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A modelling approach for allocating land-use in space to maximise social welfare, exemplified on the problem of wind power generation

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Abstract

Land-use conflicts arise if land is scarce, land-use types are mutually exclusive, and vary in their effects with regard to more than one incongruent policy objective. If these effects depend on the spatial location of the land-use measures the conflict can be mediated through an appropriate spatial allocation of land use. An example of this conflict is the welfare-optimal allocation of wind turbines (WT) in a region in order to achieve a given energy target at least social costs. The energy target is motivated by the fact that wind power production is associated with relatively low CO2 emissions and is currently the most efficient source of renewable energy supply. However, it is associated with social costs which comprise energy production costs as well as external costs caused by harmful impacts on humans and biodiversity. We present a modelling approach that combines spatially explicit ecological-economic modelling and choice experiments to determine the welfare-optimal spatial allocation of WT in Western Saxony, Germany. We show that external costs are significant. The welfare-optimal sites are therefore not those with the highest energy output (i.e., lowest production costs). However, they show lower external costs than the most productive sites. A sensitivity analysis reveals that the external costs represent about seven percent of the total costs (production costs plus external costs). Increasing the energy production target increases both production and external costs. The absolute (percentage) increase of production costs is higher (lower) than that of external costs.

1. Introduction

The scarcity of land often results in land-use conflicts. When deciding which parts of a region to use in which manner, different policy goals need to be considered and weighted. Furthermore, fulfilment of these policy goals may depend not only on the total area devoted to a certain land-use type but also the spatial location of the land-use. The basic question is, how should land use be allocated so that social welfare is maximised?

To answer this question, a decision-making and modelling approach is required that is (i) spatially explicit and (ii) able to consider multiple policy goals. Spatially explicit models are necessary to predict the effects of land-use measures when these effects are at least partly local and dependent on where the measures are carried out and/or what measures are carried out in the vicinity. Spatially explicit models have been traditionally rare in the economic literature but have recently gained considerably in importance in the fields of environmental and ecological economics (e.g., Bateman et al. 2002, Eppink and Withagen 2009, Brock and Xepapadeas 2010, Touza et al. 2010, Ranga et al. 2009) when it was realised that many environmental processes are dependent on spatial location and acting on local or regional rather than global scales.

Consideration of multiple policy goals requires knowledge of the effects of land use along different dimensions and valuing them in terms of social welfare. This requires linking multi-disciplinary models with economic valuation techniques. Multi-disciplinary models have been used successfully, e.g., in the fields of renewable resource management and biodiversity conservation, here termed ecological-economic models (e.g., Wätzold et al. 2007, Polasky and Segerson 2009, Tschirhart 2009). Ecological-economic modelling involves the coupling of state-of-the-art ecological and economic models to analyse coupled ecological-economic systems with the goal to derive better management recommendations. For example, results of contingent valuation have been integrated with an ecological-economic model by Wätzold et al. (2008) to determine the welfare-maximising level of species protection. The environmental change that was subject of this study was solely of a single dimension. In the case of multiple dimensions of the environmental change in question the increasingly applied choice experiments as an attribute-based valuation method are more appropriate (Birol and Koundouri 2008).

In the present paper we integrate ecological-economic modelling and choice experiments to determine the welfare-optimal spatial allocation of wind turbines (WT). Wind power generation is a land-use type that involves various conflicts and in which spatial location is an important issue. The first and most obvious policy goal associated with wind power is climate protection. Wind power is currently the most efficient renewable energy source and the CO2 emission per produced electricity unit is among the smallest of all energy sources (Hondo 2005). However, wind power production has considerable externalities that lead to conflicts with other important policy goals, including human health and biodiversity conservation. Human health is affected because of the shadow and noise effects produced by WT (e.g., Hau 2006, Rogers et al. 2006). Visual impacts of WT on landscapes have been considered by Krause (2001) and Möller (2006). Biodiversity is affected especially through increased mortality and habitat loss for birds and bats (e.g., Bright et al. 2008, Hötker et al. 2006). External costs of wind power production have been quantified, e.g., by Álvarez-Farizo and Hanley (2002), Ek (2006), or Dimitropoulos and Kontoleon (2008); see Meyerhoff et al. (2010) for an overview.

The quality and extent of the monetary and non-monetary externalities of wind power production considerably depend on the characteristics of the sites selected for wind power development. One the one hand the unit cost of wind-generated electricity depends on the energy produced per year and this depends on the local wind conditions. On the other hand, WT erected in the vicinity of settlements or bird habitats increase the impact on humans respectively birds. Different sites available for the installation of a WT will have different pros and cons in terms of wind power production costs and external costs and the welfare-optimal spatial allocation of WT has to balance these in accordance with the preferences of the society so that overall social costs are minimised. Such a comprehensive spatially explicit optimisation approach with the explicit consideration of the overall social costs is unique in the entire environmental economics literature. The authors are not aware of any example in the leading journals except for multi-criteria-based approaches. These, however, target social costs only in a rather implicit manner (Strager and Rosenberger 2006, Ananda and Heart 2009). Punt et al. (2009) explore in a spatially explicit modelling framework the trade-offs between the revenues of wind power production and the population sizes of two animal species in an offshore wind farm but provide no information which allocation of WT and associated levels of revenues and bird population sizes are socially optimal.

We develop a spatially explicit approach of the welfare-optimal allocation of WT and apply it to a study region in Germany to investigate a number of policy relevant questions: (i) how do society's preferences affect the welfare-optimal allocation of WT, (ii) what are the trade-offs between the monetary and external costs of wind power production, and (iii) what are the implications of the chosen policy target for the amount of energy to be produced.

The paper is structured as follows. In section 2 we will outline the modelling approach and present the study region. In section 3 we apply the modelling approach to the study region and present the results in section 4. Section 5 contains a discussion of the results and conclusions.

2. The modelling approach

The objective of the analysis is to allocate WT in the study region that a given level of electricity $E_{\min}$ is produced per year at minimal social cost C. The determination of the welfare-optimal energy target $E_{\min}$ would require the consideration of the effects of wind power production on the climate and the impacts of climate change. This, however, is beyond the scope of this study. The energy target $E_{\min}$ is an exogenous parameter which we assume to be optimally set by the political decision maker. The social cost of wind power supply is composed of the production costs C_p and external costs C_e. To determine external costs we define attributes that capture the relevant externalities as identified through stakeholder interviews (see section 3.1 below). The attributes are quantified through spatially explicit models and valued through choice experiments. In the present case the attributes comprise: the loss rate (L) of an important bird species in the study region (the red kite *Milvus milvus*), the minimum distance of WT to settlements (D), the height of the installed WT (H) and the size of wind parks (S). The attributes (D, H and S) consider the impact of WT on the landscape and ultimately the human inhabitants. Attribute H considers that WT technologies with different heights may by installed. Attribute S considers that WT may be allocated in larger or smaller wind parks. The production cost and attribute L depend on the time frame. We consider a time frame of 20 years, which is about the life time of a WT, so C_p measures production costs over 20 years and L measures species decline within 20 years.

The welfare W in the study region is assumed to depend solely on the spatial allocation of WT in the region. An allocation scenario is defined by deciding for each potential WT site whether it contains a large WT, a small WT or no WT (for details, see below).

The analysis is carried out in several steps. First we construct the social cost function

$$C = C_p + C_e(L, D, H, S) \quad (1)$$

where C_e are the external costs associated with the attributes L, D, H and S. They are determined through choice experiments. We further identify the sites that are physically and legally suitable for the installation of a WT. Given these potential sites, WT allocation strategies are formed as described above, considering that the energy target $E_{\min}$ must be fulfilled. For each allocation strategy we determine the associated attributes C_p, L, D, H and S and determine the social cost C. The allocation strategy that minimises C is determined through numerical optimisation. A sensitivity analysis is carried out to determine the impacts of different social preferences.

3. Application of the modelling approach

The modelling approach is applied to the planning region Westsachsen (appendix A). In this region the main impact of WT on biodiversity outside nature conservation areas – where WT are a priori excluded – is caused by collisions of foraging red kites (*Milvus milvus*) with WT (Eichhorn and Drechsler 2010). Attribute L therefore measures the rate by which the bird population declines as a consequences of the presence of WT in the region. Below we go through the steps of the modelling approach.

3.1 Construction of the external cost function through choice experiments

We consider an external cost function which is the sum of the partial external costs $C_y(y)$ associated with the attributes $y \in \{L, D, H, S\}$:

$$C_e(L, D, H, S) = \sum_{y \in \{L, D, H, S\}} C_y(y) \cdot \sum_{t=1}^{T} (1+r)^{-t} \quad (2)$$

The partial external cost $C_y(y)$ represents the cost for a single year. Since we are considering a time span of T=20 years, we have to aggregate the costs over these 20 years. We discount the external costs at annual rate r.

The partial external cost for each attribute y is assumed to have the following functional shape

$$C_y(y) \equiv \frac{a_y}{X - b_y} + g_y \tag{3}$$

where a_y, b_y and g_y are coefficients (determined by the signs of the coefficients a_y and b_y, the chosen functional form allows considering increasing or decreasing marginal partial cost for attribute y). The coefficients are determined (i) by the constraints $C_L(L=0)=C_D(D\to\infty)=C_H(H=0)=C_S(S=0)=0$ (considering that a zero externality is associated with zero external cost) and (ii) through choice experiments (CE) which deliver the marginal willingness to pay for a certain change in an externality (Louviere et al. 2000, Kanninen, 2007).

We denote by MWTP(y_1,y_2) the annual marginal willingness to pay for an improvement in attribute y from some level y_1 to some level y_2, and assume that this amount can be identified as the change in external costs when the attribute is varied between the two levels, so that:

$$C_y(y_2) - C_y(y_2) = -\text{MWTP}(y_1, y_2) \tag{4}$$

In other words, if a change in y from y_1 to y_2 is associated with an MWTP of magnitude α a change of y from y_2 to y_1 can be regarded to produce external costs of magnitude $-\alpha$ (which assumes that willingness to accept in absolute terms equals willingness to pay).

The MWTP are determined through choice experiments (CE). CE base on the assumption that the utility to consumers of any good (i.e., also public goods such as a landscape) is derived from its attributes or characteristics. Due to this focus CE are particularly useful for valuing multidimensional changes. In a CE, respondents are asked to make comparisons among environmental alternatives characterised by a variety of attributes and the levels of these. Typically, respondents are offered multiple choices during the survey, each presenting alternative designs of the environmental change in question and the option to choose the status quo. The record of choices serves as a basis to estimate the respondents' willingness to pay (WTP). Changes in welfare due to a marginal change in a given attribute are calculated using the marginal willingness to pay (MWTP) measure. It is defined as the maximum amount of income a person will pay in exchange for an improvement in the level of a given attribute provided.

Table 1 briefly reports the attributes and their levels used to design the choice sets in the present study. A D-optimal fractional factorial design consisting of 40 choice sets was identified. The sets were blocked into 8 subgroups with 5 choice sets and each block was presented to 44 respondents at least. A first version of the questionnaire and the choice sets were discussed with residents of West-Saxony during three focus group meetings with altogether 25 participants. Before the main survey was conducted a pilot study was carried out. Overall, 353 interviews were completed. All interviews were conducted in May and June 2008 via telephone, i.e., interviewees were contacted by random digit dialling and asked whether they were willing to participate in the survey. If they agreed, a date for the main interview was arranged and they were mailed the information about the objective of the survey, detailed descriptions of the attributes and the choice sets (for further details see Meyerhoff et al. (2010)).

Table 1: Attributes and levels used in the choice experiment. Note: Bold levels are those of the no-buy alternative (Programme A).

Attributes	Information given	Levels
Size of wind farms (*S*)	Larger wind farms generally lower the costs of electricity production but the bigger they are the bigger could be their influence on the landscape; when farms are larger in total fewer farms are needed to produce the same amount of electricity.	**Large (16 to 18 WT)** medium (10 to 12 WT) small (4 to 6 WT)
Maximum height of turbines (*H*)	The higher turbines are the more electricity can be generated because winds are stronger and more constant at higher altitudes. On the other hand visibility increases with height.	110 meter 150 meter **200 meter**
Effect on red kite; population loss (*L*)	Turbines would not be installed in conservation areas but also outside these areas conflicts may arise. For example, negative impacts on birds such as the red kite would further decrease populations. The levels indicate the loss of the population in the next 20 years in West Saxony.	5% **10%** 15%
Minimum distance to settlements (*D*)	Due to regulation turbines have to keep a minimum distance to towns and villages in order to avoid adverse effects through, e.g., noise or shading. Programme A with a minimum distance of 750 metres complies with these regulations. Visibility would	**750 meter** 1.100 meter 1.500 meter

	diminish with higher distances.	
Monthly surcharge to power bill (PR)	Programme A presents today's state of technology and enables to produce electricity from wind at low-costs. Programmes B and C would lead to higher costs, e.g., for infrastructure such as longer power cables, and thus require a surcharge to the monthly power bill.	**€0** €1 €2.5 €4 €6
Avoided carbon dioxide emissions	All three programmes would avoid the same amount of CO_2; in West Saxony 570,000 t per year.	Not included in choice sets

3.2 Specifying the decision space and modelling of the attributes

We start our analysis by identifying those parts of the landscape that are physically and legally qualified for the allocation of WT with the help of a geographical information system (GIS) of the region. Broadly speaking, these are open areas distant enough from infrastructure, settlements and nature conservation areas. The analysis focuses on two WT technologies k=1,2. The k=1 type has a hub height of 80m and rotor diameter of 82m, yielding a nominal power of 2MW, while the k=2 type has a hub height of 105m and a rotor diameter of 90m, yielding a nominal power of 3MW. The considered technologies represent the state-of-the-art. Regarding the German regulations on noise emissions (TA Lärm 1998) sound emissions are within legal limits at distances above 750m for the small WT type (k=1) and 1000m for k=2. The suitable parts of the landscape (henceforth referred to as suitability space) are subsequently filled with a grid of points with each point in the grid representing a potential site for the allocation of a WT, taking technical minimum distances between individual WT into account. Allocation scenarios are defined by deciding for each potential WT site i=1,…,N within the suitability space whether it should contain a WT of type 1 or type 2 or no WT.

The energy yield

Having specified the decision space we determine the attributes C, L, D, H and S. An important input for the calculation of the cost C is the amount of energy E_{ik} that can be produced per year at each site i with WT type k. E_{ik} is calculated by using the technical parameters of the technology in question and the relevant frequency distribution of wind speeds $f_{ik}(v)$ observed at the spatial location and altitude of the WT hub (for further details see Eichhorn and Drechsler 2010):

$$E_{ik} = t_{ik} \int f_{ik}(v) P_k(v) dv \quad (5)$$

where $P_k(v)$ is the power generated by WT type k at wind speed v and

$$t_{ik} = 8760 \int_{v_{\min}}^{v_{\max}} f_{ik}(v)dv \qquad (6)$$

is the number of operating hours of the WT per year ($v_{\min}$ and $v_{\max}$ are the wind speed bounds (depending on k) between which the WT type k operates and 8760 is the number of hours in a year). The wind speed data $f_{ik}(v)$ were bought from Eurowind GmbH (Köln, Germany). The total energy E_{tot} produced per year in the region is obtained by summing E_{ik} over all installed WT.

The wind power production cost C_p

The production cost associated with a WT comprises the construction and operating costs. The construction costs K_k for WT type k=1,2 are composed of selling prices, taken from the companies' price lists, and a 10 percent mark-up to cover on-site construction costs, including grid connection. Annual operating costs are typically estimated at 5 percent of the construction costs. Considering a time horizon of T years, the present value of production cost amounts to

$$C_{p,k} = K_k \left(1 + 0.05 \sum_{t=1}^{T} (1+r)^{-t} \right) \qquad (7)$$

where r is the discount rate.

The private revenues from wind power production

We assume that a WT is installed only if the expected revenue V_{ik} exceeds the cost $C_{p,k}$. The revenues are determined by the produced energy E_{ik} and the rules of the German Renewable Energy Sources Act (EEG 2008). These tell that in the first 5 years after construction an "initial tariff" ("Anfangsvergütung") of IT=9.2 cent is paid per kWh, given E_{ik} is at least λ=60 percent of the reference yield R_k. The reference yield represents the amount of energy that can be produced by WT type k at an average site (considering typical WT sites in Germany). An additional "system services bonus" ("Systemdienstleistungsbonus") of SSB=0.5 cent is paid on top of IT if the WT starts operating before 2014 and fulfils the requirements of an electrical engineering ordinance. The initial tariff *AV* is paid beyond those five years if E_{ik} is less than $1.5R_k$. In particular it is paid for another

$$z = \frac{(1.5R_k - E_{ik})}{6 \cdot 0.075R_k} \tag{8}$$

years. After 5+z years a "basic tariff" ("Grundvergütung") of *BT*=5.02 cent is paid per cent/kWh. Altogether, the present value revenue of a WT of type *k* at site *i* over *T* years is

$$V_{ik} = E_{ik}\left((IT + SSB)\sum_{t=1}^{5}(1+r)^{-t} + IT\sum_{t=6}^{z}(1+r)^{-t} + BT\sum_{t=z+1}^{T}(1+r)^{-t} \right) \tag{9}$$

if $E_{ik} \geq \lambda R_k$ and $V_{ik}=0$ otherwise. (Note that if $E_{ik}<\lambda R_k$ the WT operator does not only receive no subsidy, but he also has no guarantee to feed electricity into the power grid at market prices, so we set $V_{ik}=0$. Furthermore, even if subsidies were paid, WT with $E_{ik}<0.6R_k$ would not be profitable, so the constraint $\{E_{iky}<\lambda R_k$ implies $V_{ik}=0\}$ is not binding). Since V_{ik} is largely a subsidy, its magnitude has in first order no effect on social welfare (i.e. social cost *C*), so V_{ik} enters the analysis only through the constraint that a WT is installed at site *i* only if $V_{ik}-C_{p,k}>0$.

Modelling of the externalities

Ecological externalities are partly taken into account by prohibiting the erection of WT in areas protected by nature conservation laws. However, protected areas are by no means sufficient to reach the ambitious goals of biodiversity policy (BMU 2007). So the impacts of WT on biodiversity have to be considered even if the WT are installed outside the protected areas. These impacts concern mainly birds and bats and may be measured by the rate of population loss. In the present case the main species of concern is the red kite, *Milvus milvus* (Eichhorn and Drechsler 2010). We consider the percentage of the regional population *L* that is lost due to WT over the modelling time frame of 20 years. We model this loss as the sum of "marginal" losses l_i

$$L = \sum_{i=1}^{N} l_i \tag{10}$$

We assume that the contribution l_i of site i to L is determined by the probability of an individual of the focal species being found at the site. This depends, e.g., on how close the site is to a nest, whether the site is located within a migratory bird route, etc. In the case of red kites we assume that l_i is a declining function of the distances of site i to known nests. Further details are given in Appendix A.

The modelling of the remaining three attributes is straightforward. Attribute D represents the minimum distance of WT to settlements, considering all settlements and installed WT in the region. Attribute H is modelled as the average over the heights of all installed WT in the region. To determine attribute S we apply the wind park method (Schmitt et al. 2006) that clusters all WT into wind parks. S is then the average size of those wind parks.

3.3 Minimisation of the social cost *C*

Mathematically, the task is to minimise cost $C(\mathbf{x})$ as a function of vector $\mathbf{x}=(x_1,x_2,\ldots,x_N)$. Element x_i (i=1,…,N) of this vector is $x_i=0$ if there is no WT at site i, and $x_i=k$ if a WT of type k is installed. This minimisation problem is of a so-called N-P hard type and its solution requires special techniques such as integer programming (e.g., Shrijver 1998). Below we will see that our minimisation problem can be simplified so we can apply a more straight forward method to solve it. Details are given in Appendix A. As a result, we obtain the welfare optimal spatial allocation $\mathbf{x}^*$ of the WT in the region, the associated optimal levels of the attributes: C^*, L^*, D^*, H^* and S^*.

Table 2: Overview on the relevant model parameters. Note: M€ stands for million Euros.

Parameter / Variable	Meaning	Value / Range
$E_{\min}$	Energy target for the region	690 (170…690) GWh per year
AV	Initial tariff	9,2 cent per kWh
GV	Basic tariff	5.02 cent per kWh
R_k	Reference yield	5.68 GWh/year for WT k=1 6.90 GWh/year for WT k=2
λ	Minimum ratio of energy yield and reference yield	0.6
K_k	WT construction cost	2.648 M€ for WT k=1 3.489 M€ for WT k=2
r	Discount rate	0.03 per year

T	Time frame of analysis	20 years
	Number of households in the region	500,000
f_y	Factor by which MWTP for attribute y is varied	0.1…10

Society's preferences and the energy target are likely to affect the optimal allocation of WT. We vary the associated MWTP (cf. section 3.1) by factors f_y $y \in \{L,D,H,S\}$) and the energy target $E_{\min}$ and record the resulting optimal attribute levels. Table 2 shows the intervals within which the factors f_L, f_D, $E_{\min}$ are varied, together with the values of the most relevant model parameters.

4 Results

4.1 Construction of the social cost function

Table 3 presents the results from a conditional logit model (CL) and an error component logit model (ECL) analysing the responses to the choice sets. The application of the ECL (Scarpa et al. 2005, Hess and Rose 2009) was motivated by the expectation that the Programmes B and C share an extra error component because both programmes describe tighter regulations reducing potential externalities from wind power generation. Thus, correlations between the stochastic portions of utility forming these programmes may be present. Due to the additional error component there is no independence of irrelevant alternatives. The ECL therefore can also take into account that each respondent has answered a sequence of choices. Table 3 shows the estimates from the CL model and the ECL model; both show a similar pattern. The coefficients for the price variables are significant with the expected negative sign.

Increasing prices lower the likelihood that a certain alternative is chosen. The positively significant ASC_{ProA} relating to Programme A indicates that ceteris paribus respondents would experience positive utility from Programme A. Both times the parameters for red kite and minimum distance are significant showing that individuals prefer to reduce the impact of turbines on the red kite population and prefer to move turbines further away from settlements compared to the baseline of 750 metres distance. On the other hand, the parameters for wind farm size and turbine height are not significant. Whether wind power generation would take place with large or small turbines, for instance, does not influence choices systematically. The reason for this could be preference heterogeneity, i.e., respondents preferences might be strongly opposed and thus cancel each other out.[1] The error component that introduces correlation between Programme B and Programme C is highly significant and indicates heterogeneity across individuals with their preferences for the two alternatives that would reduce externalities from wind power generation. Overall, the fit of the CL is rather low while the ECL taking the panel character of the data into account performs much better. The MWTP based on the ECL is in the same order of magnitude for both attributes but the confidence intervals are smaller. Thus, in the following we use the estimates from the ECL as an input for the modelling of the optimal WT allocation.

Table 3: Estimation results for the MWTP. Note: 95% confidence intervals were calculated using the Krinsky-Robb method; MWTP = marginal willingness to pay; CL = conditional logit model; ECL = error component logit model

Attribute	**CL**		**ECL**	
	Parameter (t-value)	MWTP in € per month	Parameter (t-value)	MWTP in € per month
ASC_{ProA}	0.683 (4.778)		0.873 (2.95)	
Wind farm size: medium	0.088 (1.525)	n.s.	0.092 (1.36)	n.s.
Wind farm size: small	-0.022 (-0.384)	n.s.	-0.001 (-0.01)	n.s.
Max. Height turbine: 110	0.023 (0.414)	n.s.	0.06 (0.99)	n.s.
Max. Height turbine: 150	-0.016 (-0.297)	n.s.	-0.039 (-0.63)	n.s.
Population loss: 5%	0.417 (7.453)	2.23 (1.02 — 3.44)	0.583 (9.82)	2.13 (1.24 — 3.01)
Population loss: 15%	-0.462 (-7.534)	-3.03 (-4.50 — -1.55)	-0.639 (-9.46)	-2.81 (-4.01 — -1.61)
Settlement distance: 1100	0.142 (2.556)	3.18 (1.72 — 4.63)	0.199 (3.00)	3.18 (2.12 — 4.24)
Settlement distance: 1500	0.248 (4.528)	3.81 (2.28 — 5.34)	0.388 (6.58)	3.94 (2.82 — 5.07)
Price	-0.168 (-7.109)		-0.247 (-10.10)	
$EC_{ProBProC}$			3.658 (11.66)	
No. of observations	1765		1765	
(S)Log-L	-1742.13		-1371.86	
Pseudo R^2	0.03		0.29	

In the following only the two significant attributes are taken into account, i.e., in the associated cost function (cf. section 3.1) the components C_H and C_S are set to zero. For the other two attributes C_L and C_D we read from the last column of Table 3 that relative to

[1] An application of the latent class model reveals that preference heterogeneity is indeed present. For example, respondents in one segment prefer smaller wind farms as in Programme A (Meyerhoff et al. 2010).

Programme A (population loss L=10, settlement distance D=750m) the monthly willingness to pay of respondents is

a) positive if L is decreased from 10 to 5 (MWTP = 2.13 Euros),
b) negative if L is increased from 10 to 15 (MWTP=- 2.81 Euros),
c) positive if D is increased from 750m to 1100m (MWTP=3.18 Euros), and
d) is also positive if D increases from 750m to 1500m (MWTP=3.94 Euros).

The parameters a_L, b_L and g_L of the cost function C_L are determined by inserting responses (a) and (b) into eq. (4).The parameters a_D, b_D and g_D of the cost function C_D are determined by inserting responses (c) and (d) into eq. (4). With 500,000 households in the region the resulting cost function $C_e=C_L+C_D$ is shown in Fig. 1. The external cost C_e increases with decreasing D and increasing L, and marginal cost dC_e/dL respectively dC_e/dD declines as L becomes small respectively D becomes large. Social cost C is obtained by adding to C_e the production cost C_p.

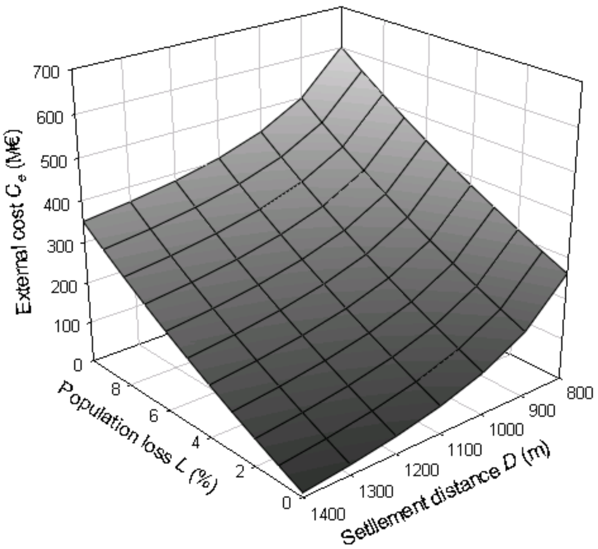

Figure 1: External cost $C_e=C_L+C_D$ for the study region as a function of population loss L and settlement distance D for the time frame of 20 years, discounted at annual rate r=3%.

4.2 Evaluation of the attributes

Figure 2 shows the energy yield E_{ik} (cf. section 3.2.1) for the small WT type (k=1) and all potential WT sites i in the region (for the large type the pattern looks the same but energy levels are about 50 percent higher for all sites). One can see that the energy yields E_{ik} are highest in the south, central and east, and lowest in the north east. The total amount of electricity produced in the region is the sum of the energy yield over all sites with installed WT. This total amount has to reach or exceed the politically required target $E_{\min}$.

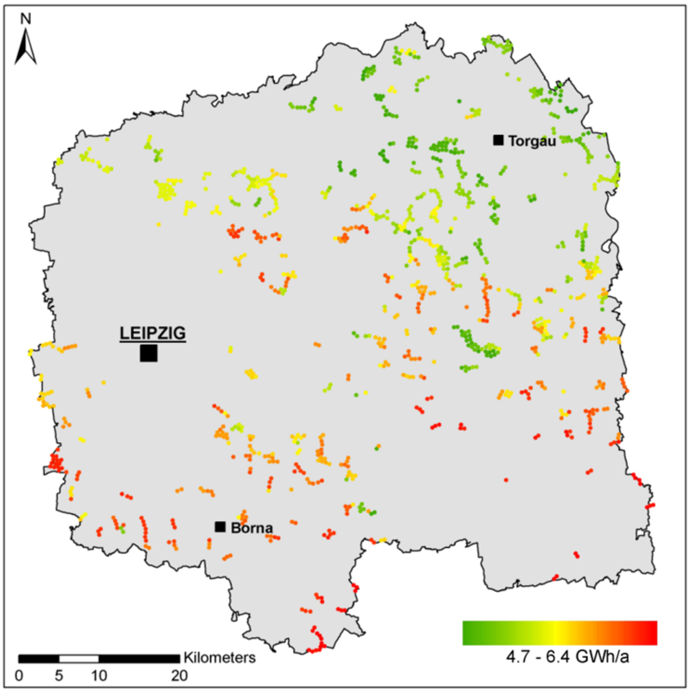

Figure 2: Predicted amount of energy E_{i2} produced on each potential site within one year with the large WT type (k=2). Each potential site in the study region is represented by one circle in the map.

Society has an interest to produce that level of energy at lowest social cost C which is composed of the production cost C_p and the external cost C_e. To minimise C_p for given energy target $E_{\min}$, it is optimal to select the sites i with the lowest production cost per energy unit, $C_{p,k}/E_{ik}$. It turns out that this ratio is about equal for both WT types k=1 and k=2. Further, for a given total nominal power, larger WT have less impact on the red kite than smaller WT, because total number of WT is more relevant than size, i.e., three 2MW turbines have more impact than two 3MW turbines. Since society has no direct preference for larger or smaller WT and the preference for red kite protection is positive, the larger WT type k=2 is more efficient from a welfare-economic point o view than the smaller WT throughout the study region. However due to regulations that limit the allowed noise immissions in settlement areas (TA Lärm 1998) the larger type may be installed only at sites at least 1000m away from settlements. We are thus able to conclude that *welfare is maximised if sites that have distance to settlements of at least 1000m contain a large WT or no WT while sites at smaller distances contain a small WT or no WT*.

The other component that affects the social cost is the external cost C_e which is determined by the red kite population loss L and settlement distance D. According to eq. (13) L is modelled as the sum over l_i where l_i measures the impact of a WT if it is installed on site i. We find that the l_i are relatively uncorrelated to the energy levels presented in Fig. 2, so there are low-conflict sites with a high (low) energy level and low (high) impact on the red kite but also high-conflict sites with high (low) energy level and high (low) impact on the red kite. Similar can be said about the distances d_i of the sites to settlements, so there is a conflict between minimising the production cost C_p, the external cost C_L and the external cost C_D. The welfare-optimal allocation minimises the sum of these three costs.

4.3 The welfare-optimal allocation of WT

The objective is to reach the energy target $E_{\min}$=690 GWh per year at minimal social cost where social cost is given by eq. (1) with production cost C_p shown in Fig. 2 and external cost determined by eq. (2). The associated optimal red kite population loss is L^*=1.0 percent within 20 years, the optimal settlement distance is D^*=1025m and the optimal production cost amounts to C^*=730 Mio Euros (sum over 20 years, present value, discounted at 3% per year). Altogether, a number of 122 large WT types but no small WT are installed.

To understand the impact of society's preferences on the welfare-optimal allocation and the trade-offs between the production costs and the externalities, we vary the MWTP associated with attributes L and D (cf. section 4.1) and determine the optimal levels of L, D and C_p. Figure 3a shows that an increase in the MWTP associated with population loss L (f_L, moving from left to right) reduces the optimal population loss L^* (changes the colour from red or orange to blue). At the same time it decreases the optimal settlement distance (moving from left to right in Fig. 3b) and the optimal level of production cost (Fig. 3c). An increase in the MWTP associated with the settlement distance (f_D, moving from bottom to top) generally increases the optimal population loss L^* (Fig. 3a), increases the optimal settlement distance (Fig. 3b) and the optimal level of the production cost (Fig. 3c). Altogether, increasing the MWTP for an externality reduces the optimal level of this externality (decreases L^* resp. increases D^*) and increases the other externality and the production cost.

This indicates that there are trade-offs between the two externalities and the production cost. An increase of the optimal population loss L^* or a reduction in the settlement distance D^* reduces the optimal production cost C_p^*. Roughly, the optimal production cost varies by about 50 million Euros as the levels of the externalities vary between the maximum and minimum levels. The price factors here cover a range from 0.1 to 10, i.e. from the case where the externalities are practically irrelevant to the case where they are very relevant. In consequence full coverage of the externalities increases production cost C_p by about 50 million Euros which corresponds to about seven percent of the production cost if externalities were irrelevant (bottom-left corner of Fig. 3c: ca. 690 million Euros).

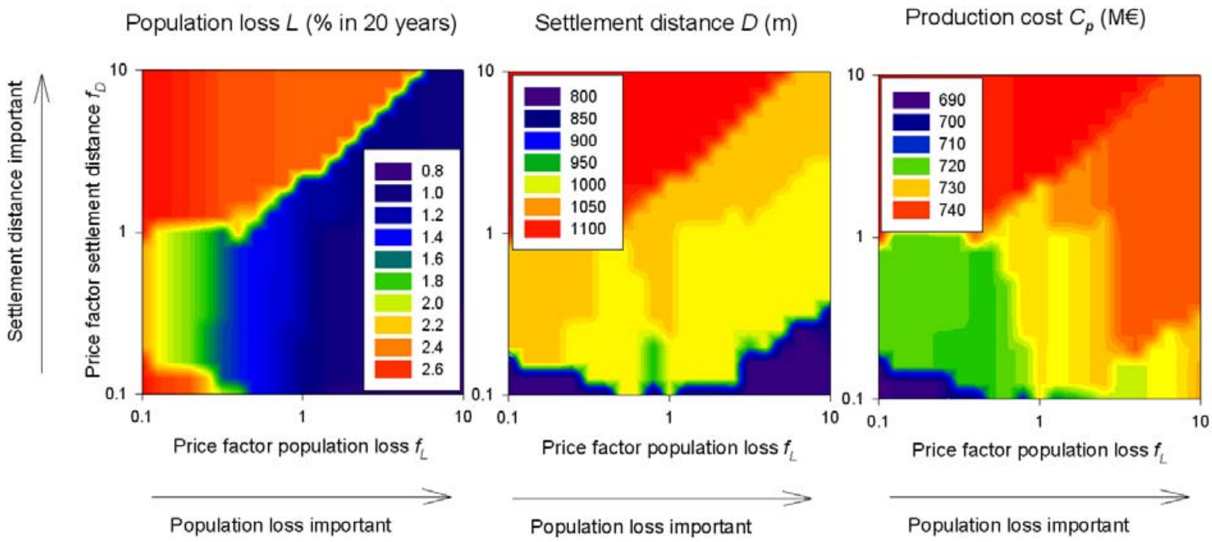

Figure 3: Optimal red kite population loss L (panel a), settlement distance D* (panel b), and production cost Cp* (panel c) as functions of the two price factors f_L and f_D. In each panel the optimal level is given by colour (e.g., for f_L=0.1 and f_D=10 we observe red colour in panel a which indicates L*=1.6). The price factor f_L (f_D) tells by which the MWTP for L (D) is multiplied compared to the level given in Table 3.*

As described in section 2.1 we do not determine the optimal level of the regional energy target $E_{\min}$, but set it exogenously. Therefore it is of interest to know how a different level of $E_{\min}$ affects the production cost and the externalities. Figure 4 shows that increasing $E_{\min}$ increases both production and external costs. As can be expected, the production cost C_p is proportional to $E_{\min}$ and increasing $E_{\min}$ by one GWh increases C_p by about one million Euros (over 20 years). Social cost C increases by about 1.2 million Euros if $E_{\min}$ is increased by one GWh, which includes the above-mentioned increase in production cost by one million Euros and an increase in the external costs C_e by 0.2 million Euros (all measured as the present value of the discounted costs over the next 20 years). This means that the increase in external costs is about one fifth of the increase in production costs. Given the above finding that external costs are only about 7 percent of the production costs, we can conclude that the relative increase in the external costs is larger than that in the production costs (i.e., the external costs multiply by a larger factor than the production costs) when the energy target is raised.

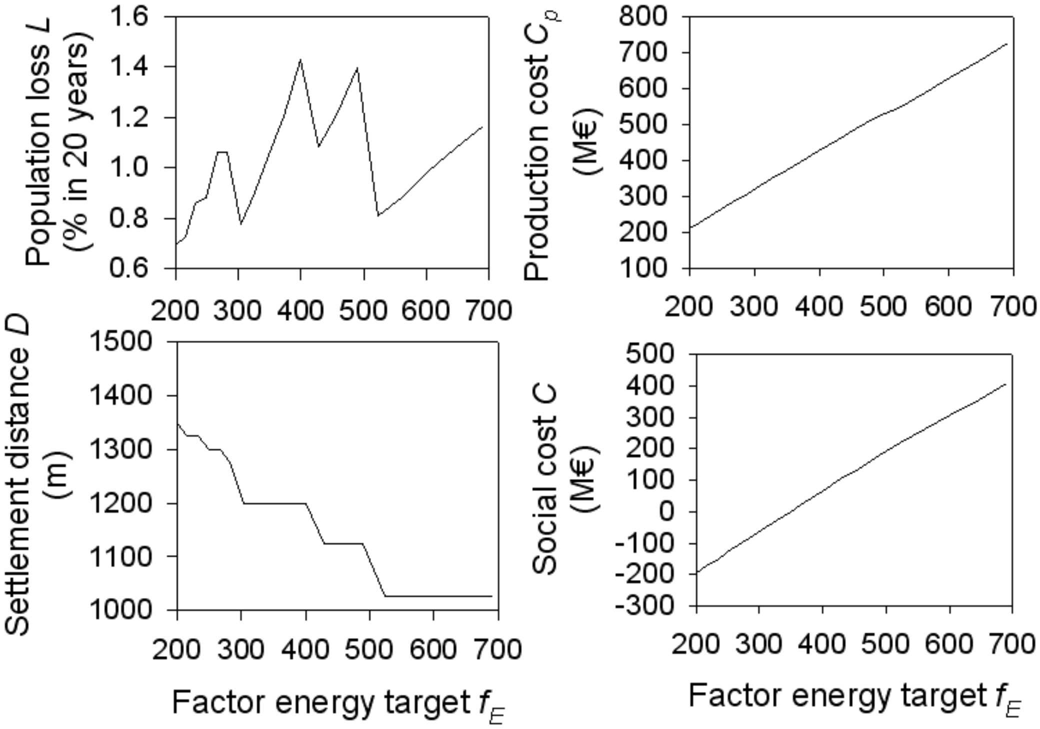

Figure 4: Optimal red kite population loss L (panel a), settlement distance D* (panel b), production cost C_p* (panel c), and social cost (C) as functions of the regional energy target E_{min}. Social costs are scaled so C=0 for the base energy target of E_{min}=345 GWh per year.*

5. Summary and Conclusions

Wind power is one of the most promising options for producing energy in a climate-friendly manner. However, it causes negative externalities in terms of adverse impacts on humans and biodiversity (esp. birds and bats). To alleviate the conflict between the positive impact of wind power on climate policy and its negative externalities, wind turbines (WT) should be allocated so that social costs (i.e., the sum of wind power production costs plus external costs) are minimised with regard to the desired climate-friendly energy target. To determine such an allocation ex ante requires the combination of different methods, including economic modelling of the production costs, modelling of the non-monetary external effects, monetary valuation of these external effects, and numerical optimisation. To our knowledge this paper is the first in the field of energy policy that combines all these items to take a comprehensive view on the problem to optimally allocate WT in a region.

The goal is to reach a certain energy target in a concrete region (E_{min}) in a welfare optimal manner, i.e. at lowest social costs. To do this, we quantitatively explored the trade-offs between production costs and externalities by combining choice experiments (CE) and spatially explicit ecological-economic modelling (EEM). It turned out that in the study region the distance of WT to settlements and the protection of a focal species, the red kite, cause significant externalities of wind power supply. The welfare-optimal allocation balances production costs and externalities and minimises the sum of production costs and external costs. Minimising the social costs in the study region increases the production costs by about 7% for the chosen energy target and compared to a reference scenario where wind the allocation of WT takes only production costs into account. This may be explained by the fact that currently the region is not heavily used for wind power production, so the externalities associated with a moderate increase of wind power production are comparatively low.

The magnitude of the chosen energy target reflects the importance of producing energy in a climate friendly manner. The optimal magnitude should be chosen such that the regional social costs of wind power production outweigh the benefits accruing from reduced CO2 emission. Determining the “globally” optimal level of the energy target, however, was beyond the scope of this study and is a matter of future research. Nevertheless, to gain insight in the relation between the social costs of wind power supply and positive climate impacts, we varied the energy target. It turned out that increasing the energy target stepwise from 170 GWh per year to 690 GWh per year, increases the external costs by a larger factor than the production costs (although in absolute terms, the increase in the production costs is higher by a factor of 5).

These numbers depend on several assumptions. In the assessment of the impacts of WT on the red kite, e.g., we ignored options of on-site management that make sites unattractive for the red kite and would thus reduce the modelled collision risk. Moreover, the search range of red kites is not circular. So WT in certain directions from the bird’s nest will have a higher impact on the collision risk than WT in other directions. Information on the search behaviour of red kites, however, is difficult to obtain and requires sophisticated field observations. If, however, this information was at hand it could be easily fed into the model. With regard to the production costs we ignored the spatial variation of grid connection costs. These very much depend on the distance of a site to the next feed in station, and also on whether a solitary WT or a wind park is connected. Generally connection costs per WT decrease with increasing size of a wind park (economy of scale). Taking these factors into account would require detailed knowledge about the present power grid and even more, assumptions how allocation of WT and expansion of the power grid co-evolve. Since the evolution of power grids and the installation of new smart technologies to make existing power grids effective for renewable energies is currently a hot topic it may be interesting to further explore this issue in future.

6. Acknowledgements

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Appendix A: Determination of the welfare-optimal allocation of WT

A1. The study region

The study region comprises the area of the planning region West Saxony which is a part of the Free State of Saxony, Germany, with about 1,000,000 residents (2005) and an area of around 4.300km² (Fig. A1). Due to its topography the region is fairly suited for wind power production but at the same time belongs to the core distributional area of the endangered red kite (*Milvus milvus*) (e.g., BirdLife International 2009). Red kites have been frequently observed to be killed by WT. The red kite therefore forms the focal bird species in our analysis.

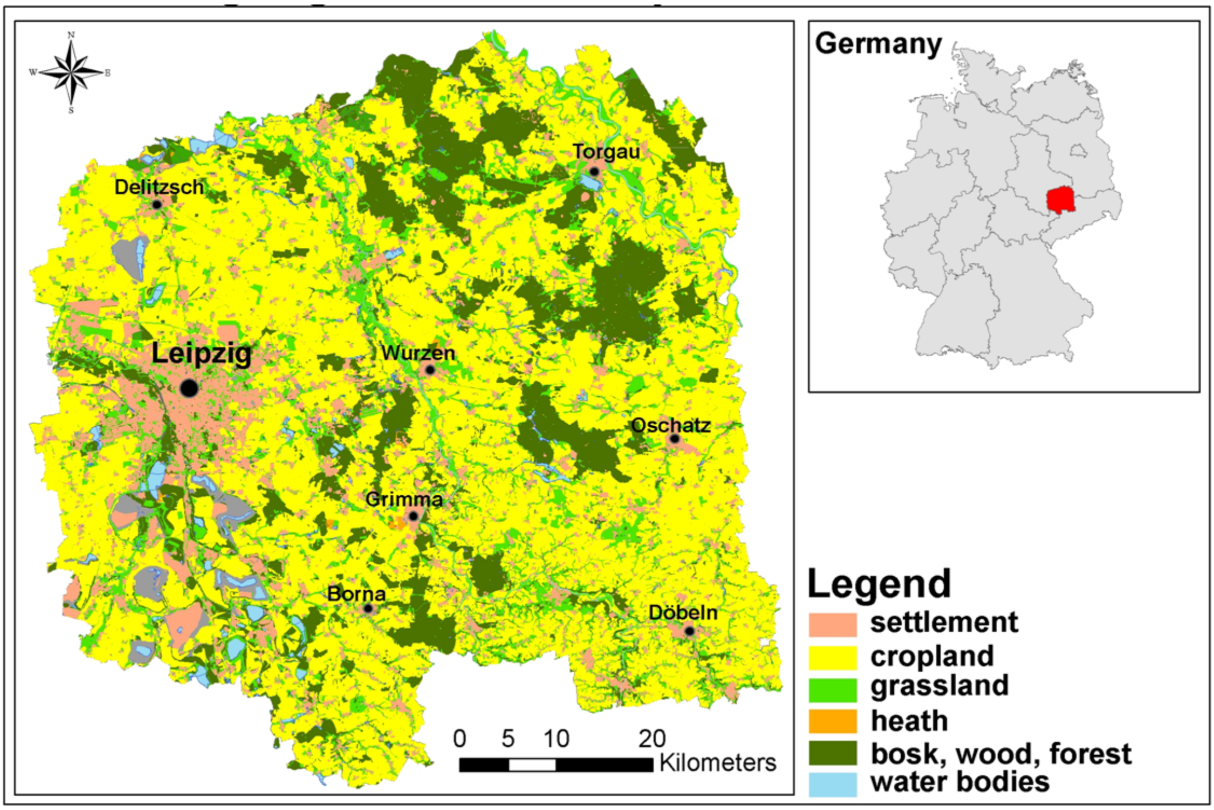

Figure A1: The planning region West-Saxony (RPV WS 2008)

A2. Modelling the loss of red kites

We assume that the probability of a red kite colliding with a WT declines with increasing distance δ between the WT and the bird's aerie via

$$\pi(\delta) = e^{-(\delta/3\text{km})^2}. \quad \text{(A1)}$$

(Eichhorn and Drechsler 2010). The probability of a red kite colliding with any of the installed WT in the study region is obtained by summing the probabilities of the individual WT. We denote the distance between the *i*-th WT and the *j*-th aerie as δ_{ij}. If there are *M* WT and *M'* aeries in the region the collision probability for the study region amounts to:

$$\pi_{tot} = \sum_{i=1}^{M} \sum_{j=1}^{M'} \pi(r_{ij}). \quad \text{(A2)}$$

For the evaluations below we need to translate the probability π into a population loss rate *L* (within the considered time frame of 20 years). Expert's observations according to Hötker et al. (2006) suggest that the population loss caused by all WT currently installed in the study region amounts to about 0.25 percent per year which corresponds to L=5. Evaluation of eq. (4) for the currently installed WT in the region delivers a value of about π_{tot}=400 (Eichhorn and Drechsler 2010). Assuming a linear relationship between L and π_{tot} we write

$$L = 5\pi_{tot} / 400 = \pi_{tot} / 80 . \qquad \text{(A3)}$$

With eq. (10), the contribution of WT i to L is

$$l_i = \frac{1}{80} \sum_{j=1}^{M} \pi(r_{ij}) \qquad \text{(A4)}$$

so that L can be written as the sum of the l_i over all WT.

A.2 Formal description of the optimisation problem

As noted in section 4.2 the large WT type k=2 is more profitable that the small type so that sites at distances to settlements below 1000m may or may not contain the small type while more distant sites may or may not contain the large type. Mathematically, the WT type k is therefore a function of the site index i: k=k(i). Objects of the optimisation are the individual sites i=1,…,N. Each site contains a WT (k=2 for distant sites and k=1 for near sites), or not. The former choice is represented by x_i=1 and the latter by x_i=0 for all i. The vector $\mathbf{x}=(x_1,x_2,\ldots,x_N)$ represents an allocation strategy that specifies for each site whether it contains a WT or not. The number of possible strategies is 2^N where N=1043 is the number of potential sites in the region.

Input data for the optimisation are

a. Attributes (cf. sections 2.1 and 3.2)

- the energy amount E_{ik} produced per year. The total amount of energy produced in the region per year is

$$E = \sum_{i=1}^{N} x_i E_{ik(i)} \qquad \text{(A2)}$$

- the contribution li to the red kite population loss L. The total loss in the study region equals

$$L = \sum_{i=1}^{N} x_i l_i \qquad \text{(A3)}$$

- the production cost $C_{p,k}$ (present value: discounted sum of costs over the next 20 years. The total production cost in the region is

$$C_p = \sum_{i=1}^{N} x_i C_{p,k(i)} \qquad \text{(A5)}$$

- the distance d_i of site i to the next settlement. The settlement distance D is the minimum distance over all sites:

$$D = \min_i \{d_i\} \qquad \text{(A6)}$$

b. the external cost function $C_e(L,D)$ of Fig. 1

c. the constraint that an energy amount of $E_{\min}$ must be produced in the region per year.

The task is now is to fulfiull the energy target $E_{\min}$ at minimum social cost C=C_p+C_e:

$$C \to \min \quad s.t.\ E \geq E_{\min}\ . \qquad \text{(A7)}$$

The resulting optimal allocation strategy is denoted as **x*** with the associated optimal attributes L^*, D^*, C_p^*, C_e^* and C*.

A.3 The numerical optimisation procedure

Since it is a minimum over all site distances d_i, it is convenient to treat the settlement distance D as a constraint and minimise the cost

$$C' = C_p + C_L \qquad \text{(A8)}$$

for a given level of D. We systematically vary D and for each level of D obtain an optimal value $C'^*(D)$. The optimal level of D minimises the social cost C=C'+C_D:

$$D^* = \arg\min_D \{C\} = \arg\min_D \{C'^*(D) + C_D\}\,. \qquad \text{(A9)}$$

The task is now to minimise C' for given D. Strictly speaking, the cost function C_L is non-linear, which complicates the optimisation. In the relevant range of L (cf. Figs. 1 and 6) C_L can however in very good approximation be regarded as linear:

$$C_L(L) = \frac{a_L}{b_L - L} + g_L \approx pL = p\sum_{i=1}^{N} x_i l_i \ . \quad \text{(A10)}$$

The social cost for given *D* then is additive:

$$C' = \sum_{i=1}^{N} x_i c'_i \quad \text{(A11)}$$

with

$$c'_i = C_{p,k(i)} + pl_i \quad \text{(A12)}$$

the social cost (without C_D) of a WT on site *i*. The additivity of C' simplifies the optimisation problem substantially. We first determine the ratio $\mu_i = E_{ik}/c'_i$ for each site *i* which tells how much energy can be produced at the site per social cost c'_i. A site with a high μ_i is to be preferred to a site with a lower μ_i. The sites are now selected for installation of a WT in decreasing order of μ_i until the constraint $E \geq E_{min}$ is fulfilled.