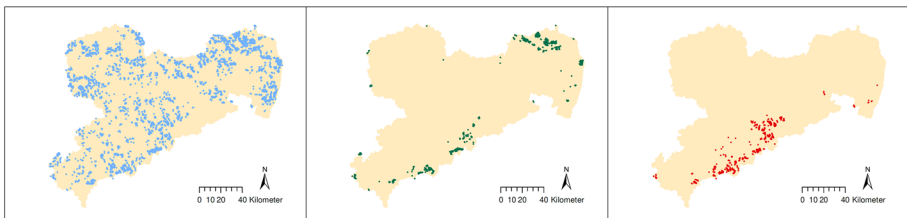


**Fig. 4** Potential sites (**a**), chosen sites in the social planner case (**b**), and chosen sites in the market solution (**c**), each based on the potential sites of the S800_R0 setback distance scenario

and 251 potential sites are exclusively used in the market solution. Therefore, the social costs of the two allocations also differ substantially from each other (Fig. 5). They are about 59% higher in the market solution than in the social planner case.

Moreover, the modeling results displayed in Fig. 5 also show that the optimal cost level of the social planner case cannot be achieved with any of the assumed setback distance scenarios in the market case. With the assumed differentiated settlement setback distances, the modeled social costs are at least 20% higher than in the social planner case. And with the assumed uniform settlement setback distances, the modeled social costs are even at least 41% higher than in the social planner case.

Three partial effects determine the social costs of setbacks. First, the production cost effect of more restrictive setbacks is relevant. When sites with good wind conditions get excluded due to more restrictive setbacks, eventually more turbines are required to achieve a certain energy production (quantity effect) and total production costs will therefore
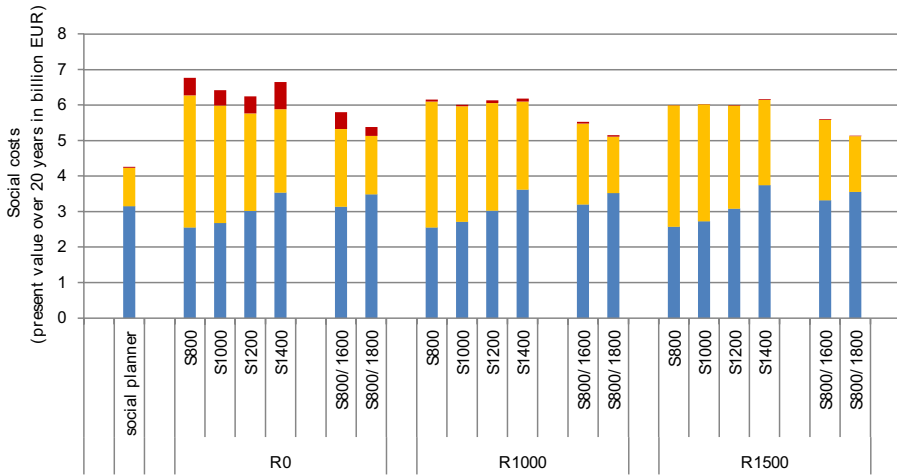
**Fig. 5** Social costs as modeled (with the baseline assumptions) for the social planner case and market solutions for the assumed setback distances scenarios

increase. Second, the effects of more restrictive setbacks on the external costs that are addressed by the respective setbacks need to be considered. This concerns the effects of more restrictive settlement setback distances on the resident costs and of more restrictive red kite setback distances on the red kite costs, respectively. We label these effects as own-cost effects. Third, it needs to be considered, how more restrictive setbacks to address one externality (i.e., for settlements or red kites, respectively) will affect the extent of the other externality. We label this as cross-cost effects.

With respect to the considered uniform settlement setbacks, no clear social cost trend of more restrictive setbacks is visible (see social cost values in Fig. 5 in each considered red kite setback option, respectively). The own-cost effects of more restrictive uniform settlement setbacks are throughout positive (i.e., cost-reducing; see yellow bars in Fig. 5). At the same time, a negative production cost effect (i.e., production cost increases) can be observed in the modeling results as the uniform settlement setbacks become more restrictive (see blue bars in Fig. 5). The cross-cost effects of more restrictive uniform settlement setbacks on red kite costs are ambiguous and weak (see red bars in Fig. 5). Quantitatively, none of the three sub-effects dominates in the modeling results across all considered increases in uniform settlement setbacks, so that there is no clear social cost trend of extending uniform settlement setbacks. Comparing in pairs all modeling results for the uniform settlement setbacks distances for each assumed red kite setback distance, we find that the modeled social costs are lower in 10 cases and higher in 8 cases with the respective more restrictive uniform settlement setback distance than with the respective less restrictive one.

In terms of both considered differentiated settlement setback distances (for inner and outer areas), the modeling results displayed in Fig. 5 show a clear social cost advantage compared to the uniform settlement setback distances. The modeled social costs are at least 14% lower in the case of the considered S800/1800 option and at least 7% lower in the case of the S800/1600 option than with all modeled uniform policies. The comparatively favorable overall social cost effect of both considered differentiated settlement setback options results from two partial effects. With the differentiated settlement setbacks, the resident

costs (see yellow bars in Fig. 5) can be limited much better than with all assumed uniform policies. At the same time, the increase in production costs (see blue bars in Fig. 5) is not overly large and does not exceed the highest production cost effects that can be observed with the uniform settlement setback distances.

Regarding the red kite setbacks, a clear social cost advantage of both 1000 m and 1500 m over 0 m can be observed. This can be seen looking at the respective social cost values of each considered settlement setback option (Fig. 5). The own-cost effects of the considered red kite setbacks are throughout positive (i.e., cost-reducing; see red bars in Fig. 5). Contrary to this are negative production cost effects (i.e., production cost increases) that are associated with the assumed red kite setbacks (see blue bars in Fig. 5). The cross-cost effects of the red kite setbacks on resident costs are ambiguous and weak (see yellow bars in Fig. 5). However, the positive own-cost effect clearly dominates in quantitative terms and leads to the observable social cost advantage of both assumed red kite setbacks compared to a situation completely without respective regulations. With the assumed red kite setbacks, the modeled social costs are between 2% and 11% lower than without a red kite setback, depending on the assumed settlement setbacks.

In the comparison of the red kite setback distances of 1000 m and 1500 m, no clear social cost trend can be identified in the modeling results (see the respective social cost values in Fig. 5 of all considered settlement setback distance options). Although the directions of the single cost effects of 1500 m instead of 1000 m red kite setbacks are as described before (i.e., negative production cost effect, positive own-cost effect, weak and ambiguous cross-cost effect), none of these effects clearly dominates quantitatively when 1500 m and 1000 m red kite setbacks are compared with each other. Depending on the assumed settlement setback option, a red kite setback of 1500 m instead of 1000 m results in either a relatively small reduction in social costs of up to 2% or in a relatively small increase in social costs of up to 1% according to the modeling results.

## 3.2 Sensitivity Analysis

Next, we turn to the modeling results obtained for the sensitivity analysis with the assumed model parameter variations for the investment and O&M costs, resident cost function, and red kite cost function (see Fig. 6 in the Appendix). First, unsurprisingly, it can be observed that the higher the assumed investment and O&M costs per turbine and the lower the assumed general external cost levels get, the more similar becomes the modeled market solution to the social planner case. Nevertheless, for all assumed parameter variations, the social costs of the market solutions modeled with all assumed setback scenarios are still at least 10% higher than the social costs of the modeled social planner cases.

The ambiguous social cost trend of more restrictive uniform setback distances observed for the base parameter assumptions remains ambiguous with all assumed model parameter variations. The described clear social cost advantage of the differentiated settlement setback distances observed for the base case can also be observed with almost all assumed model parameter variations. Only in the considered case of a very low general resident cost level (− 70% compared to the baseline assumption), allocations with lower social costs can be achieved with non-restrictive uniform settlement setback distances than with the assumed differentiated settlement setback distances. The reason for this is that, in absolute terms, reductions in resident costs achievable with the differentiated settlement setback

distances then do no longer exceed the simultaneous increases in production costs due to quantity effects.

The observed social cost advantage of both 1000 m and 1500 m over 0 m red kite setback distance persists also with almost all assumed parameter variations. Only if it is assumed that the general red kite cost level is very low or, as assumed for the sensitivity analysis, no red kite costs can exist at all (modeled by red kite cost factor of 0), red kite setbacks of 1500 m and 1000 m can be disadvantageous compared to no red kite setbacks in terms of social costs. This is because red kite setbacks then no longer have red kite cost benefits, which are 0 anyway, while there still occur quantity effects of the setbacks leading to higher production costs and in turn also to higher social costs. Besides, the social cost effect ambiguity of a 1500 m instead of a 1000 m red kite setback observed for the base case can also be observed for all assumed parameter variations—in the zero red kite cost factor case due to partially positive cross-cost effects compensating the occurring quantity effects.

## 4 Discussion

Next, we first discuss the modeling results with respect to our four research questions, and then also discuss limitations and uncertainties of the modeling approach. The first research question was: how close can a social planner case be achieved by different setback distance options? On this question, it can be observed that the social planner case is clearly missed with all of our assumed setback distance requirements: with the assumed uniform settlement setback distances by at least 41% and with the assumed differentiated settlement setback distances by at least 20%. Here, fundamental efficiency deficits of setback distance regulations become apparent which are typical for basically binary and uniformly operating command-and-control like instruments (Goulder and Parry 2008). The first reason is that binary and uniformly operating regulations are blind to gradual differences in the addressed environmental effects of different sources, which in the case of setbacks is reflected in the fact that respectively all sites within and outside the specified setback distances are treated the same. The second reason is that command-and-control approaches are typically blind to emitters' characteristics that are not addressed by the regulation, which in the case of setbacks for wind turbines is reflected in the fact that they do not account for site characteristics such as local wind conditions and externalities that are not targeted by the respective setbacks. To our knowledge, the present study is the first one examining the social cost deficits of setback distances for wind turbines in a market environment compared to the theoretical first-best wind turbine allocation chosen by a social planner.

Secondly, we asked if the social cost effects of setbacks depend on the externalities they address. Our results show that uniform settlement setbacks exceeding the legal minimum requirements do not necessarily reduce social costs. In contrast, the assumed uniform red kite setbacks do lead to clear reductions in social costs (given the assumption that wind turbines can potentially imply some external resident costs and red kite costs; see sensitivity analysis in Sect. 3.2). We identify two reasons for that. The first reason is that red kite setbacks can address the red kite externality very precisely, whereas uniform settlement setbacks can address resident costs only with comparatively little precision. This is because both setbacks by design do not take into account the numbers of affected individuals, disregarding spatial heterogeneity in this respect. In terms of own-cost effects, this is more detrimental for settlement setbacks than for red kite setbacks, since the number of residents between different settlements varies much more than the number of red kites at different

breeding grounds. The second reason for the differing social cost effects of the setbacks are differences in their land exclusion behavior which is relevant for production cost effects and cross-cost effects. Red kite setbacks do not excessively increase production costs and resident costs because the total spatial incidence of red kites is rather small. Mandating setback distances around red kite nests thus restricts relatively little land area for wind power deployment in total. In contrast, the respective potential trade-offs of uniform settlement setbacks are comparatively large, since settlements cover much more space than breeding sites. Implementing setback distances to settlements thus restricts available sites for wind power deployment much more. Hence, taken together, our analysis generally indicates that a positive social cost effect of setbacks can be rather expected for externalities that affect comparatively few individuals (e.g., red kites) with low heterogeneity in local incidence (as it is the case for red kite nests). Vice versa, setbacks addressing externalities that affect comparatively many individuals (e.g., residents) with high heterogeneity in local incidence (as it is the case between larger and smaller settlements) may generally have lower chances of a positive social cost effect. These insights may also provide some first guidance for assessing the cost-effectiveness of setbacks for further externalities. As far as we know, to date only the study by Salomon et al. (2020) also examines social cost effects of setbacks for multiple externalities considering also red kites and residents. While they do not explicitly discuss their modeling results in terms of the perspective considered here, their presented modeling results do fit to the finding elaborated above.

Thirdly, we were interested in understanding how the restrictiveness of setback distances affects the social costs of market solutions. Looking at the results for the considered uniform settlement and red kite setback distances, it is not the case that extending setback distances necessarily leads to lower social costs. Partially, respective social cost reductions can be observed, but partially more restrictive setbacks also lead to higher social costs. Findings from Drechsler et al. (2011, 2017) considering social planner cases and from Salomon et al. (2020) considering market cases also indicate that more restrictive uniform setbacks for wind turbines are not necessarily beneficial from a social cost perspective. With regard to the two assumed differentiated settlement setback options in our modeling, the social costs of the more restrictive option are lower than that of the less restrictive option. However, it is hardly possible to recognize a general trend here since only two options are compared. With respect to the partial cost effects of more restrictive setbacks, the modeling results for our study region first show that production-cost effects (quantity effects) play a relevant role for the changes in social costs: if, as a result of more restrictive setbacks, high-yield sites can no longer be used and therefore lower-yield sites have to be used, production costs can increase substantially because more turbines are then needed to achieve a targeted energy production. However, this is contrasted by positive own-cost effects (i.e., decreases in the respective external costs addressed by the setbacks) which we observe in the modeling results when setbacks are extended. These effects are also relevant in their magnitude for the changes in social costs. Theoretically possible negative own-cost effects that may occur as a result of quantity effects (i.e., of a higher number of installed turbines when less productive sites need to be used) are not seen in our modeling results. This means that with regard to the two addressed externalities, the modeled own-cost benefits of additional exclusions due to extended setbacks are always higher than the own-cost disadvantages that can occur due to an increase in installed turbines when setbacks are extended. This could possibly change if, for example, forest areas were generally excluded as potential wind turbine sites (see below). In this case, implementing more restrictive settlement setbacks and red kite setbacks would no longer shift deployment to forest sites that may exhibit low residential and red kite externalities because neither humans nor red

kites typically live deep in forests (Heuck et al. 2013). Cross-cost effects (i.e., changes in the respective external costs not addressed by the setbacks) do not play a relevant role in our modeling results for the social cost effects associated with setback distance expansions because the effects are ambiguous in their directions and weak in their magnitude. This is because there are no clear spatial correlations between settlement setbacks and red kite occurrences and between red kite setbacks and household occurrences in our study region. At least in our model setting, this does not validate concerns raised by environmental NGOs that more restrictive settlement setbacks have undesirable side effects for the protection of species like the red kite since the pressure to use red kite-sensitive sites could increase with more restrictive settlement setbacks (BUND et al. 2020).

The fourth question that we raised was whether spatial differentiation may help to improve cost-effectiveness of setback distances. To our knowledge, the present study is the first one exploring social cost effects of differentiated settlement setbacks. Our modeling results suggest that differentiated settlement setbacks (with more restrictive setbacks for the inner area and less restrictive setbacks for the outer area) can help to attain a wind energy production target at lower social costs than uniform settlement setbacks. This is because spatial differentiation between inner and outer areas at least partially accounts for the actual number of residents affected by wind turbines. Hence, differentiated setback distances mitigate external resident costs more cost-effectively than uniform setbacks. At the same time, the non-restrictive requirements for the outer area only exclude comparatively few potential sites preventing larger cross-cost and production cost effects.

As shown in the sensitivity analysis, the social cost advantage of differentiated setbacks may disappear if a generally low potential external resident cost level is supposed (see Sect. 3.2). Yet, it seems to be rather unlikely that we highly overestimate the external resident cost level in our modeling, since the study by von Möllendorff and Welsch (2017) suggests that the external costs for residents living in the vicinity of wind turbines might be even higher than what is assumed for the calibration of the used external resident cost function drawing on estimates by Krekel and Zerrahn (2017). In this case, the social cost advantage of differentiated settlement setbacks would presumably be even more pronounced than our modeling indicates.

It may be noted, however, that restrictive uniform setbacks might have an additional value in themselves, which is not considered in our model, because they ensure a certain minimum protection for all individuals. Results of choice experiments suggest that there indeed might be general preferences of people for more restrictive setbacks in themselves (Meyerhoff et al. 2010; Drechsler et al. 2017). Thus, regardless of whether individuals are actually affected in a particular way by a turbine, more restrictive setbacks could have additional benefits that are not accounted for in our modeling. While this does not directly change the social costs as we have modeled them, it may be that more restrictive uniform setbacks can thus be viewed as more beneficial than our modeling results suggest.

In general, there are some more uncertainties and limitations that need to be considered in the interpretation of our modeling results. Two issues in this regard are that we are only looking at a rather short-term time horizon with the assumed energy production target for the reference year 2030, and that we are possibly overestimating the available pool of potential sites. Several reasons can be given why the potential sites might be overestimated.

First, in contrast to the practice in our study region, we assume that forests are in principle eligible for wind energy. This is already legally possible in some other regions in Germany (Bunzel et al. 2019). Our assumption to not categorically exclude forests is also in line with a recent ruling by the German Federal Constitutional Court that forests must not

be excluded per se for wind turbines (BVerfG 2022). We also include forest areas because otherwise, there would not be enough potential sites given the assumed uniform settlement setbacks of 1200 m and 1400 m to achieve the assumed energy production target. In other words, if all forests were excluded for wind energy use in Saxony, the assumed yearly energy production target of 4.5 TWh could not be attained given a uniform settlement setback of about 1200 m or more (irrespective of the selected red kite setback). Partially, more than half of the potential sites identified for the setback scenarios are located in forests. The proportion of forest sites is increasing with more restrictive settlement setbacks and red kite setbacks. This illustrates that there are additional land use trade-offs that need to be considered in the context of setback distances.

Another reason for an overestimation of the potential sites may be our assumption that all areas which we identify as suitable for wind turbines can actually be used. This ignores the fact that in some cases it may not be possible to build wind turbines on identified potential areas, for example because there are species protection conflicts with wind energy-sensitive birds other than the red kite, or because landowners are just not willing to make these areas available for wind turbines.

Both with more ambitious long-term energy production targets and with fewer actually available potential sites, the options for choosing which of the potential sites (not) to use decline. The social costs that result from the market solution with setbacks are then probably higher overall, but at the same time they are probably also closer to the social planner case, since the social planner case is then also associated with higher social costs due to the overall decreased degree of freedom for choosing sites. This generally suggests that in practice, and especially in the long-term, the social cost effects of setbacks may be less politically relevant than our modeling suggests, simply because no particularly restrictive setbacks can be set anyway if certain energy production targets are to be achieved. Simultaneously, this also implies that over time the shadow price of setbacks—in terms of unattainable expansion targets—will be very high.

Basic uncertainties in the performed modeling also concern the shapes of the assumed cost functions and the role of non-distance variables, such as the terrain-dependent visibility of wind turbines, or implications of heterogenous preferences (Betakova et al. 2015; Sunak and Madlener 2016). For our sensitivity analyses, we varied the levels of the assumed cost functions, but not their general shapes. However, analyses by Lehmann et al. (2021) show that also if a linear distance decay function is assumed instead of a hyperbolic resident cost function, local disamenities exhibit high spatial variations due to high differences in the number of affected residents at potential sites. Therefore, it may well be that our findings are fairly robust against uncertainties concerning the shapes of the assumed cost functions.

Another limitation of our modeling is that we only consider production costs and two externalities for our social cost analysis. We could only speculate about the effect of settlement and red kite setbacks on other environmental external costs (e.g., impacts on bats) and other energy system costs (e.g., balancing costs) that are not considered in our social cost analysis. Theoretically, positive as well as negative cost effects with respect to further cost types are possible, depending on the prevailing spatial correlations. However, the observed production cost and own-cost effects, which have a stronger impact on the social cost effects of setbacks in our analysis than the cross-cost effects considered, would not change even if further cost types implying further cross-cost effects were taken into account. Therefore, it is well possible that our findings do not strongly depend on the modeling limitation of only considering the three selected cost types.

Furthermore, concerning production costs, it may be noted that we do not consider network connection costs in our modeling. Grid connection costs can potentially increase the actual energy production costs of a wind turbine substantially (McKenna et al. 2021). Although we have not explicitly modeled this, we have at least implicitly included such additional costs in our sensitivity analysis by varying investment and O&M costs per turbine (see Sect. 3.2). Our sensitivity analysis suggests that our general findings on the cost effects of the examined setback distances are fairly robust, even if the assumed amount of production costs is substantially increased (e.g., due to grid connection costs). However, future studies could also integrate (spatially heterogeneous) grid connection costs into the presented modeling approach to also explicitly investigate their relevance for the studied cost effects of setback distances. The same could also be done with respect to potentially spatially heterogeneous investment and O&M costs, which may differ, for example, between sites on farmland and in forests. In this context, it could also be considered how several different types of turbines could be included in the model instead of only using one single reference turbine for the optimizations. This would not only affect the site-specific investment and O&M costs, but also the potential energy yields and could thus lead to different turbine allocations. However, it is questionable whether this would essentially change the fundamental results of the analysis compared to the simplifying assumption of only one reference turbine. This is because, firstly, the assumed reference turbine is basically suitable for the wind conditions at all sites in the study region (DIBt 2022; Nordex Energy GmbH). And secondly, the ranking of sites by production costs would in general not change (though heterogeneity among sites would decrease) if different types of turbines were assumed. Therefore, we expect actual differences in the modeled allocations and production costs to be small if more turbine types were included.

In addition, different turbine types would not matter for the modeled external costs since we are modeling them purely based on distance functions. Alternatively one could consider that larger turbines might increase impacts on red kites (due to larger surfaces for collisions) and on residents (due to increased audio-visual impressions) (Brennan and van Rensburg 2020). However, substantially varying turbine heights should occur mainly on spatial scales larger than the case study region, with more pronounced spatial differences in wind speeds.

Moreover, we assume that external costs and energy production costs of a wind turbine at a given site are independent of how many wind turbines are installed nearby. However, in reality, marginal external and private costs of a turbine may decrease with an increasing number of turbines in their close vicinity. Regarding investment and O&M costs, local economies of scale might exist. In the case of red kites, there might be local saturations in collision risks. With respect to external costs for residents, though the literature is inconclusive on that (Oehlmann and Meyerhoff 2017), decreasing visual impacts of additional turbines may explain a respective negative cumulative cost effect (Betakova et al. 2015; Dröes and Koster 2021). Therefore, local clusters of wind turbines may have cost advantages. In our model framework, factoring in all the cumulative cost effects mentioned would tend to result in increased clustering of turbines both in the social planner case, where total social costs are minimized, as well as in the modeled market solution, where production costs are minimized. However, the possibility of clustering turbines decreases when setbacks are getting more restrictive because the freedom to choose sites then becomes smaller. Therefore, due to negative cumulative effects, the more restrictive setback scenarios analyzed might actually lead to higher costs of all three types considered than our modeling

indicates. Future studies may seek to estimate quantitatively the extent to which this could potentially alter the general findings of our analysis.

A further limitation of our analysis is that it only covers the study region under consideration. The strength and partly also the signs of the three considered cost effects may strongly depend on specific spatial conditions and related spatial correlations. However, the basic characteristics of setbacks that, as argued, are key for the modeled production cost and own-cost effects, and thereby for our findings, also exist in other spatial contexts. Therefore, a particularly relevant question with respect to other geographical areas could be whether there are also no clear cross-cost effects in other areas with respect to settlement and red kite setbacks and the two associated externalities. The fact that we do not find a clear direction in the cross-cost effects could be due to rather special spatial conditions in our study region, Saxony. Indeed, analyses for Germany as a whole suggest that there are in fact clear spatial trade-offs between residents' and bird conservation interests (Tafarte and Lehmann 2023). Therefore, at least our results with respect to the cross-cost effects should not be generalized spatially without further analysis.

## 5 Conclusion

Using a spatially explicit modeling approach, we studied the question how different options for setback distances for wind turbines affect the social costs of wind power generation in a setting with multiple externalities. For this purpose, we considered the impacts of different settlement setbacks and red kite nest setbacks on energy production costs and on external costs for both residents and red kite impacts. We applied our model for the German State of Saxony and a given annual wind energy production target for the year 2030.

Our analysis shows that introducing setback distances to red kite nests substantially lowers the social costs of wind power generation. In all scenarios with red kite setbacks, the modeled social costs are lower than without red kite setbacks. However, in a comparison of a red kite setback distance of 1000 m and a red kite setback distance of 1500 m, the modeling for Saxony does not show a relative social cost advantage in favor of one of the named two setback options. According to our modeling results for Saxony, the question of the preferred level for a red kite setback distance therefore includes a question of political priorities, whether more weight should be given to better red kite protection or to lower energy production costs. Thus, the modeling results generally suggest that this question of priorities needs to be explicitly negotiated when red kite setback distances are discussed politically.

In the case of uniform settlement setback distances, the modeling results do not show a clear direction in the social cost effect of more restrictive setbacks. Thus, our modeling results for Saxony indicate that the matter of whether settlement setbacks should be made more restrictive or less restrictive involves a political priority decision to put greater weight on either better protection of residents or lower energy production costs. Hence, our modeling results generally suggest that this prioritization should be explicitly negotiated in the policy discussion on settlement setbacks. Concerning the political discussion on settlement setbacks, our modeling results also show that spatially differentiated settlement setback distances, even if they are only differentiated in two steps according to the size of settlement structures, can be clearly superior to uniform settlement setback distances in terms of

social costs. This suggests that such approaches should be pursued when setbacks are to be used.

However, our modeling also indicates, in line with the literature on typically binary and uniformly working command-and-control instruments, that the social cost optimum of a social planner case will be missed clearly with all assumed red kite and settlement setbacks, even in the case of some spatial differentiation of the setbacks. Yet, in this context, our modeling also suggests that the social optimum deviations of setbacks are potentially larger for such externalities that affect in total many individuals and very different numbers of individuals per source (as seen for settlement setbacks) than for externalities that affect in total few individuals and similar numbers of individuals per source (as seen for red kite setbacks).

With regard to discussions about possible undesirable side effects of more restrictive settlement setbacks on nature conservation and species protection, our modeling results show that more restrictive settlement setbacks can increase the pressure on protected species (such as the red kite) but can also reduce it, so that a per se negative effect cannot be supposed.

To address the discussed uncertainties and limitations of the modeling, future research could vary the assumed energy production target and assumptions for identifying potential sites. Moreover, the shapes of the assumed cost functions could be varied and non-distance dependent variables and varying assumptions for cumulative effects could be included into the modeling. Furthermore, additional system costs and wind energy externalities could be added to the modeling as well as additional setback regulations, for example, for further bird species. In subsequent studies, also other spatial areas such as Germany as a whole or other countries could be examined.

Another avenue for future research is to also model and analyze possible economic instruments providing siting incentives. First analyses on tax approaches already exist (Grimsrud et al. 2021). A next step might be to not only assume ideal set-ups of such incentives but also imperfectly shaped incentives due to possible real-world information deficits of regulators in practice (Reutter 2022). Respective economic incentive approaches can then be compared with setback regulations and instrument mixes of both approaches can also be explored.
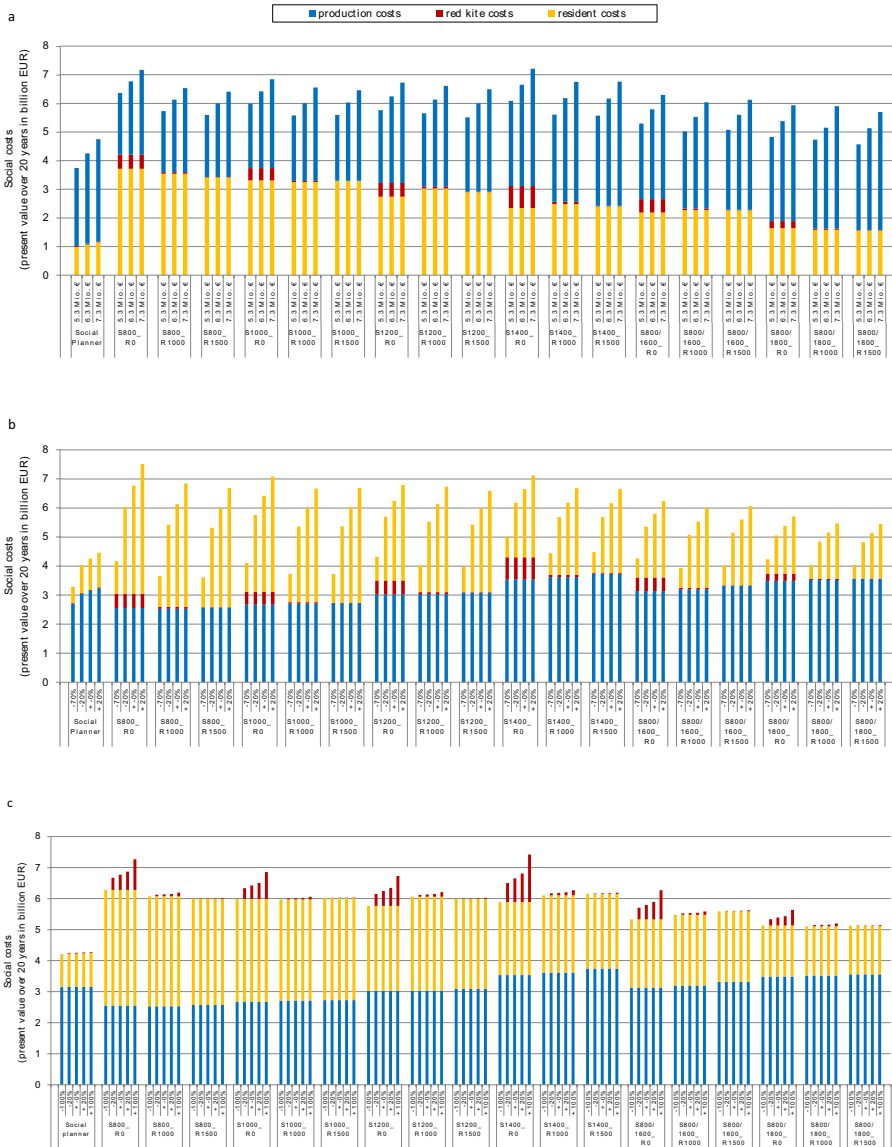
# Appendix

See Fig. 6.

**Fig. 6** Social costs as modeled with the sensitivity analysis assumptions for the social planner case and market solutions for the assumed setback policy scenarios (panel **a** variation of investment and O&M costs by ± €1 million; panel **b** variation of resident cost function by − 70%, − 20%, + 20%; panel **c** variation of red kite cost function by − 100%, − 20%, + 20%, + 100%)

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