Salomon, H., **Drechsler, M.**, **Reutter, F.** (2020):
Minimum distances for wind turbines: A robustness analysis of policies for a sustainable wind power deployment
Energy Policy **140** , art. 111431

http://dx.doi.org/10.1016/j.enpol.2020.111431

Minimum distances for wind turbines: a robustness analysis of policies for a sustainable wind power deployment

Hannes Salomon, Helmholtz Centre for Environmental Research – UFZ

Martin Drechsler*, Helmholtz Centre for Environmental Research – UFZ, and Brandenburg University of Technology Cottbus-Senftenberg

Felix Reutter, Helmholtz Centre for Environmental Research – UFZ

(*) Corresponding author: Helmholtz Centre for Environmental Research – UFZ, Department of Ecological Modelling, Permoserstr. 15, 04318 Leipzig, Germany, martin.drechsler@ufz.de.

Abstract

The deployment of wind power is a major contribution to the decarbonisation of societies. Yet, wind turbines can cause some negative externalities to humans and nature. These largely depend on the spatial allocation of the wind turbines. Therefore the question is how to design policies that minimise the social costs of wind power generation which are defined as the sum of production and external costs. An instrument which is used in Germany and elsewhere to control the externalities of wind turbines is the prescription of minimum distances to sensitive landscape features like human settlements and bird nests. The efficient (i.e. minimising social costs) magnitude of such minimum distances, however, depends on uncertain parameters. We apply a robustness analysis to an ecological-economic model for the assessment of the social costs of wind power deployment in order to identify policies, each defined by certain minimum distances, which are favourable within wide ranges of various uncertain parameters. In the examined study region in Germany, rather large minimum distances to nests of the red kite (a raptor bird) and moderate minimum distances to settlements turn out to be most favourable taken the considered uncertainties into account.

Keywords

Externalities, spatial allocation, social costs, parameter uncertainty

Highlights

- The social cost assessment of wind power deployment policies depends on assumptions
- We assess the robustness of deployment policies to various uncertain parameters
- As policies we consider different minimum distance prescriptions for wind turbines
- Concerning human settlements, moderate minimum distances lead to best results
- Concerning red kite nests, rather large minimum distances lead to best results

1 Introduction

Climate change is one of the most pressing issues humankind is currently facing. In 2015, most countries of the world signed the Paris Agreement to keep the increase in global average temperature to well below 2 °C above pre-industrial levels (UN 2015). For this the emissions of greenhouse gases must be reduced drastically. Germany, for instance, committed itself to a greenhouse gas reduction by 2030 of at least 55% compared to the level in 1990 (BMU 2016). In the electricity sector the main strategy to achieve this goal is the substantial deployment of renewable energy technologies like photovoltaics (PV) and wind turbines which have an excellent CO_2 balance (Sovacool et al. 2016).

In 2018, the share of renewables in Germany's gross electricity consumption was 38% (UBA 2019). Onshore wind power is the dominating source here, with about 41% of Germany's renewable electricity generated by onshore wind turbines in 2018 (ibid.). Between 2000 and 2018 the installed wind power capacity in Germany has multiplied from about 6 GW to about 53 GW (BWE 2019). In 2018 already about 29,000 wind turbines have been operating in Germany (Deutsche WindGuard 2019). According to the German Renewable Energy Sources Act (EEG 2017) further high increases in wind power generation are planned for the coming years and decades.

However, despite its undeniable advantages, wind power can also have a number of negative effects on the environment. These effects include noise, impairment of landscape aesthetics and impacts on the biodiversity, especially regarding bats and birds that collide with wind turbines (Dai et al. 2015). With rising numbers of installed wind turbines these conflicts are getting more and more pronounced and call for increased attention.

In order to control these effects in the further deployment of wind power, German federal, state, and regional authorities have established a number of regulations and planning approaches. Next to safety regulations like the exclusion of wind turbines from the vicinity of roads, airports and other infrastructure, these include the German Immission Control Act that limits the tolerable noise immissions in human settlements (TA Lärm 1998), and thus implies certain minimum distances for wind turbines to settlements, and the German Federal Conservation Act (BNatSchG 2009) that forbids the installation of wind turbines in nature protection zones.

Despite these regulations, wind turbines can still have negative effects on the environment, because even if their noise levels comply with the regulations they may still emit a sound level that is perceived as disturbing by residents and cause visual disamenities, and even if placed outside nature protection zones they may still cause fatal collisions of birds. To reduce these negative effects, many German federal states have specified minimum distances for wind turbines to human settlements going beyond the standards of the German Immission Control Act (FA Wind 2019a). Recommendations for minimum distances for wind turbines to the habitats and breeding sites of sensitive bird species have been formulated by ornithological experts in the so-called 'Helgoland paper' (Working Group of German State Bird Conservancies 2007) and updated in 2014 (Working Group of German State Bird Conservancies 2014). They are widely applied in planning practice (Ruß 2016).

The prescription of minimum distances for wind turbines to landscape features like human settlements or bird nests involves difficult trade-offs. Smaller minimum distances might lead to an increase of the external effects while larger minimum distances might lead to exclusions of sites with good wind conditions, which can increase the electricity production costs and reduce the total amount of electricity that can be generated (and thereby even threaten the achievement of a given electricity production target).

Such trade-offs can be explored by multi-criteria approaches like the ones by Eichhorn et al. (2017) and Eichhorn et al. (2019) or approaches rooted in environmental economics. The latter approach has been applied by Drechsler et al. (2011) to the planning region of West Saxony in Germany. The authors determined cost-effective minimum distances for wind turbines to human settlements and nests of the red kite, a collision-endangered protected bird of prey, that minimise the social costs associated with a given regional electricity production target. Social costs comprised the electricity production costs, i.e. installation plus operation and maintenance (O&M) costs of wind turbines, as well as external costs which affect social welfare but are usually ignored by economic actors. External costs measured the impacts of wind turbines on humans and red kites on a monetary scale as functions of minimum distances between wind turbines and human settlements and red kite nests. The monetary cost functions for these impacts were obtained through a choice experiment (Meyerhoff et al. 2010).

Based on the approach of Drechsler et al. (2011), Reutter (in prep.) carried out a similar analysis for the whole federal state of Saxony with about 4 million inhabitants. He compared different regulatory policies for the deployment of wind power in Saxony with regard to the incurred social costs associated with a given electricity production target. Besides economic incentive policies Reutter (in prep.) analysed policies that are defined by combinations of minimum distances to human settlements and red kite nests.

A potentially critical factor in the analysis (as in the previous analysis by Drechsler et al. 2011) is the quantitative assessment of the production costs and the external costs. These costs are subject to considerable uncertainty. This leads to two questions: (1) How sensitive is the rank order (in terms of social costs) of different minimum distance policies to the uncertainty? And (2) are some policies more robust to the uncertainty than other, in the sense that under many circumstances they perform relatively well?

Questions of the first type are typically analysed in a sensitivity analysis (e.g. Saltelli et al. 2009) that explores how a model output (e.g. the predicted social costs of a policy) depends on model parameters (e.g. the installation costs of a wind turbine). The second type of analysis is called a robustness analysis (e.g. Ben-Haim 2001) that explores under which conditions (values of model parameters) a particular statement like “Policy x outperforms policy y” is true. These two types of analysis are related because in order to make a robust statement one has to vary the model parameters in a sensitivity analysis and investigate how this variation affects the relative performances of policies x and y.

To compare several policies, it is practical to rank the policies’ performances from lowest to highest social costs. On an absolute scale, the performances of policies can vary considerably with changing model parameter values. For instance, if the social costs of a policy are dominated by the installation costs of wind turbines, a doubling of these costs will consequently have a strong impact on the social costs. However, since a doubling of the installation costs will increase the social costs of all policies in a similar way, the ranking of the policies is not necessarily changing but might be robust. In a different context, Drechsler et al. (2003) have already found that rankings of the relative performances of management strategies are much more robust to model parameter uncertainty than the absolute performances of the individual management strategies.

In the present study we are interested in the relative performances of different minimum distance policies for wind turbines. For this, the social costs incurred by all policies are transformed into so called z-scores that measure the policies' deviations from the mean over all policies (e.g. Triola 1995). A below-average level of social costs is represented by a negative z-score and characterises an above-average performing policy.

In the following methods section we will outline the model used to assess the different wind power deployment policies and introduce the considered policies. Further, we describe how uncertain model parameters are varied to explore their impacts on the policies' performances, and depict the analytic approach that is applied to rank the policies. The methods section is followed by the presentation of the results, focusing on the ranking of the policies and the robustness of this ranking to parameter uncertainty. After a discussion of the results, we conclude with the derivation of policy recommendations.

2 Methodology

2.1 Model description and parameterisation

The main data input for the used model comes from a GIS data base for the federal state of Saxony containing information about human settlements, land cover, traffic infrastructure, etc. (Bundesamt für Kartographie und Geodäsie 2016). Taking physical and legal constraints like maximum feasible terrain slopes, safety distances to infrastructure, and nature protection zones into account (cf. Masurowski 2016, Permien and Enevoldsen 2019), these and some other data are used to identify areas that are suitable for wind power in the study region. For this, we consider twelve policy scenarios that differ with regard to the required minimum distances for wind turbines to settlements and red kite nests (described in more detail in section 2.3).

In a second step, we use the software MaxPlace which determines concrete potential wind turbine sites within each suitable area so that the number of wind turbines sites is maximised (Masurowski 2016). For the spacing between neighbouring wind turbines, MaxPlace follows DWIA (2003) and presumes distances between neighbouring wind turbines of five rotor diameters in mean wind direction and three rotor diameters perpendicular to that (so that each wind turbine is surrounded by an elliptically shaped empty space). 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 (FA Wind 2019b).

Drawing on wind data (DWD 2014) and the power curve of the N131 (Nordex 2013) the possible annual energy production (AEP) is calculated for all potential sites as described, e.g., by Eichhorn et al. (2017). As in other studies (e.g., McKenna et al. 2014), energy production losses due to wake effects by other wind turbines, natural barriers (like large trees) or nearby infrastructures, inactivity during servicing and repairs, downtimes forced by environmental regulations (e.g. during bat activities), and curtailment in times of grid congestion are accounted for by a flat reduction of all sites' potential energy yields by 15 %.

In the model we assume that private investors maximise their profits, so that wind turbines are installed at the most profitable sites. The external costs of wind turbines for residents and red kite losses (see below) are ignored by the private investors. Installation and operation and maintenance (O&M) costs are assumed to be identical for all sites (see below). The revenues from electricity production are composed of the market price for electricity (ct/kWh) and a subsidy rate (ct/kWh), both multiplied by the potential energy yields (kWh). Reflecting a characteristic (so called Referenzertragsmodell) of the German Renewable Energy Sources Act (EEG 2017), the subsidy rate is assumed to be spatially differentiated depending on the local wind conditions: it is up to 21% lower if a site is very windy and up to 29% higher if a site is very calm compared to a legally defined reference site. Despite the site-dependent subsidy rates first and foremost those sites with the best wind conditions generate the highest revenues and are chosen.

We use a greenfield approach, starting from an empty landscape without any wind turbines. Referring to about the year 2030, we assume for all scenarios that in total an amount of 4.5 TWh/a wind energy needs to be generated in the study region. Having the current auctioning wind power support scheme in Germany in mind, the subsidy level is assumed to be just as high that the energy target can be reached. The assumed market price is 2.7 ct/kWh which is in the range of the average German onshore wind electricity market prices of the last years (50Hertz et al. 2019).

Each modeled allocation is associated with a value for the total production costs C_{prod} which are the sum over the investment and O&M costs, c_{wt}, of all installed wind turbines. According to Wallasch et al. (2015) the investment costs for turbines like the assumed N131 with a nominal power of 3 MW are about €1,567/kW or in total about €4.70·10^6. For the annual O&M costs, Durstewitz et al. (2016) report €30/kW for the first five years of operation and €50/kW for years 6 – 20. We assume a total time span of 20 years for the modeling as this is the typical lifetime of a wind turbine and the time over which subsidies are paid in Germany. Multiplying the named costs with 3 MW, discounting at a private annual discount rate of 5 % (cf. Drechsler et al. 2017) and summing up over the 20 years of operation leads to total O&M costs of about €1.61·10^6. Adding the investment and O&M costs we obtain c_{wt} = €6.31·10^6.

In addition to the production costs we consider two dimensions of external costs in the calculation of the social costs of the modeled wind turbine allocations: the costs arising from disturbances to humans living in the vicinity of wind turbines and the costs arising from collision losses of the red kite, a bird species of special conservational concern in the study region (Nachtigall & Herold 2013).

The external costs imposed by a wind turbine on humans is modeled as a function of the distances of the wind turbine to all households in the study region. The function is based on results of an economic valuation study by Meyerhoff et al. (2010) and a study that uses a life satisfaction approach by Krekel and Zerrahn (2016). These results are cast into the following functional form for the monthly external resident costs c_{res} (measured in Euros) accruing to household h from wind turbine i (Drechsler et al. 2011, Reutter in prep.):

. (1)

Deviations from this form by local particularities, such as the installation of a wind turbine in the context of a citizens' wind farm which might decrease the external costs experienced by residents, are not considered. By the assumed function, the resident costs are zero for turbine-household-distances $d_{ih} > 4{,}000$ m and increase with declining d_{ih}. This increase is comparatively weak for large d_{ih} and becomes stronger if d_{ih} is further reduced so that marginal costs increase with decreasing distances. The overall resident costs C_{res} of a particular allocation of wind turbines are obtained by applying eq. (1) to all wind turbines i and households h in the study region, summing up the obtained resident costs c_{res} and multiplying this sum by the factor

(2)

which considers discounting of all costs at an annual rate of $r = 0.03$ (cf. Drechsler et al. 2011) and summing up over the 20 years time frame of the analysis.

For the calculation of the external costs associated with the loss of red kites we follow Drechsler et al. (2011) who assumed that the impact of a wind turbine i on a red kite j declines exponentially with increasing distance d_{ij} between the wind turbine and the red kite's nest at a rate of $(350\ \mathrm{m})^{-1}$. The population loss caused by the wind turbines, measured in percent over 20 years, is then obtained by summing over all these impacts and multiplying by a factor $\alpha = 0.26$:

,   (3)

where N is the total number of wind turbines installed and M the total number of red kite nests in Saxony. The factor α is obtained by equating the impact modeled by eq. (3) for the present allocation of wind turbines in Saxony with the population loss that could be expected due to the wind turbines according to experts (Reutter in prep.).

As determined in the economic valuation study by Meyerhoff et al. (2010), the monthly external red kite costs per household (measured in Euros) associated with a red kite population loss L (measured in %) can be approximated by (cf. Reutter in prep.)

.   (4)

Multiplying c_{rk} with the number of households in Saxony, $2.17 \cdot 10^6$, and factor R of eq. (2) we obtain for a given allocation of wind turbines the overall red kite costs C_{rk} in Saxony for a time of 20 years. The total social costs of a given allocation then are calculated as

.   (5)

2.2 Uncertainty assessment

As calculated above, the investment and O&M costs c_{wt} per wind turbine (over 20 years) can be assumed to be €$6.31 \cdot 10^6$ for the considered N131. However, Wallasch et al. (2015) point out that there is some degree of uncertainty concerning the actual future cost values: investment costs could e.g. decrease due to technical progress or increase due to rising commodity prices. Also, changes in interest rates can either increase or decrease the costs of projects. To take this into account, in our analysis we vary the respective costs c_{wt} from the given baseline value of €$6.31 \cdot 10^6$ up and down by one million Euros (i.e. by about ±16%).

There are also uncertainties concerning the modeling of the resident costs. A major factor of uncertainty here is the actual willingness of households to pay for increasing wind turbine distances to their homes as a measure of the respective external costs. Krekel and Zerrahn (2016) e.g. find that five years after a wind turbine has been installed, residents could get used to it, implying reduced external costs over time. Moreover, considerable differences in the valuation of external resident costs can be noticed comparing the two valuation studies of Krekel and Zerrahn (2016) and von Möllendorff and Welsch (2017). Therefore, eq. (1) might also underestimate the actual resident costs. To capture the outlined uncertainties, we multiply c_{res} of eq. (1) by a resident cost factor q_{res}, with lower and upper bounds of 0.3 (–70% compared to the baseline value) and 2 (+100% compared to the baseline value).

For the calculation of the red kite costs we draw on assumptions on the population decline in the study region caused by presently installed wind turbines (see above). However, such outlooks are highly uncertain and come with large confidence intervals (Grünkorn et al. 2016). In addition, the economic valuation study by Meyerhoff et al. (2010) concerning people's willingness to pay for red kite protection on which the red kite cost function of eq. (4) is based, includes uncertainties. The study results might underestimate today's economic value of the red kite externality owing to the influence of inflation, simply because the study was conducted almost 10 years ago. On the other hand, the economic value of the red kite derived in the study from stated preferences could also be overestimated as the study participants possibly did not value the focal species alone but maybe implied 'birds', 'wild animals' or 'biodiversity as a whole'. Therefore, the actual economic valuation of the red kite could also be much lower than determined in the study.

To capture these uncertainties, we multiply c_{rk} of eq. (4) by a red kite cost factor q_{rk}, with lower and upper bounds of 0 and 2, respectively. A value of $q_{rk} = 0$ would eliminate the red kite cost component which could be the case if the installed wind turbines did not harm the red kite population at all and/or that a population decline was not perceived as a loss by the people. A value of $q_{rk} = 2$ implies that the red kite population loss induced by a given wind turbine allocation is considerably larger than assumed with the baseline value and/or people value a given loss of red kites higher (by 100% ceteris paribus) than assumed by the baseline values.

2.3 Policies

Given the described uncertainties in the social costs of wind power generation, the main objective of the present study is to compare a number of regulatory policies, namely minimum distance regulations, with regard to their expected performance (social costs) and robustness to these uncertainties. The policies are defined by combinations of minimum distances for wind turbines to human settlements, termed 'minimum settlement distances' and minimum distances to all red kite nests, termed 'minimum red kite distances'.

Minimum settlement distances are not uniform across the German federal states. On the national level the smallest legally possible minimum settlement distance for the N131 is about 800 m (Eichhorn et al. 2017) implied by the German Immissions Control Act (TA Lärm 1998). However, several federal states (and also some regional planning authorities) in Germany prescribe more restrictive minimum settlement distances. The most restrictive regulation is set in Bavaria. Here a distance of 10 times the wind turbine's height is demanded (Bayerischer Landtag 2014), which for the N131 corresponds to nearly 2000 m. In preliminary analyses we found that the assumed energy target for Saxony of 4.5 TWh/a cannot be met with minimum settlement distances above approximately 1400 m, since then too many potential sites would be excluded. Therefore, we consider the following four levels of minimum settlement distances: 800 m, 1000 m, 1200 m and 1400 m.

Possible values for the minimum red kite distance are taken from the 'Helgoland paper' which recommends in a first version a 1000 m minimum distance to red kite nests (Working Group of German State Bird Conservancies 2007) while in a later version 1500 m are recommended (Working Group of German State Bird Conservancies 2014). Completely ignoring red kite protection would imply a minimum red kite distance of zero. Considering this as an extreme case, we study altogether three minimum red kite distances: 0 m, 1000 m and 1500 m. In total, we thus consider twelve different policies as combinations of different minimum settlement and red kite distances (Table 1).

Table 1: Policies considered in the analysis. Each policy is defined by a combination of a minimum settlement distance (S) and a minimum red kite distance (R).

Min. red kite distance (R) Min. settlement distance (S)	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

2.4 Model analysis

By the rules described in the model description, each of the twelve policies leads, for a given choice of model parameters, to a unique allocation of wind turbines in Saxony. The twelve policies then can be ranked according to the levels of the social costs associated with the respective wind turbine allocations. We are primarily not interested in the absolute social costs but rather in their relative differences. In this respect, a policy k that generates social costs C_k (eq. (5)) below the average $\hat{C}$ of all twelve policies performs above average, and a policy k that generates social costs C_k above average $\hat{C}$ performs below average. To distinguish policies far from the average $\hat{C}$ and policies close to it we introduce the ratio

(6)

which in statistics is known as the z-score and used to standardise data for analyses (Triola 1995).

Parameter σ here denotes the standard deviation over all twelve social costs, so that for instance a z-score of $z_k = -1$ indicates that the social costs C_k of policy k are one standard deviation σ below the average social costs $\hat{C}$ of all considered policies.

We use the z-score concept to measure the relative performance of the policies. If the difference between the social costs of a policy and the average social costs $\hat{C}$ is negative (positive) and rather large compared to the standard deviation σ we obtain a rather large negative (positive) z-score for this policy. Hence, a large negative z-score indicates a strongly outperforming policy, while a large positive z-score indicates a clearly inferior policy.

The advantage of this approach is that the relative performance of a particular policy k can immediately be read from its z-score z_k without any further consideration of the policy's social costs and the social costs of the other policies. This feature enables us to analyse how the relative performance of a policy depends on the uncertain model parameters c_{wt}, q_{res}, and q_{rk} by only examining the z-scores z_k alone.

To encompass the uncertainty in the model parameters c_{wt}, q_{res} and q_{rk} we consider five levels in the former parameter and nine levels in each of the two latter ones within the assumed parameter ranges (see above) and form all 405 possible combinations of levels. For each of these 405 parameter combinations we then determine the z-scores z_k for the twelve policies $k = 1, \ldots, 12$, and determine for each k the mean z-score $\mathrm{E}(z_k)$ and the standard deviation of the z-scores $\mathrm{SD}(z_k)$ over all 405 parameter combinations. The former statistic, $\mathrm{E}(z_k)$, measures the expected relative performance of policy k, while the latter, $\mathrm{SD}(z_k)$, measures the uncertainty in the relative performance z_k of policy k, which represents the likelihood that z_k deviates from the expected value $\mathrm{E}(z_k)$.

Using the described statistical values, we examine the robustness of the policies in four steps and ask:

1. How do the twelve policies, $k = 1, \ldots, 12$, rank with regard to their social costs C_k and corresponding z-scores z_k in the baseline parameter combination ($c_{\mathrm{wt}} = €6.31 \cdot 10^6$, $q_{\mathrm{res}} = q_{\mathrm{rk}} = 1$)?

2. How do they rank on average (considering $E(z_k)$) if the uncertainty in the three model parameters c_{wt}, q_{res}, and q_{rk} is taken into account?

3. How large are the uncertainties in the policies' relative performances (considering $SD(z_k)$), and how do these uncertainties relate to the expected relative performances $E(z_k)$? Which policies are most favourable and which are most unfavourable with regard to expected performance under uncertainty?

4. How do the performances of the most favourable and most unfavourable policies depend on the model parameters c_{wt}, q_{res}, and q_{rk}?

The main steps of the model analysis are depicted in Fig. 1.

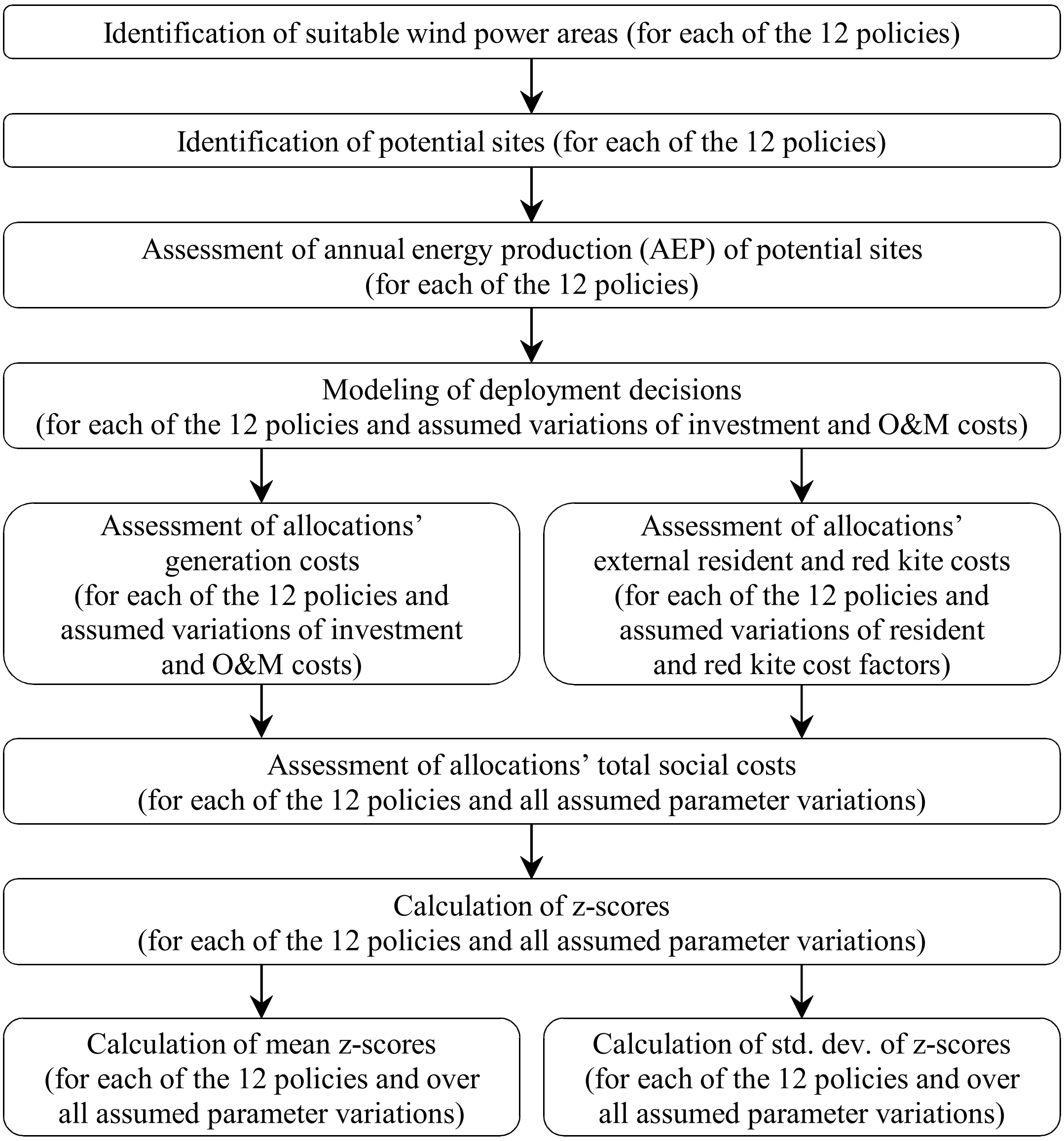

Figure 1: Flow chart of the modeling approach.

3 Results

Figure 2 shows the performances of the twelve policies with regard to their social costs C_k and z-scores z_k for the baseline parameter combination. The best performing policies with the lowest social costs C_k and z-scores z_k are S800_R1500, S1000_R1000, S1000_R1500, and S1200_R1500.

Figure 2: Social costs C_k measured in billion Euros (black bars; average represented by the dashed line), and associated z-scores z_k (grey bars) of the twelve policies for the base line values of investment and O&M costs (c_{wt} = €6.31*10^6) and settlement and red kite cost factors ($q_{\mathrm{res}} = q_{\mathrm{rk}} = 1$).

A very similar result is obtained if the average z-scores E(z_k) taken over all values of the uncertain model parameters c_{wt}, q_{res}, and q_{rk} are considered (Fig. 3): again the best policies are S800_R1500, S1000_R1000, S1000_R1500, and S1200_R1500.

Figure 3: Mean z-scores E(z_k) of the twelve policies over all parameter combinations formed by systematically varying investment and O&M costs c_{wt} and the external cost factors q_{res} and q_{rk} within their specified bounds.

The relationship between the policies' mean z-scores of Fig. 3, E(z_k), and their standard deviations, SD(z_k), is shown in Fig. 4. One can see that for all assumed settlement distances (S800, S1000, S1200, S1400; indicated by the grey scale of the circles) the R0 policies with zero minimum red kite distance (small circles), have both relatively large means and standard deviations of the z-score. Thus, the R0 policies perform poorly with regard to their expected rank and the uncertainty in their rank.

In contrast, for the policies with medium or large minimum red kite distances (R1000 and R1500) and medium minimum settlement distances (S1000 and S1200) (light grey and dark grey circles of medium or large size in the lower left part of the plot) both mean and standard deviation of the z-scores are small compared to those of most other policies. Thus, these policies perform well both with regard to their expected rank and the uncertainty in their rank.

Figure 4: Standard deviations of z-scores SD(z_k) versus mean z-scores E(z_k) (cf. Fig. 3) of the twelve policies, determined over all parameter combinations formed by systematically varying investment and O&M costs c_{wt} and the external cost factors q_{res} and q_{rk} within their specified bounds.

Explanations for these findings can be found in Fig. 5. The figure shows how the z-scores of policy S800_R0 which performs very poorly with regard to both E(z_k) and SD(z_k), and policy S1200_R1500 which performs very well with regard to both E(z_k) and SD(z_k), depend on the model parameters c_{wt}, q_{res}, and q_{rk}. The modeled allocation patterns induced by these two policies with the assumed base line investment and O&M costs c_{wt} are shown in Fig. 6.

Except for very small resident and red kite cost factors, q_{res} and q_{rk}, the z-score of policy S800_R0 is large (yellow to red colour) indicating a rather poor performance. Due to its small minimum distances to both red kite nests and human settlements the policy allows wind turbines to be installed close to these sensitive features. Only if these proximities are valued weakly, represented by very small q_{res} and q_{rk}, the external costs C_{res} and C_{rk} and consequently the social costs $C_{\mathrm{S800\_R0}}$ are comparatively small (Fig. 5a–c).

The investment and O&M costs c_{wt} have only little influence on the z-score of policy S800_R0 (Fig.

5b,c). As further analyses (not presented) reveal, this holds not only for the S800_R0 policy but also for all considered policies. The reason is that the investment and O&M costs c_{wt} only marginally affect the wind turbine allocations so that the external costs do not vary substantially and the total production costs C_{prod} (number of installed wind turbines multiplied by c_{wt}) are affected very equally over all policies.

In contrast to policy S800_R0, policy S1200_R1500 has a low z-score (blue colour) in most of the parameter space (Fig. 5d–f). A medium z-score (green colour) is observed only if the resident cost factor q_{res} is large or small and the red kite cost factor q_{rk} is very small. A high z-score (yellow to red colour) cannot be observed within the considered parameter ranges.

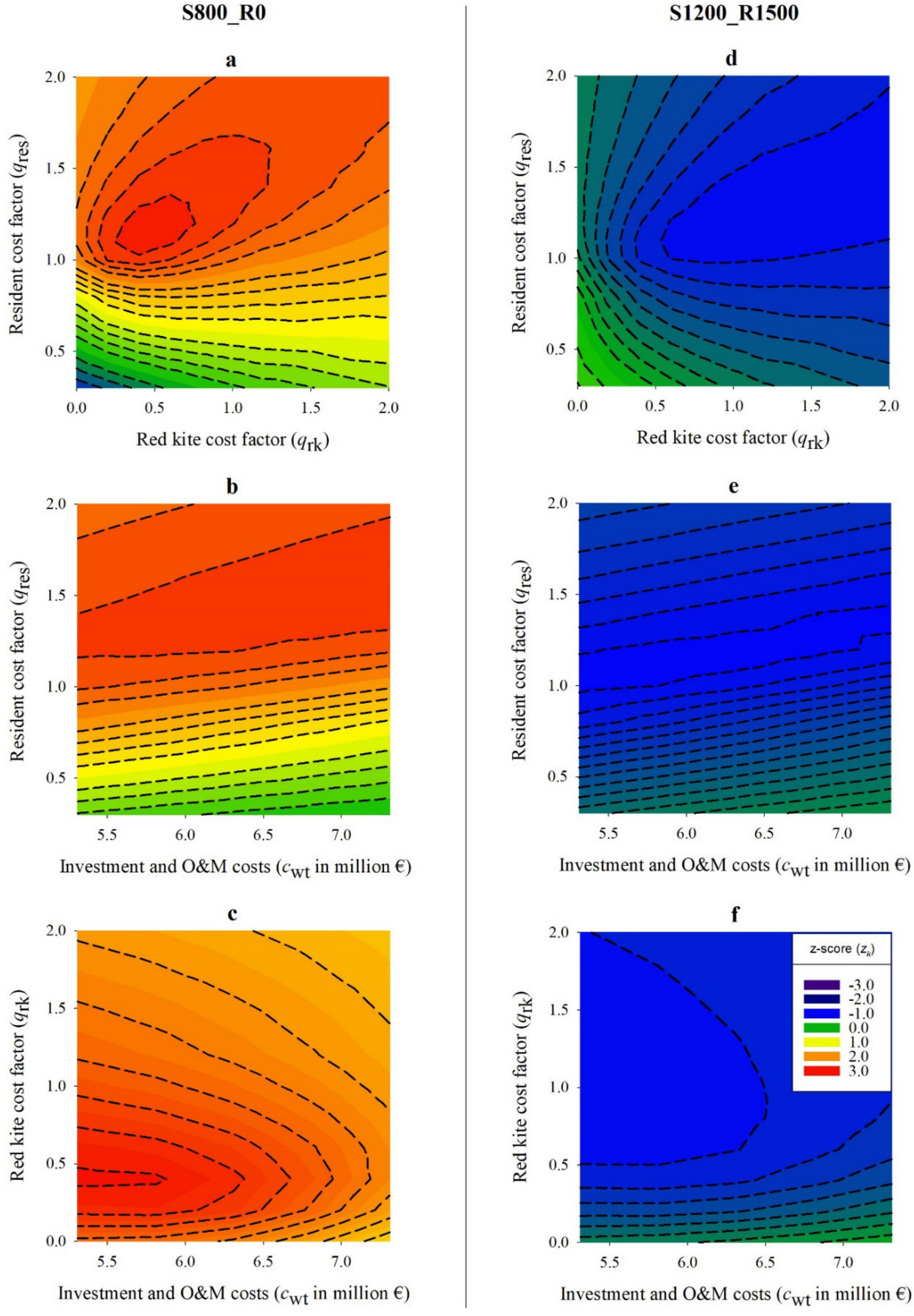

Figure 5: Z-scores z_k (indicated by the colouring) of the policies S800_R0 (left panels) and S1200_R1500 (right panels) as functions of investment and O&M costs c_{wt} and resident cost factor q_{res} (upper panels), investment and O&M costs c_{wt} and red kite cost factor q_{rk} (middle panels), and resident cost factor q_{res} and red kite cost factor q_{rk} (lower panels).

Kilometer

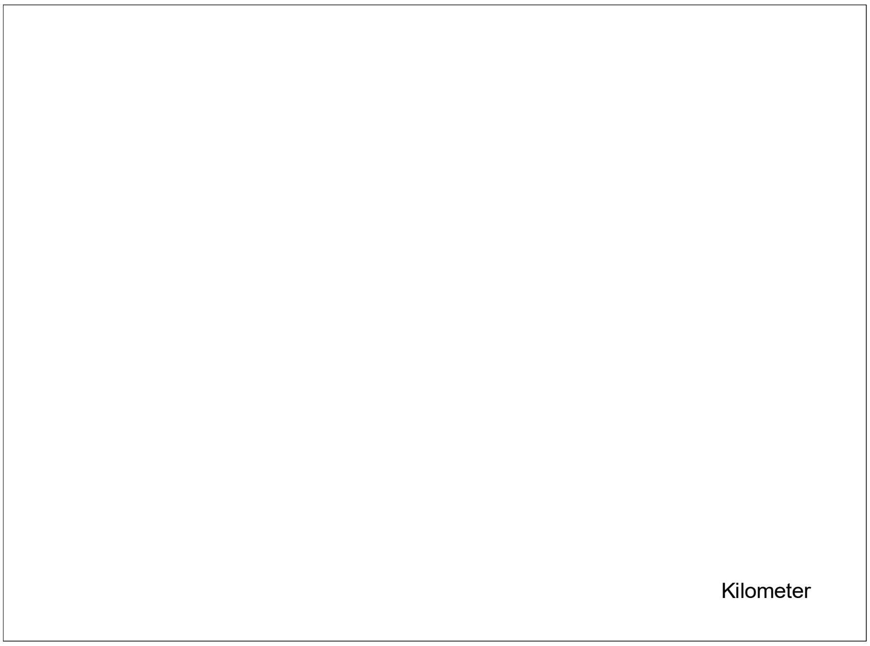

Figure 6: Potential wind turbine sites (blue dots) and selected sites (red dots) for the two deployment policies S800_R0 (panel a) and S1200_R1500 (panel b) as modeled with the assumed base line value of investment and O&M costs c_{wt}. Variations of c_{wt} affect the allocation patterns only marginally. The external cost factors q_{res} and q_{rk} have no impact on the allocations, since they only affect the external cost assessment of the allocations. Under policy S800_R0 there are sufficiently many sites in the mountainous and windy south to reach the state's energy target, while under the more restrictive policy S1200_R1500 sites have to be selected also from other, less windy, parts of Saxony.

The reason for a low z-score of policy S1200_R1500 at a moderate or large red kite cost factor q_{rk} is the large minimum red kite distance of the policy which ensures large distances of wind turbines to red kite nests and allows keeping social costs low even if q_{rk} is moderate or large. Only at very small q_{rk} the saving in external red kite costs C_{rk} associated with the large minimum red kite distance is so small that it is surpassed by the concurrent increase in the policy's production costs C_{prod} caused by the coincidental exclusion of windy sites that would be available with a smaller minimum red kite distance – resulting in the moderate z-scores observed for very small q_{rk}.

The observation of a low z-score of the policy S1200_R1500 at a wide range of resident cost factors q_{res} can be explained in a similar manner. Within a wide range of the considered q_{res}, an increase of the minimum settlement distance would coincidentally exclude too many windy sites and increase production costs C_{prod} more than it would reduce the external resident costs C_{res}, while a decrease of the minimum settlement distance would raise C_{res} more than it would reduce C_{prod}. Only for small q_{res} the minimum settlement distance could be reduced without overly increasing C_{res} while for large q_{res} a larger minimum settlement distance may be necessary to keep C_{res} acceptably low.

Altogether, the z-score of policy S800_R0 is large in most of the parameter space and small for a few extreme parameter values. Therefore, the policy has a large mean and a large standard deviation within the model parameter ranges considered. In contrast, the z-score of policy S1200_R1500 is small in most of the parameter space and medium for a few parameter values, resulting in a small mean z-score and a small standard deviation.

4 Discussion

Taking a social costs perspective this paper explores the impact of different uncertainties on the relative performances of twelve wind power deployment policies for the German federal state of Saxony. The considered uncertain parameters are the future investment and O&M costs of wind turbines, the willingness of residents to accept wind turbines close to their homes, and the potential impact of wind turbines on the red kite population together with society's willingness to accept a population decline. The twelve policies are defined by prescribed minimum distances for wind turbines to human settlements and to red kite nests.

The performance of a particular policy relative to the other policies is measured by the policy's z-score. The z-score indicates how many standard deviations (taken over all twelve policies) the policy's modeled social costs are above or below the mean of the social costs of all policies. The social costs of a policy are considered as the sum of the production costs (investment and O&M costs of all installed wind turbines), the external costs associated with the disturbance of humans living next to wind turbines, and the external costs associated with the fatal collisions of red kites with wind turbines.

The main results of the model analysis can be cast into a few simple rules for the robust design of a sustainable wind power deployment policy which has comparatively small social costs over large ranges of the uncertain parameters:

1. Minimum distances to human settlements should be moderate (around 1000–1200 m). The reason for this is that within wide ranges of the considered parameter uncertainties, smaller minimum settlement distances would generally cost more in terms of increased external resident costs than they would gain in terms of reduced production costs, while larger minimum settlement distances would generally cost more in terms of increased production costs than gain in terms of reduced external resident costs.

2. Minimum distances to red kite nests should be around 1000-1500 m, because within wide ranges of the considered parameter uncertainties, the production costs saved by reducing the minimum red kite distance are likely to be smaller than the concurrent increase in the external red kite costs. Only if the wind turbines' potential impact on the red kite population were considered to be very low and/or society's willingness to accept a population loss were very high, social costs could be minimised by reducing the minimum red kite distance to values considerably below 1000 m.

3. Within their considered range, the investment and O&M costs of wind turbines have a negligible influence on the social-costs-minimising minimum settlement and red kite distances. The reason for this is that the assumed variations of the investment and O&M costs have no remarkable impact on the modeled wind turbine allocations and thereby have very similar impacts on the external and internal costs that are modeled with all policies.

The accuracy of the model results is limited by a number of simplifying assumptions.

- We considered only uniform minimum settlement distances. In practice, minimum distances are often differentiated between cities or towns on the one hand and small villages or solitary buildings on the other. Such differentiated policies are likely to lead to lower social costs and could be more robust than the considered uniform policies.

- We considered only a single turbine technology. The simultaneous consideration of several technologies could imply more complex policies (e.g., different minimum distances for different technologies) and/or differentiated external cost functions. This would certainly affect the quantitative results of our study, but we are confident that the main conclusions would still hold.
- Grid connection costs of wind turbines were ignored in the calculation of the investment costs and may add another spatial element to the analysis.
- External effects were represented only by impacts on the red kite and on residents. Other externalities like negative impacts on bats or the general landscape quality were not considered.

The numerical results are specific to the chosen electricity production target of 4.5 TWh/a for Saxony (which is aspired for about 2030) and the characteristics of the study region. Achieving a higher, more long-term electricity production target may require smaller minimum distances below the robust ones identified in the present analysis because otherwise too many sites could get excluded preventing that the production target can be reached. So in the long term, with increasing targets, there will be less room for optimizing the spatial wind turbine allocation to minimize social costs.

As seen in the above discussion, the results depend on the trade-offs between production costs and the two dimensions of external costs, which to some extent depend on the spatial distribution of, and correlations among, wind speeds, red kite nests and human settlements. Therefore, in other regions with different electricity production targets, different minimum distances may be more favourable robust policies.

Future research might address the above mentioned aspects and consider different electricity production targets, differentiated minimum settlement distances, several wind turbine technologies, grid connection costs, more externalities, and assess whether our qualitative results also hold in other geographical regions. In addition, one might add the consideration of market-based incentive instruments for the spatially targeted deployment of wind power, such as spatially differentiated compensation obligations or wind power support payments depending on the environmental characteristics of the wind turbines' sites.

5 Conclusions and Policy Implications

For a sustainable deployment of wind power it is important to take the external costs incurred by wind turbines into account and balance them with the electricity production costs. This balance can be controlled by setting minimum distances for wind turbines to sensitive landscape features in order to minimise the overall social costs of wind power deployment. In the face of uncertainty, however, it is necessary that such a goal can be achieved in a robust manner so that a deployment policy identified as efficient keeps this property within a wide range of uncertain parameters. In the present paper an approach for such a robustness analysis is developed and applied to wind power deployment in Saxony, Germany. For the case of Saxony and the assumed wind power expansion target for the year 2030, the most robust of the investigated policies consist of minimum distances between wind turbines and settlements of around 1000–1200 m and minimum distances between wind turbines and red kite nests of around 1000–1500 m.

Acknowledgements

We are grateful for the helpful comments of two anonymous reviewers on a previous version of this manuscript.

References

50Hertz, Amprion, TransnetBW, TenneT TSO, 2019. Marktwertübersicht. URL: https://www.netztransparenz.de/EEG/Marktpraemie/Marktwerte (last access: August 12, 2019).

Ben-Haim, Y., 2001. Information-gap decision theory: decisions under severe uncertainty, Series on decision and risk. Academic Press, San Diego, CA.

Bundesamt für Kartographie und Geodäsie, 2016. Digitales Basis-Landschaftsmodell (AAA-Modellierung).

BMU, 2016. Klimaschutzplan 2050. Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit. URL: https://www.bmu.de/fileadmin/Daten_BMU/Download_PDF/Klimaschutz/klimaschutzplan_2050_bf.pdf (last access: August 12, 2019).

BNatSchG, 2009. Gesetz über Naturschutz und Landschaftspflege (Bundesnaturschutzgesetz - BNatSchG) vom 29. Juli 2009 (BGBl. I S. 2542), das zuletzt durch Artikel 8 des Gesetzes vom 13. Mai 2019 (BGBl. I S. 706) geändert worden ist.

BWE, 2019. Windenergie in Deutschland - Zahlen und Fakten. Bundesverband Windenergie. URL: https://www.wind-energie.de/themen/zahlen-und-fakten/deutschland/ (last access: August 12, 2019).

Dai, K., Bergot, A., Liang, C., Xiang, W.-N., Huang, Z., 2015. Environmental issues associated with wind energy – A review. Renewable Energy 75, 911–921. https://doi.org/10.1016/j.renene.2014.10.074.

Deutsche WindGuard, 2019. Status des Windenergieausbaus an Land in Deutschland – Jahr 2018. URL: https://www.wind-energie.de/fileadmin/redaktion/dokumente/pressemitteilungen/2019/20190129_Factsheet_Status_des_Windenergieausbaus-Jahr_2018.pdf (last access: August 12, 2019).

Drechsler, M., Egerer, J., Lange, M., Masurowski, F., Meyerhoff, J., Oehlmann, M., 2017. Efficient and equitable spatial allocation of renewable power plants at the country scale. Nature Energy 2. https://doi.org/10.1038/nenergy.2017.124.

Drechsler, M., Frank, K., Hanski, I., O'Hara, R.B., Wissel, C., 2003. Ranking metapopulation extinction risk: from patterns in data to conservation management decisions. Ecological Applications 13, 990–998. https://doi.org/10.1890/1051-0761(2003)13[990:RMERFP]2.0.CO;2.

Drechsler, M., Ohl, C., Meyerhoff, J., Eichhorn, M., Monsees, J., 2011. Combining spatial modeling and choice experiments for the optimal spatial allocation of wind turbines. Energy Policy 39, 3845–3854. https://doi.org/10.1016/j.enpol.2011.04.015.

Durstewitz, M., Berkhout, V., Cernusko, R., Faulstich, S., Hahn, B., Hirsch, J., Kulla, S., Pfaffel, S., Rohrig, K., Rubel, K., Spriestersbach, S., 2017. Windenergie Report Deutschland 2016. Fraunhofer IWES. URL: http://windmonitor.iee.fraunhofer.de/opencms/export/sites/windmonitor/img/Windenergie_Report_2016.pdf (last access: August 12, 2019).

DWD Climate Data Center, 2014. 200m x 200m Rasterdaten der mittleren jährlichen Windgeschwindigkeiten in 10 m bis 100 m Höhe (in 10m Stufen) und Weibullparameter für Deutschland, Version V0.1. Deutscher Wetterdienst. URL: ftp://opendata.dwd.de/climate_environment/CDC/grids_germany/multi_annual/wind_parameters/resol_200x200/ (last access: August 12, 2019).

DWIA, 2003. Park Effect. DanishWind Industry Association. URL: http://drømstørre.dk/wp-content/wind/miller/windpower%20web/en/tour/wres/park.htm (last access: August 12, 2019).

EEG, 2017. Gesetz für den Ausbau erneuerbarer Energien (Erneuerbare-Energien-Gesetz - EEG 2017), das zuletzt durch Artikel 5 des Gesetzes vom 13. Mai 2019 (BGBl. I S. 706) geändert worden ist.

Eichhorn, M., Tafarte, P., Thrän, D., 2017. Towards energy landscapes – “Pathfinder for sustainable wind power locations.” Energy 134, 611–621. https://doi.org/10.1016/j.energy.2017.05.053.

Eichhorn, M., Masurowski, F., Becker, R., Thrän, D., 2019. Wind energy expansion scenarios – A spatial sustainability assessment. Energy 180, 367–375. https://doi.org/10.1016/j.energy.2019.05.054.

FA Wind, 2019a. Überblick zu den Abstandsempfehlungen zur Ausweisung von Windenergiegebieten in den Bundesländern (Stand Februar 2019, auf Grundlage einer Zusammenstellung der Bund-Länder Initiative Windenergie vom Mai 2013). Fachagentur Windenergie an Land. URL: https://www.fachagentur-windenergie.de/fileadmin/files/PlanungGenehmigung/FA_Wind_Abstandsempfehlungen_Laender.pdf (last access: August 12, 2019).

FA Wind, 2019b. Ausbausituation der Windenergie an Land im Jahr 2018 – Auswertung windenergiespezifischer Daten im Marktstammdatenregister für den Zeitraum Januar bis Dezember 2018. Fachagentur Windenergie an Land. URL: https://www.fachagentur-windenergie.de/fileadmin/files/Veroeffentlichungen/FA_Wind_Zubauanalyse_Wind-an-Land_2018.pdf (last access: August 12, 2019).

Grünkorn, T., Blew, J., Coppack, T., Krüger, O., Nehls, G., Potiek, A., Reichenbach, M., von Rönn, J., Timmermann, H., Weitekamp, S., 2016. Ermittlung der Kollisionsraten von (Greif-)Vögeln und Schaffung planungsbezogener Grundlagen für die Prognose und Bewertung des Kollisionsrisikos durch Windenergieanlagen. Schlussbericht zum durch das Bundesministerium für Wirtschaft und Energie (BMWi) im Rahmen des 6. Energieforschungsprogrammes der Bundesregierung geförderten Verbundvorhaben PROGRESS, FKZ 0325300A-D. URL: https://bioconsult-sh.de/site/assets/files/1561/1561-1.pdf (last access: August 12, 2019).

Krekel, C., Zerrahn, A., 2017. Does the presence of wind turbines have negative externalities for people in their surroundings? Evidence from well-being data. Journal of Environmental Economics and Management 82, 221–238. https://doi.org/10.1016/j.jeem.2016.11.009.

Bayerischer Landtag, 2014. Gesetz zur Änderung der Bayerischen Bauordnung und des Gesetzes über die behördliche Organisation des Bauwesens, des Wohnungswesens und der Wasserwirtschaft, 2132-1-I, 200-25-I, 17.11.2014 (Bayerisches Gesetz- und Verordnungsblatt Nr. 19/2014, S. 478, 20.11.2014).

Masurowski, F., 2016. Eine deutschlandweite Potenzialanalyse für die Onshore-Windenergie mittels GIS einschließlich der Bewertung von Siedlungsdistanzenänderungen. PhD thesis, Universität Osnabrück. URL: https://repositorium.ub.uni-osnabrueck.de/bitstream/urn:nbn:de:gbv:700-2016071114613/7/thesis_masurowski.pdf (last access: August 12, 2019).

Masurowski, F., Drechsler, M., Frank, K., 2016. A spatially explicit assessment of the wind energy potential in response to an increased distance between wind turbines and settlements in Germany. Energy Policy 97, 343–350. https://doi.org/10.1016/j.enpol.2016.07.021.

McKenna, R., Hollnaicher, S., Fichtner, W., 2014. Cost-potential curves for onshore wind energy: A high-resolution analysis for Germany. Applied Energy 155, 103–115. https://doi.org/10.1016/j.apenergy.2013.10.030.

Meyerhoff, J., Ohl, C., Hartje, V., 2010. Landscape externalities from onshore wind power. Energy Policy 38, 82–92. https://doi.org/10.1016/j.enpol.2009.08.055.

Nachtigall, W., Herold, S., 2013. Der Rotmilan (Milvus milvus) in Sachsen und Südbrandenburg, Jahresber. Monitoring Greifvögel und Eulen Europas, 5. Sonderband. Förderverein für Ökologie und Monitoring von Greifvogel- und Eulenarten e.V., Halle (Saale), Germany.

Nordex Energy GmbH, 2013. Nordex N131/3000 - Schallemission, Leistungskurven, Schubbeiwerte.

Permien, F.H., Enevoldsen, P., 2019. Socio-technical constraints in German wind power planning: An example of the failed interdisciplinary challenge for academia. Energy Research & Social Science 55, 122–133. https://doi.org/10.1016/j.erss.2019.04.021.

Reutter, F., in prep. Ökologisch-ökonomische Analyse von Politikoptionen zur räumlichen Steuerung des Windenergieausbaus [Ecological-economic analysis of policy options for governing future wind power deployment]. PhD thesis, Universität Leipzig.

Ruß, S., 2016. Windenergie und Artenschutz – Größere Abstände für den Rotmilan nach dem Neuen Helgoländer Papier und dem bayerischen Winderlass 2016: Urteilsanmerkung VGH München, Urteil vom 29.3.2016 – 22 B 14.1875, 22 B 14.1876. Natur und Recht 38, 686–690. https://doi.org/10.1007/s10357-016-3087-7

Saltelli, A., Chan, K., Scott, E.M., 2009. Sensitivity analysis, Paperback ed. Wiley, Chichester.

Sovacool, B.K., Munoz Perea, M.A., Matamoros, A.V., Enevoldsen, P., 2016. Valuing the manufacturing externalities of wind energy: assessing the environmental profit and loss of wind turbines in Northern Europe: Valuing the externalities of wind energy. Wind Energy 19, 1623–1647. https://doi.org/10.1002/we.1941.

TA-Lärm, 1998. Sechste Allgemeine Verwaltungsvorschrift zum Bundes-Immissionsschutzgesetz (Technische Anleitung zum Schutz gegen Lärm) vom 26. August 1998 (GMBl Nr. 26/1998 S. 503), zuletzt geändert durch Verwaltungsvorschrift vom 01.06.2017 (BAnz AT 08.06.2017 B5).

Triola, M.F., 1995. Elementary Statistics (6th edition). Addison-Wesley, Reading, MA.

UBA, 2019. Erneuerbare Energien in Deutschland - Daten zur Entwicklung im Jahr 2018. Umweltbundesamt. URL: https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/uba_hgp_eeinzahlen_2019_bf.pdf (last access: August 12, 2019).

UN, 2015. Paris Agreement. United Nations. URL: https://unfccc.int/sites/default/files/english_paris_agreement.pdf (last access: August 12, 2019).

von Möllendorff, C., Welsch, H., 2017. Measuring renewable energy externalities: evidence from subjective well-being Data. Land Economics 93, 109–126. https://doi.org/10.3368/le.93.1.109.

Wallasch, A.-K., Lüers, S., Rehfeldt, K., 2015. Kostensituation der Windenergie an Land in Deutschland - Update. Deutsche WindGuard. URL:

https://www.windguard.de/veroeffentlichungen.html?file=files/cto_layout/img/unternehmen/veroeffentlichungen/2015/Kostensituation%20der%20Windenergie%20an%20Land%20in%20Deutschland%20-%20Update.pdf (last access: August 12, 2019).

Working Group of German State Bird Conservancies (Länderarbeitsgemeinschaft der Vogelschutzwarten – LAG VSW), 2007. Recommendations for distances of wind turbines to important areas for birds and breeding sites of selected bird species. Ber. Vogelschutz 44, 151–153.

Working Group of German State Bird Conservancies (Länderarbeitsgemeinschaft der Vogelschutzwarten – LAG VSW), 2014. Recommendations for distances of wind turbines to important areas for birds as well as breeding sites of selected bird species. Ber. Vogelschutz 51, 15–42.