Sustainable Land Use through Wind Power –
A Conflict between Climate Protection and Nature Conservation

Dissertation

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Wenn der Wind des Wandels weht, bauen die einen Schutzmauern, die Anderen bauen Windmühlen.
Chinesische Weisheit

When the wind of change blows, some build protective walls, others build windmills.
Chinese wisdom

Summary

The energy sector is the largest emitter of carbon dioxide, one of the main greenhouse gases responsible for climate change. One way to reduce these emissions and to simultaneously reduce dependence on finite fossil fuels such as coal or oil is the use of renewable energies (RE) in the energy sector. In Germany, this conversion is encouraged through legislation which obligates net operators to guarantee RE access to their grids and reimbursement to suppliers since the early 1990s. In the power sector, wind energy is currently the most important and most economical renewable energy source and will remain so in the coming years according to recent studies. Its expansion is expected to progress in the German coastal waters (offshore) as well as inland (onshore).

The expansion of onshore wind power, however, reaches its limits already. The designation of priority and suitability areas for wind energy production is associated with a high consumption of land. In addition, further conflicts arise, because wind turbines (WT) are high, largely visible and technical facilities dominate the landscape; which causes noise, shadow and light emissions. This can disturb the welfare of humans or even endanger the health of residents. Furthermore, disturbance and displacement of birds and bats from ancestral habitats or even their death due to collision were observed.

Therefore, the wind power production is in conflict between energy- and climate policy objectives on one hand and the objectives of emission control, nature and open-space protection, on the other hand. The resulting land use conflicts will intensify in the future, because the resource "land" becomes a more scarce good due to an increasing general land use, for example for settlement or infrastructure area. Thus, the additional space, required for the wind power, will become more difficult to realize. So, the question arises, if a sustainable, resource efficient land use is possible with the integration of wind power development.

The present work deals with this issue, as part of the BMBF-funded research project "Strategies for sustainable land use in the context of wind power generation". The focus was set on the investigation of energy and nature conservation as areas of concern. The overall aim of this PhD was to contribute to the minimization of the described land use conflicts, in order to promote the development of wind power, to maintain their acceptance in public opinion and to fulfill the objectives of nature conservation and environmental protection.

At first, a comparative analysis of two German study areas: West Saxony and North Hesse was done. Based on land use and land cover data as well as wind data, the effectiveness of the designated priority and suitable areas (VE areas) for wind power production was investigated. In addition, the repowering potential (replacing old turbines with new, more efficient wind turbines) was analyzed for different technology options. Then, these results were compared to a further scenario, which identified alternative sites for wind turbines (reallocation). The emphasis of this approach was placed on the energetic quality of the sites additional to the adherence to legal and nature-conservation criteria and the minimum distance from settlements. It was shown that the efficiency of the current spatial allocation of VE-areas could be improved by repowering, reallocation of sites or a combination of both, for the two regions. This enables significant performance gains in both regions.

Beyond that, this PhD thesis has investigated possible adverse impacts of wind turbines on the avifauna and has developed methods to minimize these. In fact, WTs are not built into nature or bird conservation areas. However, not all bird species are restricted to these protected areas due to their mobility. Therefore, areas around nesting sites as well as protection corridors of known bird migration routes outside protected areas are designated by the regional planning authority as buffer zones that must be kept free from wind turbines. However, this approach excludes large proportion of areas of the region for wind power development, thereby continuing the reduction in the availability of land. Thus, there is a conflict between the goals of nature conservation and the need for further expansion of wind energy.
This conflict was investigated based on the example of red kite (Milvus milvus), a predatory bird, frequently colliding with WTs, studied in West Saxony. Based on wind energy and ornithological data, different WT sites were evaluated on their annual energy yield and their influence on the local red kite population. To estimate the impact on the red kite a special, distance-based indicator was developed - “impact function”, hereafter. This function evaluates the risk of collision of the red kite with a WT in an easy-to-use manner, as function of the distance between the WT and the bird´s aerie. The mathematical relationship was derived from literature and the experiences communicated by ornithologists. As part of an ecological-economic modeling process pareto optimal land use scenarios were developed using an “efficiency frontier” by incorporation of energy yield and threatened for the red kite. These scenarios are certain WT allocation patterns which maximize energy yield without increasing the collision risk for the red kite. A comparison between current allocation patterns and the identified pareto optimal land use scenarios present inefficiencies of the current one.

By using the efficiency frontier another indicator was deduced to measure the severity of the conflict between wind power and red kite protection. This indicator makes it possible to compare different regions or wind farms with each other to select those with the lowest conflict.
Furthermore, the effect of another area related parameter was examined - the minimum distance of WT to settlements. It turned out that with increasing distance from the settlement the conflict between wind energy and red kite protection worsened.

So, an individual-based model (IBM) was developed, to gain a better understanding of the conflict between wind energy and red kite protection. This model simulates the foraging flight of a red kite, starting from its aerie, in a heterogeneous landscape. These simulations contribute to the determination of the collision probability of a red kite with a WT, depending on the distance between the nest and a WT, placed at different distances to the aerie. Based on this, an impact function was calculated. The determination of an impact function by individual-based modeling is also a suitable approach for other endangered bird species.

The developed methods and indicators are open to regional planners, environmental agencies and organizations as well as scientists. They are mostly easy-to-use tools that can make the planning of VE areas effective for both plant operators and environmental protection.

Zusammenfassung

Der Energiesektor ist der weithin größte Emittent von Kohlendioxid, einem der wesentlichen Treibhausgase, die für den Klimawandel verantwortlich sind. Ein Weg, diese Emissionen zu reduzieren und gleichzeitig die Abhängigkeit von endlichen, fossilen Energieträgern wie Kohle oder Öl zu verringern, ist der Einsatz von erneuerbaren Energien im Energiesektor. In Deutschland wird dieser Umbau seit Anfang der 1990er Jahre durch gesetzliche Einspeise- und Vergütungsgarantien gefördert. Im Stromsektor ist die Windenergie der derzeit bedeutendste und wirtschaftlichste erneuerbare Energieträger, und sie wird es nach neuesten Studien in den nächsten Jahren auch bleiben. Ihr Ausbau soll sowohl in den deutschen Küstengewässern (off-shore) als auch im Binnenland (on shore) voranschreiten.

Der Ausbau der Windenergie an Land stößt jedoch heute schon oft an seine Grenzen. Die Ausweisung von Vorrang- und Eignungsgebieten für die Windenergiegewinnung ist mit hohem Flächenverbrauch verbunden. Darüber hinaus können sich weitere Konflikte ergeben, da Windenergieanlagen (WEA) große, weithin sichtbare und das Landschaftsbild prägende, technische Einrichtungen sind, von denen Schall-, Schatten- und Lichtemissionen ausgehen können. Diese können das Wohlbefinden oder sogar die Gesundheit von Anwohnern gefährden. Weiterhin wurden bei verschiedenen Vogel- und Fledermausarten Vertreibungen aus angestammten Habitaten oder sogar der Tod durch Kollision mit WEA beobachtet.

Die Windenergiegewinnung befindet sich somit in einem Spannungsfeld zwischen energie- und klimapolitischen Zielsetzungen auf der einen Seite und den Zielen des Immissions-, Natur- und Freiraumschutzes auf der anderen Seite. Die sich daraus ergebenden Landnutzungskonflikte könnten sich zukünftig noch verstärken, da die Ressource Land durch den allgemeinen Flächenverbrauch, beispielsweise für Siedlungs- und Infrastrukturfläche, bereits ein immer knapperes Gut wird. Dem entsprechend ist der zusätzliche Flächenbedarf für die Windenergie immer schwieriger zu realisieren. Es stellt sich somit die Frage, ob eine nachhaltige, ressourcenschonende Landnutzung unter Integration der Windenergie möglich ist.

Die vorliegende Arbeit leistet im Rahmen des vom BMBF geförderten Forschungsvorhabens „Nachhaltige Landnutzung im Spannungsfeld umweltpolitisch konfligierender Zielsetzungen am Beispiel der Windenergiegewinnung - FlächEN“ einen Beitrag zur Klärung dieser Fragestellung. Der Schwerpunkt lag auf der Bearbeitung energie- und naturschutzfachlicher Problemfelder. Das übergeordnete Ziel dieser Promotion war es, zur Minimierung der beschriebenen Landnutzungskonflikte beizutragen, um damit den Ausbau der Windenergie zu

fördern, ihre Akzeptanz in der Bevölkerung zu erhalten sowie den Zielen des Natur- und Umweltschutzes gerecht zu werden.

Vor diesem Hintergrund erfolgte zunächst eine vergleichende Analyse zweier deutscher Untersuchungsgebiete: West-Sachsen und Nord-Hessen. Basierend auf Landnutzungs-, Landbedeckungs- und Winddaten wurde die Effektivität der ausgewiesenen Vorrang- und Eignungsgebiete (VE-Gebiete) zur Windenergieproduktion in den beiden Regionen untersucht. Darüber hinaus wurde das Repowering-Potenzial (Ersetzen alter WEA durch neue, effizientere WEA) für unterschiedliche Technologieoptionen analysiert.
Die Ergebnisse wurden dann einem erweiterten Ansatz gegenüber gestellt, der alternative Standorte für WEA (Reallokation) zu den bereits ausgewiesenen VE-Gebieten ermittelte. Dabei wurde, neben der Einhaltung rechtlicher und naturschutzfachlicher Kriterien sowie dem Mindestabstand zu Siedlungen, der Schwerpunkt auf die energetische Qualität der Standorte gelegt. Es konnte gezeigt werden, dass die derzeitige, räumliche Allokation der VE-Gebiete in beiden Regionen durch Repowering, durch die Reallokation von WEA sowie durch die Kombination beider Ansätze energetisch noch effizienter gestaltet werden kann. Damit sind deutliche Leistungszuwächse in beiden Regionen möglichen.

Im Rahmen der Promotion wurden weiterhin die Auswirkungen von WEA auf die Avifauna analysiert und Methoden zur Konfliktminimierung entwickelt. Grundsätzlich dürfen WEA nicht in Natur- oder Vogelschutzgebieten errichtet werden. Jedoch sind nicht alle Vogelarten aufgrund ihrer Mobilität an diese Schutzgebiete gebunden. Von der Regionalplanung werden daher Pufferzonen um Brutplätze sowie Schutzkorridore für bekannte Vogelzugrouten außerhalb von Schutzgebieten ausgewiesen, die von WEA freigehalten werden müssen. Jedoch schließt dieses pauschale Vorgehen weite Flächen der Region von einer Nutzung durch WEA aus, wodurch sich die Flächenverfügbarkeit weiter reduziert. Somit besteht ein Konflikt zwischen den Zielen des Artenschutzes und dem notwendigem, weiteren Ausbau der Windenergie.
Deshalb bestand ein wichtiges Ziel dieser Arbeit darin, speziell für dieses Problemfeld Lösungen aufzuzeigen. Der Konflikt wurde am Beispiel des Rotmilans (*Milvus milvus*), einem besonders häufig mit WEA kollidierendem Greifvogel, in der Region Westsachsen untersucht. Basierend auf windenergetischen und ornithologischen Daten wurden die verschieden WEA-Standorte hinsichtlich ihres jährlichen Energieertrags und ihres Einflusses auf die lokale Rotmilanpopulation bewertet. Für die Abschätzung der Auswirkungen auf den Rotmilan wurde ein spezieller, abstandsbasierter Indikator entwickelt: eine sogenannte Impact

Funktion. Diese Impact Funktion bewertet in einfacher Weise das Kollisionsrisiko des Rotmilans als Funktion des Abstandes zwischen Vogelhorst und WEA. Ihre funktionelle Form wurde aus Literaturangaben und den Erfahrungen von Ornithologen hergeleitet.
Im Rahmen eines ökologisch-ökonomischen Modellierungsverfahrens wurden dann, unter Berücksichtigung der potenziellen Energieerträge und des zu erwartenden Risikos für den Rotmilan, mit Hilfe einer sogenannten *efficiency frontier*, pareto optimale Landnutzungsszenarien identifiziert. Das sind Allokationsmuster für WEA, die den Energieertrag maximieren, ohne gleichzeitig das Kollisionsrisiko des Rotmilans zu erhöhen. Ein Vergleich zwischen dem derzeitigen Allokationsmuster der WEA und den identifizierten pareto optimalen Landnutzungsszenarien zeigt deutliche Defizite bei ersterem auf.
Unter Verwendung der ermittelten *efficiency frontier* wurde ein Indikator abgeleitet, mit dessen Hilfe die Schwere des Konflikts zwischen der Expansion der Windenergie und dem Schutz des Rotmilans innerhalb der Untersuchungsregion gemessen werden kann. Dadurch ist es möglich, verschiedene Regionen oder Windparks miteinander zu vergleichen, um jene auszuwählen, die den geringsten Konflikt aufweisen.
Darüber hinaus wurde der Einfluss eines weiteren flächenrelevanten Parameters, des Mindestabstandes von WEA zu Siedlungsflächen, untersucht. Dabei stellte sich heraus, dass sich mit zunehmendem Siedlungsabstand der Konflikt zwischen Windenergie und Rotmilanschutz verschärft.

Um ein besseres Verständnis des Konflikts zwischen Windenergie und Rotmilanschutz zu erlangen, wurde ein Individuen basiertes Modell (IBM) entwickelt. Dieses Modell simuliert den Nahrungssuchflug eines Rotmilans ausgehend von seinem Horst in einer heterogenen Landschaft. Mit Hilfe dieser Simulationsrechnungen konnte die Kollisionswahrscheinlichkeit eines Rotmilans, in Abhängigkeit vom Abstand zwischen dem Horst und einer WEA, die in verschiedenen Abständen zum Horst aufgestellt wurde, bestimmt und daraus eine Impact Funktion berechnet werden. Diese Herangehensweise zur Bestimmung der Impact Funktion mittels Individuen basierter Modellierung ist auch für andere gefährdete Vogelarten geeignet.

Die entwickelten Methoden und Indikatoren stehen Regionalplanern, Umweltbehörden und Organisationen sowie Wissenschaftlern offen. Es sind weitestgehend einfach zu verwendende Werkzeuge, welche die Planung von VE Gebieten effektiver sowohl für Anlagenbetreiber als auch für den Naturschutz gestalten können.

Danksagung

Während meiner Forschungsarbeit zur vorgelegten Dissertation und deren Niederschrift wurde ich von vielen Menschen begleitet und unterstützt, denen ich an dieser Stelle danken möchte.

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List of Abbreviations

ABM	Agent-Based Modeling/ Agent-Based Model
ATKIS	Amtliches Topographisch-Kartographisches Informationssystem
a.g.	Above Ground
AUC	Area Under the Curve
BWE	Bundesverband Windenergie e.V.
CE	Choice Experiments
CO_2	Carbon Dioxide
DWD	DeutscherWetterdienst
EE	External Effects
EEM	Ecological Economic Modeling
GHG	Greenhouse Gas
GIS	Geographic Information Systems
IBM	Individual Based Modeling/ Individual-Based Model
IF	Impact Function
ISEE	International Society of Ecological Economics
IWES	Fraunhofer Institute for Wind Energy and Energy System Technology
NABU	Naturschutzbund Deutschland e.V.
POM	Pattern Oriented Modeling
VE	Vorrang und Eignungsgebiet *(Priority and Suitability Area)*
WEA	Windenergieanalge
WT	Wind Turbine

Chapter 1

Introduction

1.1 Background

Climate change is one of the biggest challenges faced by mankind in the twenty-first century. It is scientific consensus that climate change happens and represents serious global risks for both biosphere and the human socio-economic system (IPCC 2007). The timeframe to successfully mitigate climate change is short. Furthermore, the costs of the outcome of unabated climate change could be about five times higher than the costs for fast and early intervention to reduce greenhouse gas emissions (Stern et al. 2006). Hence, mitigation strategies have been developed. The main strategies are saving energy, improving energy efficiency, and moving energy supply systems towards renewable energy sources with the effect of reducing carbon dioxide (CO_2) emissions which are the main driver of climate change. In addition to their potential for reducing CO_2 emissions, renewable energies also enhance energy security by minimizing import dependencies and support sustainable development while assuring economic growth.

Germany has played a pioneering role in this development. Its leading position in Europe in generating energy using renewable energy sources (BMU 2010 p. 43) is backed by legislation, for example the "Stromeinspeisegesetz" *(Electricity feed-in Act)* (StromEinspG 1991) and the "Erneuerbare-Energien-Gesetz" (*Renewable Energy Sources Act*) (EEG 2000, 2004, 2009). By 2009, 16.1 % of electricity generation and 10.3 % of the end energy consumption in Germany originated from renewable energies. Consequently, in that year around 107 million tons of CO_2 emissions were prevented by substituting fossil fuels with renewable energies (BMU 2010).

By 2020 Germany's federal government aims to produce 30 % of its electricity from renewable energies (BMU 2009, EEG 2009). Current studies show that electricity produced from 100 % renewable energies is feasible in Germany by 2050 (FVEE 2010, SRU 2010, UBA 2010). Energy efficiency measures, energy reconstruction and electro mobility could lead to a reduction in energy-induced CO_2 emissions by 85 % (BMWi 2010, LEIT 2011) to 95 % (UBA 2010) in 2050 over 1990 levels.

In the process, wind power generation will play a large role in this through the extension of onshore and offshore installed capacity (FVEE 2010, SRU 2010, UBA 2010, LEIT 2011). The BMU (2010 p.38) estimates 50,000 MW onshore and 80,000 MW offshore as long term sustainable potential of installed capacity, while the UBA (2010) assumes a technical-ecological potential of 60,000 MW onshore and only 45,000 MW offshore. The latest study carried out by the Fraunhofer Institute for Wind Energy and Energy System Technology (IWES) on behalf of the BWE (2011), calculated an onshore potential of 198,000 MW if 2 % of the land were to be used for wind power generation. Based on these scenarios and an installed capacity of 25,777 MW in 2009, at least a doubling of onshore installed capacity by 2050 can be expected. To encourage this development the Renewable Energy Sources Act of 2009 raised the feed-in tariffs for wind power from onshore turbines from a current 0.0787 EUR per kilowatt hour (€/kWh) to 0.092 €/kWh (initial reimbursement for the first 5 years of operation).

However, there are two sides of the coin for extending wind energy supply. On one hand, there is a reduction of CO_2 emissions as well as a growing independence away from fossil fuels, motivating an investment in wind power technologies. On the other hand, the so-called negative externalities lead to resistance by the public at a local level. Negative externalities include negative health effects on humans through the light, shadow and noise emissions created by the turbines (e.g. Hau 2006, Rogers et al. 2006), the risk of disturbance, displacement or collision by birds and bats (e.g. Hoetker et al. 2006, Bright et al. 2008) as well as the impairment of the landscape (e.g. Krause 2001, Bishop 2002, Moeller 2006).

To minimize these externalities, the legal requirements for wind turbine (WT) sites were intensified by the federal government. The EEG (2004) only grants a feed-in tariff, when the energy produced by a WT reaches at least 60 % of a pre-defined reference yield level. In addition, the site selection for WT is defined largely by regional planning authorities in the federal states in order to avoid an uncontrolled extension of wind power developments. The planning authorities are increasingly concentrating wind power development in so-called "Vorrang-und-Eignungs-Gebieten" (*priority and suitability areas*, VE areas).

Wind power is given priority in these VE areas but at the same time WTs are excluded from all other parts of the planning region under consideration (Koeck and Bovet 2008). This leads to a concentration as well as a limiting of areas for wind power generation. Hence, planning authorities play a large role in the future development of wind energy. The identification and evaluation of WT sites is a challenging task for regional planning authorities. While in the early 1990s wind turbines had a total height of around 80 to 90 m with a nominal capacity of 500 Kilowatt (kW), recent onshore WTs reach total heights of 200 m with nominal capacities of 6 MW. These new technologies demonstrate improved performance and better utilization of the wind energy potential. Hence, the replacement of older turbines is encouraged through an additional reimbursement by the EEG. However, most of the existing VE areas were designated during the 1990s according to the requirements of the state-of-the-art technology of that time. This raises various questions. Do VE areas designated in the 1990s satisfy the requirements of wind farm operators with respect to current and future technologies? Is there enough space for wind power generation using new technologies to fulfill climate protection aims? If not, what can be done to support planning authorities in identifying new sites for wind power development by taking into account the needs of wind farm operators, the interests of the public and the negative externalities of wind power production? These questions point towards a sustainability problem that must be solved quickly.

In this context, the interdisciplinary research project “Strategies for sustainable land use in the context of wind power generation” was established at the Helmholtz-Centre for Environmental Research – **UFZ,** funded by the “Bundesministerium für Bildung und Forschung” (*Federal Ministry for Education and Research,* BMBF) (Contract number: 01UN0601A, B)**.**

1.2 The Research Project “Strategies for sustainable land use in the context of wind power generation”

The interdisciplinary research team consists of four UFZ departments – (i) Economics (ii) Ecological Modeling (iii) Environmental and Planning Law and (iv) Environmental Informatics - as well as the Department of Landscape Economics at the Technical University Berlin (TU Berlin). The scientific community was supported by experts and affected stakeholders like the regional planning authorities of West Saxony and North Hesse, the Bundesverband WindEnergie e.V. (*Federal Wind Power Association*, BWE) and the “Deutscher Naturschutzbund” (*Nature and Biodiversity Conservation Union*, NABU).

The project was named FlächEn-project (a German acronym for area - "Fläche" and energy - "Energie") and was conducted at the UFZ between 2007 and 2010. The FlächEn-project aimed to develop a methodology for identifying economically optimal sites for wind power plants in the landscape. An important new focus and challenge of this project was the inclusion of external costs and thus a wider context to define economic optimality. Therefore, operational costs and benefits are not the only criteria for determining an economically optimal allocation, but external costs are as well. "External costs" is a term used in the field of economics. Such costs arise when the social or economic activities, (here the erection and the operation of wind power plants) of one group of people have an impact (see below) on another group and when that impact is not fully accounted or compensated for by the first group (EUC 2003). As such external costs are especially important in the context of wind power generation, the project focuses on the quantification of these costs and their integration in a GIS-based ecological-economic modeling process to identify economically optimal allocation patterns for wind power plants in the landscape. A detailed project description can be found in the book "Ein Verfahren zur optimalen räumlichen Allokation von Windenergieanlagen: Anwendung in zwei Planungsregionen" (Drechsler et al. 2010). Figure 1 displays the general structure of the FlächEn-Project.

External costs depend on the External Effects (EE) of wind power generation. Such EE are e.g. impairment of the landscape by the erection of wind turbines, the emission of noise, light and shadows as well as adverse effects of wind turbines on avifauna and bats. The external costs were determined using Choice Experiments (CE). These are survey-based tools for the economic and monetary valuation of external effects (Bateman et al. 2002, Hanley and Barbier 2009). CEs can evaluate not only changes in one single attribute but also changes in multiple attributes independently of one another. This is revealed to be a great advantage of these surveys. For the current study, the following attributes and their changes were evaluated: the size of the wind farm, the maximum turbine height, the impact on the red kite and the minimum distance to a settlement. A detailed description of the CEs and their results can be found in Meyerhoff and Drechsler (2010), Meyerhoff et al. (2010). The results of the CEs allow for the determination of the so-called demand function for wind energy production sites (Fig. 1, left side).

These empirical investigations provide information on the extent and scope of the externalities of wind power for a given development scenario and the preferences of the respondents.

All of the information was incorporated into an ecological-economic modeling framework, assessing the planning and regulatory procedures for the designation of WT sites and giving recommendations for optimization and re-optimization of land use by WTs. The ecological-economic model is based on spatial wind power data, stored and processed in a Geographical Information System (GIS). The spatial data includes regional wind energy potential, settlement structure, location and status of conservation areas and nesting locations of the species under consideration. Based on this data, the land use conflicts of wind power developments and the negative externalities were qualitatively and quantitatively analyzed. The energetic potential of the study region in relation to these negative externalities, identified by the spatial analysis, form the supply function (Fig. 1, right side).
Finally, the ecological-economic modeling procedure merges the demand function with the supply function, identifying economically optimal sites for wind power development.

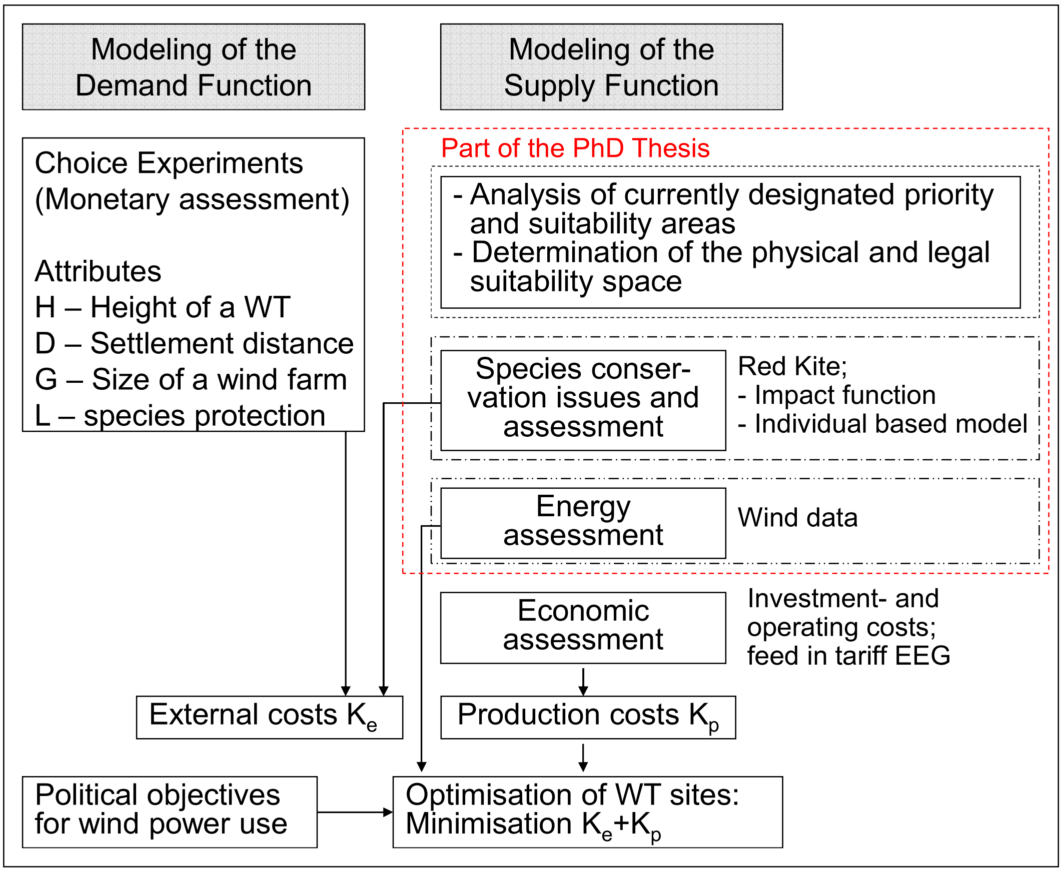

Figure 1.1: Structure of the FlächEn project. (Based on Figure 16.1, (Johst 2010))

1.3 The PhD Thesis "Sustainable land use through wind power – A conflict between climate protection and nature conservation" in the FlächEn-project

This PhD thesis was conducted at the Department of Ecological Modeling. It analyzes the wind energy potentials of two study regions: West Saxony and North Hesse with regard to their natural and anthropogenic restrictions. These findings are an essential part of the development of the supply function (Fig. 1). The work focuses on analyzing the impact of WTs on nature conservation using the red kite as an example of a species particularly threatened by collision with WTs. Thereby, the development of appropriate assessment procedures plays a central role. The red dashed square in Figure 1 represents the scope of this PhD thesis.

Within this PhD thesis, the following four aspects of the FlächEn-project were investigated (see Fig. 1.1):

1. Analysis of land availability and site quality for wind power development

2. Development of a methodology for:
    a. Identifying wind turbine sites with low collision risk and high energy yield
    b. Assessing the severity of the conflict between certain species and wind power developments
3. Establishment of an Agent- or Individual-Based Model for the determination of a functional relationship between the wind turbine-aerie distance and the collision risk

4. Energy output assessment of potential wind turbine sites

1.4 Objectives of the PhD Thesis

The transfer of knowledge from scientific findings to planning practice is a challenging task. Planning authorities do not have sufficient information on how to cope with different inevitable externalities (Madders and Whitfield 2006). Nonetheless, they allocate VE areas for the development of potential wind power projects. Therefore, this work tackles the challenge of supporting regional planning authorities with new scientifically-based methods and tools which are easy to adopt for in the designation of VE areas.

In this PhD thesis current and future VE areas will be investigated for the two study regions of West Saxony and North Hesse. These have similar current wind power development characteristics, but they differ in their land use attributes, most particularly in the settlement density. The thesis starts with a detailed analysis of the current wind farm allocation patterns in the two study regions and an investigation of the origin of these patterns.

Possible fields of conflict are identified if wind energy production will be further extended. In a next step, several options are analyzed that are deemed appropriate for easing such conflicts. The study regions are also evaluated based on their potential to contribute to the renewable energy supply system in Germany.

The extension of wind power goes along with the debate among the general public on the negative impact of WTs on the well-being of humans and on nature. Even if the WTs are in compliance with legal restrictions and the EEG reference yield criterion, they can have negative externalities. Particularly birds, which cannot be enclosed in protected areas, are susceptible to collision with wind turbines. In this case, predatory birds are particularly prone to collision (Mammen and Duerr 2006, Lekuona and Ursúa 2007, de Lucas et al. 2008). In current practice, collision risks are addressed by declaring buffer zones around known nesting locations (RPW 2008). However, the definition of these buffer zones is often arbitrary and does not consider bird population density. Therefore, a new method is developed in this PhD thesis to evaluate the impact of a wind turbine site on a predatory bird using the red kite as an example. This method allows the WT sites to be analyzed according to their energy output and their potential impact on the local red kite population. Thus, WT sites can be ranked with regard to their suitability for energy production and their impact on nature. Various WT allocations can be compared on this basis.

Despite the already existing buffer zones, many bird collisions with WTs are documented every year. Although investigations into the collision frequency of birds with WT have been made, empirical studies on the relationship between the distance of the WT to the aerie and the resulting collision risk are lacking. However, it is this specific information that is needed for the optimal allocation of WTs in the landscape. To gain this information, computer simulation models can be used. They offer the possibility of carrying out virtual experiments on birds flying and foraging in a given virtual landscape and of determining the resulting collision risk in relation to WT aerie distances. In this PhD thesis an Agent-Based Model (ABM) is developed for this task. In a first step, the flying and foraging behavior of the predatory bird is modeled. During these foraging flights, the bird enters areas occupied by a WT. Even when this happens there is only some probability of a bird colliding with a WT because of its avoidance behavior among other factors. This probability is derived in a second step by combining different information and data from literature. Finally, the ABM calculates collision risk as a function of WT aerie distances and according to the behavioral rules of the foraging bird.

In summary, this PhD thesis aims to minimize land use conflicts arising from the need to extend wind power onshore and the need to protect the health and well-being of humans and nature conservation, by addressing three main questions:

1. Does the current planning practice for wind power project development encourage an efficient extension of wind power generation to achieve climate protection aims? And if not, what are the measures to improve the extension of wind power?
2. How can suitable sites for wind turbines be identified with the objective of increasing wind energy production and minimizing ecological impact on, for example, a threatened focal species?
3. Is it possible to simulate bird-wind turbine interactions by determining a functional relationship between aerie and wind turbine distance and the respective collision risk in order to assess the ecological impact of different WT sites?

1.5 Overview

The PhD thesis consists of eight chapters. Chapter 4, 6 and 7 correspond to journal articles and 5 to a book contribution including supplementary material and reference sections (Table 1.1). The respective references can be found at the end of each chapter.

Table 1.1: Publications used for this cumulative PhD thesis.

Chapter 4	Ohl, C. and **M. Eichhorn**. 2010. The mismatch between regional spatial planning for wind power development in Germany and national eligibility criteria for feed-in tariffs—A case study in West Saxony. Land Use Policy 27: 243–254.
Chapter 5	Monsees, J., **Eichhorn, M**. and C. Ohl. 2010. Securing energy supply at the regional level – The case of wind farming in Germany: A comparison of two case studies from North Hesse and West Saxony. In. Ed. Barbier, F. and S. Ulgiati. 2010. Energy options impact on regional scale. The NATO peace and security program. Springer.
Chapter 6	**Eichhorn, M**., and M. Drechsler. 2010. Spatial trade-offs between wind power production and bird collision avoidance in agricultural landscapes. Ecology and Society 15**:**10.
Chapter 7	**Eichhorn, M**., Johst, K., Seppelt, R. and M. Drechsler. In review. Model-based estimation of collision risks of predatory birds with wind turbines. Ecology and Society.

Chapter 2 gives a more detailed description of the two study regions in terms of topographic, climatic, and anthropogenic characteristics related to wind power which supplements the given descriptions within the journal publications. Chapter 3 introduces the methodological and scientific approaches which this work is based on.

Chapter 4 provides the analysis of the current allocation patterns of wind farm sites and a selection process for additional sites incorporating legal restrictions and energy outputs for the West Saxony study region. In Chapter 5 this analysis is extended to the study region of North Hesse and the findings are compared and discussed for both study regions. In Chapter 6, a new method of evaluating wind turbine sites from an energy and ecological perspective is developed and an approach is presented to determine the severity of the conflict between wind power development and red kite protection. Chapter 7 investigates the possibilities of modeling bird behavior and collision fatalities. It describes the development and application of the Agent-Based Model.

In Chapter 8 the findings of all investigations, presented in the individual chapters, are brought together and highlights and conclusion with respect to the objective of this PhD thesis are displayed. Thereby, attention is turn to its relevance for the planning and decision process of wind farms.

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Chapter 2

Study Region and Data

Two regions, West Saxony and North Hesse, were studied as part of the research project and of this PhD thesis. The two study regions are introduced below with a focus on wind power-related (natural) potentials and expected areas of conflict. This is done for both study regions in a similar manner, pointing out the differences and similarities of the two regions. The administrative boundaries, geography, land use and climatic considerations are described. In addition to this, the habitation conditions for the focal species in the study regions were briefly sketched. Finally, conclusions were drawn according to the physical conditions for wind power developments and the potential for conflict in terms of human well-being and nature conservation. For further information about the reasons for selecting these study regions, see Monsees and Eichhorn (2010).

2.1 The West Saxony Study Region

Administrative Boundaries

The West Saxony study region is situated in the northwest of the federal state of Saxony, Germany. It comprises the area of the Regional Planning Authority of West Saxony as per the boundaries of 2007 (prior to the District Area Reform). The planning region consists of the independent city of Leipzig and the five surrounding districts of Delitzsch, Torgau, Döbeln, Muldentalkreis and Leipziger Land. It is bordered by the Saxon planning regions Upper Elbe Valley, Eastern Ore Mountains and South Saxony, the federal states of Saxony-Anhalt, and Brandenburg to the north/northeast and Thuringia to the southwest.

Geography

The West Saxony study region comprises an area of about 4,400 km² and has a population of about one million people. It has a high population density of 252 inhabitants per km² (in comparison, Germany has a population density of 231 inhabitants per km²).

The geographical classification of the study regions refers to the geographical classification of natural landscapes provided by the Bundesamt für Naturschutz (*Federal Agency for Nature Conservation*) (BfN 2008) based on the work of (Meynen and Schmithüsen 1953-1962). It is applied to both study regions of West Saxony and North Hesse.

West Saxony belongs to the regional landscape ("Großlandschaft") of the "North German Lowland" and is subdivided in two natural regions, the "Elbe-Mulde-Tiefland D10" and the "Erzgebirgsvorland und Sächsische Hügelland D19".

There are also more common regional classifications of the natural landscape which are not used in this work. This was first developed by Neef (1960) and later enhanced by Bernhardt et al. (1986) and Mannsfeld and Richter (1995).

The topography of the region is generally flat with altitudes ranging between 90 m above sea level in the northwest of the region to 325 m above sea level in the southeast (Fig. 2.1). Areas below 90 m are predominantly former or current mining areas. Most of them are scheduled to be flooded.

The Elbe and Mulde, two important rivers, run through the study region. The Elbe crosses the region from south to north in the northeastern part of the study region. The Mulde also flows in a northeasterly direction and runs through the central part of the region after the Zwickauer und Freiberger Mulde join. The Pleiße and the Weiße Elster are two smaller rivers in the western part of the region.

Land use

Only 16 % of West Saxony is covered by forests. Compared to the federal average of 29.5 %, it is one of the most sparsely wooded regions in Germany. This low proportion of forest is in contrast to an exceptionally high proportion of agricultural land amounting to approximately 63 % (Table 2.1) of the total area (the federal German average is around 53 %). The agricultural areas in the northwest and southeast are characterized by a predominantly high soil quality.

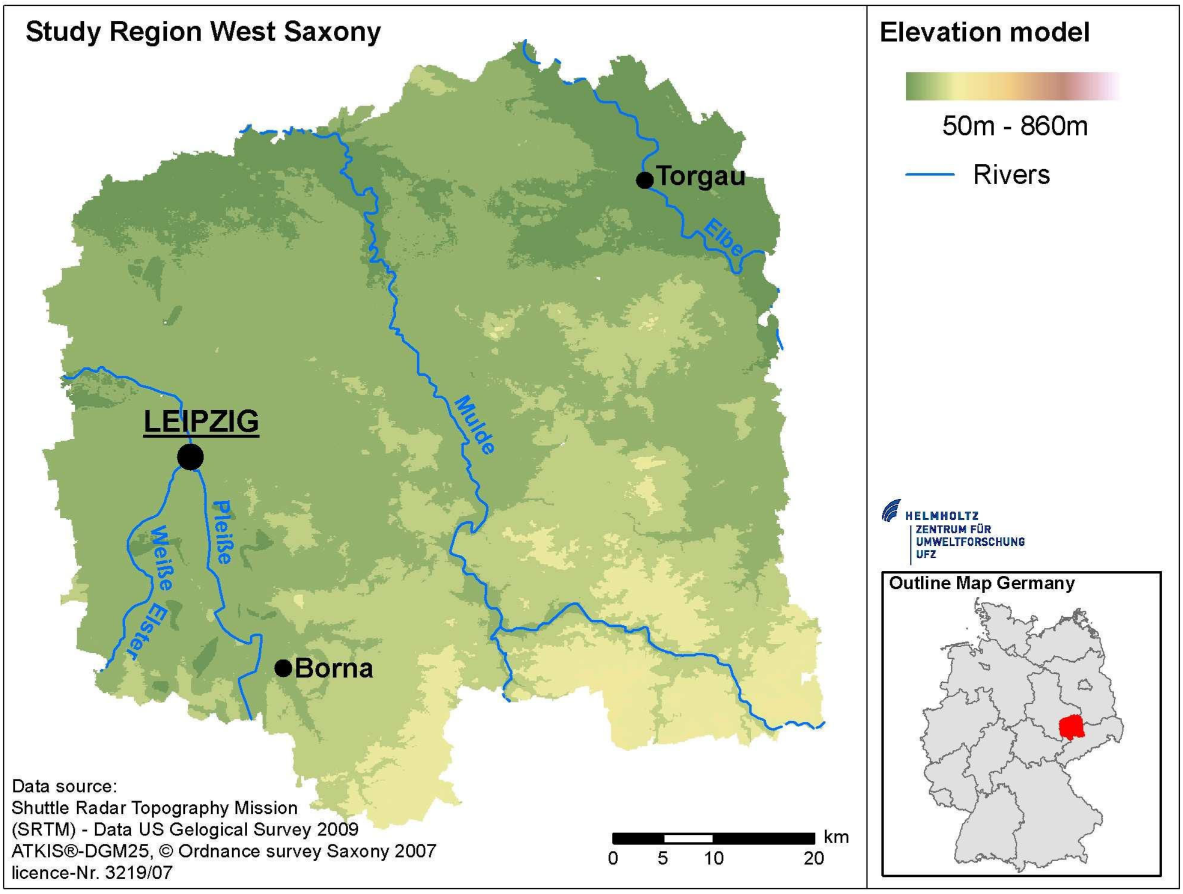

Figure 2.1: Digital elevation model of the West Saxony study region.

Table 2.1: Land use in the West Saxony study region.

Land use	**Proportion of land use area to total area (%)**
Settlement and transportation	12.5
Agricultural land	63.1
Forest	16.2
Bodies of water	1.9
Mining land	4.0
Miscellaneous	2.3

Source: (RPW 2008)

The wide-spread brown-coal mining of the last decades as well as a high number of mineral production sites results in a high portion of deposit areas, which, at 4 %, are double the average for the state of Saxony and eight times higher than the federal average (RPW 2008). Figure 2.2 illustrates the proportion of the main land use types in the West Saxony planning region.

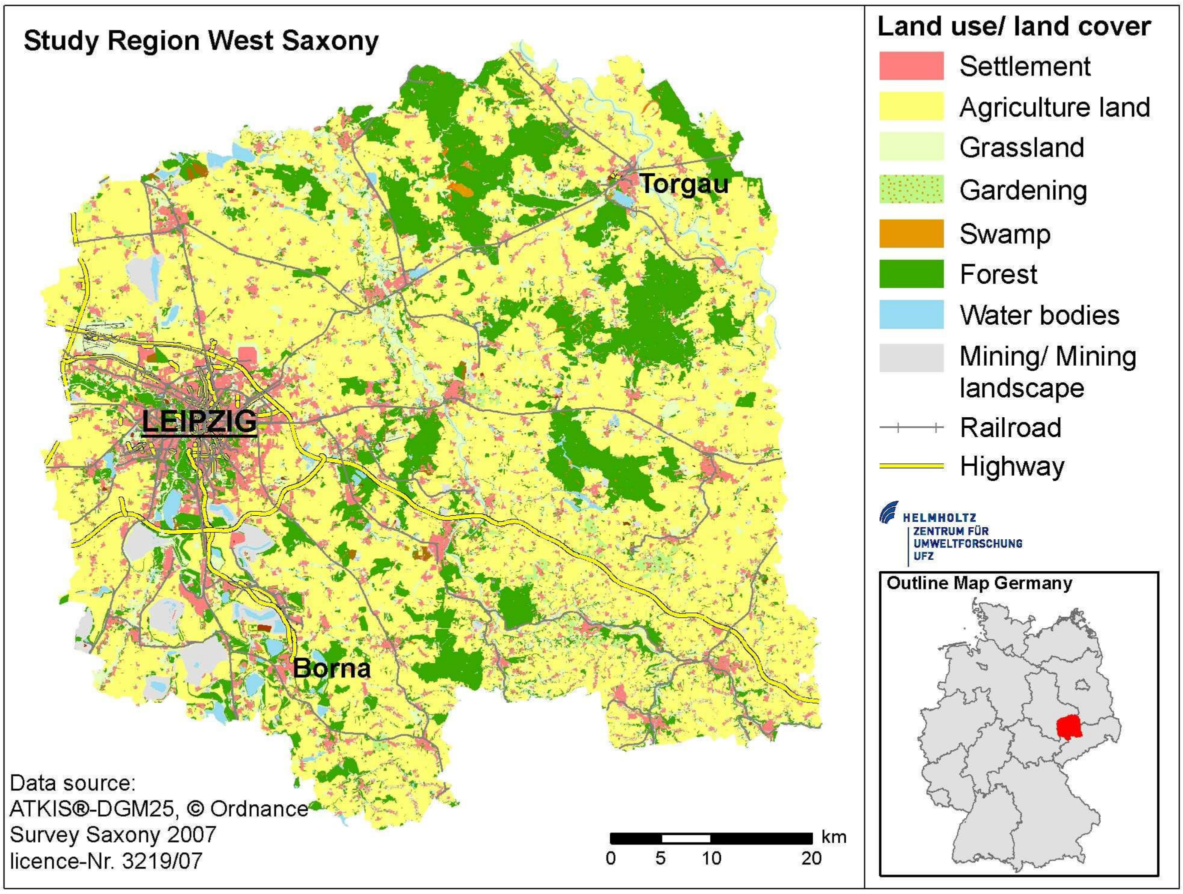

Figure 2.2: Land use in the West Saxony study region.

Climate

Germany, as well as Saxony, lies in the warm, temperate rain climate of the middle latitudes. It is situated in the transition area between the oceanic climate of Western Europe, where western air currents provide rainfall and mild temperatures year-round, and the continental climate of Eastern Europe, which is characterized by strong seasonal temperature fluctuations. The annual mean temperature is around 8° Celsius and the annual precipitation varies between 500 and 700 mm (Mannsfeld and Richter 1995). There has been an average of 150 hour of sunshine per month over the last twenty years. The annual wind speed at 10 meters above ground (a.g.) range from 1.6 to 4.0 meters per second (m/s); at 80 m a.g. from 3.8 to 5.7 m/s (DWD 2007) (Fig. 2.3).

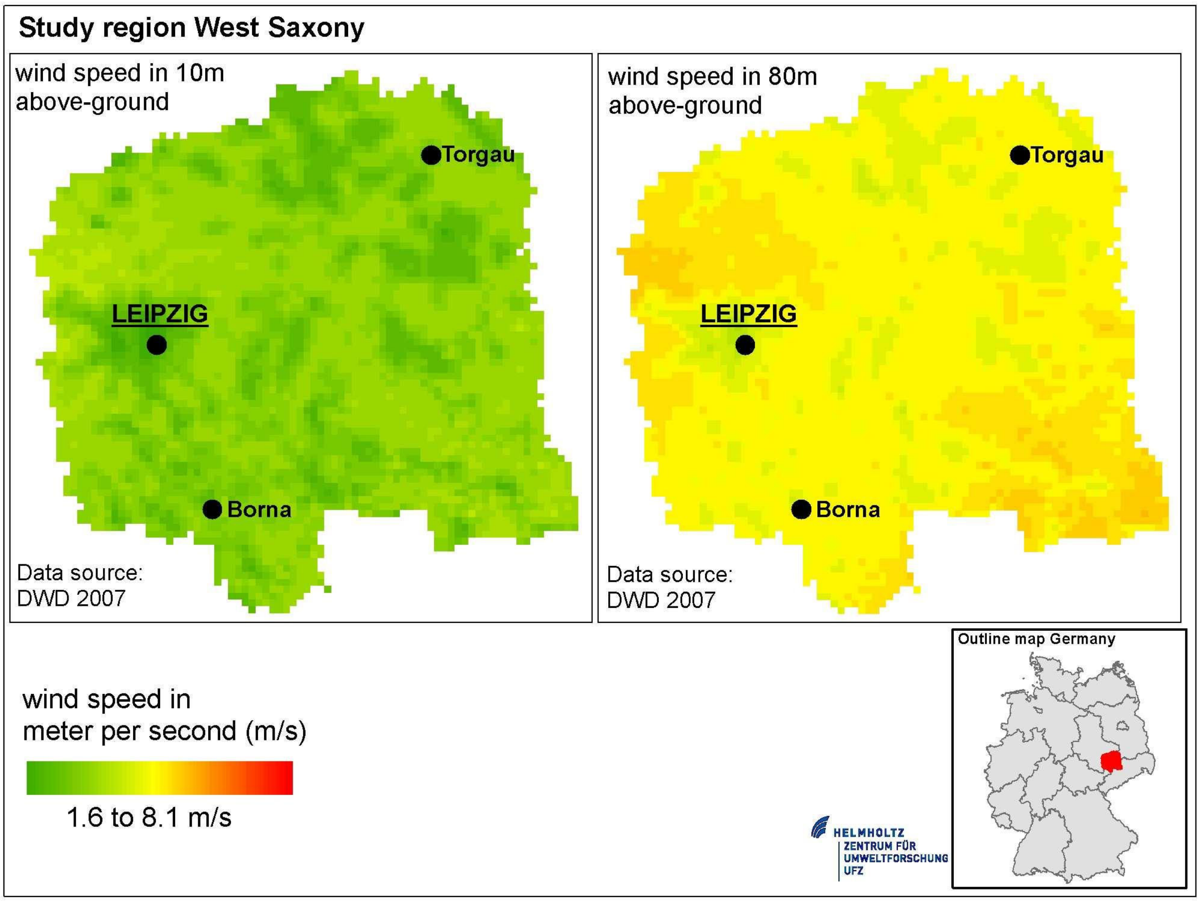

Figure 2.3: Average annual wind speed at 10 m and 80 m above ground.

The Red Kite in West Saxony

West Saxony's land use structure meets the needs of the red kite. The high proportion of open agricultural land offers good feeding conditions. The population in Saxony in 2000 is assumed to be 800 breeding pairs (Franz and Hormann 2003). According to the "Atlas of Saxon breeding birds" (Steffens 1998), West Saxony, in particular, is relatively densely populated. With 12.9 breeding pairs per 100 km² (Nachtigall and Ulbricht 2001) West Saxony is home to the highest number of red kites in Saxony.

Relevance of the Study Region for Research

West Saxony offers good conditions for wind power developments in terms of topography and land use (see Section 2.1 *Geography, Land use*). The mean annual wind speeds vary between 3.2 m/s (at 10 m a.g.) and 5 m/s (at 80 m a.g.). Hindering factors are the high population density (Section 2.1 *Administrative Boundaries*) and the high occurrence of the red kite as one of the species most prone to collision with wind turbines. This make conflicts with human well-being and nature conservation very probable.

2.2 The North Hesse Study Region

Administrative Boundaries

The study region of North Hesse is situated in the northwest of the state of Hesse in the centre of Germany (Fig. 2.4, overview map). It is part of the planning region North Hesse. Since this planning region is around twice the size of the planning region of West Saxony (8,289 km² vs. 4,388 km²), only a section was considered in order to keep the results comparable. The selected part, hereafter referred to as the North Hesse study region, comprises the districts of Kassel, Waldeck-Frankenberg, Schwalm-Eder-Kreis and the city of Kassel. It borders North Rhine-Westphalia to the west and northwest, Lower Saxony to the north, the Northern Hesse districts of Werra-Meißner-Kreis and Hersfeld-Rotenburg to the east and the planning region Middle Hesse to the south.

Geography

The study region has an area of 4,786 km² and a population of about 785,000 with an above-average population density of 164 inhabitants per km².

According to the geographical classification of natural landscapes (Section *2.1 Geography*), the study region is located completely in the Central European low mountain range land. It is divided into four natural regions: the "Bergisches Land, Sauerland (Süderbergland) (D38)", "Unteres Weserbergland und Oberes Weser-Leinebergland (D36)", "Osthessisches Bergland (Vogelsberg und Rhön) (D47)" and - making up the largest part - "Westhessisches Berg- und Beckenland (D46)" (BfN 2008). North Hesse is characterized by widely forested, heterogenic topography. Elevation ranges from around 100 m along the Weser in the northern-most part to around 850 m in the foothills of the Rothaargebirge near Willingen (Upland) located in the east of the study region. Further mountain ranges are the "Kellerwald (675 m)", "Habichtswälder Bergland (615 m)", "Reinhardswald (472 m)" and the "Knüllgebirge (635 m)". A clear elevation gradient as in West Saxony (northwest to southeast) cannot be ascertained (Fig. 2.4).

The Weser, which is created through the joining of the Fulda and Werra near Hanoversch Münden in the northeast of the study region, is the most significant river. It runs around 40 km in a south to north direction through the outer northeastern part of the region. Further important rivers are the Fulda, the Diemel, the Schwalm and the Eder forming the Eder-reservoir, one of the biggest reservoirs in Germany.

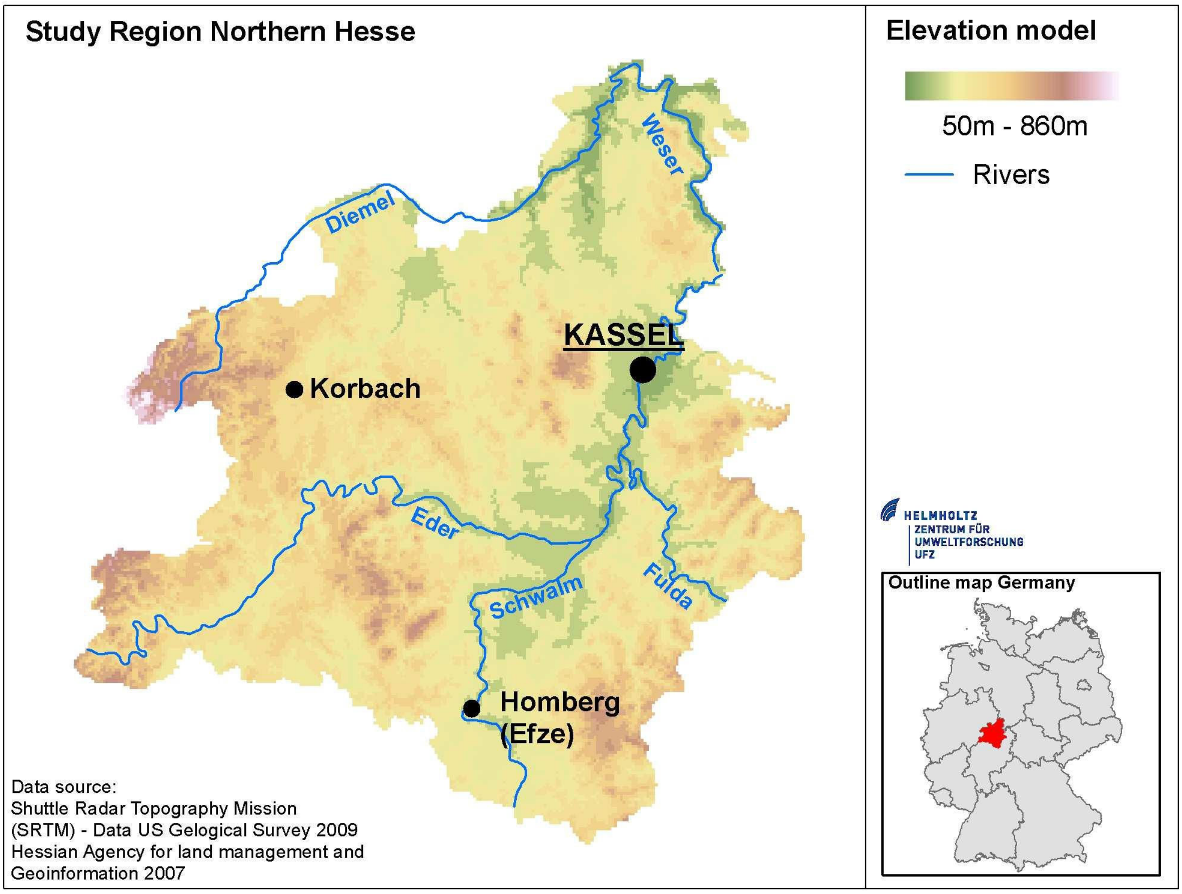

Figure 2.4: Digital elevation model of the North Hesse study region.

Land use

The land use of the study region is dominated by agriculture and forest in similar proportions (Table 2.2). North Hesse is more densely forested (40 %) than West Saxony (16 %) and the federal average (31 %, (BWI 2002)). Figure 2.5 illustrates the proportion of the main types of land use in the North Hesse planning region.

Table 2.2: Land use in the North Hesse study region.

Land use	**Proportion of land use area to total area (%)**
Settlement, transportation, miscellaneous	13.8
Agricultural land	44.8
Forest	40.0
Bodies of water	1.4

Source: (HSL 2008, RVN 2009)

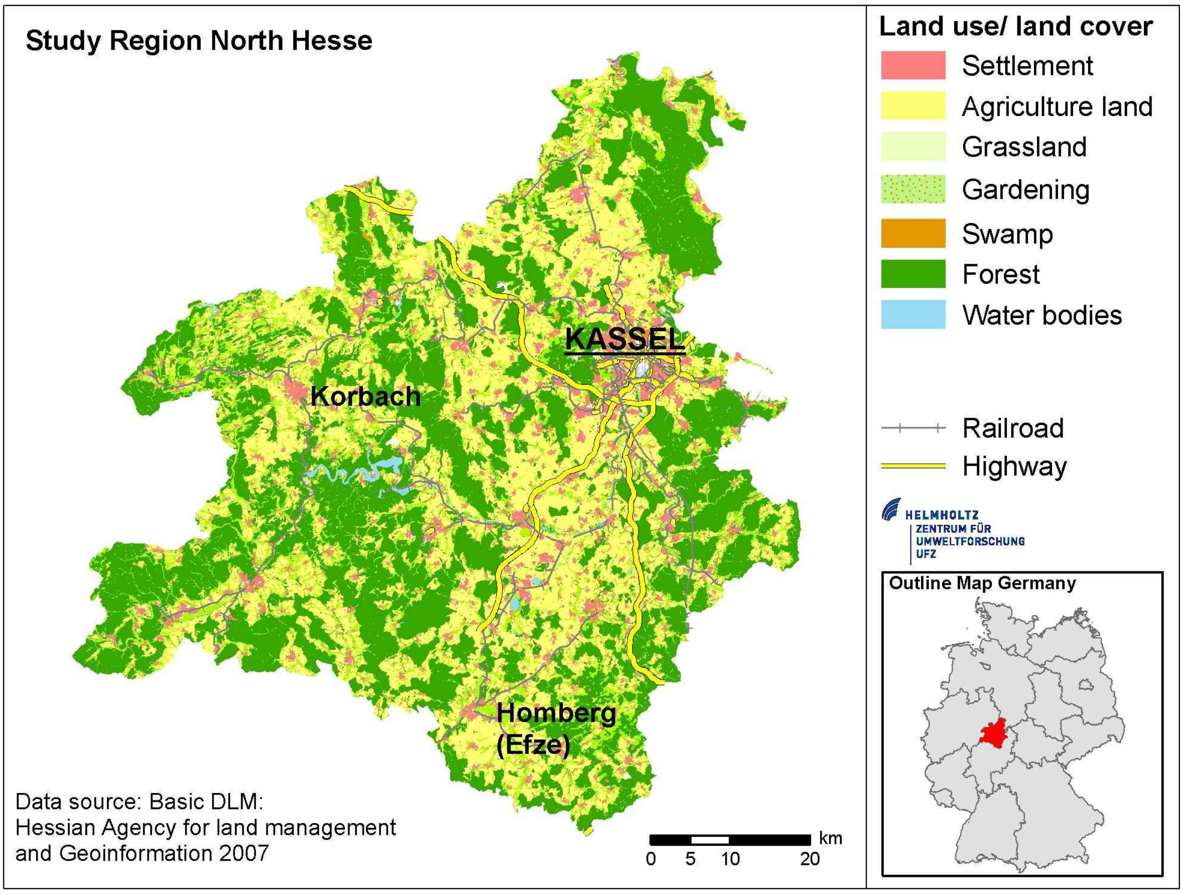

Figure 2.5: Land use in the North Hesse study region.

Climate

Hesse, like Saxony, is also located in the warm, rain climate of the temperate zone (Pletsch 1989). Dominated by westerly winds, wet air masses producing rain are brought in from the Atlantic throughout the year.

The climate is highly structured due to the topographic structure of the region, with its low mountain ranges that include various flat landscapes. The temperature is mainly affected by altitude. The annual mean temperature in Kassel (231 m) is 8.9° C whereas in Willingen (580 m) the annual mean temperature is 6.4° C (HSL 2010).

Precipitation in the region depends on the location of the mountains in relation to the main wind direction. On the windward side of mountains, the forced uplift of air increases cloud formation and rainfall while on the leeward side of the mountains, falling air dissipates clouds so that these areas are relatively dry. Thus, rainfall varies between 698 mm in Kassel and 1,226 mm in Willingen (HSL 2010). The annual wind speeds at 10 meters above ground (a.g.) range from 2.0 to 5.4 m/s; at 80 m a.g. from 4.3 to 8.1 m/s (DWD 2007). A regional distribution of wind speeds is illustrated by Figure 2.6.

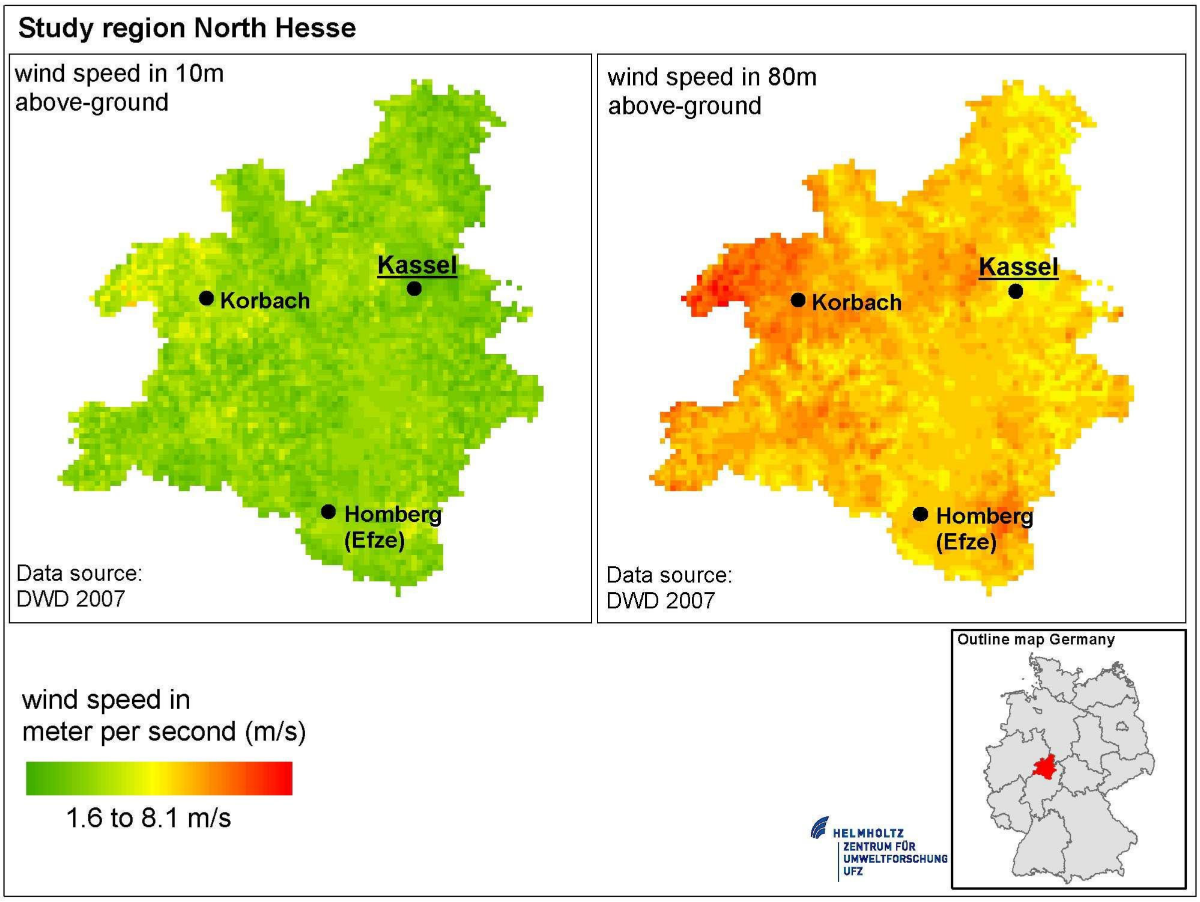

Figure 2.6: Average annual wind speed at 10 m and 80 m above ground.

The Red Kite in North Hesse

The land use structure and topography of North Hesse differs to that of West Saxony. North Hesse has low mountain ranges, a high proportion of forests and a low proportion of agricultural land. Indeed, the altitudes of the North Hesse mountain ridges (on average 325 m) allow a closed dispersal of the red kite (Walz 2005). However, a smaller percentage of open land and, thus, a greater scarcity of foraging habitats, hinder a higher abundance of the species. The mean abundance for Hesse is 4.5 breeding pairs per 100 km² (Walz 2005). A study concerning red kite breeding population and reproduction in North Hesse, looking at a 900 km² wide area in the Schwalm-Eder-Kreis, shows an average abundance of 8.3 pairs per 100 km² with a minimum of 5 pairs and a maximum of 11.7 pairs (Gelbke and Stübbing 2009).

Relevance of the Study Region for Research

The topography and land usage of North Hesse are different to that of West Saxony. While West Saxony is dominated by open, slightly hilly areas with a low percentage of forest areas, North Hesse is characterized by low mountain landscapes with an abundance of forest. Therefore a smaller percentage of open area is available. This restricts both the available sites for wind turbines and the foraging habitat for the red kite. However, higher annual average wind speeds (3.4 m/s [10 m a.g.] to 5.6 m/s [80 m a.g.]) and a lower population density makes this region interesting for wind power operators. Thus, conflicts between different land use demands and the protection of the red kite also arise in the context of limited space.

In conclusion, both regions physically allow (i.e. in terms of available area and atmospheric conditions) the development of wind power projects. As wind turbines are commonly erected in wide open areas, West Saxony offers a greater potential than North Hesse (63.1 % to 44.8 % of open agricultural land).

However, both regions have limiting factors that make them susceptible to conflicts both in terms of satisfying all land use demands and reaching climate and nature protection objectives. Therefore, both regions were selected in order to analyze such conflicts and to demonstrate the applicability of new methods and tools for minimizing such conflicts.

2.3 Data

To address the research questions of this PhD thesis (Section 1.4) a large amount of data was necessary and prepared. There are three main types of data:

1. Geographical data
2. Wind data and power curves of wind turbines
3. Empirical data on the red kite's flying and foraging behavior

The geographical data includes land use/ land cover data and elevation models in the form of ATKIS and CORINE data and different types of conservation areas. They were used to identify potential wind turbine sites.

The wind data were provided as Weibull parameters at different heights above ground. A detailed description of Weibull parameters in relations to wind power generation was provided by *The Danish Wind Industry Association: http://wiki.windpower.org/index.php/The_Weibull_distribution)* and respective literature (Hau 2006, Wizelius 2007).

Based on this data, the potential annual energy output was calculated for the wind turbines considered at the potential sites. The results were used for the economic evaluation and comparison of the different sites.

To analyze the collision risk of the red kite with a wind turbine, different empirical data concerning use of space, flight speed, flight duration and the like were explored by reviewing literature (Chapters 6 and 7). Table 4 shows the relevant geographical and wind data and their providers. The sources of the empirical behavior data for the red kite can be obtained in the references for Chapters 6 and 7.

Table 2.3: Data.

Land use data	**Contact**
ATKIS®-DGM25-West Saxony © Ordnance survey Saxony 2007 licence-Nr.3219/07	Ordnance Survey Saxony Olbrichtplatz 3, 01099 Dresden
ATKIS®-DGM25-North Hesse	Hessian Agency for Land Management and Geoinformation Schaperstrasse 16, 65195 Wiesbaden
Corine	Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR) Deutsches Fernerkundungsdatenzentrum (DFD) Oberpfaffenhofen D-82234 Wessling
Designated areas of the regional plan	Regional Planning Authority West Saxony Bautzner Str. 67, 04347 Leipzig
Designated areas of the regional plan Wind turbine locations North Hesse	Regional Planning Authority North Hesse Steinweg 6, 34117 Kassel
Wind turbine locations West Saxony	Agency for Environment, Agriculture and Geology Saxony Zur Wetterwarte, 01109 Dresden
Wind data	
Annual average wind speed on a 1 km grid for North Hesse and West Saxony at 10 m and 80 m	Deutscher Wetterdienst Klima- und Umweltberatung Frankfurter Strasse 135, 63067 Offenbach
Weibull parameter a and k on a 1 km grid for North Hesse and West Saxony at 10 m and 80 m	Deutscher Wetterdienst Klima- und Umweltberatung Frankfurter Strasse 135, 63067 Offenbach
Annual average wind speed on a 1 km grid for North Hesse and West Saxony at 78 m, 105 m and 140 m	EuroWind GmbH Sperberweg 2, D-50858 Köln
Weibull parameter a and k on a 1 km grid for North Hesse and West Saxony at 78 m, 105 m and 140 m	EuroWind GmbH Sperberweg 2, D-50858 Köln

2.4 References

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Chapter 3

Methodological and Scientific Approaches

The basic tool for all of the investigation was a Geographical Information System (GIS) which provided the spatially relevant information needed to develop the spatial models and, building on this, it is the methodological basis for further analyses. Section 3.1 will explain its application in detail.

The scientific approaches this PhD thesis is based on are Ecological-Economic Modeling (EEM) and Individual- or Agent-Based Modeling (IBM/ABM). EEM is used to identify optimal WT sites (Chapter 6). Furthermore, it establishes the framework for the analysis of the severity of the conflict between wind power developments and predatory bird conservation. ABM is used for investigating the existence of a relationship between the aerie-wind turbine distance and the resulting collision risk for the species of concern (Chapter 7). These two scientific approaches are considered in more detail below. Figure 3.1 illustrates the embedding of the scientific approaches within the PhD thesis.

3.1 GIS Based Modeling

Most of the data used for these investigations and analyses are geographical data or at least geo-related data (Section 2.3). Therefore, the Geographical Information System (GIS) is an important tool for editing and analyzing such data. This allows geographic (spatial) models of the study regions to be generated. These models form the basis of all applied analyses and investigations.

At the beginning, a criteria catalog for identifying physically and legally suitable sites for WTs was created (Eichhorn and Bovet 2010). It is similar in part to the restriction criteria defined in the regional plans (RPW 2008, RVN 2009), but is less restrictive. Only legally obligate restriction criteria were considered in the catalog. This catalog can also be used to select suitable sites for WTs in planning regions other than those used in this PhD thesis.

The GIS-based analysis consists of three steps. First, suitable and unsuitable sites for the erection of WTs are identified and isolated based on this catalog and in combination with the geographic models (Chapters 4, 5, and 6). Second, energy distribution maps are generated using wind energy data from Eurowind and the (DWD 2007). These are combined with the suitable sites for WT erection to determine the site and WT specific annual energy yield (Chapters 4, 5 and 6). Third, the spatial locations of red kite aeries are analyzed in relation to potential WT sites in order to identify the risk of endangering this bird through wind energy production (Chapter 6).

3.2 Ecological – Economic Modeling

Ecological-economic modeling is an ecological economics (EE) method. EE is created by combining the two disciplines of ecology and economics.

Ecology is commonly defined as the science of the relationship of plants and animals to their biotic and abiotic environment. Economics, in a broad sense, can be seen as the study of how human beings satisfy their needs and desires.

For long times both disciplines coexisted, more or less, without acknowledging one other. However, early economists did incorporate natural environment specifically in terms of the availability of land (classical economics (Smith 1776)).

Later, in neoclassical economics, established in around 1950, theories ignored the relationship between human economic activity and natural environment. They assumed that, given proper economic management, the living standard could go on rising indefinitely (Comen and Stagl 2005).

However, in the 1970s and 1980s it was concluded that indefinite growth is not possible (Meadows et al. 1972). Human economic activity depends on as well as impacts on the ecosystem and the services which it provides it provides. So a logical step was to incorporate the knowledge and experience of both disciplines, ecology and economy, to tackle the challenges of sustainable economic growth.

The first formal effort of bridging the gap between ecologists and economists was the 'Integrating Ecology and Economy' Symposium in Sweden in 1982 (Jannson 1984). Then in 1988 the *International Society for Ecological Economics* (ISEE) was formed (Costanza 2003). This established the first formal basis of ecological economics, even though a clear definition of EE was still lacking. According to Baumgärtner (2008) there are two central characteristics of EE. First, EE aims to “study how ecosystems and economic activity interrelate” (Proops 1989) and second it sees itself as “the science and management of sustainability” (Costanza 1991). Thus, EE investigates the relationship between the socio-economic and the ecological system with the aim of providing knowledge for a sustainable management of this relationship. This concept is used along this line to develop methods that enable wind turbines to be sustainably allocated in a specific landscape (Chapter 6).

In the field of ecology and economics, models play an important role in developing management recommendations. On the one hand, ecological models analyze the effect of conservation methods, management strategies or political decisions on spatiotemporal dynamics, the persistence of ecosystems and the viability of populations (Frank and Wissel 2002, Leslie et al. 2003). However, the use of modeling results in a political practice that is at times limited because such models often neglect socioeconomic requirements.

On the other hand, economic models address economic, institutional or political needs (Smith and Shogren 2002, Bulte and Horan 2003), but their practical use is often limited because of oversimplified or out-dated assumptions about the ecological impact of management measures.

To negotiate the limitations of disciplinary modeling, an integrated approach of economic and ecological knowledge is necessary (Waetzold et al. 2006, Drechsler et al. 2007, Baumgärtner 2008). Based on this requirement, the interdisciplinary approach of Ecological – Economic Modeling (EEM) has been established as part of ecological economics. Currently EEM is a widely-used tool to evaluate the impact of land use and to establish management strategies (Bockstael et al. 1995, Johst et al. 2002, Drechsler and Waetzold 2007, Huth and Tietjen 2007, Baumgärtner and Quaas 2009).

In this thesis, EEM is used within a spatially explicit multi-criteria framework. Here a typical conflict between economic interests of the wind farm operators and nature conservation is analyzed. For a given set of legally and physically suitable potential wind turbine (WT) sites those are identified that maximize energy output and minimize ecological impact (Fig. 3.1). This inclusion of the ecological impact and related external costs in the EEM of this thesis is a novel approach to optimally allocate WTs in a landscape. Thus EEM aims to identify wind turbine sites that maximize profit for a given level of external cost, here the impact on threatened predatory bird species (Fig. 3.1).

3.3 Agent- or Individual-Based Modeling

The method of agent- or individual-based modeling (ABM/IBM) dates back at least to the 1960s (Newnham 1964) but has become an explicitly delineated approach of ecological modeling through the work of (Huston et al. 1988). Lomnicki (1992) points out that "The essence of the individual-based approach is the derivation of the properties of ecological systems from the individuals constituting these systems." A more detailed definition for individual-based modeling is given by DeAngelis and Mooij (2005). As part of their comprehensive review, they state that "…IBMs simulate populations or systems of populations as being composed of discrete agents that represent individual organisms or groups of similar individual organisms, with sets of traits that vary among the agents. Each agent has a unique history of interactions with its environment and other agents. IBMs attempt to capture the variation among individuals that is relevant to the question being addressed."
Therefore, IBMs are more complex than classic analytical models because they incorporate many entities, spatial scales, heterogeneities and stochastic events among other things. This is both an opportunity and a challenge. On one hand, it is possible to explain observations that could not be made by classic models. On the other hand, there is the tendency to incorporate more detail than necessary and make the model too complex (Grimm and Railsback 2005).
A way to verify IBMs and to identify the right level of detail is to compare resulting patterns and dynamics with patterns observed in real systems. Such type of modeling is called pattern–oriented modeling (POM) (Grimm 1994, Grimm and Berger 2003, Wiegand et al. 2003, Grimm et al. 2005). This approach is very useful for IBMs but is also recommended for modeling exercises in general.

Many IBMs have been developed in the last twenty years. Early influential models are, for instance, JABOWA, named for the three scientists involved in its programming: JANAK-BOTKIN-WALLIS which describes the succession of a mixed-species forest to predict species composition (Botkin et al. 1972) or the fish population of DeAngelis et al. (1979) and Tyler and Rose (1994), and the fish school models of Huth and Wissel (1992, 1994). Today IBMs are used for a wide range of purposes. Out of 900 studies DeAngelis and Mooij (2005) seven groups of biological processes have been established for which IBMs have been developed. These are:

- Movement through Space
- Formation of Patterns Among Individuals
- From Foraging and Bioenergetics to Population Dynamics
- Explorative Species Interactions
- Local Competition and Community Dynamics
- Evolutionary Processes
- Management Related Processes

Within this PhD thesis, an individual-based model was developed in combination with a pattern-oriented modeling approach to predict the collision risk between a wind turbine and a central-place foraging raptor in relation to the WT to aerie distance (Fig. 3.1, Chapter 7). The work is related to two of the above mentioned groups of biological processes. First it belongs to the group "Movement through Space" that comprises models of local animal movement and includes their interactions with complex landscape structures and other entities. The movement of the "raptor-agent" was adapted to a predatory bird and parameterized to reproduce empirically-derived space use patterns. The movement behavior responds to landscape structure and habitat quality. Furthermore, the "raptor-agent" interacts with the wind-turbine entity. Under certain conditions (Chapter 7) the raptor dies by collision if it uses the air space close to the wind turbine. The IBM/ABM enables the calculation of the distances between the raptors' aerie and the wind turbines that lead to sufficiently low impact on individuals and thus on the raptor population. Therefore, the ABM also falls under the category of "Management Related Processes".

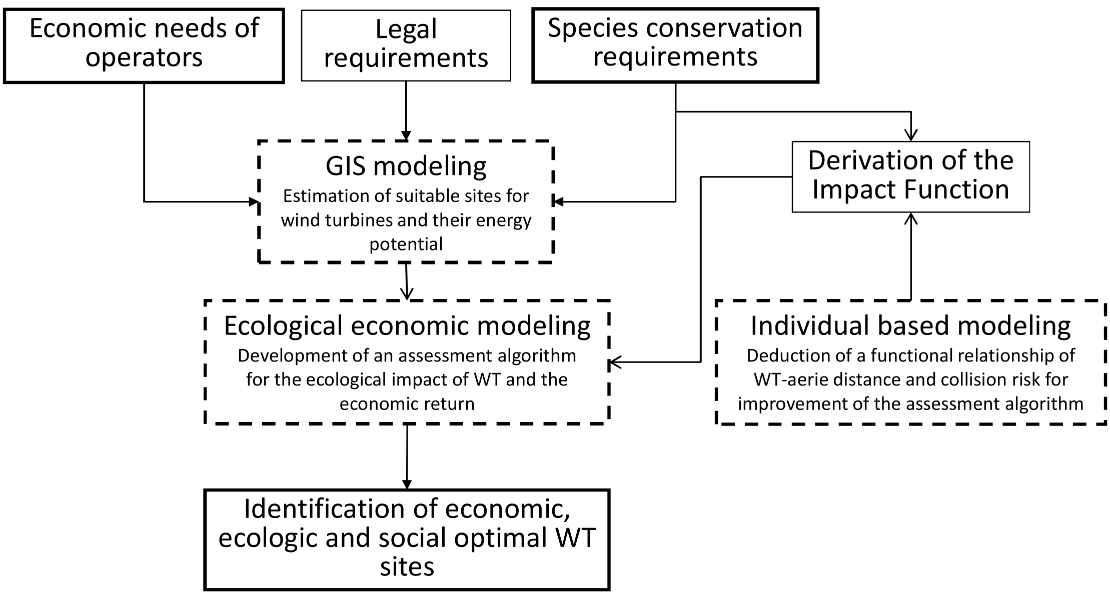

Figure 3.1: An overview of the scientific approaches and how they are embedded into the PhD thesis.

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Chapter 4

Regional Spatial Planning and Wind Power Development

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The mismatch between regional spatial planning for wind power development in Germany and national eligibility criteria for feed-in tariffs—A case study in West Saxony

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ABSTRACT

In future, wind power is to contribute decisively toward achieving climate policy goals. It can accomplish this, however, only if sufficient space for erecting wind turbines (WTs) is made available. In Europe we currently observe the trend that administrative landscape protection counteracts the desired development. Especially in Germany, the country that leads the world thus far in terms of installed capacity for wind power, the planning authorities are moving toward limiting locally available sites by designating so-called priority and suitability areas. These areas give the erection of WTs priority over other types of land uses but prohibit the erection of WTs outside these areas. The scale and the placement of these areas will be of great significance in future for securing wind energy supply at the regional level and thus for accomplishing national goals in climate policy. According to the regulations in the law revising the legal status of the Renewable Energy Sources Act (Erneuerbare-Energien-Gesetz, EEG, 2009), payment for wind power feed-in to the grid is granted only if, with regard to energy production, the WT to be erected yields at least 60% of a pre-defined standard performance level. With this regulation, the EEG wishes to prevent erecting WTs at locations inefficient for energy production. At the same time, however, higher standards are placed on the allocation of VE areas (priority and suitability areas) as a result. This poses the question: Does regional planning conform to such standards? With the example of the planning region West Saxony, we will evaluate the role the designation of VE areas plays in achieving Germany's wind energy ambitions. The case study reveals that the strategic search of VE areas by the regional planning authorities, involving local stakeholders and the public, hampers investment in state-of-the-art WTs as fostered by the EEG (2009). This leads us to the general conclusion that, even with a participatory design of strategic planning and a determined governmental policy, deployment of the wind resource is not a fast-selling item that in future may contribute decisively toward achieving the ambitious goals in energy and climate policy.

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Introduction

Countries all over the world are setting sails for increasing renewable energy supply, including the deployment of the wind resource. While, for example, the US has started to set targets for increasing renewable energy supply, countries in Europe, like the UK, France and Denmark, already concentrate on changing their institutional frameworks for accomplishing their ambitious energy targets. For an analysis of the redesign of feed-in tariffs for wind power after the liberalisation of the electricity market in Denmark, see, for example, Munksgaard and Morthorst (2008) for the present wind-first policy strategy in the UK, e.g., Cowell (2009) and for the new "flexible decentralized planning" approach in France, e.g., Nadaï (2007). With regard to these institutional changes, results from two branches of international studies in particular are important: studies that engaged in different aspects of national policy and institutional development (e.g., Lauber and Mez, 2004; Jacobsson et al., 2009; Toke et al., 2008; Wizelius, 2007) and studies more focused on the local aspects of wind power development by drawing upon different case studies (e.g., Breukers and Wolsink, 2007; Hull, 1995; Kellet, 2003). The results from the first branch of studies reveal that a determined governmental policy is an essential basic step for a broad implementation of renewable energies, including wind power development. On the other hand, results from the case studies point out that a prosperous and sustainable

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deployment of wind energy depends largely on local acceptance that can be fostered by the possibility and the improvement of public participation (e.g., Simão et al., 2009; Higgs et al., 2008) as well as by adequate placement of the wind turbines (e.g., Cowell, 2007; Gamboa and Munda, 2007). In contrast to the first branch of literature most of these studies take the investment in wind power development for granted. The results from the two branches of studies reflect the Janus face of wind energy supply: The advantage of reducing CO_2 emissions and dependency on fossil fuels by wind power development motivates the setting of incentives for investment in wind technology. On the other hand undesired impacts on humans and nature (so-called negative externalities) meet with resistance against implementation at the local level. Besides the negative health effects on people through light and noise emissions created by the turbines (e.g., Hau, 2006; Rogers et al., 2006), the risk of collision for birds and bats (e.g., Bright et al., 2008; Hötker et al., 2006,) as well as the impairment of the landscape (e.g., Bishop, 2002; Krause, 2001; Möller, 2006) can be cited.

Two different approaches are being discussed in order to make headway in wind power development: (1) a strategic search for acceptable wind power locations (e.g., see Cowell, 2009 in the UK context and Nadaï, 2007 for the French approach introducing the search of wind power development zones) and (2) a locally driven planning approach, involving local stakeholders and the public in the course of siting decisions (e.g., see McLaren Loring, 2007, for case studies in England, Wales and Denmark, highlighting the role public participation plays in planning of wind power development). The first approach is able to guarantee the efficiency of the sites for wind power development in terms of energy output; and the second approach is able to contribute to fostering the acceptance for local wind power development. Both aspects are crucial for increasing the quota of renewable energy supply by means of wind power. A combination of both approaches should thus be supportive for deployment of the wind resource.

This paper is structured as follows: In *Energy goals of German climate policy and the regional perspective—example: wind power* we will introduce the energy goals of climate policy in Germany, the prominent role wind power development will play in this regard and how development is fostered at the level of the planning regions. In *Study area and method* we will introduce a case study. Using the example of the German planning region West Saxony we will examine the potential for wind power development at the regional level with the help of a GIS-based framework. In *Results* we will point out a gap between available sites for wind power development in the region and the demand on the part of investors for sites with regard to the erection of state-of-the-art WTs. As a next step, we will sketch what decisions should be made as to location for the WTs, in order to maximize the developmental potential at the regional level (*Discussion*). On the basis of the insights gained, we will finally discuss a proposal to promote local wind power development (*Summary and prospects*).

Energy goals of German climate policy and the regional perspective—example: wind power

Germany's renewable energies program

The development of renewable energies in Germany is a primary strategy toward fulfilling the climate policy goals (BMU, 2008a, p. 2). As early as 2007, renewable energies were able to reduce CO_2 emissions by around 115 million metric tons (BMU, 2008b). The amended Renewable Energy Sources Act is now set to aid in raising the percentage of renewable electric energy from the current about 15% (BMU, 2008b) to at least 30% by 2020 and to continue beyond that date (EEG, 2009). To achieve this goal, expansion of wind power is planned as part of this development, both onshore as well as offshore. According to the regulations of the new Renewable Energy Sources Act, feed-in tariffs for wind power from onshore turbines are to be raised to 0.092 Euro per kilowatt hour (€/kWh) instead of the current 0.0787 €/kWh (initial reimbursement for the first 5 years of operation) and for electricity from offshore turbines 0.13 €/kWh instead of the current 0.0874 €/kWh.[1]

The German EEG is internationally recognised and serves as an archetype for the promotion of renewable energy supply in Europe and other parts of the world (BMU, 2007, p. 19). Analysing the incentives set by the regulations in the law revising the legal status of the Renewable Energy Sources Act (Erneuerbare-Energien-Gesetz, EEG, 2009) is therefore important for wind power development beyond the geographical boundaries of Germany. In this paper we will focus on the incentives set for onshore wind power development. In contrast to offshore sites, where in Germany the first wind farms with 60 MW installed power are not to go online until 2009/2010 (Netinform, 2008), the replacement of existing turbines onshore (so-called repowering) is being discussed heatedly. Repowering is the replacement of WTs that have been online for at least 10 years[2] by turbines that must deliver at least twice or, at a maximum, 5 times the power[3] of the replaced turbines in the same or in an adjacent district (Section 30 EEG, 2009). The new EEG will reward the repowering with a bonus payment in the amount of an additional 0.005 €/kWh to the initial reimbursement (Section 30 EEG, 2009). The additional payment should serve as a measure to promote the spread of state-of-the-art WTs which are expected to significantly increase the energy output simultaneously by drastically reducing the surface area required for onshore wind power development.[4]

State-of-the-art WTs are often taller than the existing turbines. At present, 2 MW turbines are offered by the three market leaders in Germany, Enercon, Vestas and Repower, with a total height of 100 m and more; at maximum state-of-the-art WTs may reach a total height of around 200 m. Since wind is stronger and more constant at higher levels than near to the ground, the height of the WTs is frequently a critical factor for guaranteeing the repowering bonus provided in the EEG. Therefore, given the local wind conditions, the additional performance required for repowering at the existing facility, or for repowering in the region in question, can be achieved frequently only with greater turbine height, i.e. with investment in state-of-the-art WTs. These turbines, however, are often seen at long distances and thereby create higher visual impact on the landscape than do smaller ones. Moreover, the effects of noise and light emissions from the turbines are altered as well. For these reasons, not only different feed-in tariffs apply to WTs used for repowering; they must also satisfy more restrictive legal requirements than those for the existing turbines. Greater light and noise impact requires higher standards for the mandatory minimum distance from built-up areas (for Germany see the Federal Emission Control Act, BImSchG, 2007). Also, regulations as to height may apply, for example, to protect air traffic (see, for example, Sec-

[1] For further ruling details, see http://erneuerbare-energien.de/inhalt/print/41897/, accessed: 28 August 2008.

[2] In comparison, the life span of WTs is an average of 20 years.

[3] The performance of a turbine is defined in Section 18 Clause 2 of the Renewable Energy Sources Act, EEG 2009. This may be understood generally as the quotient of the total of the feed-in electricity of the respective calendar year divided by the total of the rounded-off hours of the respective calendar year.

[4] As an example, the dena grid study calculated a decline of 7 hectares in the area use per megawatt (ha/MW) to 5 ha/MW solely through an increase in performance by 40 % (dena, 2005, p. 41). This relationship is in particular important for countries facing problems of land scarcity—which may, for example, be induced by the growth of settlement areas or restrictive land use policies for wind power development.

tion 12 of the German Air Traffic Act, LuftVG, 2008). That could prohibit the use of tall WTs and thus the spread of the-state-of-the-art technology at certain locations. Achieving the national targets for wind power development requires higher standards on the allocation of suitable sites as a result. This poses the question: Does regional planning conform to such standards?

Regional planning at the German Länder Level

Regional planning is the link between area development at the German Länder level (i.e. the State Development Plan) and the planning at the town and county level. The objectives of the regional planning are roughly defined in the respective State Development Plan (SDP); it deals with the efficient placement of land use activities, development of infrastructure and settlement area. The guidelines and tools to realise the objectives are given by the Federal Regional Planning Act (ROG, 2008). All German Länder follow this administrative structure (compare dena, 2005, pp. 4–7). At present, the German Länder are free to define their own targets for renewable energy supply in their SDPs. These targets are often unspecific regarding a desired regional development of different energy sources. As a result, the planning authorities are free to define their own benchmarks for the region.

Regarding regional development goals the Federal Regional Planning Act supports different types of land utilization (Köck and Bovet, 2008, p. 532).[5] Important for wind power development is the designation of priority areas (Vorranggebiete), suitability areas (Eignungsgbiete) and a combination of both, the designation of priority areas with the impact of suitability areas (Vorrang- und Eignungsgebiete; here, referred to as VE area). With regard to wind power development *priority areas* are defined as sites where the erection of WTs takes priority over other types of land uses while *suitability areas* are defined as sites where wind power development is feasible and then, as a result of this assessment, prohibited in other parts of the region. Combining both types of regulations leads to the designation of *VE areas* which, on the one hand, guarantee that the erection of WTs takes priority over other types of land uses but, on the other hand, prohibit the erection of WTs outside these areas. The scale and the placement of these areas are thus decisive for the amount of wind energy supply at the regional level and, on the national level for accomplishing the climate policy goals.

In Germany, more and more planning authorities make use of VE areas in order to control the expansion of wind energy in the region. This is due to the fact that in the 1990s the location of WTs was mainly a bilateral process between wind power operators (commercial and private) and authorities on the level of local municipalities. As a result, a dispersed placement of WTs (in Germany termed as “Verspargelung der Landschaft”)[6] took place which was fostered by the institutional settings that increased deployment of the German wind resource and led to Germany’s outstanding position in terms of installed capacity worldwide (compare BMU, 2008b): (1) the feed-in tariffs provided by the Electricity feed-in Act (1991), the EEG (2000, 2004) and the amendment of Section 35 of the German Federal Building Code in 1997, which gives priority to the erection of WTs in *outskirt areas* (in the Code referred to as “Außenbereich”). At present, the “Verspargelung der Landschaft” is counteracted by the designation of VE areas and the definition of minimum standard performance levels in the EEG (2004, 2009). Standard performance levels are defined in Clause 2 of Annex 5 of the EEG (2009). The definition focuses on the potential five-year energy output of a specific WT at a reference site in order to compare the quality of potential sites in terms of their energy productivity. Based on this assessment the payment for feed-in to the grid is tailored for each potential turbine type to a WT specific standard performance level (compare http://www.wind-fgw.de/). As a result, in order to receive the EEG-payment, operators of new WTs need to prove that the erection of the turbine in focus will yield at least 60% of the required standard performance level at the site considered for its erection. This should hamper investment in wind power at places where wind conditions are inefficient for WT erection. In this sense it supports the efforts of the planning region to foster a controlled expansion of wind power development by means of strategic planning. Against this background the qualities of the VE areas in terms of geographical scale and wind potential are especially important. Since the erection of WTs is prohibited outside the VE areas, their scale is decisive for the number of WTs which can be erected; and the wind potential of the site is crucial for receiving the payment for wind power feed-in to the grid according to EEG (2009), as the energy output of a WT must comply with the postulated standard performance level.

The following case study shows that regional planning is expected to pose a barrier to producing more wind energy if the relationship between the regional wind potential and available turbine types (especially the height of state-of-the art WTs) on the one hand and the resulting energy output on the other hand is not adequately taken into account when identifying the VE areas.

Study area and method

Regional planning in West Saxony

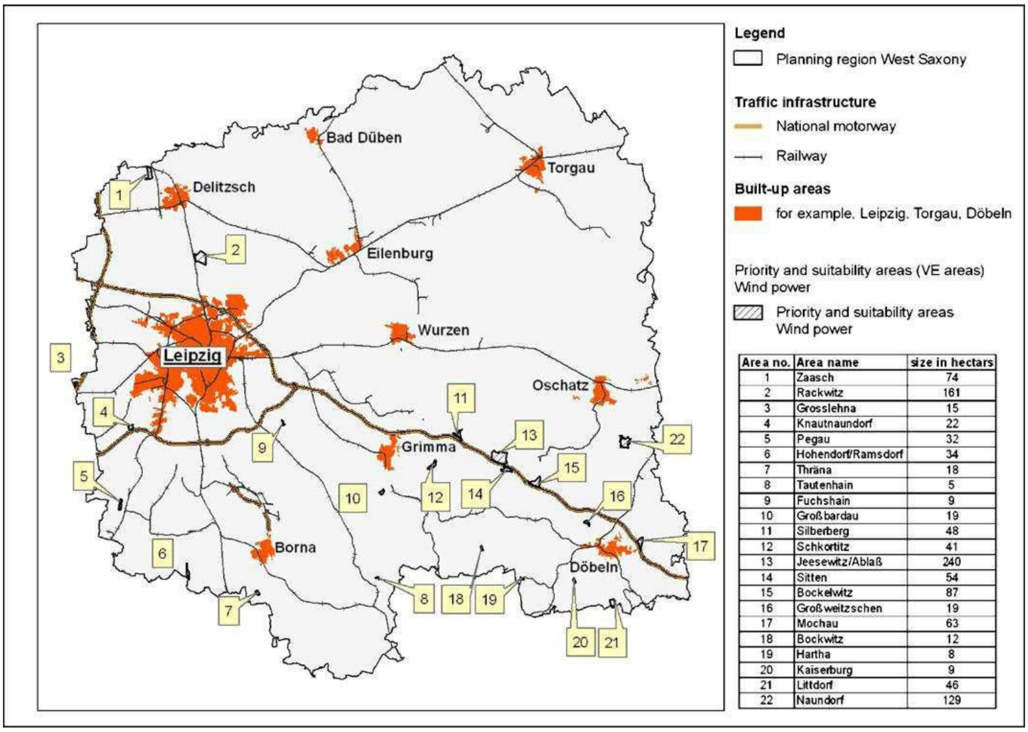
In order to analyse the interplay of national regulations for renewable energy supply and regional planning efforts, we will focus on the planning region West Saxony, a region in the state of Saxony (one of in total 16 German Länder) located in the east of Germany. The region comprises 3964 km^2 (1530 square miles) surface area and, in December 2007, had roughly one million inhabitants. By mid-2007, 221 WTs had been installed in the study region with a capacity of 235 MW. These turbines produced approximately 345 GWh electricity and avoided roughly 296,000 t CO_2 per year.[7] In the latest regional plan for West Saxony the planning authorities make use of the designation of VE areas (compare Regionaler Planungsverband Westsachsen (RPW), 2008).

The process of VE area identification is not standardized in Germany. The regional planning authorities have a relative widely ranging freedom regarding the utilization of regional land area, including the designation of VE area for wind energy supply. In accordance with their regional targets they follow a stepwise approach for VE area identification. Each step follows the rules of positive planning as the designation of VE areas prohibits the construction of WTs outside these areas and therefore does not allow for negative planning (e.g., Köck and Bovet, 2008). First of all, for wind power development ‘unsuitable’ areas are excluded according to a set of different criteria. There are hard criteria such as the Federal Nature Conservation Act (2008) or the Federal Emission Control Act which have to be adhered to and soft criteria such as the subjective value of the common landscape and the buffering of cer-

[5] For detailed Information see the Federal Regional Planning Act (2008).

[6] In this context also see the higher administrative court decision: Urteil des Oberverwaltungsgerichts Rheinland-Pfalz vom 20. Februar 2002, Aktenzeichen:8 A 11089/01.OVG.

[7] The information on existing turbines is based on H. J. Schlegel. Energy Efficiency Centre in the Saxony Office for the Environment and Geology. Information given personally, 11 February 2008. The saving in CO_2 was set at 0.856 kg per kW/h, according to Ragwitz et al. (2005, p. 28).



Area no.	Area name	size in hectars
1	Zaasch	74
2	Rackwitz	161
3	Grosslehna	15
4	Knautnaundorf	22
5	Pegau	32
6	Hohendorf/Ramsdorf	34
7	Thräna	18
8	Tautenhain	5
9	Fuchshain	9
10	Großbardau	19
11	Silberberg	48
12	Schkortitz	41
13	Jeesewitz/Ablaß	240
14	Sitten	54
15	Bockelwitz	87
16	Großweitzschen	19
17	Mochau	63
18	Bockwitz	12
19	Hartha	8
20	Kaiserburg	9
21	Littdorf	46
22	Naundorf	129

Fig. 1. VE areas in West Saxony based on the West Saxony Regional Plan (RPW, 2008).

tain land use types which are subject to local weighing procedures.[8] During the planning process, many stakeholders and the public are involved in order to reach consent on the rules and the weighing of the soft criteria. In the case of conflicts, rule inconsistencies are clarified by the court. Based on such a process altogether 22 VE areas were identified in the study region with about 1200 ha (with 1 ha = 2.5 acres) of total designated site area (Fig. 1).

The regional area development plan was completed with regard to the use of 2–2.5 MW turbines (RPW, 2008, pp. 142–143). And, in order to avoid negative planning, data on wind speed as provided by the Saxon wind measurement program (Hirsch and Rindelhardt, 1996) was taken into account. At present, only about one-third of the erected WTs are still located outside the VE areas. Where they have been placed, no more WTs may be built in future after the designation of VE areas. In West Saxony, wind power is thus already produced for the most part within the VE areas which already can be qualified as generally used to capacity (compare explanation map 13.1–13.18, RPW, 2008). Consequently, the development potential for wind energy in the region of West Saxony will be determined essentially by the repowering potential in the VE areas, as is the case in other parts of Germany.

Method for calculating the regional energy potential

In order to determine the energy output potential of the region we take the frequency distribution of wind speeds, obtained with a horizontal resolution of 1 km × 1 km from the German National Weather Service (DWD, 2007) into account as well as parameters specific to the type of the WTs in question (ENERCON, 2008).[9] In order to determine the energy output potential in the designated VE areas we focus on the wind data of their spatial location and the scale of VE land area as given by RPW (2008). Fig. 2 shows the grid data set that represents the annual energy output of one WT in a grid cell.

The potential annual energy output is calculated with regard to a 2 MW turbine (and later on with regard to a 3 MW turbine, cf. *Discussion*): On the one hand, we use the power curve of the considered WT delivering the amount of electric energy which can potentially be produced at a certain wind speed (information provided by the WT manufactures). On the other hand, we take into account grid-based data for the wind speed and wind frequency in the form of Weibull-Parameters (form and scale parameters) for the study region as obtained by (DWD, 2007). On the basis of these data, we calculate the annual energy output for one turbine within one grid cell.[10] Moreover, in order to arrive at the possible energy output within the VE areas, we overlay the grid data on annual energy output and the geographical information on the size and the location of the VE areas (see the boundaries drawn in black in Fig. 2). The darker the colour of the grid cells, the less energy output is to be expected. The different shadings are chosen with regard to the standard performance level valid for the WT under consideration.

In order to assess (cf. *Discussion*) whether the VE areas are most efficient in terms of energy output regarding the state-of-the-art WT in question, we follow a procedure similar to that of the regional planning authorities. In particular, we use GIS analysis to firstly exclude all parts of the landscape in the region with land cover types physically unsuitable for the construction of WTs. This means primarily the exclusion of settlements, infrastructure, forests and bodies of water. In a next step we remove all areas that are not legally qualified for the construction of WTs (the relevant crite-

[8] The exclusion criteria used for identifying the VE areas in the study region are explained in detail in the Regional Plan West Saxony (RPW, 2008, pp. 146–154) and in the Environmental Report (included in RPW, 2008, U-56 ff).

[9] This is motivated by the fact that the wind data used by the planning authorities and provided in the regional measurement program (Hirsch and Rindelhardt, 1996) was not available.

[10] For more detailed information on the calculation of the energy output, see, e.g., Wizelius (2007).

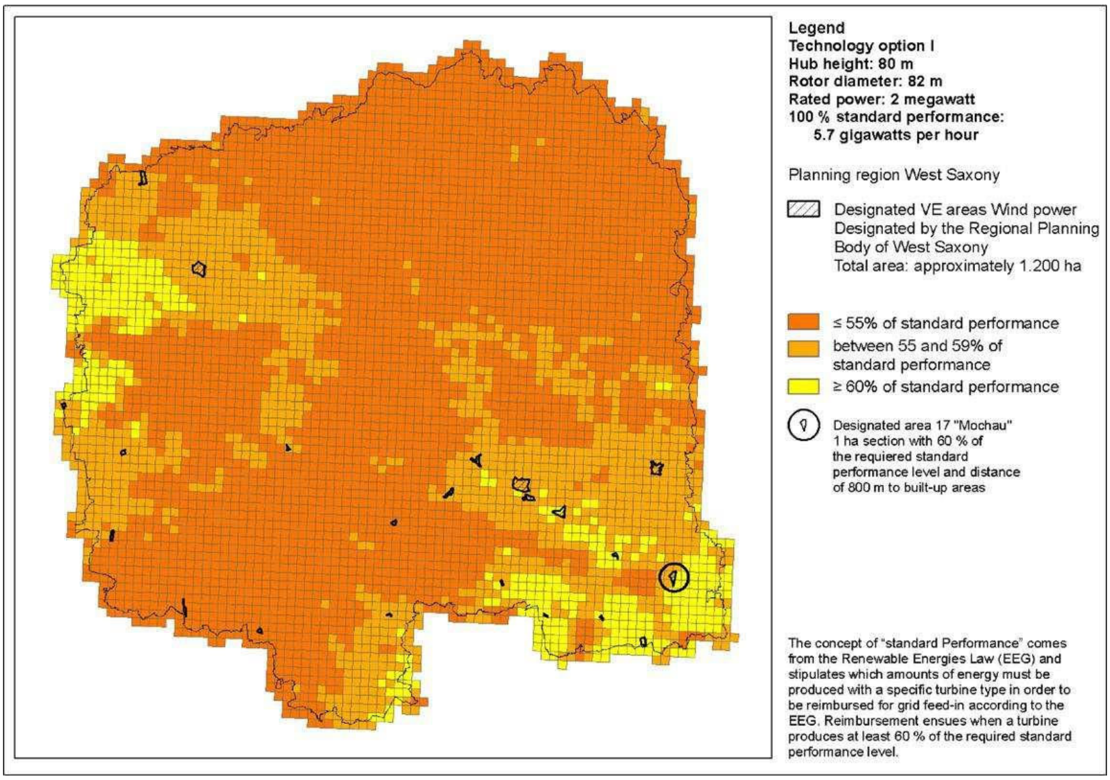


Fig. 2. Energy output of a 2 MW turbine in the West Saxony Planning Region.

ria are listed in Appendix B). Based on this procedure, we identify potential sites (later called 'PT areas') for the erection of WTs that conform to legal regulations. Consequently, there should be no legal objections to the erection of WTs within our PT areas.[11] In a last step, we overlay these sites with the energy output data set in order to determine the sites with the highest energy output and to contrast them with the regional VE areas (cf. *Re-allocation of VE areas*). Finally, in order to determine the repowering potential of the VE and PT areas, we take into account data on the area taken up by state-of-the-art WTs (cf. *Area taken up by WT I (2 MW turbine with 121 m total height)*), the WT-dependent minimum distances to built-up areas (cf. *Minimum distances to built-up areas*) and the existing height regulations in the region (cf. *Height limitations in VE areas*).

Results

Repowering potential of the VE areas

The wind farms located in the designated areas were erected in the period between 1994 and 2007. The repowering potential in West Saxony could thus be completely finished by 2018 (taking into consideration a minimum age of 10 years for the existing turbines). To be able to assess this potential, information is necessary on the area taken up by WTs, on the required minimum distances to built-up areas, on existing height regulations as well as on the performance potential of the existing turbines.

Area taken up by WT I (2 MW turbine with 121 m total height)

The space needed for WTs depends on various factors (Ohl and Eichhorn, 2008): on the choice of technology, the size and configuration of the wind farms as well as on the selected method for calculating the land area taken up, i.e., on whether the method takes only the basement of the WTs into account or additional other aspects such as landscape needed for their accession[12]. In order to be able to assess the repowering potential in the VE areas, we must therefore refer to a concrete turbine type. For illustrative purposes, we assume here that the VE area of about 1200 ha will be used exclusively for producing electricity with 2 MW turbines with 80 m hub (HH) and 121 m total height (TH)—a supposition we will alter in Section *Discussion*. The turbine type under consideration requires a minimum area of 4.6 ha per turbine when the calculation applies the so-called "Kipp formula".[13]

[11] The main differences between PT and VE areas is that the PT areas are not identified in a participatory approach more or less taking into account the preferences of involved stakeholders and residents. One way to cope with this deficit is to carry out a survey among the local residents of West Saxony. Such a survey was performed in May and June 2008 (see Meyerhoff et al., submitted for publication). Using the results of this survey to analyze the comparative advantages of VE and PT areas, however, is beyond the scope of this paper. Although, it is a task for future research to highlight the relevance of the findings in this paper by the results of the survey, a first hint is given in FN 22.

[12] For different calculations of area needed by WTs, e.g., dena, 2005; Hau, 2006; Wizelius, 2007.

[13] The "Kipp" formula refers to the HH and 1/2 rotor diameter. These two values added together form the radius of the minimum surface area to be calculated. The area itself is figured by the formula for a circle $A = \pi r^2$. The result for the technology chosen here (2 MW WT) is radius of minimum area = 80 m hub height plus 0.5 m × 82 m = 121 m ⇒ $A = \pi \times (121\ \text{m})^2$ = 45,996 m² = 4.6 ha. For the 3 MW turbine we obtain a radius of minimum area = 105 m hub height plus 0.5 m × 90 m = 150 m ⇒ $A = \pi \times (150\ \text{m})^2$ = 70.685 m² = 7.1 ha. The Kipp formula tends to specify a minimum of required land area to erect a WT. The calculations in this paper can thus be seen as a lower limit for land taken up by WTs. In this context also see FN 4 and the calculations by Ohl and Eichhorn (2008).

[14] The data given here refer to the distances between WTs and built-up areas as determined by the Official Topographical and Cartographical Information Systems

Minimum distances to built-up areas[14]

The choice of HH and TH is decisive in determining the required distance to built-up areas. According to the Federal Emission Control Act, the spread of height-dependent noise emissions is especially relevant. For the turbine type chosen here, a minimum distance to built-up areas must be at least 500 m to achieve a limit of 40 decibels (dB(A)) and about 800 m to achieve 35 dB(A). Furthermore, the currently valid regional plan for West Saxony (only recently approved and thus provisionally valid until 2018) prescribes that up to 750 m distance to residential areas the height of the turbine is limited to 100 m. When a turbine is as close as 750–1000 m distance to the built-up area, the distance may not fall below ten times the HH (RPW, 2008).[15] The example of the 2 MW turbine with a TH of 121 m could thus be erected only in areas with a minimum distance of 800 m (10 m × 80 m HH) to built-up areas. In general, only a few of the areas designated in West Saxony for wind power have significant size available with a distance of at least 800 m to built-up areas. These are primarily in the designated area "Rackwitz" north of Leipzig, "Jeesewitz/Ablass" between Döbeln and Grimma and the designated area "Naundorf" south of Oschatz. In addition, a few smaller areas exist (see Appendix A: Table A.1). In the VE areas, a total of 323 ha have been provided with a distance requirement of over 800 m to a built-up section (see Appendix A: Table A.1, Column 4).

Height limitations in VE areas

In addition to the height limitations near built-up areas, the permitted total height is limited to 100 m in the designated areas of "Rackwitz" and "Zaasch" due to their closeness to the Leipzig-Halle Airport, so that the 2 MW turbine used in our scenario cannot be erected in these areas. Thus altogether 109 ha for our repowering scenario are lost. A total height of 100 m for state-of-the-art WTs is rather a minimum height than an upper limit (see *Germany's renewable energies program*, above). It can therefore be concluded that other turbine types with similar height generally available for repowering also have no prospects of being built in these designated areas. The repowering potential in West Saxony is thus likely to be concentrated on essentially 11 of altogether 22 areas; in these 11 areas considered for the technology option here, around 214 ha are available in scattered sections (see Appendix A: Table A.1, Column 5).[16]

Performance potential of existing WTs

The potential performance of existing WTs is commercially sensitive data and therefore not freely available. In order to address this type of information deficit, in a first approach, we will assume that not all but at least a portion of the existing turbines can be replaced by the turbine type chosen here. West Saxony regional planning also views the use of 2–2.5 MW turbines as a realistic future scenario; the area designation was completed with such WT types in mind (see *Regional planning in West Saxony*). Operating on the supposition that the WT in focus here is in fact suitable for repowering, turbines could be erected on altogether about 214 ha. If the "Kipp formula" is taken into consideration, about 46 individual turbines have space available.[17]

Energy output potential in VE areas and private investment decisions

The site requirement in regional planning does not offer any final conclusions on investment decisions for a concrete wind power project. Such decisions require commercial determinations oriented primarily on aspects of efficiency. Whether erecting a WT at a specific site pays off is decided by, among other things, the guarantee of a feed-in payment according to the Renewable Energy Sources Act (EEG). Based on the regulations of the EEG (2009), the grid operators are obligated to provide payment for feed-in wind power electricity only when the erected WTs achieve at least 60% of the standard performance level valid for these turbines (see *Regional planning at the German Länder Level*)—i.e., here, 3.4 GWh annually. Therefore, the question arises whether the designated areas will actually be used for repowering with the chosen turbine type.[18]

On the basis of the processed wind data seen in Fig. 2, it can be shown that the energy output would only remotely permit paying the feed-in tariffs for wind power production in the VE areas with the WT in question. Only the designated area "Mochau", with a section of approximately one hectare fulfils the standard performance level criterion (see also Appendix A: Table A.1, Area no. 17). The potential energy output at this site would amount to 3.4 GWh per year. However, since the minimum requirement for land area is not fulfilled (4.6 ha per WT), it is to doubt whether incentives for repowering exist at all. Three additional sections in three VE areas miss the mark for the standard performance level criterion only by very little, with energy output between 59% and 60% of the standard performance level. If, with a compromise, feed-in would be reimbursed according to the EEG at these sites, there would be altogether approximately 38 ha more for repowering (see Appendix A: Table A.1, Column 7) which in total would allow for an additional energy output of roughly 23.5 GWh per year by means of repowering.

Under the assumption that EEG payment is key to erecting WTs and thus to implementing repowering, a disparity would arise in the study area between the space available in the VE areas as identified above (altogether 214 of 1200 ha) and the area in demand for repowering (1 ha or 39 ha if the compromise is included). Use of the remaining available area at a distance of 800 m to built-up areas (213 ha without or 175 ha with the compromise) would be unattractive under the repowering scenario chosen here, as the grid operators would not be obligated to reimburse the feed-in.

To sum up, the energy output potential of the VE areas is, to a large extent, not suitable for repowering, given the WT and data basis chosen for our study. Only around 1 ha (or around 39 ha if the compromise is included) of the entire approximate 1200 ha VE area is suitable for erecting 2 MW turbines with 80 m HH. Thus the

(ATKIS®-DGM25 ©Saxony State Ordnance Survey Office, 2007), taking into account all objects of the thematic layers that contain settlement structures (i.e., all objects at the levels SIE01_F, SIE02_F and SIE03_F). In contrast, the West Saxony Regional Planning Authority uses additional and more detailed data such as city and country plans, which permits more differentiation while buffering built-up areas. Therefore the distances introduced here between built-up areas and WTs do not necessarily correspond to the data on distances between built-up areas and VE areas given in the regional plan.

[15] The height limitation in case of up to 750 m distance to residential areas is motivated by the precautionary principle in order to avoid legal objections (the blaming for negative planning). Beyond a distance of 1000 m to built-up areas there are no prescribed height limitations. Information given personally by M. Friedrich, Regional Planning Office, Leipzig, 30 September 2008.

[16] This area is further reduced as soon as new turbines with HH over 80 m go into operation; in this case, the required minimum distance of 10 times the HH would outstrip the permissible minimum limit of 800 m for the turbine type chosen.

[17] Installing the turbines according to energy output aspects would increase the necessary surface area per turbine. But, because comparatively small individual sites become relevant here, the calculation according to the "Kipp" formula for the necessary area appears to be appropriate.

[18] In this context see also Nadaï and Labussière (2009), pointing out for France that high feed-in tariffs are not sufficient for wind power development, regional planning has to be in favour as well—with regard to the analysis of Nadaï and Labussière i.e., the involvement of the public.

question arises as to how the expected disparity between the total available area and the demand for sites on the part of potential investors can be reconciled.

Discussion

In *Energy output potential in VE areas and private investment decisions* we demonstrated that only approximately one hectare of the designated area is available for the chosen repowering scenario (erecting 2 MW turbines with 80 m hub height, referred to as WT I). As a result, there is a disparity between the available sites in the VE areas – altogether 1200 ha with about 214 ha suitable area for WT I, taking the required distance to built-up areas and height limitations into consideration – and the expected investor demand for local repowering, a demand concentrated on a maximum of around 39 ha, if the compromise is included. Different possibilities exist to reconcile this disparity. In this paper we focus, firstly, on a different type of technology choice and secondly, on a re-allocation of the VE areas.

Altering the technology choice (WT II: 3 MW turbine with 150 m TH)

Altering the technology choice can, but need not necessarily, close the gap between available sites and demand. To demonstrate this, we consider the use of 3 MW turbines at a hub height of 105 m (optimal for the chosen turbine type), instead of 2 MW turbines at a hub height of 80 m. This requires fulfilling a higher EEG standard performance level. The 3 MW turbine must generate at least 4.1 GWh annually (compared to 3.4 GWh required for the 2 MW turbine) to fulfil the 60% clause. However, the energy output potential for the site also alters with the variation in height of the turbine because wind blows more strongly and more constantly at higher altitudes than near the ground. Thus more available area for repowering could be calculated than is the case for WT I. Fig. 3 shows that now almost all designated areas fulfil the standard performance level criterion, despite a higher standard.

Considering WT II with a HH of 105 m requires taking into account greater minimum distances to built-up areas. Thus, according to the requirements of the West Saxony Regional Plan (minimum distance: ten times the HH at sites with distances to built-up areas between 750 and 1000 m), only sites starting at 1000 m distance could be considered, because these are sites for which no height limitation was established in the regional plan.[19] Thus the portion of sites for this repowering scenario is reduced from altogether 1200 ha to approximately 82 ha (as opposed to 323 ha in scenario I). These sites, as with the 2 MW turbine, are concentrated mainly on sites in the VE areas “Rackwitz”, “Jeesewitz/Ablass” and “Naundorf” (see Appendix A: Table A.1, Column 8). As in scenario I, the height regulation for the area “Rackwitz” also entails in scenario II losing the designated site (approximately 35 ha) for repowering, so that only 47 ha from a total 1200 ha can be used. In comparison to repowering scenario I, for which altogether 214 ha were designated, less area in total is available for the 3 MW turbine. The reason is the required greater minimum distance to built-up areas. However, the 47 ha available are suitable to a greater extent from an energy output point of view as opposed to only about 1 ha in scenario I (allowing, if at all, for an energy output of 3.4 GWh annually). The repowering with a 3 MW turbine would yield a feed-in payment according to EEG for around 23 ha (see Appendix A: Table A.1, Columns 6 and 10) and a potential energy output of 12.6 GWh annually. Nevertheless, the above-mentioned disparity between supply and demand cannot be reconciled with this scenario; it can only be reduced. From a total of 1200 ha in scenario II, only 47 ha could be used. Of these 47 ha, about 23 ha fulfil the standard performance level and can thus be classified as a potential area for private investment in state-of-the-art technology.[20]

The demonstrated cause and effect relations apply as well to alternate turbine types, so that state-of-the-art WTs produce higher energy output, and need to fulfil a higher standard performance level. However, in order to produce electricity efficiently state-of-the-art WTs frequently require permission to exceed a certain hub height. But they also then raise the required minimum distance to built-up areas, so that not all VE sites are necessarily attractive for erecting state-of-the-art WTs. As a result, not even an altered technology choice is suitable to reconcile the disparity between available areas and demand for repowering space.

Re-allocation of VE areas

To close the gap between supply and demand in VE areas, a re-allocation of VE sites might be considered. In the process, priority must be placed on the energy output potential in suitable areas. Such an approach would, so to speak, shift (at least to a certain degree) the current concept of the standard performance level specified at the national level for individual turbines to the choice of VE areas and thus the regional planning level. In a next step, we would like to clarify this and compare the above-mentioned VE areas with the sites in West Saxony that deliver the highest returns from an energy output aspect—our PT areas (cf. *Method for calculating the regional energy potential*; see Fig. 4a and b).

The sites shown in Fig. 4a and b have a total suitable area of altogether approximately 188 ha for repowering scenario I (sections larger than 4.6 ha). These sites adhere throughout to the required minimum 800 m distance to built-up areas. For scenario II, a total of 926 ha are available (with individual sections larger than 7.1 ha) with a universal minimum 1000 m distance to built-up areas. Thus, from an energy output point of view, a re-allocation of the VE sites would, in any case, bring about a greater supply of sites for repowering. That means that more turbines could be erected (in comparison with the VE sites permitting only 1 or 23 ha according to EEG regulations) and would, as a result, produce more electricity and save on CO_2: the WT I scenario would deliver in total 140 GWh (saving in CO_2: 119,840 t) per year and the WT II scenario in total 546 GWh (saving in CO_2: 467,376 t) per year.[21] In comparison to that, the VE areas would deliver only (if at all) 3.4–12.6 GWh (saving in CO_2: 2910–10,785 t) per year.

Closing a gap between site supply and demand by re-allocating the VE areas according to energy output aspects thus brings advantages. In future, it could be worth examining which arguments speak against an area choice in terms of energy output.[22] It can be seen as well that the sites favourable to a 3 MW turbine also contain those sections suitable for 2 MW turbines eligible for payment

[19] In the case of noise emissions, a minimum distance to built-up areas of at least approximately 650 m is required to achieve a limit of 40 dB and approximately 1000 m to achieve a limit of 35 dB would be the conditions.

[20] It must be mentioned additionally that designated sections of the VE area for repowering larger than those in this study could be available if other technology options are chosen. For example, primarily 660 kW turbines are currently installed in the VE area “Zaasch”, with a total height of 97.5 m. These could be replaced by, for instance, 1800 kW turbines with a total height of 100 m, in order to receive the repowering payment according to the EEG.

[21] Calculations are based on the average energy output of the grid cells covered by the PT areas.

[22] Especially because the implementation of state-of-the art WTs (in particular their height) seems not to be a critical issue for residents in West Saxony. See Meyerhoff et al. (submitted for publication).

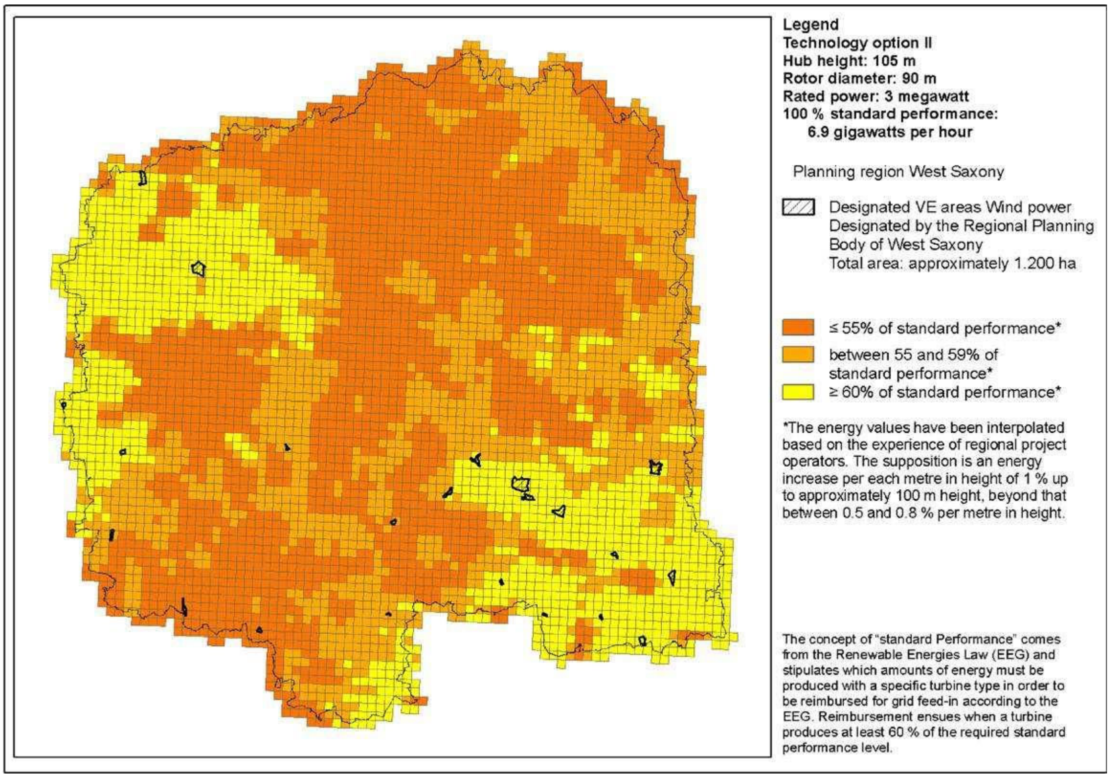


Fig. 3. Energy output of a 3 MW turbine in the West Saxony Planning Region.

according to EEG (2009). Even if the selection of suitable sites for the 2 MW turbines does not coincide with the selection of suitable sites for the 3 MW turbines due to different requirements for minimum distance to built-up areas, it is worth discussing whether in future the concept of standard performance level would not be better placed at the regional planning level instead of at the investor level. It would offer orientation for the regional planners in choosing VE areas and may substitute for the verification of the standard performance of an individual WT. Acceptance of a verification of standard performance at the regional planning level would, however, have to be examined in advance. It would also imply that a (top down) specification of a national quota goal for wind power – and thus perhaps even for renewables altogether – would not be possible but rather indirectly be determined by the local conditions at the regional planning level (bottom up). As an additional effect, the gap between site supply and demand would be closed, if at an altered level.

Summary and prospects

If onshore wind power is to make a significant contribution toward achieving climate policy goals, regional planners must make sites available for erecting wind turbines (WTs). Germany leads the world thus far in its installed capacity for wind power. Currently, however, there is a trend in Germany toward securing local sites through designation of so-called priority and suitability areas (here, referred to as VE areas) which, at the same time, show trend toward limiting them. Their design affects development of onshore wind power in two ways: *first*, it favours erecting WTs within the VE area over other forms of land use but, *second*, it targets the space for erecting WTs by prohibiting them outside these areas. With regard to climate policy goals, there are generally two ways for wind power to contribute to CO_2 reductions that could be followed simultaneously: (a) by supplementing the current WTs with new ones and, (b) by replacing existing turbines with more powerful WTs (repowering). Both variants are supported by the Renewable Energy Sources Act (EEG, 2009). Receiving reimbursement for wind power feed-in to the grid according to the EEG depends, however, on local conditions, especially the local wind conditions. A chosen WT type must return a definite energy output (referred to here as standard performance level). With this ruling, the EEG wishes to make certain that, with respect to energy output, wind power does not pay off at inefficient locations. To expand the development of wind power, the VE areas must therefore fulfil certain energy output standards that are dependent on the placement and the height of the chosen WT. Our case study in West Saxony shows that the local wind conditions in already designated VE areas are not always suitable to generate the required standard performance level according to the EEG. Rather, a gap exists between site supply offered by regional planning and the potential investor demand for sites, even with varying technology choices altering the height of the turbines. The reason is that, according to EEG regulation, grid operators are obligated to reimburse feed-in from wind power only if the required standard performance level has been achieved, not always feasible due to the local wind conditions in the VE areas. Improving the energy output by erecting taller WTs as a measure to fulfil required standard performance levels is also not always feasible due to regulations on the height of the turbines and the distance of the VE sites to built-up areas. In order to support national climate and energy goals, regional planning must thus not only make sufficient sites available for erecting WTs, but these sites must also provide certain features relating to wind conditions and their distance to settlement areas. Thus, even in the face of a determined governmental policy – as provided by the EEG (2009) – and a general public support for wind power development – as pointed out in several surveys for the German population (e.g., Kuckartz and Rheingans-Heintze, 2006; Zoellner et al., 2008) – the erection of new WTs may be deficient at the regional level. Our case study points to a mis-

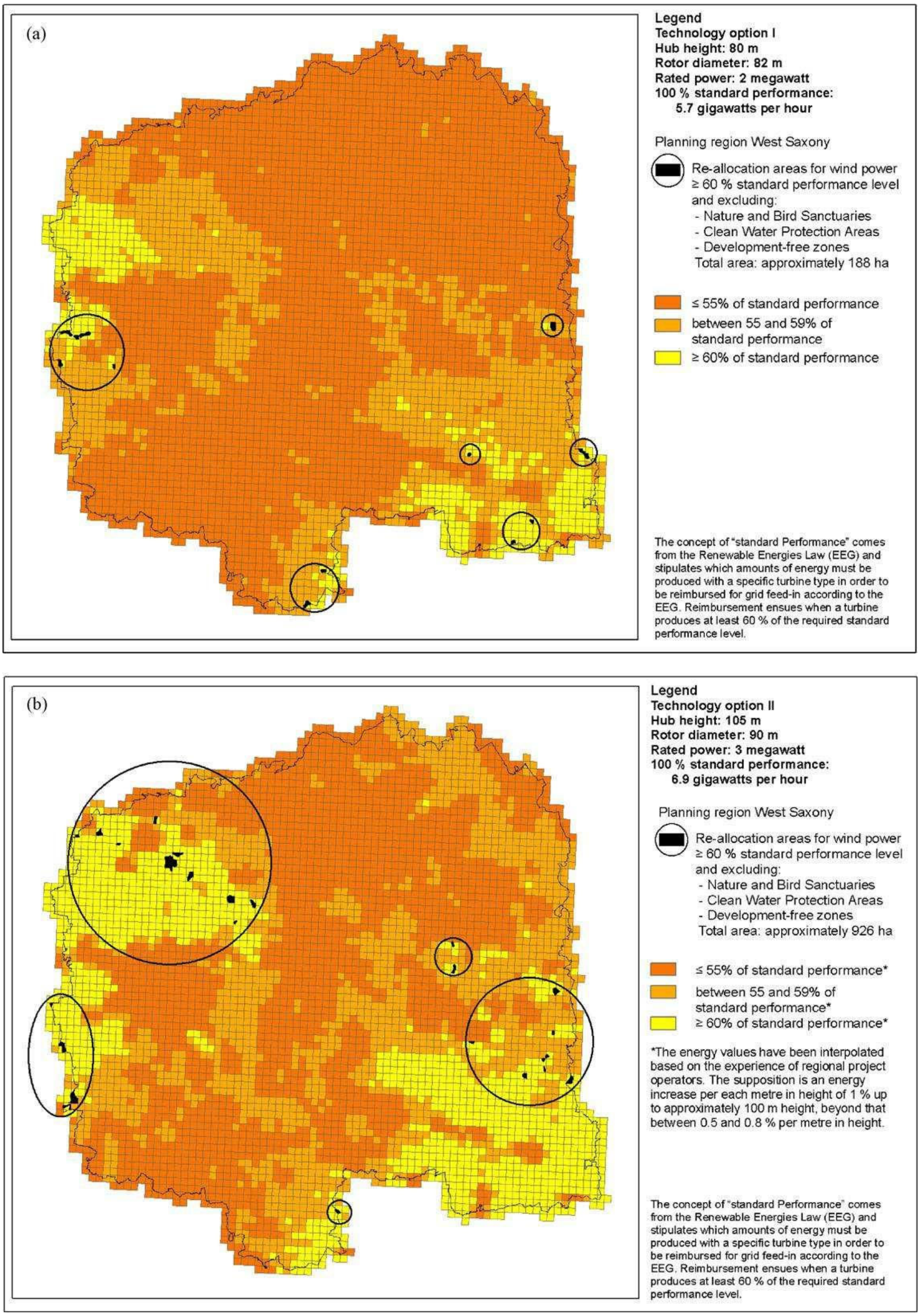


Fig. 4. (a) Re-allocation of areas for technology scenario I (2 MW with 80 m HH), (b) re-allocation of areas for technology scenario II (3 MW with 105 m HH).

match between the national eligibility criteria for feed-in tariffs and the trend followed by the regional planning authorities—the designation of VE areas.

VE area in Germany is selected on the basis of a strategic search by local planning authorities involving local stakeholders and the public. Though, in general, a strategic search for sites could allow for an efficient deployment of the wind resource, it shows shortcomings in West Saxony. One reason is the deficient tailoring of the planning decision and the national eligibility criteria for feed-in tariffs, requiring the compliance of the energy output of erected

WTs with a turbine-specific standard performance level. A second reason is the designation of VE areas at places where in the past turbines were erected. In West Saxony only one third of the present turbines are found outside the designated VE areas. This can be motivated by the participatory approach of the strategic search, allowing the landlords of the land area where turbines were erected to claim for continuation permit (the preservation of the status quo). This should make sure receiving permanent rents from deployment of the wind resource, be it because the landlords are (1) owners or shareholders of WTs or (2) being paid by other operators. Moreover, a third reason is that it is not originally the task of regional planning in Germany to provide for adhering to national goals concerning climate and energy policies. The planning authorities rather follow the targets set on the German Länder level as specified in the respective State Development Plan. These targets, at present, fail to foster national projections on installed wind power development. In most of the cases the regional planning authorities are free to set their own benchmarks. As a result, it is questionable whether Germany will keep leadership in terms of installed wind power capacity. In order to make leeway in deployment of the wind resource, France, for example, makes use of offering feed-in tariffs if WTs are erected in so-called wind power development zones (WPDZ). In comparison to the German approach WPDZ are not selected in a participatory way and can therefore focus on wind conditions in the first place. The disadvantage, however, is that this type of strategic search may come up with higher resistance against wind power development at the local level (e.g., Nadaï, 2007). The strategic participatory search of VE areas in Germany is able to avoid this shortcoming. In order to improve the German approach, however, it would be helpful to place the concept of standard performance level at the regional planning level rather than at the operator level. While, on the one hand, this would target the options for allocating the VE areas, it would, on the other hand, provide a link between the goals of different administrative levels, and the strategic process of site selection would be better oriented toward local wind conditions at different altitudes. It is to be seen whether this approach will be seized upon and implemented in future. But it could mean that the standard performance criterion for specific turbines in the German EEG would be replaced by a regional criterion for suitability that is not primarily set to follow political goal requirements at the national level but is oriented mainly toward local conditions concerning wind and distances between the wind power sites and the built-up areas. Thoughts on the matter are certainly worthwhile in any case, if the standard performance criterion is not to become a stumbling block for a supply of renewable energies in Germany.

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Appendix A.

Table A.1
VE areas of the West Saxony Planning Region, status 2/2007, based on ATKIS®-DGM25, ©Saxony State Ordnance Survey Office 2007 (see also FN 14) and RPW, 2008. The calculation of the energy output is based on the average energy output of the corresponding grid cells and the calculated (rounded off) number of WT minimum area requirement. Energy output is shown in Gigawatt hours per year; *no energy output since areas do not fulfil minimum area requirement.

Area no.	Area name	Area (ha)	Area segment starting at 800 m ha				Area segment starting at 1000 m ha		
			Not considering height limitations according to LuftVG	Considering height limitations according to LuftVG	Considering EEG standard values from 60%	Accommodating performance levels between 59 and 60%	Not considering height limitations according to LuftVG	Considering height limitations according to LuftVG	Considering EEG standard values of 60%
1	Zaasch	74	11 ha/6.3 GWh						
2	Rackwitz	161	98 ha/71.4 GWh				35 ha/21.7 GWh		
3	Großlehna	15	1 ha/0 GWh*	1 ha/0 GWh*					
4	Knautnaundorf	22							
5	Pegau	32	13 ha/9.1 GWh	13 ha/9.1 GWh					
6	Hohendorf/ Ramsdorf	34	31 ha/20.5 GWh	31 ha/20.5 GWh			7 ha/3.8 GWh*	7 ha/3.8 GWh*	
7	Thräna	18	4 ha/0 GWh*	4 ha/0 GWh*					
8	Tautenhain	5							
9	Fuchshain	9							
10	Großbardau	19	8 ha/5.9 GWh	8 ha/5.9 GWh					
11	Silberberg	48	12 ha/9.8 GWh	12 ha/9.8 GWh					
12	Schkortitz	41	1 ha/0 GWh*	1 ha/0 GWh*					
13	Jeesewitz/ Ablaß	240	60 ha/43.7 GWh	60 ha/43.7 GWh		34 ha/23.5 GWh	10 ha/4.3 GWh	10 ha/4.3 GWh	10 ha/4.3 GWh
14	Sitten	54	3 ha/0 GWh*	3 ha/0 GWh*		3 ha/0 GWh*			
15	Bockelwitz	87							
16	Großweitzschen	19							
17	Mochau	63	2 ha/0 GWh*	2 ha/0 GWh*	1 ha/3.4 GWh*	1 ha/0 GWh*			
18	Bockwitz	12							
19	Hartha	8							
20	Kaiserburg	9							
21	Littdorf	46							
22	Naundorf	129	79 ha/54.7 GWh	79 ha/54.7 GWh			30 ha/16.5 GWh	30 ha/16.5 GWh	13 ha/8.3 GWh
Total		1145	323 ha/221.4 GWh	214 ha/143.7 GWh	1 ha/3.4 GWh*	38 ha/23.5 GWh	82 ha/46 GWh	47 ha/24.6 GWh	23 ha/12.6 GWh

Appendix B.

B.1. Legal restriction criteria concerning nature conservation and water protection

Different types of nature conservation areas with certain protection aims exist in Germany. Protection aims restrictions for the construction of WTs are defined according to these types. The Federal Agency of Nature Conservation (BfN) has conducted a study that aims to investigate the interaction between renewable energies and nature conservation concerns. Some findings that are important for this paper are listed in Table B.1 (R&D Project 'The relevance of space-related effects of the new energy policy on nature conservation'. F&E-Vorhaben FKZ 806 82 110 Naturschutzrelevanz raumbedeutsamer Auswirkungen der Energiewende. 2. Zwischenbericht Stand: 18.02.2008 unpublished, publishing of the final report in progress).

B.2. Legal restriction criteria concerning infrastructure (Table B.2)

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B.3. Legal restriction criteria concerning human settlements

Because of light shadow and sound emissions of WTs, distances to built-up areas have to be adhered to. No legal regulations currently exist regarding light emissions. Shadow emissions occur only under certain atmospheric conditions and can also be handled by temporary switch-off of the turbines. Within this paper sound emissions were used to define buffer distances to built-up areas. Limit values for emissions are defined by the German Federal Emission Control Act, Technical Instruction on Noise (TA Lärm, 1998). According to this Act the permitted amount of noise depends on the type of settlement (Table B.3). In the paper at hand we have chosen a conservative level by setting the maximum level of allowed sound emissions to 35 dB(A). The minimum distance calculation that corresponds to that maximum sound level of the turbines was done by a wind consultant office with the software WINDPRO (For further information see, URL: http://www.emd.dk/WindPRO/Frontpage). The minimum distance amounts to roughly 800 m for a 2 MW WT and to around 1000 m for the 3 MW turbine (see also Wizelius, 2007). Consequently, all built-up areas were surrounded by a buffer of 800 m respectively 1000 m distance and the buffer together with the settlement area was excluded from the available space in the study region.

Table B.1
Restriction criteria concerning nature conservation and water protection.

Nature conservation	
Nature conservation area	WTs restricted
National park	WTs restricted
Landscape conservation areas	WTs restricted if there is no specific previous impacts
Biosphere reserve	WTs restricted in core zones
Natural parks	WT possible, but restricted from parts that are declared as nature conservation areas or landscape conservation areas without specific previous impacts
Natural monument	WTs restricted
Protected landscape components	WTs restricted
Protected biotope	WTs restricted
Natural habitats (Natura 2000)	WTs restricted
Special protected areas (SPA)	WTs restricted
Water protection	WTs restricted
Flood plain	WTs restricted
Water protection area	WTs restricted

Table B.2
Existing laws and guidelines for buffer distances regarding technical and transportation infrastructure.

Infrastructure type	Buffer distance (m)	Relevant law/Commendation
German freeway	40	Section 9 Federal Highway Act (2007) (BFernStrG)
Federal road	40	Section 9 Federal Highway Act (2007) (BFernStrG)
Country road	20	Section 9 Federal Highway Act (2007) (BFernStrG)
County road	20	Section 9 Federal Highway Act (2007) (BFernStrG)
Rural road	20	Section 24 Saxonian Road Act (2004) (SächsStrG)
Railroad	250	Section 3 Common Railroad Act (2008) (AEG)
High tension cable	200	Guidelines of regional power authorities

Table B.3
Standard emission values permitted by TA Lärm (1998).

Types of settlement	Allowed emissions during daytime in decibel dB(A)	Allowed emissions during nighttime in decibel dB(A)
Industrial area	70	70
Commercial area	65	50
Centre zone, rural settlement, mixed-use zone	60	45
General residential area	55	40
Absolute residential area	50	35
Cure area, hospital, care home	45	35

B.4. Height restriction criteria according West Saxony Regional Plan

In compliance with the precautionary principle and according to the Federal Emission Control Act the regional panning authority of West Saxony prescribes a minimum distance to settlement for WTs with certain heights (RPW, 2008,p. 137, Z11.3.3–Z11.3.9).

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Chapter 5

Securing Energy Supply at the Regional Level

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SECURING ENERGY SUPPLY AT THE REGIONAL LEVEL – THE CASE OF WIND FARMING IN GERMANY: A COMPARISON OF TWO CASE STUDIES FROM NORTH HESSE AND WEST SAXONY

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Abstract Wind power is one way we can reduce our dependency on fossil fuel imports and mitigate climate change. However, wind power can play this important role only if sufficient space for wind farming is made available off-shore as well as on-shore including sites far away from the seashores. Against this background this paper presents a comparative analysis of two hinterland case studies from Germany. Applying GIS and official wind speed data we evaluate the effectiveness of designated wind farming areas in the regions of West Saxony and North Hesse in terms of their expected wind energy yields and potential for repowering. We show that, in this respect, the current spatial allocation for wind power generation in both study regions is not as effective as it could be, but for different reasons. We contrast this finding with an alternative proposal which not only meets the legal requirements for wind power generation but also yields better results in terms of expected energy output. This proposal takes into account the availability of different turbine types and a spatial re-allocation of wind farming areas within the study regions.

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1. Introduction

Wind power is contributing considerably to replacing fossil fuels and to reducing CO_2 emissions. Of all the renewable energies, it is wind power that has experienced the most impressive growth in the last 2 decades. Globally, the installed capacity has multiplied by a factor of 15 between 1996 and 2007, from 6.1 to 93.9 GW rated power. By the end of 2007 Germany was in the lead in absolute terms with 22.3 GW, followed by the USA (16.8 GW), Spain (15.1 GW), India (7.8 GW), and China (5.9 GW), whereas Denmark was leading in relative terms with a 21% wind power share in the country's electricity supply (GWEC and Greenpeace 2008). However, to achieve more ambitious climate policy targets that are now being set, for example, by the European Union or the German Federal Government (BMU 2007), it is necessary for wind power to maintain its growth trend in the coming decades. In terms of on-shore expansion, the installation of wind turbines requires suitable land which, in Germany, needs to be designated by regional planning agencies.

Our paper examines if and how the regional planning agencies of West Saxony and North Hesse manage to secure suitable space for wind power generation by designating land for this purpose in their regional plans. The paper is organized as follows. Section 2 briefly refers to wind farming regulations in Germany insofar as they are relevant for our analysis, i.e. the planning system with a focus on the regional level and the Renewable Energy Sources Act. In Section 3 we describe our calculation method for analysing the wind energy potentials at the regional level. Sections 4 and 5 feature the two case studies by introducing the study regions and their regional planning as regards wind farming, applying our method and presenting and discussing the results. Section 6 compares the main findings from the two case studies and, finally, Section 7 draws conclusions with regard to secure wind energy supply at the regional level.

2. Case-Relevant Wind Farming Regulations in Germany

Within the German multi-level governance system the regional level forms the link between the sub-national level, which is represented by the *Bundeslaender*, i.e. state level, and the county level. Overriding spatial planning guidelines and tools are provided by the Federal Regional Planning Act which is enacted at the federal and national level respectively.

The law defines a framework which leaves ample scope for the *Bundeslaender* to design long-term oriented state development plans, including principles and objectives for regional planning in their domain. Based on this, central responsibility for the designation of land for wind power is assigned to regional planning agencies. The state (*Bundesland*) of Hesse, for example, is comprised of three planning agencies called *Regionalversammlung*, whereas the state of Saxony has four which are called *Regionaler Planungsverband*. These agencies establish legally binding regional plans.

On the regional level, regional planning agencies make use of specific spatial predeterminations in order to secure space for wind farming as well as other certain types of land use. In legal terms, the agencies either designate priority areas (*Vorranggebiete*), or suitability areas (*Eignungsgbiete*), or a combination, i.e. priority areas with the impact of suitability areas (*Vorrang- und Eignungsgebiete*; here referred to as VE areas). In so far as wind power is concerned, priority areas are where the installation and operation of wind turbines is prioritized over other land-use. In contrast, suitability areas are considered appropriate for wind power generation, however priority is not given for it. At the same time, suitability areas also preclude any other sites in the planning region from being used for wind power generation. The combination in the form of VE areas, assures that in areas designated as such wind farming is given priority over other land-use on the one hand, while at the same time prevent any other sites in the planning region from being used for wind farming (Koeck and Bovet 2008).

The number, dimensions and energy potential of such areas on the regional level obviously play a crucial role in achieving national energy and climate policy targets in terms of lowering the dependence on fossil fuel imports and reducing greenhouse gas emissions. Having said this, priority, suitability and VE areas serve as a means of controlling the further expansion of wind farming, which otherwise could lead to an unwanted spreading of wind turbines across landscapes throughout a whole region. The Renewable Energy Sources Act (EEG), an instrument that promotes renewables from 1991[1] onwards, provides a second means to counteract uncontrolled growth of wind farming in Germany since its 2004 amendment. The EEG now stipulates that grid system operators shall pay a tariff for electricity from a wind turbine only under the condition that this turbine generates a minimum yield according to a technical definition which is given in Appendix 5 of the law. Thus, a wind turbine operator is obliged to prove that his/her turbine at

[1] In fact, the EEG itself came into force in the year 2000; however, its predecessor, the electricity-feed-in-law had already become effective in 1991.

the site under consideration will produce at least 60% of the so-called reference yield for that turbine type (EEG 2009). But the EEG also rewards repowering, i.e. the replacement of existing small turbines by tall state-of-the-art turbines which reduce the specific land demand for wind farming (ha/MW).

The designation of VE areas usually is the outcome of a complex, criteria-based selection process, but does not follow a nationwide standardised procedure. Rather, it is partly based on binding legal provisions, and partly on the discretion of the regional planning agency (RPW 2008). However, case law established at the highest judicial level bars negative planning i.e., designating VE areas for wind farming which are unfeasible for economical reasons and in fact impede wind power generation instead of fostering it (Koeck and Bovet 2008). A systematic and stepwise approach is typical whereby a set of exclusion criteria is applied one after another to disqualify those parts of a planning region which are not suitable for wind farming for whatever reason. In addition to a number of mandatory criteria which are derived from the Federal Immission Control Act (noise protection etc.) and the Federal Nature Conservation Act, there are many flexible criteria regarding, for example, the visual impact of wind turbines on the landscape or the dimension of buffer zones to specific types of land use. Furthermore, many stakeholders and the general public are invited to participate in the planning process.

3. Method Applied to Evaluate Potential Sites for Wind Farming

The method applied in this paper is based on Ohl and Eichhorn (2009).[2] It draws on regional planning criteria, EEG requirements, wind potential data, technical wind turbine parameters and a geographic information system (GIS). In order to find appropriate land for wind farms, we follow a selection procedure as described in detail by Ohl and Eichhorn (2009). Using GIS analysis we begin by excluding physically unsuitable parts of the landscape, which mainly comprise settlement areas, infrastructure facilities, water bodies and forests. Then, we eliminate those areas from the available space which are not legally qualified for the erection and operation of wind turbines, e.g. nature conservation areas and the like. Accordingly, we obtain a number of potential sites that are legally and physically suitable for wind farming.

[2] A similar approach, but on a smaller spatial scale, has been applied by Krewitt and Nitsch (2003).

Next, sites selected in this way are overlaid with the grid data on annual energy yield to identify the most promising sites. The database for the calculation of the wind energy potential in the two study regions is provided by the national meteorological agency of Germany (DWD 2007). We employ grid-based frequency distributions of wind speeds as Weibull parameters for form and scale with a horizontal resolution of 1 by 1 km. To determine the energy yield, we utilize the power curves of state-of-the-art wind turbines which are able to deliver the highest amount of electric energy possible at a certain wind speed. The grid cells are the focal units for the computation of energy yields. For every cell there is a certain predicted energy potential per turbine that is ready for exploitation. Grid cells may have one or more turbines subject to the conditions of their optimal spatial arrangement.[3] We consider two different turbine types: at first a turbine of 2 MW rated power, 82 m rotor diameter, 80 m hub height and 121 m total height (type I) and, afterwards, a turbine of 3 MW rated power, 90 m rotor diameter, 105 m hub height and 150 m total height (type II).

Special attention is paid to the priority, suitability and VE areas designated in the regional plans of both study regions. Applying GIS data as to their location and size, we evaluate the suitability of these areas for the operation of turbine type I, and II respectively under the constraints given by the regional plans. Both turbine types can be assumed to be proper means for repowering in the future. This is of particular importance if existing priority, suitability and VE areas are already occupied with low-performing small turbines which then may block more ambitious regional renewable energy and CO_2 reduction targets. Our assessment takes into account the land demand of the two turbine types under consideration, their required minimum distances to built-up areas and, as the case may be, also height limitations for wind turbines. In a final step, we then aim to identify possible reallocation areas which may better fit the purpose of repowering than the designated priority, suitability and VE areas in the regional plans.

4. Case Study West Saxony

4.1. STUDY REGION

West Saxony is one of a total of four planning regions in the German state (*Bundesland*) of Saxony. By the end of 2007 the region had a population of nearly one million and a surface area of 4,388 km² which equals a density

[3] Cf. park layout recommendations of the Danish Wind Industry Association (2009).

of 245/km². 221 wind turbines with a total capacity of 235 MW rated power were in operation in the region, generating around 345 GWh of electricity and averting roughly 296,000 t CO_2 per year (Ohl and Eichhorn 2009). The regional plan for West Saxony, in force since 2008, designates 22 VE areas covering a total of 1,145 ha (11.45 km²) which represents 0.26% of the region's total surface area (RPW, 2008).[4] The location of the VE areas within the planning region West Saxony is depicted in Fig. 1 (no. 1–22). The size of individual VE areas ranges between 5 and 240 ha. Since priority, suitability and VE areas are recent planning devices, a number of older wind turbines in West Saxony had previously been erected outside of the 22 VE areas and are now operating under a continuation permit (RPW 2008). Notwithstanding, the bulk of wind power in West Saxony today is generated in VE areas which are already used to capacity with turbines that have been installed between 1994 and 2007. Therefore, an increase of wind power generation in the future will largely depend on repowering. Since the EEG repowering bonus requires that the turbines that are replaced be in operation for at least 10 years, it would take at least until the end of 2017 to repower all existing turbines.

The designation of the 22 VE areas in West Saxony is based on a similar approach as described in the previous section. It follows the objectives and principles for the planning region which in turn are required to be in accordance with the state development plan of Saxony. Neither the state development plan, nor the regional plan quantify targets for wind power in terms of electricity consumption quotas or overall installed rated power. However, the regional planning agency is committed to, and achieves, designating at least 0.25% of the region's surface area as VE areas for wind farming (RPW 2008). Accordingly, a total of 20 exclusion criteria have been applied during the selection process. The criteria are described in detail in the regional plan. Most of these deal with nature conservation and landscape protection matters. Several others prescribe minimum distances of wind turbines to residential areas and infrastructure facilities. In addition, a minimum distance of 5 km between two wind farms is required. Also height restrictions are set, some of which apply to all VE areas and a few are defined specifically for certain VE areas (RPW 2008).

[4] The data provided here originates prior to a territorial reform in the state of Saxony as from 1 August 2008. In consequence of a consolidation of counties and planning regions the planning region West Saxony lost one of its former member counties and was scaled down to a surface area of 3,964 km². Nevertheless, the Regional Plan West Saxony effective since 25 July 2008 has remained in force unchanged.

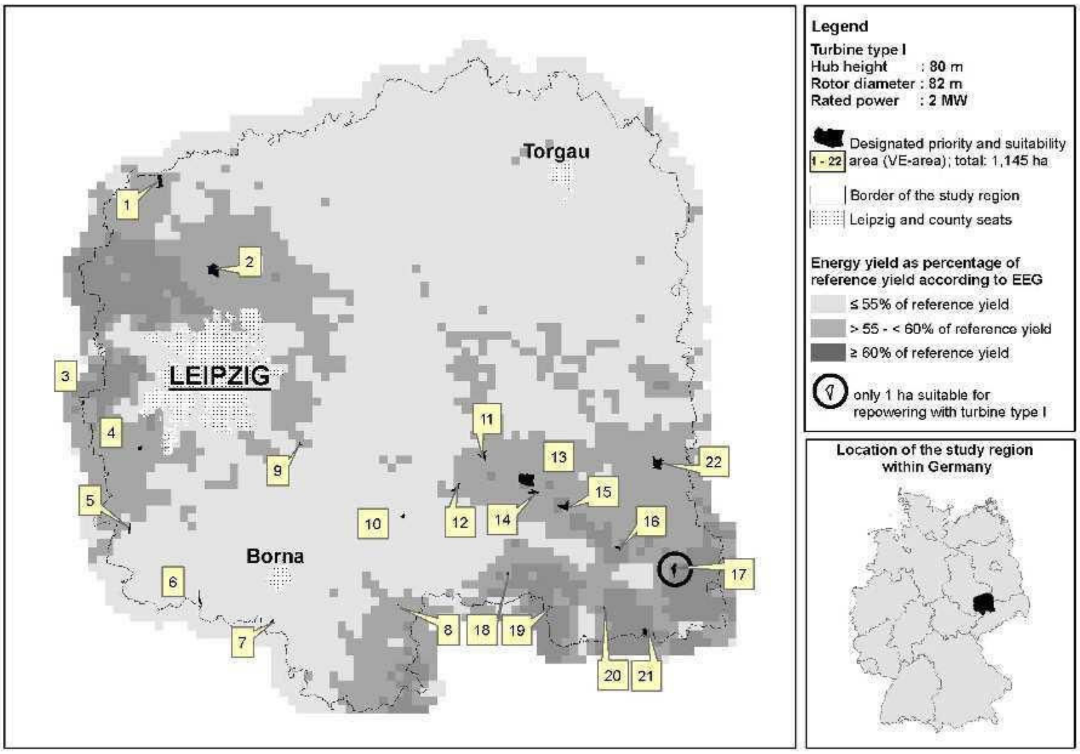

Figure 1. Study region of West Saxony with designated wind farming areas and expected energy yields for turbine type I

4.2. RESULTS

We have to first mention that the results presented here are calculated for state-of-the-art turbines of 2 MW rated power (here called type I) which are qualified to replace most of the existing turbines in the future. As these turbines will fall under the new EEG it will be crucial to meet the reference yield criterion (cf. Section 2). The reference yield for our turbine type I is 5.7 GWh/a, 60% of the amount required by the EEG equates to 3.4 GWh/a. Existing turbines installed prior to the 2004 EEG amendment receive tariffs regardless of their performance, i.e. for these turbines the reference yield is insignificant.

4.2.1. *Land demand*

In order to assess the theoretical potential for repowering we now need to thoroughly apply the requirements of the West Saxony regional plan to some specific parameters of the turbine type I considered here, including land demand, height and noise level. In terms of the land demand of wind turbines, there is no unique method at hand to provide an accurate measure but rather a range of calculation methods depending on context (Ohl and Monsees 2008). A good estimate in the context of our investigation is the toppling distance circular area which measures the hub height plus the rotor blade width in every direction. It amounts to 4.6 ha for every single type I turbine.

4.2.2. *Minimum distance to built-up areas*

The absolute minimum distances of wind turbines to built-up areas in Germany are stipulated by the Federal Emission Control Act (BImSchG). They are based on the spread of a turbine's noise emissions which is mainly influenced by the wind speed, the turbine height and the generator size. The allowed maximum noise level according to the BImSchG is 35 dB dB(A) in residential-only areas and 40 dB(A) in mixed-use areas. For turbine type I, this requirement corresponds to a distance of at least 800 or 500 m, respectively.[5]

4.2.3. *Combined distance and height regulations*

In addition to the universal provisions of the BImSchG, the West Saxony regional plan sets even more restrictive distance regulations linked to turbine heights. According to this, the total turbine height is limited to 100 m in a zone up to 750 m from residential areas. In a zone from 750 to 1,000 m from residential areas, a turbine must be at least ten times its hub height (RPW 2008) away. As a result, type I turbines (hub height: 80 m) may only be erected 800 m or more away from residential areas. Taking into account the location of the 22 VE areas only three (nos. 2, 13 and 22) do have substantial space available beyond 800 m away, while most others are either closer to residential areas or relatively small. In all, just 323 ha (28%) out of the total of 1,145 ha designated for wind farming are sited beyond 800 m.

4.2.4. *Height limitation in some VE areas*

Apart from the aforementioned height regulations that are applicable for the entire planning region, in two VE areas (no. 1 and 2) located close to the Leipzig–Halle airport, the total height of a wind turbine is strictly limited to 100 m. Thus, these areas are also completely unavailable for repowering with type I turbines (total height: 121 m). A further 109 ha have to be subtracted from the VE sectors potentially suitable for repowering so that only 214 ha (19%) remain.

[5] According to a wind power expert from Saxony, personal communication, 22 July 2008.

4.2.5. *Expected energy yields*

Figure 1 illustrates the grid data set representing the annual energy yield to be expected for turbine type I. The darker the colour of the grid cells, the higher the expected energy yield. Of particular importance are the dark grey sectors because they indicate that turbine type I achieves 60% or more of its reference yield. Only wind farmers in these sectors will be paid a tariff for wind powered electricity by grid system operators according to the EEG. Figure 1 clearly indicates that only few parts in the northwest and southeast of West Saxony fulfil this criterion. This means that wind farming with turbine type I is unprofitable for most parts of this planning region. With regard to the 22 VE areas designated in the West Saxony regional plan (black spots in Fig. 1) obviously only one VE area (no. 17, circled in black) is partly located in a dark grey sector. This is the only place that a wind farmer has an incentive to repower, i.e. to replace his/her existing turbines with type I turbines.

4.2.6. *Repowering potential in VE areas*

Due to the distance and height regulations referred to above, only 214 ha (19%) out of a total of 1,145 ha designated for wind farming in West Saxony are actually available for repowering with turbine type I. The suitable sectors are located in 11 of the 22 VE areas. Assuming a land demand of 4.6 ha for a single turbine (cf. Section 4.2.1), it is possible to fill this space with 46 type I turbines which would total 92 MW rated power. However, the land available is essential but it is not sufficient. For wind farmers, the key to repowering is achieving the reference yield criterion. As mentioned above (cf. Section 4.2.5) just one too small portion of 1 ha in just one VE area (no. 17) can be expected to meet this criterion, i.e. there is nearly no incentive to repower at all. This unsatisfactory result gives reason to reconsider the selection of VE areas as well as the technical repowering option and will be addressed in the following section.

4.3. DISCUSSION

The analysis carried out in Section 4.2 has revealed that from the total VE area designated for wind power generation only a fraction, 19%, is legally suitable for turbine type I and that an even lesser portion (1%) is economically viable. This considerable discrepancy raises questions as to whether and what alternatives may exist to reconcile it. Ohl and Eichhorn (2009) have primarily identified two options which will be reproduced below – the utilisation of another type of wind turbine, and the spatial re-allocation of VE areas.

4.3.1. *Utilisation of a different type of wind turbine*

Because wind force is stronger and more regular the higher the altitude, it can be expected that a taller turbine would yield more energy than type I at every given location. Therefore, we now reproduce the energy appraisal for turbine type II which is characterised by 3 MW rated power, 90 m rotor diameter, 105 m hub height, 150 m total height and a toppling distance circular area of 7.1 ha to represent its land demand. The EEG reference yield for turbine type II is fixed at 6.9 GWh/a, which results in at least 4.1 GWh/a for EEG tariff eligibility (60% of reference yield). Thus, it requires a 20% higher energy yield for turbine type II to pass the reference yield criterion compared with type I. The expected energy yields for turbine type II are shown in Fig. 2. Despite the more demanding performance standard, EEG tariffs can be expected for turbine type II in more parts of the study region than for type I which makes, in principle, type II the economically superior choice. To a large extent, this can be attributed to the 30% increase in hub height.

However, because of the above-mentioned combined distance and height regulations (cf. Section 4.2.3.) the legally suitable VE area for type II turbines is considerably reduced since these are higher than type I. Only sites of at least 1,000 m distance from built-up areas can be taken into account this time. As a result, just 82 ha or 7% of the total designated space for wind farming remain which are situated in three (no. 2, 13, 22) out of a total of 22 VE areas. Considering the particular height restriction around the airport (cf. Section 4.2.4.) leads to the omission of VE area no. 2, so that just 47 ha (4%) are left for turbine type II compared to 214 ha (19%) for turbine type I. But finally applying the EEG reference yield criterion to the remainder only yields 23 ha (2%) located in two VE areas (no. 13, 22) which are useful from an economic point of view. This leaves space to operate three turbines of 9 MW rated power in total which may potentially yield 12.6 GWh/year. Since the use of other state-of-the-art turbines instead of type II would also face limitations in terms of distance and height, it is obvious that the disparity cannot be resolved by simply altering the turbine type.

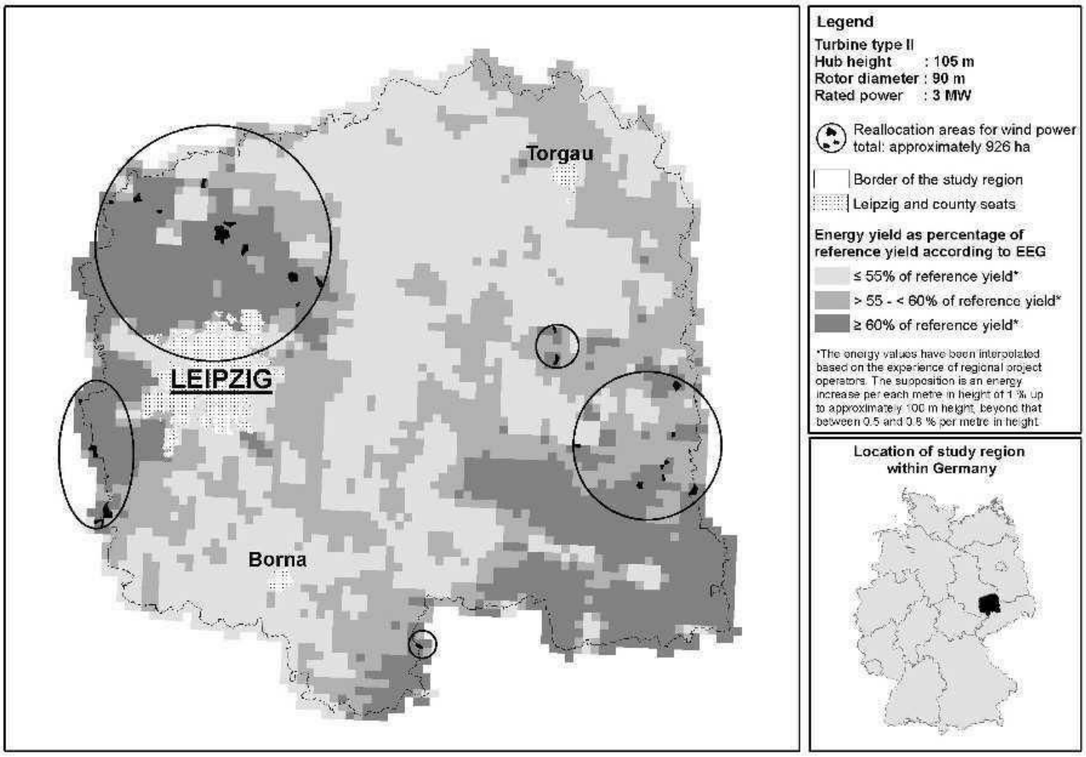

Figure 2. Expected energy yields and potential re-allocation areas in West Saxony for turbine type II

4.3.2. *Spatial re-allocation of wind farming areas*

As a second means to reconcile the disparity between the currently designated wind farming space and that which is economically viable for repowering, we now consider the spatial re-allocation of VE sites. In doing so, we particularly emphasise the energy potential per unit area to economically select more feasible areas for wind farming than those designated in the West Saxony regional plan. We carry out this analysis for both turbine types. The results for turbine type I are shown in Fig. 3. A total of 188 ha partitioned into 11 individual plots (depicted in Fig. 3 inside the six circles) have been identified which satisfy the legally binding selection criteria and the specific distance and height regulations in West Saxony as well as the EEG reference yield criterion. The identified area equates to 16% of the total surface area of the currently designated 22 VE areas and allows for the operation of 40 type I turbines of 80 MW rated power in total which would yield 140 GWh and save 119,840 t CO_2 per year. The equivalent results for turbine type II are illustrated in Fig. 2. Overall, 926 ha partitioned in 21 individual plots (within the five circles in Fig. 2) have been identified in this case which equals 81% of the currently designated VE areas. This enables 130 type II turbines of 390 MW rated power in total to be operated which would yield 546 GWh and save 467,376 t CO_2 per year. Thus, a re-allocation of the VE areas designated at present could bring about more economically viable space for repowering, a larger energy yield and higher CO_2 savings (Ohl and Eichhorn 2009).

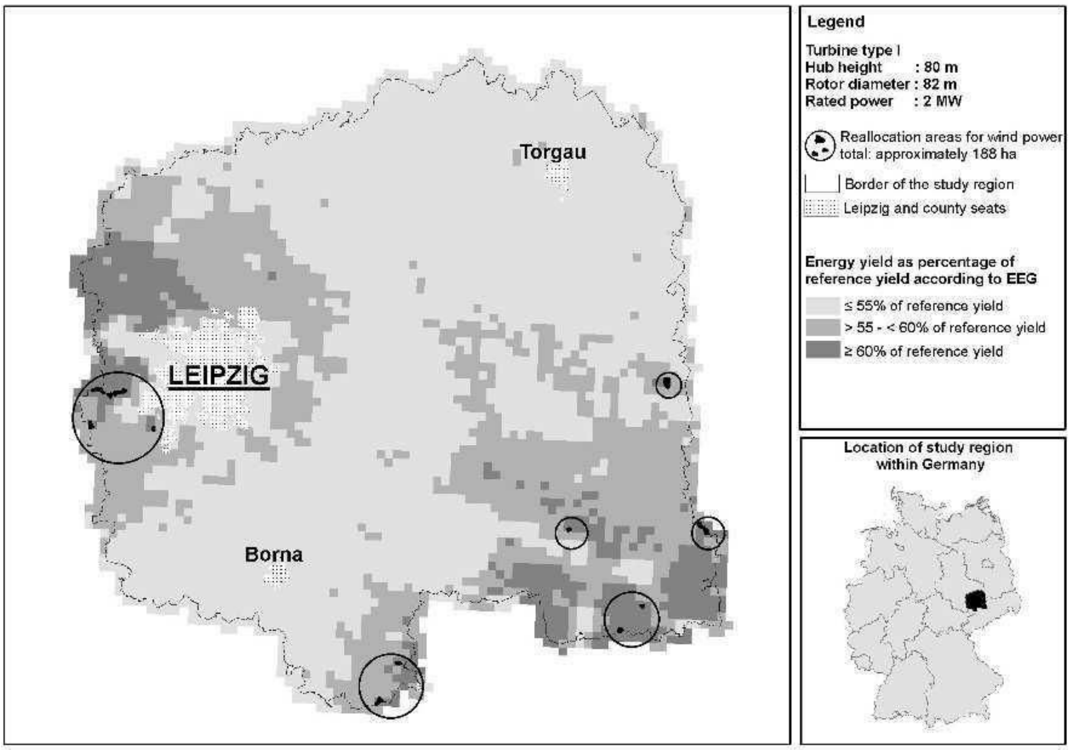

Figure 3. Potential re-allocation areas in West Saxony for wind farming with turbine type I

5. Case Study North Hesse

5.1. STUDY REGION

North Hesse is one of a total of three planning regions[6] in the German state (*Bundesland*) of Hesse. By the end of 2007 the region had a population of little more than 1.2 million and a surface area of 8,289 km². Because this surface area is almost twice as large as West Saxony, we decided to consider only a part of North Hesse of approximately the same size as West Saxony. The selected part comprises the three counties of Kassel, Schwalm-Eder and Waldeck-Frankenberg and the city of Kassel. These will be considered below as our study region North Hesse. It has roughly 785,000 inhabitants and a total surface area of 4,786 km². With a density of 164/km² this study region

[6] Although the official term in Hesse is administrative district (*Regierungsbezirk*), we use the term planning region here as well for the sake of comparison with Saxony.

is much less populated than the study region West Saxony. 223 wind turbines with a total capacity of 183 MW rated power were in operation in the region by the end of 2007, generating around 270 GWh of electricity per year (RVN 2009) and averting roughly 230,000 t CO_2.[7] About two-thirds of these turbines have been installed outside VE areas – which were designated at a later date – and are now operating under a continuation permit (RVN 2009). This represents a much larger fraction compared to West Saxony.

The regional plan for North Hesse has been revised lately and waits now for the approval of the government of Hesse to become effective. The plan designates areas for wind farming as the West Saxony regional plan does, but it names these differently. While West Saxony designates VE areas, North Hesse designates priority areas for wind power generation (cf. Sections 2 and 4.). However, referring to the state planning law (*Landesplanungsgesetz*) of Hesse, Section 6 (3), the North Hesse regional plan defines priority area in such a way that the installation of wind turbines outside these areas is not allowed. That is to say, the legal impact of priority areas in North Hesse is exactly the same as that of VE areas in West Saxony (RVN 2009). Hence, for the sake of comparison, we will phrase the priority areas for wind power generation in North Hesse as VE areas as well. Furthermore, unlike West Saxony, North Hesse distinguishes between VE areas already in operation (*Bestand*), i.e. partly occupied with wind turbines, and VE areas not yet in operation (*Planung*), i.e. still without wind turbines (RVN 2009). Eighteen VE areas covering 1,073 ha that are already operating and 17 VE areas covering 1,025 ha that are not yet operating are designated for wind farming. The location of VE areas of both categories is depicted in Fig. 4 (no. 1–18 and 19–35 respectively). The size of individual VE areas ranges from 5 to 114 ha. Overall, 35 VE areas covering 2,098 ha or 20.98 km² are designated for wind farming (RVN 2009). This represents 0.44% of the region's total surface area, a proportion that is almost twice as high as in West Saxony.

The selection procedure of the VE areas in North Hesse also resembles the approach described in Section 3. It follows the objectives and principles as laid down in the regional plan taking the state planning law and the state development plan of Hesse into consideration. As in West Saxony, neither the state development plan nor the regional plan give quantifiable targets for wind power. However, the regional plan conveys that the designation of further VE areas for wind farming in North Hesse is to support the ambitious renewable energy policy targets of the German Federal Government (RVN

[7] CO_2 savings are set at 856 t/GWh according to Ragwitz and Klobasa (2005), cited in Ohl and Eichhorn (2009).

2009). The set of exclusion criteria to designate VE areas is similar to West Saxony and exemplified in detail in the regional plan. However, in contrast to West Saxony a few exclusion criteria in North Hesse discriminate between VE areas already in operation and those not yet in operation. First of all, this concerns differing minimum distances between VE areas and built-up areas. Moreover, VE areas that are not yet operating require a minimum surface area of 20 ha unless they are attached to a VE area that is already in operation (RVN 2009). A large portion in the north of the study region is situated within a military radar range, where it is necessary that turbines are staggered.[8] The impact of these requirements on the repowering potential will be analysed in Section 5.2.

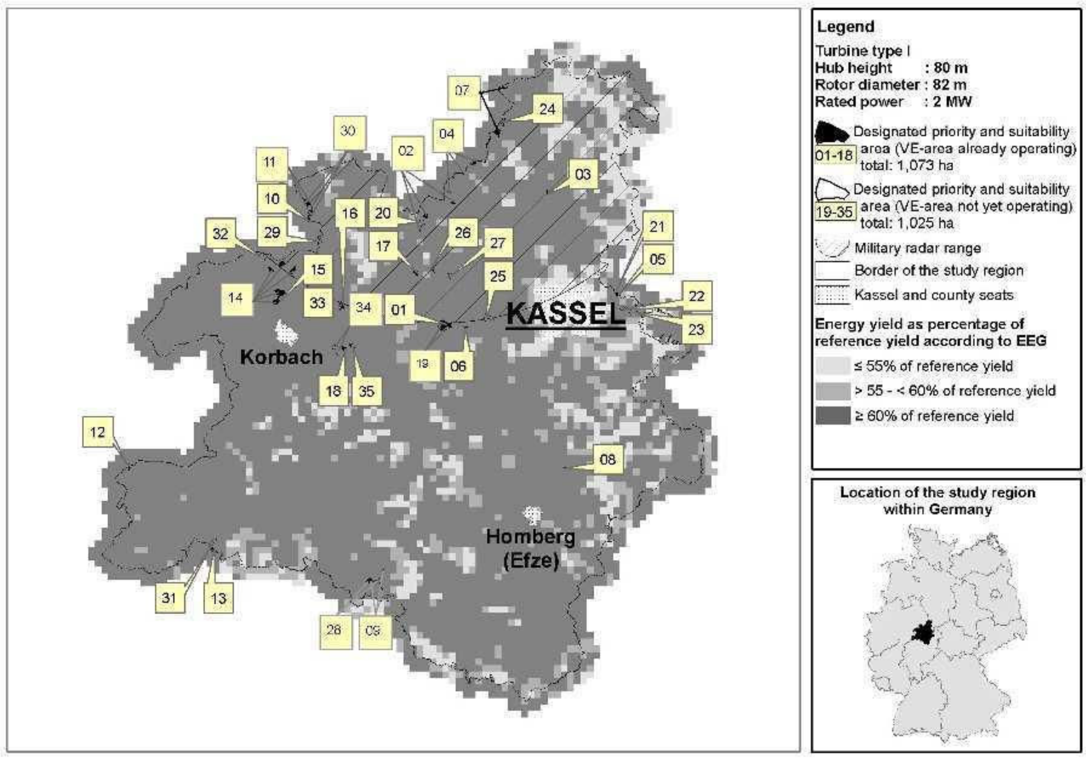

Figure 4. Study region of North Hesse with designated wind farming areas and expected energy yields for turbine type I

[8] This condition derives from appeals of the military district administration in the course of building permit procedures on the local level for two repowering sites. Although not a requirement imposed by the regional plan, it has to be considered when it comes to repowering; personal communication: *Regierungspräsidium* (district government) Kassel, 1 October 2009.

5.2. RESULTS

The results presented here again are calculated for state-of-the-art turbines of 2 MW rated power which qualify to replace existing turbines in the years to come and for which it will be crucial to meet the EEG reference yield criterion (cf. Sections 2. and 4.2). In order to make fair comparisons we use the same approach to assess the theoretical repowering potential in North Hesse as in West Saxony. Accordingly, we now apply the requirements of the North Hesse regional plan to turbine type I.

5.2.1. *Land demand*

The land demand per wind turbine is again set at 4.6 ha which represents the toppling distance circular area of type I turbines (cf. Section 4.2.1.).

5.2.2. *Distance requirements*

As already explained in Section 4.2.2, type I turbines need minimum distances of approximately 800 m from residential-only areas and 500 m from mixed-use areas to be in accordance with the BImSchG. Apart from that, the North Hesse regional plan requires that VE areas not yet in operation are at least 1,000 m away from residential areas and 500 m from commercial areas. In contrast, VE areas already in operation only require distances of 750 and 300 m respectively (RVN 2009). The difference can be attributed to the characteristics of the smaller turbines which were common by the time the VE areas already in operation were designated. Compared to West Saxony, the North Hesse region plan does not specify combined distance and height regulations. However, the northern portion within a 40 km military radar range (shaded sector in Fig. 4) requires a distance of at least 750 m between two turbines. This has a significant impact on the utilisation level of VE areas located within this range and affects 901 ha or 43% of the total of designated VE areas. This requirement leads to a virtual increase in the land demand per turbine from 4.6 to 44 ha and, therefore, to a reduction of the number of turbines allowed per affected VE area. Consequently, the energy yields achievable in the affected VE areas are also considerably reduced.

5.2.3. *No height limitation*

Unlike West Saxony, the North Hesse regional plan does not explicitly limit turbine heights. Thus, the repowering potential is not restricted in this respect.

5.2.4. *Expected energy yields*

Figure 4 illustrates the grid data set representing the annual energy yield to be expected for turbine type I. The darker the colour of the grid cells, the higher the expected energy yield. As in Fig. 1, again the dark grey sectors represent those areas where turbine type I is expected to achieve 60% or more of its reference yield and thus qualifies for EEG tariffs. In sharp contrast to West Saxony (cf. Fig. 1), Fig. 4 shows that in North Hesse every single VE area designated for wind farming regardless whether already in operation or not does meet the reference yield criterion. That is to say, from this point of view, turbine type I can be profitably operated without reservation throughout the 35 VE areas or 2,098 ha respectively. However, the effective energy yields are considerably reduced because of the separation requirements within the said radar range. The magnitude of this impact and possible solutions are discussed in the following subsections.

5.2.5. *Repowering potential in VE areas*

Due to less restrictive distance and height regulations, turbine type I can be legally deployed and EEG eligibly operated in every VE area in North Hesse without limitation (cf. Section 5.2.4). Thus, compared to West Saxony, the repowering of existing turbines in VE areas is not hampered in that respect. Yet on the other hand, the above-mentioned distance requirement between turbines has a negative effect on the repowering possibilities in 18 VE areas which are situated within the 40 km radar range in the northern part of the study region. Compared to an unrestricted use of these areas this would lead to a loss of 146 type I turbines with a total capacity of 292 MW, which implies a wind power loss of some 700 GWh/a. However, this requirement would affect repowering by other turbine types in a similar manner.

5.3. DISCUSSION

Although the results obtained so far have shown that the currently designated VE areas in North Hesse are entirely suitable for type I turbines we now discuss the options raised in the West Saxony case study (cf. Section 4.3.) for North Hesse as well, to deal with the loss of space due the military radar range.

5.3.1. *Utilisation of a different type of wind turbine*

The first option we analyse is the use of the taller turbine type II. The energy appraisal is depicted in Fig. 5. It resembles the picture for type I, i.e.

the study region North Hesse in general qualifies for the most part for EEG tariffs and type II could be operated in every designated VE area above the reference yield criterion. Hence, in terms of EEG eligibility there is no difference between type I and II turbines. But turbine type II requires a minimum distance of 1,000 m to residential areas for sound diffusion reasons, which exceeds the requirement for type I by 200 m. However, since VE areas not yet in operation are planned 1,000 m away from human settlements, they are not impacted at all. Of the possibly affected 18 VE areas already in operation, only a few are located closer than 1,000 m to settlements. Therefore, this point can be ignored in our analysis without distorting the results. Apart from that, the use of type II is constrained as well by the said radar range (shaded sector in Fig. 5). In contrast to an unrestricted use of the affected VE areas this would lead to a loss of 77 type II turbines with a total capacity of 231 MW, which implies a wind power loss of approximately 470 GWh/a or 67% in terms of losses for type I.

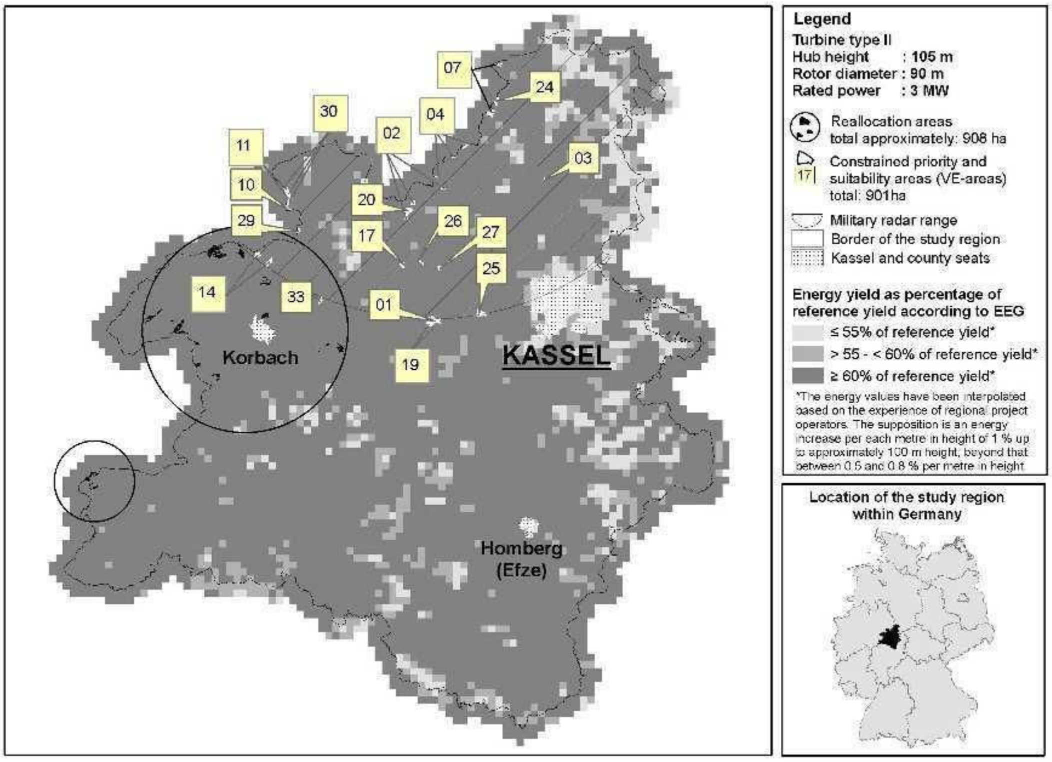

Figure 5. Expected energy yields for turbine type II and potential re-allocation areas in North Hesse

5.3.2. *Spatial re-allocation*

In North Hesse, the need for re-allocation does not arise, as in West Saxony, from turbine height limitations or an underperformance in terms of the EEG, but from the significant utilisation constraint in VE areas within the radar range. We therefore identify a number of spatial re-allocation areas in North Hesse which also qualify for wind farming in terms of legal and physical exclusion criteria and EEG eligibility, but are located outside the radar range. Potential re-allocation areas for turbine type II are illustrated in Fig. 5 (within the black circled sectors). By using such areas instead of the constrained ones, it would be possible, without increasing the total of land designated for wind farming, to regain space for 129 type II turbines with a total capacity of 387 MW rated power which could yield around 970 GWh/a. For turbine type I, in principle, the same sectors of the study region can be considered for a re-allocation. In that case, they could accommodate 199 type I turbines with a total capacity of 398 MW generating approximately 1,270 GWh/a.

6. Comparative Evaluation of the Two Case Studies

When we started our research on wind farming in West Saxony we were somewhat surprised about the initial findings that the designated VE areas to a large extent do not allow for a profitable operation or even an installation of state-of-the-art turbine types which normally can be considered as the logical alternatives for repowering in the next years. This motivated us to investigate another hinterland region, North Hesse, in order to verify whether the results obtained from the West Saxony case study can be viewed as typical for a hinterland in general or not.

First of all, we have to mention two main differences between the two study regions which most likely have a major influence on the outcome. Firstly, the average wind speeds in North Hesse are constantly higher than in West Saxony which is obvious from a comparison of Figs 1–5. This enables the operation of both considered turbine types above the reference yield criterion almost throughout North Hesse, whereas this is guaranteed only at a few sites in West Saxony. Secondly, West Saxony is much more densely populated than North Hesse which, under the given distance requirements towards built-up areas, considerably restricts the search-space for VE areas in West Saxony. The coincidence of these two differences, an unfavourable wind regime and a higher population density makes it even more difficult for the regional planning agency in West Saxony to designate VE areas for wind farming which not only qualify with regard to the applied exclusion criteria but also for a profitable management of wind farms. Hence, we can ascertain that we have no evidence that our findings from West Saxony are representative of German hinterland regions in general.

A detailed comparison of the two case studies reveals some other interesting findings which relate to the two options discussed: the utilisation of another turbine type and a spatial re-allocation of wind farm areas. The effect of the switch from turbine type I to type II, for instance, is more noticeable in West Saxony than in North Hesse. This is because type II can be expected to operate in more sectors of West Saxony above the reference yield criterion than type I (cf. s. 1 and 2). In contrast, in North Hesse there is no such difference regarding this criterion. Although we have found that turbine type II would allow for a better utilisation of VE areas in West Saxony than type I, this option has not proven to be a solution due to the combined distance and height regulations that must be observed (cf. Section 4.2.3.).

That has led us to the consideration of a spatial re-allocation which has revealed that it is possible to find sites other than the designated VE areas which would yield better results from an energetic point of view without compromising the legal requirements for wind farming. In this respect, we can conclude that, subject to our chosen framework, the current spatial allocation of wind farm areas in West Saxony is not as effective as it could be. In North Hesse, on the other hand, the need for a spatial re-allocation of wind farm areas may arise from the constraint imposed by a military radar range. 43% of all the land designated for wind farming is affected by the turbine separation requirement. This implies a significant loss in potential wind power, whereby the potential loss is considerably higher in case of turbine type I than for type II because, in the absence of such a constraint, type I could be arranged more densely than type II. Since we have shown that potential re-allocation areas are available instead, we can conclude that, again according to our chosen framework, the current spatial allocation in North Hesse is also not effective as it could be.

7. Conclusions

What general conclusions for securing wind energy supply at the regional level can now be drawn from the comparative evaluation of the two case studies? In the first place, our investigation clearly shows that even for hinterland regions it should be possible in the near future to produce more wind power than today. Our proposals illustrate that through a repowering with state-of-the-art turbines and a spatial re-allocation of wind farm areas, the current regional wind power quotas could nearly double (in West Saxony) or even more than double (in North Hesse). However, to achieve this ambitious goal it would be necessary to overcome a number of constraints. Distance and height regulations turned out to be major obstacles for a full utilisation of existing VE areas. It should be scrutinised whether such requirements are justified in each particular case and whether technical devices could be made available to mitigate adverse effects on humans and nature. Of course, regional plans are devised for long periods of time and need to take into account numerous criteria and balance many interests. Therefore, a re-allocation of VE areas cannot be expected to take place shortly. Just as well as the wind turbines operating today are usually scheduled to run for 20 years or more. Hence, economic incentives for wind farmers are required if repowering is to start earlier. A step in this direction has been made in Germany with the recent amendment of the EEG (2009). To sum up, the findings from our comparative evaluation of two German case studies clearly indicate that wind farming can play a major role in securing energy supply at the regional level. However, wind power generation in the hinterland will not have reached its limit for a long time to come. We suppose that this holds true not only for Germany but for many other European countries as well.

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Chapter 6

Wind Power Production and Bird Collision Avoidance

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"Spatial trade-offs between wind power production and bird collision avoidance in agricultural landscapes"

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Research

Spatial Trade-Offs between Wind Power Production and Bird Collision Avoidance in Agricultural Landscapes

Marcus Eichhorn[1] *and Martin Drechsler*[1]

ABSTRACT. The expansion of renewable energy production is seen as an appropriate way to mitigate climate change. Renewable energies are not free of negative external effects on humans and the natural environment. We analyzed the conflict between wind power production and bird protection through the example of one of the most sensitive species, the red kite (*Milvus milvus*) in West Saxony, Germany. We investigated a large number of potential land use scenarios, defined by whether or not each potential site contained a wind turbine (WT). Based on meteorological and ornithological data, we evaluated the land use scenarios for their annual energy supply and impact on the red kite. We identified the efficient land use scenarios that maximized energy supply for a given ecological impact. Within the scope of our analysis, the current allocation of WTs in the study region was considered inefficient. The set of efficient scenarios allowed us to draw conclusions on the trade-offs involved. We developed an indicator that measures the severity of the conflict between wind power production and bird protection. Increasing the minimum distance of WTs to settlements beyond the legal requirements in order to minimize the impact on humans further intensifies the conflict. Our results can support planning authorities in their development of long-term regional plans by identifying areas that are most suitable for wind power production from an integrated point of view.

Key Words: *bird protection; efficiency frontier; land use optimization; spatial allocation; trade-off; wind power*

INTRODUCTION

Innovative technologies are developed to reduce emissions and slow down global warming in times of climate change caused largely by CO_2 emissions from human-related energy production, population growth, and consumption patterns. One of these CO_2 neutral energy generation technologies is wind power production. Wind is a renewable energy source that can be used nearly all over the world, and is limited only by atmospheric conditions and the capacity and spatial extent of electricity networks. Compared to other types of renewable energy production, the use of wind energy is one of the economically most efficient (BMU 2008).

But like most human land use activities, wind power production is not free of environmental impacts (Bishop 2002, Langston and Pullan 2003, Möller 2006, Bright et al. 2008, Carmen et al. 2009, Tsoutsos 2009). On the one hand, humans are impacted through sound emissions, shadow emissions, and the disturbance of the scenic value of the landscape. On the other hand, nature is impacted through loss of habitat, disturbance and displacement of birds, and increased collision risk for bats and birds, particularly for raptors.

Commercial wind power production started in the 1970s in California. At that time there was little or no experience with the environmental impact of wind turbines (hereafter referred to as WTs), so site selection was based mainly on energetic considerations. Later research on the impact of WTs on birds in the USA indicated that these impacts can be substantial (Hunt 2002, Lowitz 2008). Most bird kills were recorded at Altamont Pass, where about 4900 wind turbines are installed. An estimated 880–1300 birds of prey were killed annually. This included up to 116 Golden Eagles, a federally protected species, 300 Red-tailed Hawks, 380 Burrowing Owls, and hundreds of other raptors,

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including kestrels, falcons, vultures, and other owl species (CBD 2009).

In recent years, bats have also been identified as being affected by WTs. An extensive review of studies about the impacts of WTs on birds and bats is provided by Hötker et al. (2006). Despite this knowledge about the environmental impacts of WTs, the integrated analysis of the conflict between wind power production and bird protection is still a challenge. Important questions are how severe these conflicts are, and how the severity of the conflicts depends on external factors such as legal requirements and social concerns.

A conflict between wind power production and bird conservation occurs if areas occupied by the birds concerned are suitable for wind power production. We present a multi-criteria approach for the analysis of this conflict which integrates expert knowledge about the ecological impacts of WTs (e.g., Reichenbach et al. 2004) with information about the energy productivity of individual sites in a spatially explicit optimization framework. For other applications of multi-criteria analysis of environmental problems, see Brown and Cobera (2003), Kiker et al. (2005), Huth et al. (2005), and Moffett and Sarkar (2006). In our approach, the physically suitable sites for wind power production are identified and land use scenarios are defined by deciding whether each potential site is used for wind power production or not. We determine the potential energy productivity and the ecological impact for each site. Based on these data, all Pareto-optimal land use scenarios (the so-called efficiency frontier: e.g., Calkin et al. 2002, Polasky et al. 2008, Ehsan et al. 2009) are determined where a scenario A is Pareto-optimal if there is no other scenario that outperforms A in at least one criterion (in the present case: lead to higher total wind power production) without underperforming in any other criterion (in the present case: lead to a higher impact on the focal bird species). The shape of the efficiency frontier allows us to assess the severity of the conflict between wind power production and bird protection in the region.

Bird protection and energy production are not the only relevant criteria for the allocation of WTs. In an economic valuation study, Meyerhoff et al. (2008) found that the public is highly concerned about the distance of WTs to settlements; larger distances are significantly preferred to smaller distances. This additional constraint is likely to affect the trade-off between wind power production and bird protection. We apply our approach to evaluate the trade-off between wind power production and bird protection in a German planning region and investigate how this trade-off is affected by the consideration of the distance between WTs and settlements.

METHODS

Study region

The study region comprises the area of the planning region West Saxony, which is a part of the Free State of Saxony. It has about one million residents and an area of approximately 4300 km² (Fig. 1).

We chose this area for various reasons. On the one hand, West Saxony has a relatively low amount of installed wind power capacity compared to other regions. In 2007 there were 221 wind turbines with a nominal capacity of 235 MW (megawatts). For comparison, the planning region Anhalt-Bitterfeld-Wittenberg, bordering West Saxony to the northeast, has an almost similar area (3627 km²) but 445 WT with 627 MW installed capacity (RPG ABW 2007). Since the West Saxony region has a high proportion of open areas (only 16% of the area is covered by forest [RPV WS 2008]) and since open landscapes imply a high ground level wind speed (Wizelius 2007), conditions for the further development of wind power in the region are promising.

On the other hand, the region is part of the world's core habitat of the endangered red kite (*Milvus milvus*) (Glutz von Blotzheim 1989, Mebs and Schmidt 2006, BirdLife International 2009). Approximately 50% of the world's red kite population lives in Germany, nearly 10% of which is found in Saxony. The red kite, a synanthropic species, uses anthropogenically used open rural areas for foraging and (partly) for breeding (Nachtigall 2008). It has no natural enemies, except for human beings, so avoidance behavior has not evolved in the species (Mammen and Dürr 2006, Dürr 2008). Since red kites and WTs "use" very similar landscapes, we expect a substantial conflict between prospective wind power production and red kite protection in our study region, and measure the ecological impact of a WT by its predicted impact on the local red kite population. Other biodiversity issues are considered in the definition of the

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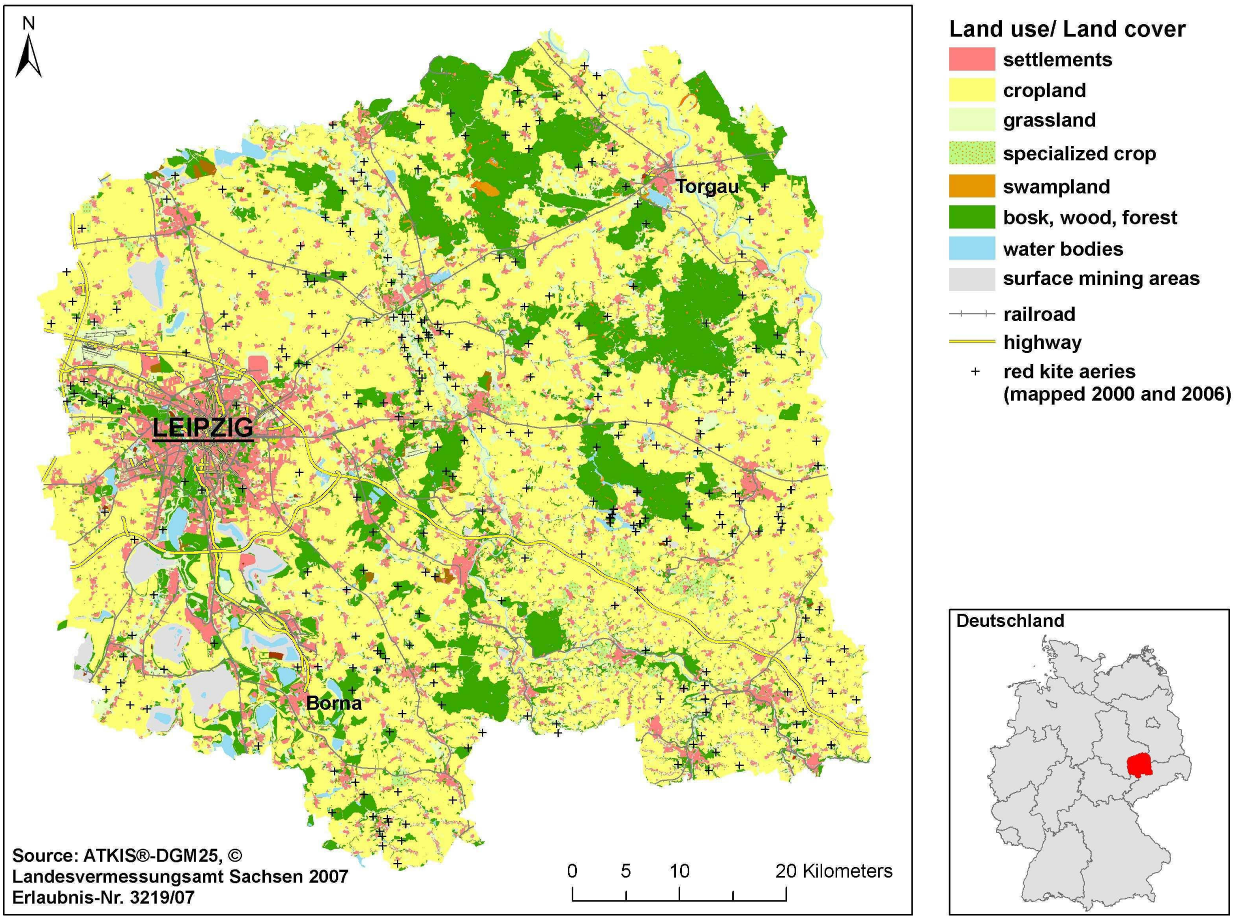
Fig. 1. The planning region West Saxony.



suitability space (*Methods: Determination of the suitability space*).

Data sources

We used real land use/land cover data available as vector data provided by the public survey for Geo Base Information and Measurement Saxony to identify suitable areas for the construction of WTs. The calculation of the amount of wind power produced was based on the frequency distribution of wind speeds, obtained with a horizontal resolution of one-by-one kilometer from the German National Weather Service, and parameters specific to the type of WT, obtained from ENERCON (2008). The determination of the impacts of the WT on the local red kite population was based on the spatial locations of known aeries in the study region. These locations were mapped in 2000 and 2006 by volunteer ornithologists and were provided by the Saxon State Office for Environment and Geology.

Determination of the suitability space

The suitability space comprises those parts of the landscape that are physically and legally qualified for the allocation of WTs. To delineate these parts of the landscape, we began by identifying all areas in the region with land cover types physically

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suitable for the construction of WTs. These land cover types include all open areas of the landscape, i.e., cropland, grassland/pasture, heath, scrubland, vegetation-free areas, and acclivity/reclaimed land. Then we removed all areas that are not legally qualified for the construction of WTs according to LANUV NRW (2002), TA Lärm (1998), BfN (2008), and several laws, such as article 9 of FStrG–Bundesfernstraßengesetz, article 24 of SächsStrG–Sächsisches Straßengesetz, and article 3 of LEisenbG-Landeseisenbahngesetz).

To allocate WTs within the suitability space, we used a Monte Carlo Simulation, programmed by Dr. Ralf Guckel, to determine potential sites for WTs. The program fills the suitability space with the maximum possible number of potential sites while considering minimum distances between individual sites. These minimum distances are required to avoid the wind park effect, which denotes the reduction of the energy output of a WT located at the lee side of other WTs (Wizelius 2007: pp. 234–236). For the chosen type of WT, the minimum distance to avoid the wind park effect amounts to 410 m, which is five times the WT's rotor diameter. We obtained a number of $N = 1022$ potential WT sites.

Multi-criteria evaluation

To analyze the conflict between wind power production and red kite protection, the policy criteria needed to be defined as measurable quantities, and all land use scenarios had to be evaluated by these quantities. To generate a land use scenario, we decided whether or not each potential WT site within the suitability space should contain a WT. For simplicity's sake, we assumed that all WTs were of the same type and had a state-of-the-art wind turbine with a hub height of 80 m, a rotor diameter of 82 m, and a nominal power of 2 MW. One land use scenario, for example, may be to construct a WT on site 1 and no WT on the others. Another scenario may be to construct a WT on site 2 and none on the others. A third scenario may be to construct a WT on each of sites 1 and 2 and none on the others, etc. With $N = 1022$ sites available, there is a number of 2^N of these combinations, i.e., 2^N different land use scenarios.

Energy production

To calculate the energy production for the selected WT technology at a given site, we needed the frequency distribution of the wind speed at 80 m above ground level and the power curve for the selected WT technology, which tells how much electrical power the WT will produce at a given wind speed.

The frequency distribution of the wind speed v is suitably described by a Weibull distribution (Hau 2006: pp. 509–514, Wizelius 2007: pp. 49–50), which is characterized by a scale and a shape parameter (denoted as A and k):

$$f(v_m) = k / A(v_m / A)^{(k-1)} \exp\{-(v_m / A)^k\} \quad (1)$$

(Fig. 2 left panel). Since we are considering a discrete wind speed distribution, v_m in Eq. 1 denotes the wind speed in the m^{th} interval. The power $P(v_m)$ generated by the chosen WT technology for a given wind speed v_m is shown in Fig. 2 (right panel). The expected energy produced by the WT in one year (E_a) is therefore the sum of all values $P(v_m)$ weighted by the frequency $f(v_m)$ by which the wind speed v_m is observed at the site under consideration, multiplied by the expected number of hours per year ($t_a = 8760$ h):

$$E_a = t_a \sum_{m=0}^{m_{\max}} f(v_m) P(v_m) \quad (2)$$

Here $m_{\max}$ represents the upper bound of the wind speed range within which the WT operates (Fig. 2, right panel). For each site within the suitability space, we obtained the values for the parameters A and k from the German National Weather Service (*Methods: Data sources*), and using Eqs. 1 and 2, calculated the annual energy production levels. To evaluate land use scenarios with several WTs, we determined the annual energy production of each WT according to Eq. 2 and took the sum of these values. For simplicity's sake, we have omitted the term "annual" so that energy production always refers to the amount of energy produced per year.

Red kite protection

Most red kite collisions with WTs occur during foraging flights in the breeding season. Depending

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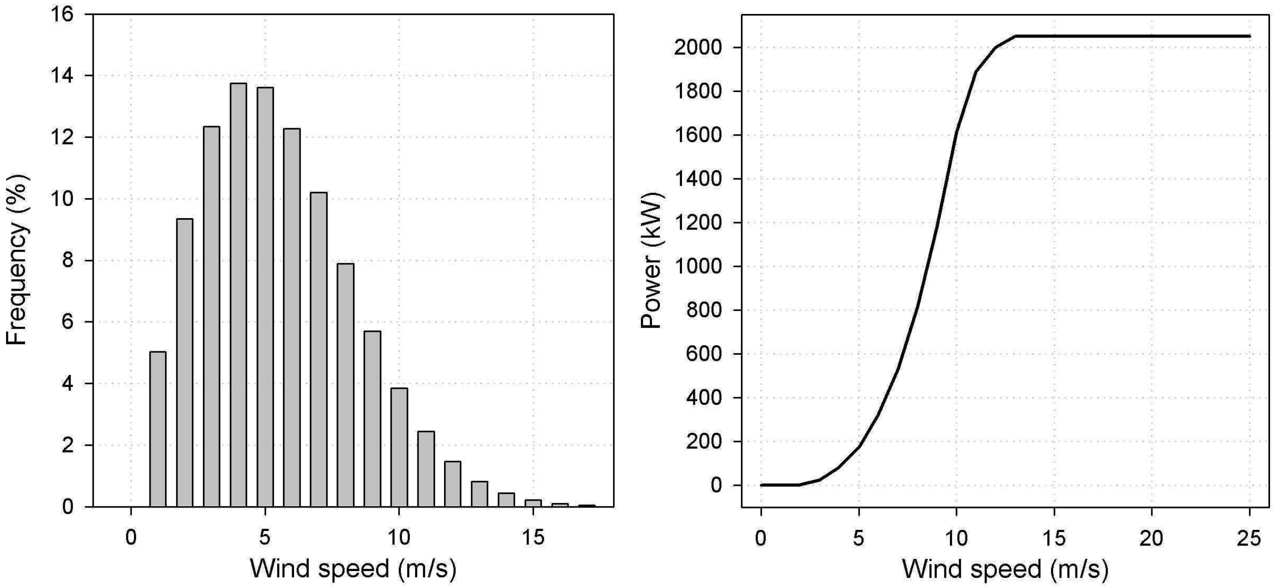
Fig. 2. Calculation of the produced wind power for a particular site. Left panel: example of a wind speed frequency distribution; right panel: power curve for the selected technology option (ENERCON 2008).



on habitat quality, defined by frequency and availability of prey, these flights occur at different distances to the aerie. Based on information received from Nachtigall (2008) and other experts, we modelled the likelihood, *L*, of observing a red kite at a distance *d* from its aerie using Eq. 3:

$$L(d) = \exp\{-(d / k)^2\} \quad (3)$$

Since the bird is most frequently (about 90% of the time) observed at distances less than 3000 m from the aerie (see Nachtigall 2008: pp. 61–62), we set *k* = 3000 m (the results are not very sensitive to moderate changes in *k*).

The probability of a red kite colliding with a WT is proportional to the likelihood of the bird occupying the same physical space as the WT. Therefore, given that *L*(*d*) is the likelihood of a bird being observed at a distance *d* from the bird's aerie, the probability of the bird colliding with a WT located at distance *d* from the aerie is proportional to *L*(*d*). In other words, a WT at distance *d* from a red kite's aerie has an adverse impact of αL(*d*) where α is some proportionality factor. Assuming there is *M*>1 aerie within our study region, the total impact, *I*, of a WT at a particular site on all aeries is the sum of the impacts obtained for each aerie:

$$I = \alpha \sum_{j=1}^{M} L(d_j) \quad (4)$$

where d_j is the distance of the WT to the j^{th} aerie. Since we are interested only in the relative suitability of the different sites, we can set the proportionality factor α to 1. Varying α changes only the scale of the total impact in the region (the horizontal axis in Fig. 5), and the choice of α = 1 implies no loss of generality within the scope of the present study.

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To evaluate land use scenarios with several potential WT sites, we determined their individual impacts according to Eq. 4 and took the sum of these impacts. This sum, henceforth termed "ecological impact", is related to the mortality of the birds. It has an arbitrary scale, which, however, is sufficient within the scope of this study. WTs at the boundary of the study region will also have an impact on aeries close to, but outside, the study region. Since no data about these aeries were available, we generated a 13 km wide buffer around the study region. Aeries are randomly distributed within this buffer at the same density observed within the study region. To remove sampling stochasticity, we sampled 10 different buffers, analyzed our allocation problem for each buffer replicate, and took the average of the results.

Analysis of the trade-offs

Each land use scenario can be plotted by its energy production level and ecological impact. A higher energy production is preferred to a lower one and a lower impact is preferred to a higher one. To analyze the trade-off between energy production and ecological impact, we determined the Pareto-optimal land use scenarios and ranked the potential WT sites by their ratio of energy production and ecological impact. The first Pareto-optimal scenario, therefore, was obtained by allocating one WT to the site with the highest ratio and no WT to all other scenarios. The next Pareto-optimal scenario was obtained by allocating a WT to each of the two sites with the highest ratios and no WT to all other sites. We proceeded by adding sites one by one with decreasing ratios until all N sites of the suitability space were filled with WTs. The N land use scenarios that we obtained through this procedure were all Pareto-optimal.

This procedure worked because (i) we considered only two criteria, (ii) the criteria were additive so that the energy production and impact of two sites was the sum of the respective values for the individual sites, and (iii) the number of potential sites was very large and each site contributed only marginally to the criteria. With conditions (i) and (ii), our optimization problem qualified as a so-called knapsack problem (e.g., Hajkowicz et al. 2008) in which a number of items was selected under a budget constraint so that for a given budget the sum of the items' benefits was maximized. If it were possible to select only fractions of items, we would be confronted with a fractional knapsack problem, which is solved by selecting the items in decreasing order of benefit-cost ratio, with the addendum that if the selection of the last item violated the budget constraint, only a corresponding fraction of the last item is selected (e.g., Dantzig 1963). Although WTs cannot be selected in fractions, due to condition (iii) the associated error was negligible and our procedure of selecting WTs in decreasing order of energy-impact ratio was identical to the approach developed by Dantzig (1963) and correctly identified the Pareto-optimal land use scenarios.

If one or more of conditions (i)–(iii) are not fulfilled, linear programming (e.g., Schrijver 1998, Öhman and Eriksson 2002, Meyer and Grabaum 2008, Ehsan et al. 2009) or heuristics such as tabu search (e.g., Bettinger et al. 2007) or simulated annealing (e.g., Kirkpatrick et al. 1983, Öhman and Eriksson 2002, Westphal et al. 2007, Bettinger et al. 2008) need to be used.

Plotting the Pareto-optimal scenarios by their performances in the two criteria yields a line called the efficiency frontier (e.g., Polasky et al. 2008). The shape of this line represents the nature of the decision conflict. Below we show that the area under the efficiency frontier indicates the severity of the decision conflict.

As stated in the Introduction, another relevant issue is the minimum distance D of WTs to settlements. We expected that varying this minimum distance would affect the shape of the efficiency frontier. Therefore, we generated an efficiency frontier for different levels of D. Alternatively, we may assume that the political will exists to produce certain amounts of energy in the region. Then it is of interest to discuss the trade-off between D and the impact of the WT on the red kite for a given energy level. We investigated this trade-off for different levels of energy production.

RESULTS

Performances of the wind turbine sites

Fig. 3 shows the energy that can be produced per year at each potential WT site. The sites with the highest productivity are in the northwestern and eastern parts of the study region. Fig. 4 shows the impact that a WT would impose on the local red kite population for each potential WT site. The highest impacts would be imposed at sites in the north and the east. Combining Figs. 3 and 4 shows an overlap

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of the regions that are both ecologically sensitive and suitable for wind power production, implying there is a conflict between red kite protection and wind power production.

Trade-off between ecological impact value and energy output

Fig. 5 illustrates the efficiency frontier for our study region. Each point on the curve represents a land use scenario. As described in *Methods: Analysis of the trade-offs*, we obtained the points by gradually filling the region with WTs. At the lower left point of the curve, the locations that have the highest energy output ("gain") for a given ecological impact are selected ("cost"). It is sufficient to use only these optimal locations if only a small amount of energy is to be produced. As a consequence, relatively a lot of wind power can be produced with relatively little ecological impact, implying a high slope of the efficiency frontier. In order to produce a larger amount of energy in the region, increasingly more WTs have to be installed at locations with worse gain-cost ratios, implying a gradually declining slope of the efficiency frontier until the suitability space is completely filled with WTs. At this point, both the ecological impact and the energy production are maximal (end point of the curve, upper right corner of Fig. 5).

The resulting curve is termed an efficiency frontier (e.g., Polasky et al. 2008). Its positive slope reveals that any increase in the energy output can be achieved only at a higher ecological impact. At the lower left corner, the ecological impact is small as is the amount of energy produced, while at the upper right corner, energy output is at a maximum as is the ecological impact. The area under the curve can be used to measure the severity of the decision conflict. To understand this, consider the dashed line in Fig. 6, which represents a fictitious efficiency frontier. About 85% of the maximum energy output (2500 out of 3000 GWh) can be produced at only 20% of the maximum ecological impact (400 out of 1900 impact units). Conversely, with the dotted line, representing another fictitious efficiency frontier that might apply in the presence of a more complex, non-additive ecological impact function, the same energy output can be achieved only at more than 95% of the maximum ecological impact. Obviously, the decision conflict represented by the dotted line is much more severe than that represented by the dashed line. In fact, no conflict would exist in the extreme case where the maximum energy output could be obtained at zero ecological impact, while a most severe conflict would exist if any non-zero energy output could be obtained only at maximum ecological impact.

A geometric quantity that characterizes these different shapes of the efficiency frontiers is the area under the curve (AUC) (shaded area in Fig. 6). Curves with a large (small) AUC are associated with a weak (severe) decision conflict. Denoting the maximum energy output as E_{max} and the maximum ecological impact as I_{max}, the conflict severity, S, is defined in Eq. 5 as

$$S = 1 - \frac{AUC}{E_{max} I_{max}} \qquad (5)$$

AUC ranges from zero (most severe conflict) to $E_{max} I_{max}$ (no conflict); therefore, S ranges from zero (no conflict) to one (most severe conflict). The conflict severity in our WT allocation problem (solid line in Figs. 5 and 6) is about 0.35.

In addition to the shape of the efficiency frontier and the associated severity of the conflict, another relevant question is how the current situation relates to the efficiency frontier. The current situation is characterized by a number of 221 installed WTs supplying an energy output of 345 gigawatt hours (GWh) and imposing an ecological impact of 401 (point i in Fig. 5). Point i is located below the efficiency frontier, which means that under our chosen constraints, the current situation is not Pareto-efficient. In Fig. 5, points i, j, and k span the space of possible Pareto-efficiency gains. On the one extreme, the energy output could be increased without changing the ecological impact. Compared to the current level of 345 GWh, the energy production would be quadrupled (point j in Fig. 5). This shift would involve reallocating, repowering (replacing older and underperforming turbines with new ones that have higher performance levels), and installing additional WTs. On the other extreme, the ecological impact could be reduced without changing the level of energy production (point k in Fig. 5). At point k, the same amount of energy is produced with nearly half the number of WTs. In the scenario associated with point k, the WTs tend to have greater distances to the aeries than in the

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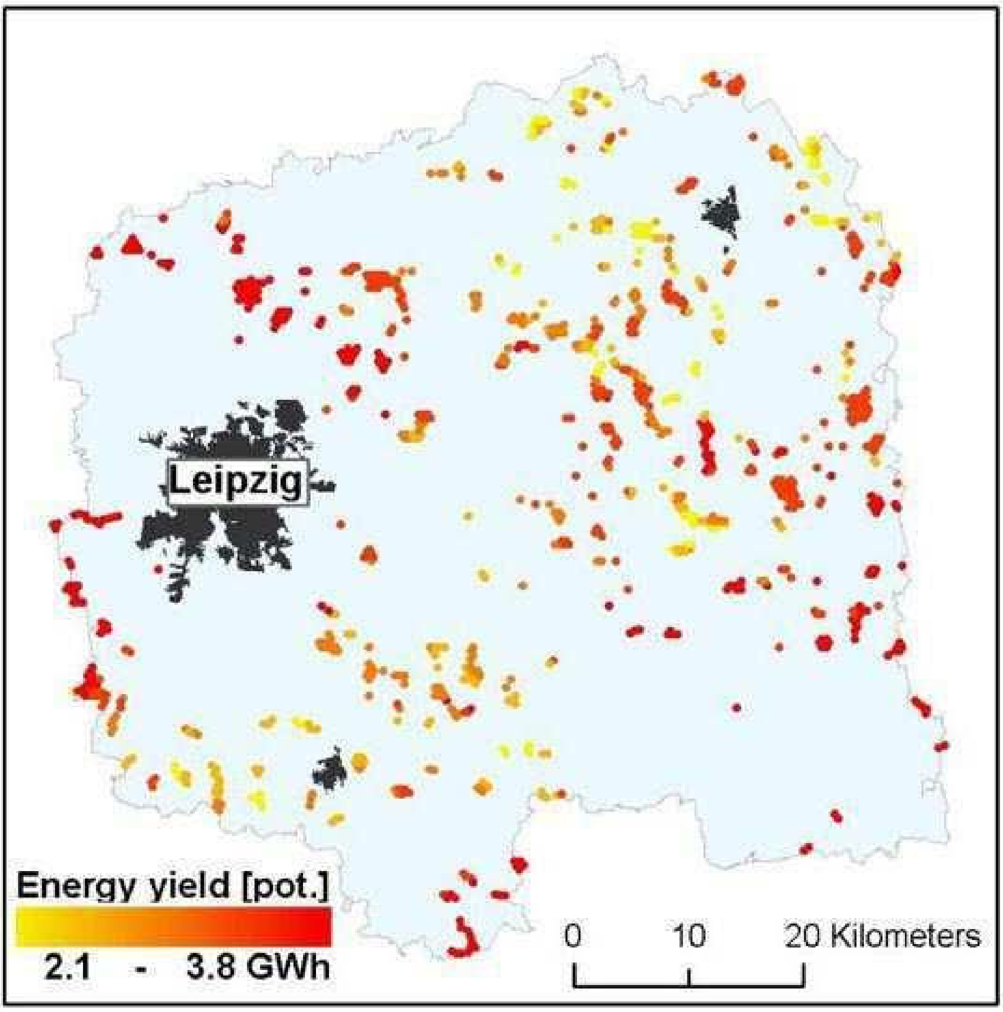
Fig. 3. Energy production map. Each dot represents a potential wind turbine site. Color represents the amount of energy that can be produced per year at the site. Black represents settlements.



scenario associated with point j, resulting in a much smaller ecological impact.

Effects of incorporating social constraints

Another important criterion is the minimum distance of WTs to settlements. In Fig. 5, this distance was set at 800 m based on legal constraints (*Methods: Determination of the suitability space*). Fig. 7 shows how the efficiency frontier changes if the settlement distance is increased. First, the maximum possible energy production and the associated maximum ecological impact are reduced because fewer sites are available for WTs. Raising the settlement distance from 800 m to 1000 m, for example, reduces the maximum energy production from about 3000 GWh to about 1000 GWh. At a settlement distance of more than 1200 m, even the current level of 345 GWh cannot be maintained. Second, an increase in the settlement distance aggravates the trade-off between red kite protection and energy production. At a settlement distance of 800 m, about 2100 GWh can be produced at an ecological impact of 800 units; at a settlement

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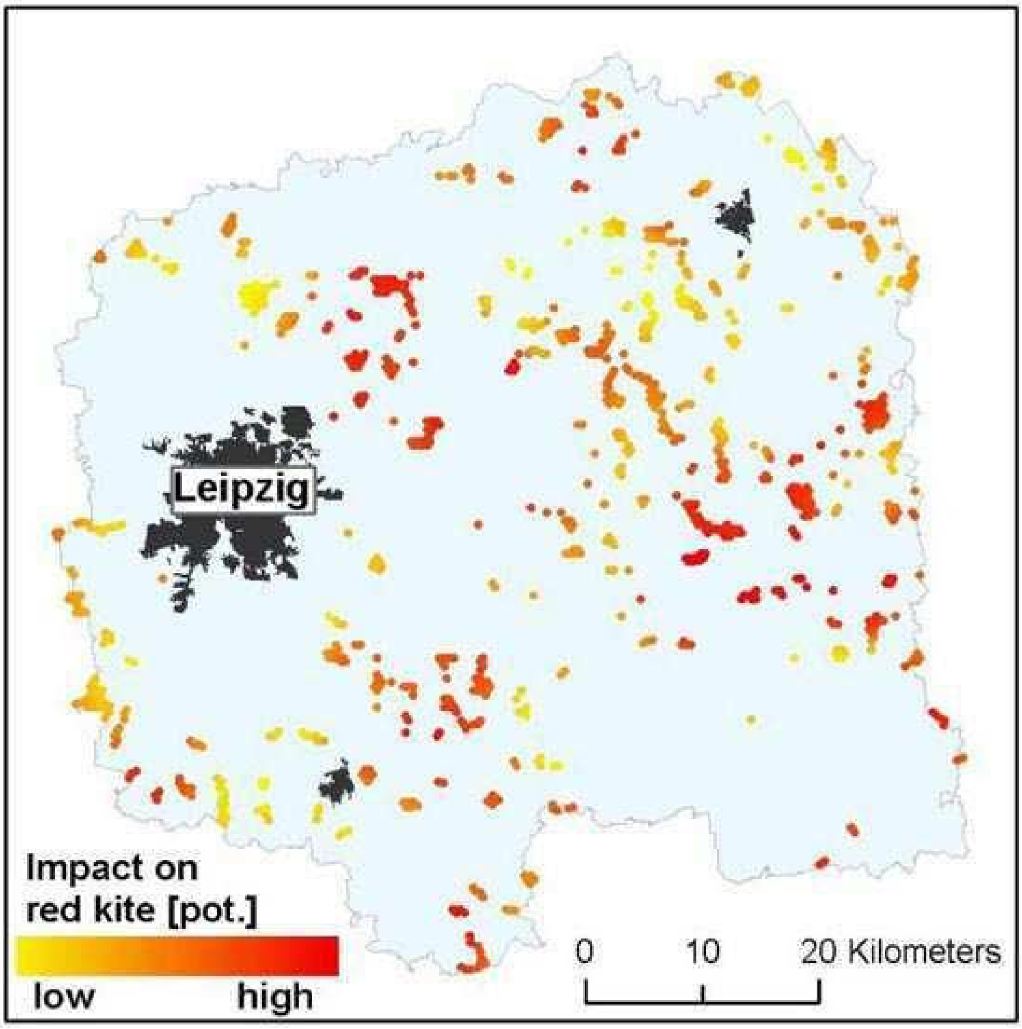
Fig. 4. Impact map. Each dot represents a potential wind turbine site. Colors represent the ecological impact of a wind turbine at the site. Black represents settlements.



distance of 900 m (1000 m), the energy production at the same ecological impact drops to 1600 GWh (1200 GWh). The reason is that not only does the total number of suitable sites decline with increasing settlement distance, but so does the number of sites where energy can be produced with little ecological impact.

This indicates that a trade-off exists not only between energy production and red kite protection but also between these two criteria and settlement distance. Fig. 8 depicts the trade-off between the ecological impact and the settlement distance at given levels of energy production. An increased settlement distance is associated with an increased ecological impact because at large settlement distances the number of available WT sites is small and sites close to red kite aeries have to be selected to meet the given energy production level: a classic trade-off between the well-being of humans (absence of WTs in their vicinity) and the survival demands of species. The trade-off between settlement distance and ecological impact is aggravated if more energy is produced (Fig. 8). At

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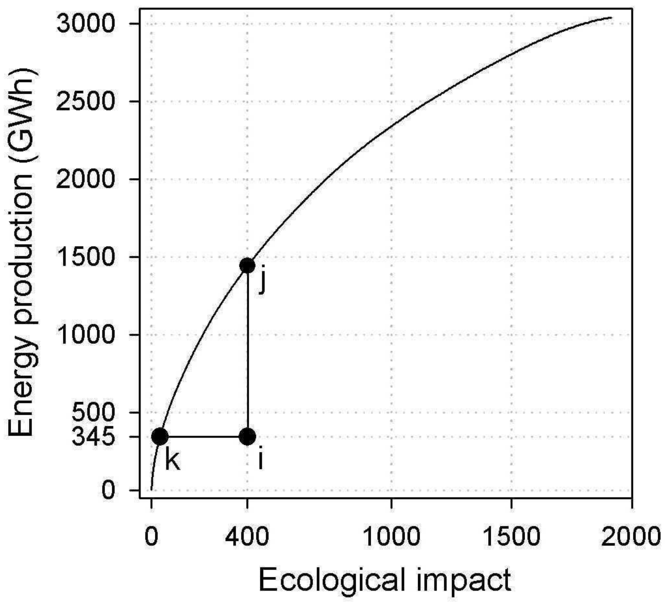
Fig. 5. Efficiency frontier. Energy production versus ecological impact. Solid line: as calculated for the study region. Point i represents the current situation in the study region; the other two points represent two possible ways of increasing efficiency (see *Results: Trade-off*).



the current energy production level of 345 GWh, an increase in the settlement distance of 100 m increases the ecological impact by about 25 units; at a doubled energy production level of 690 GWh, the ecological impact increases by about 50 units per 100 m settlement distance.

DISCUSSION

Since space is generally limited, it is important to allocate WTs efficiently. We employed the concept of Pareto-optimality in order to identify efficient allocation scenarios with regards to wind power production, red kite protection, and disturbance of humans in West Saxony, Germany. For a given minimum distance of WTs to settlements, the Pareto-optimal scenarios form a line (efficiency frontier) in the space spanned by the two criteria "energy production" and "ecological impact". The area under this line (AUC) can be used to measure the severity of the conflict between the criteria. A large AUC means that the land use scenarios are close to the "ideal point" where both criteria are optimally fulfilled. According to Polasky et al. (2008), for example, protecting all relevant species in the Willamette Basin, Oregon would cost about US$27 billion. But in scenario D of Polasky et al. (2008), 98% of these species can already be protected for only about US$2 billion, meaning that scenario D is close to the ideal point where all species would be protected at zero cost. In Eq. 5, we proposed a measure of conflict severity, S, that ranges from zero (no conflict) to one (most severe conflict). The conflict severity in Polasky et al. (2008) is about $S = 0.15$; in this study, $S = 0.35$. This value is considerably higher than those in many other environmental studies, such as Calkin et al. (2002), Nalle et al. (2004), Polasky et al. (2008), and Bladt et al. (2009). As we could demonstrate, additional constraints, such as an increased minimum distance of WTs to settlements in our study, may further increase the severity of a conflict.

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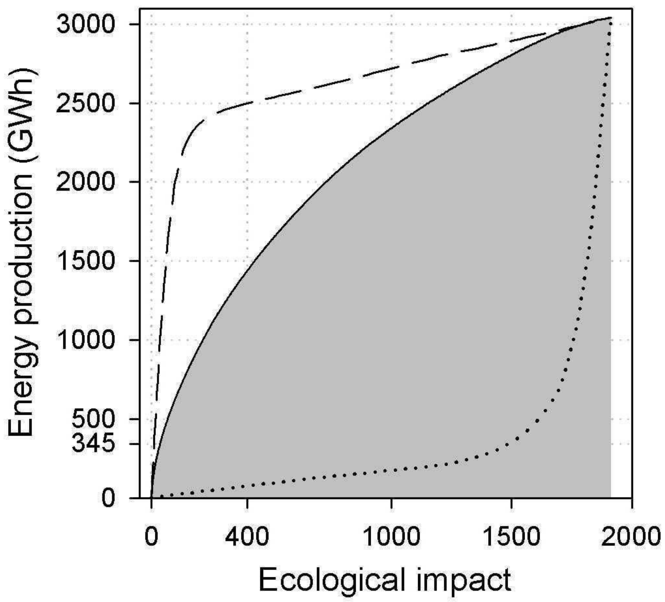
Fig. 6. Efficiency frontier. Energy production versus ecological impact. The solid line is as calculated for the study region, dashed and dotted lines are two fictitious efficiency frontiers. Shaded area: the area (AUC) under the solid efficiency frontier.



In addition to the discussion about the shape of the efficiency frontier, we compared its position with the current situation and found that efficiency gains can be achieved by reallocating WTs so that energy production can be increased without increasing the ecological impact, or the impact can be reduced without reducing energy production.

It should be noted, however, that we disregarded planning constraints that were considered to be relevant in the current allocation of WTs in the study region. We also neglected the site-specific private economic costs for land tenancy, foundation, and grid connection of WTs, etc., which also influence the optimal spatial allocation of WTs. In addition, this influence is reciprocal; i.e., the number, density, and dimension of wind farms and their distribution across the landscape affect the economic costs so that economies of scale and scope can be expected. However, since economic profits (benefits minus costs) from WTs are largely correlated with the local wind energy level, we can expect that many of our sites that were identified as Pareto-optimal with regards to wind power production would also be Pareto-optimal with regards to economic profits.

In addition to site-specific costs, the spatial reallocation of WTs would involve construction costs, transport costs, and potential fines associated with premature termination of lease contracts between WT operators and landowners, which would reduce the magnitude of the efficiency gains determined in our analysis. The consideration of monetary costs and benefits of wind power production will be the focus of future research.

Further simplifying assumptions were made in our study. We focused on the most relevant species, the red kite, and ignored other species that are less relevant but still need to be considered in real world landscape planning. Other species could be considered in our approach, although this would increase complexity because more criteria would have to be considered in the analysis and/or

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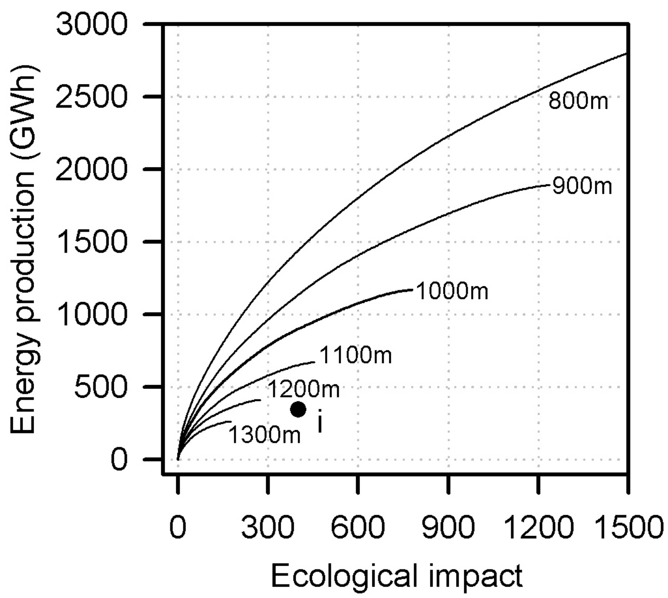
Fig. 7. Efficiency frontiers for different settlement distances. Settlement distances increase from top to bottom in steps of 100 m from 800 m to 1300 m. Point i represents the current situation in the study region.



assumptions would have to be made on the aggregation of several species into one or a few joint impact criteria. Furthermore, we measured the ecological impact on an arbitrary scale, which was sufficient within the scope of our study but may be insufficient if the trade-offs are to be considered more concretely in making an actual planning decision. In that case, our impact index would have to be translated into a concrete parameter such as annual bird mortality or annual population decline. This would require the use of a behavioral model that simulates the foraging behavior of the species and quantitatively predicts the probability of a bird colliding with a WT at a particular location relative to the bird's aerie. Such a model might also take into consideration that some species are disturbed by WTs and avoid being around them. This reduces the amount of available habitat and poses another risk to biodiversity.

Nevertheless, our study demonstrates that it may be worthwhile to (i) reconsider some of the existing constraints and procedures of current landscape planning to open opportunities for efficiency gains in the context of wind power production, and (ii) use existing information such as species distribution maps and wind speed data more efficiently by employing formal decision making frameworks. Despite the negative impacts of WTs on some species, and given that wind power is a very emotional topic for many people, the pros and cons of WTs need to be assessed and valued carefully. Our study attempts to support this process.

Responses to this article can be read online at:
http://www.ecologyandsociety.org/vol15/iss2/art10/responses/

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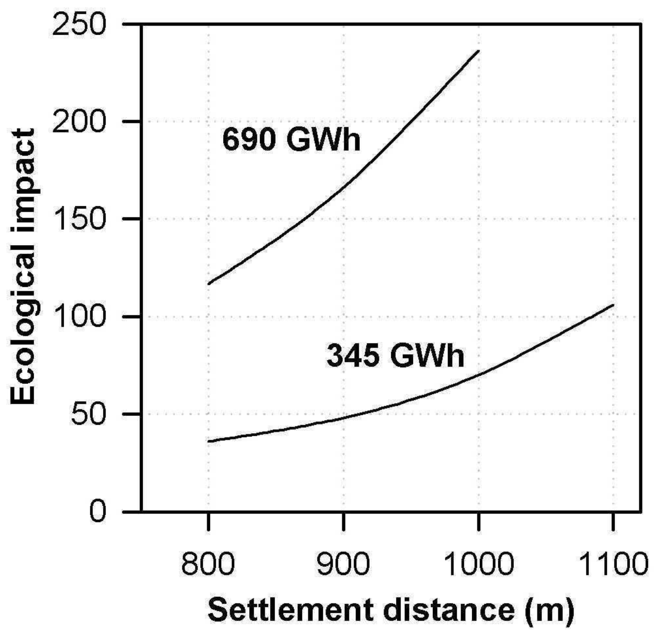
Fig. 8. Efficiency frontier. Impact value versus settlement distance. Upper line: energy production of 690 GWh; lower line: energy production of 345 GWh.



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Chapter 7

Collision Risk Modeling of Predatory Birds

This chapter is submitted as:

” Model-Based Estimation of Collision Risks of Predatory Birds with Wind Turbines”

Marcus Eichhorn, Karin Johst, Ralf Seppelt and Martin Drechsler. 2011. Ecology and Society.

7.1 Abstract

The expansion of renewable energies such as wind power is a promising way of mitigating climate change. Due to the risk of collision with rotor blades, wind turbines have negative effects on local bird populations, particularly on raptors like the red kite. Appropriate assessment tools for these effects have been lacking. To close this gap, we developed an individual-based spatially explicit model which simulates the foraging behavior of the red kite around its aerie in a landscape consisting of different land use types. We determined the collision risk of the red kite with the turbine as a function of this distance and other parameters by placing a wind turbine at varying distances to the aerie. Based on the model simulations we derived an impact function that relates collision risk to the distance between aerie and wind turbine. The impact function comprises the synergistic effects of species-specific foraging behavior and landscape structure. The collision risk declines exponentially with increasing distance. The strength of this decline depends on the raptor's foraging behavior, its ability to avoid wind turbines and the mean wind speed in the region. The collision risks, which are estimated by the simulation model, are in the range of values observed in the field. The present modeling approach and the derived impact function show that the collision risk can be described as an aggregated function of distance between the wind turbine and the raptor's aerie. This allows an easy and rapid assessment of the ecological impacts of (existing or planned) wind turbines in relation to their spatial location. Furthermore, it implies that minimum buffer zones for different landscapes can be determined in a defensible way. This modeling approach can be extended to other bird species with central-place foraging behavior. It provides a helpful tool for landscape planning aimed at minimizing the impacts of wind power on biodiversity.

Key words: collision risk; foraging behavior; impact assessment; individual-based model; red kite; spatial model; wind power

7.2 Introduction

The expansion of renewable energy production is encouraged across Europe to mitigate climate change. In many European countries this entails increasing the number of new on-shore wind power plants and the replacement of 'old' wind turbines (WTs). Land scarcity and land use conflicts make this a challenging task (Ohl and Eichhorn 2010). The determination of suitable sites for WTs requires not only the incorporation of the demands of wind farm operators, but also the consideration of relevant adverse effects of wind power generation, and in particular the potential impact on human health and on wildlife.

Biologists raised the focus on the potential consequences for bird populations such as disturbance and displacement (Percival 2000, Percival 2005, Drewitt and Langston 2006, Larsen and Guillemette 2007, Pearce-Higgins et al. 2009). Collisions result in high mortality rates, in particular for raptors, observed in the vicinity of WTs (Erickson et al. 2001, Hunt 2002, Barrios and Rodriguez 2004, Smallwood and Thelander 2007, Lekuona and Ursúa 2007, de Lucas et al. 2008, Krijgsveld et al. 2009).

The present study concentrates on the risk of the red kite *Milvus milvus* colliding with WTs. This predatory bird belongs to the species with the highest frequencies of rotor blade strikes (Mammen and Dürr 2006, BSBCC 2010). The reasons for these exceptionally high collision rates are not fully understood, but some facts are important. First of all, WTs are often located in open agricultural landscapes which represent the primary habitat of the red kite. In addition, the ranging behavior of the raptor within these landscapes fosters collision fatalities. Observations have shown that red kites are not disturbed by wind farm sites, on the contrary they are attracted to the areas close to the turbine because they usually have little vegetation cover and high prey abundance.

To reduce the impact of WTs on raptors such as the red kite, WT sites have to be chosen carefully. In Germany, which hosts about half of the world's red kite population, an uncontrolled growth of wind farm sites in the 1990s occurred. Thereupon, the federal states have tended to steer the allocation of WT by regional planning. As a result, WTs are concentrated in certain areas while being excluded from others. However, as Madders and Whitfield (2006) point out, planning decisions tend to be based exclusively on subjective judgments, due to the paucity of information on the processes that determine collision risk. To minimize the negative impact of wind power development on the red kite the current practice in Germany is to establish circular buffer zones around known nest sites in which the installation of WT is excluded. However, there is no general agreement on the required size of these buffer zones. For example, the working group of the German State Bird Conservancies recommends a distance of 1 km (WGG SBC 2007), while the regional planning authority of West Saxony applies a distance of 3 km within their regional plan (RPA WS 2008). Since large buffer zones imply that fewer WTs can be installed in a region either energy production targets cannot be met or the other impacts of WT are increased (Eichhorn and Drechsler 2010). Therefore, it is mandatory to know the minimum size of the buffer zone to maintain the impacts on the bird population within acceptable bounds. To determine a minimum size, objective tools are required to assess the WT collision risk for birds like the red kite in a quantitative manner.

Different scientific approaches have been established for this assessment. *Spatial models* that predict the ranging activities of the species of interest represent one possibility (Williams et al.1996, McGrady et al. 1997, McLeod et al. 2003). Madders and Whitfield (2006) rated *spatial models* as good starting points for impact assessments because they are cost effective and can identify critical locations. However, statements about the resulting collision risk are hardly to derive because the foraging behavior and flight patterns of the species are not considered.

A second approach is the use of *collision risk models* (CRM), first developed by Tucker (1996) and further developed by Biosis Research (2003) and Podolsky (2003, 2005). These consider explicitly the interaction of WTs and birds. The CRMs are based on mathematical equations that incorporate empirical data according to the number of birds observed in the area of the proposed wind farm and the proportion of flight time within the rotor swept volume. Furthermore, the WT parameters and the size, flight direction and flight speed of the prospected birds are considered (Madders and Whitfield, 2006). The so-called 'Band-Collision Risk Model' (Band et al. 2007) is a CRM widely used in the UK.

Both of these approaches have their strengths and weaknesses. The spatial models are able to predict the residence of a species in a certain area but provide no information on collision risk. In contrast, CRMs are able to predict collision risks but are designed for specific wind farm projects and need a lot of input data based on field surveys (Band et al. 2007).

Aspects of both approaches were incorporated into a spatially explicit simulation model, taking into account the red kite's flying and foraging behavior and the spatial structure of the landscape. We investigate how the collision risk in a landscape depends on the distance between the WT and the red kite's aerie. Such an *impact function* (IF) has been proposed in a landscape-planning context by Eichhorn and Drechsler (2010). It describes collisions risk in a spatially explicit but aggregated way and therefore represents a fast and practical tool for collision risk assessment of candidate WT sites. However, the IF used by Eichhorn and Drechsler (2010) predicts impacts only in a qualitative manner and is based on a number of ad-hoc assumptions. Thus, its actual form and how it depends on species and landscape characteristics remained unclear.

To gain insights into the large-scale effects of species behavior in specific landscapes, agent- or individual-based models (ABM/IBM) are well suited (Huston, et al. 1988, DeAngelis and Mooij 2005, Grimm and Railsback 2005). We developed an ABM for the quantitative prediction of collision risk as a function of the aerie - WT distance and combined it with specific findings from the Band CRM. In our ABM, the 'agent' represents a single raptor individual with a ranging behavior depending on habitat requirements and landscape characteristics. To determine collision probabilities for variable aerie – WT distances, virtual experiments were carried out with the ABM. To validate the ABM, a pattern-oriented approach was accomplished whereby sensitivity analyses are carried out to compare model outputs with field observations (Wiegand et al. 2003, Grimm et al. 2005).

7.3 Methods

Model description

The model description follows the ODD (Overview, Design concepts, Details) protocol for describing individual- and agent-based models (ABM/IBM) (Grimm et al. 2006).

Purpose

The purpose of the ABM is to determine the annual mortality of a central place forager, here the red kite, as a function of the distance between the bird's aerie and the WT. For this the ABM considers the species' foraging behavior as well as the landscape characteristics. The model incorporates the processes essential to understand the interaction between birds and WTs during foraging.

Based on the modeling results, we inferred an impact function comparable to Eichhorn and Drechsler (2010) and explored the extent to which such an aggregated approach can capture the synergistic effects of species-specific foraging behavior and landscape structure on collision risk.

State variables and scales

The ABM includes three types of entities: grid cells that constitute the landscape, a red kite, and a WT (compare Table 1). In the present study we consider a model landscape that has a land use pattern similar to West Saxony, Germany. We choose this region as study region since it belongs to the core area of the red kite's world wide distribution.

The red kite agent is designed to behave like a typical raptor during foraging flights. Information about its behavior and response to the landscape was derived from field observations and expert interviews (Mammen personal communication 2008, Nachtigall personal communication 2009). Only male raptors were considered because of their higher flight activity during the breeding season. Resting behavior was not considered as it does not contribute to the collision risk.

The WT is determined by its spatial location relative to the red kite aerie - which is located in the center of the model world - and the cell's land use type.

Most collisions occur during the breeding season when frequent foraging flights take place to feed the nestlings (Mammen and Dürr 2006, Dürr 2009). The breeding season of the red kite lasts 85 days (April to June), which defines the length of a model run. The 24 hours day includes not only foraging flights but also resting periods and nocturnal behavior. Based on absence times from the aerie observed by Nachtigall (2008) we calculated an average flight activity of 10.6 hours per day. Resting periods were estimated by Nachtigall (2008) to be about 50% of the total absence time, so the bird flies for about 5.3 hours per day, or 450 hours per 85 days. One model year thus corresponds to 450 hours of flying. To calculate the elapsed time during each model run we recorded the flown distance and divided it by the raptor's flight speed (Table 1).

Table 7.1: Variables and model parameters.

Variables	**Brief description**
Landscape Cells	
Coordinates	Determine the position of the cell in the model landscape.
Size	The size of a cell (length (*l*); width (*w*)) represents a real- world dimension of 100 m by 100 m.
Number	10.201 cells, which corresponds to 102 km².
Habitat quality *hq*	The cells can take integer values for habitat quality (*hq*) between zero and three. *hq*=0 represents unsuitable foraging habitat like forest. *hq*=3 represents the best foraging conditions like grassland with a favorable mowing regime.
Red Kite	
Coordinates	Determine the position of the red kite in the model landscape.
Flight distance	Length of a straight-forward flight: 100 m per model step.
Circling radius	Radius of a soaring circle during foraging flight: 100 m.
Flight speed	Average speed of the red kite: 15 km/h (Bruderer and Boldt 2001).
Flight height probability (p_{fh})	Probability of observing the raptor at a certain flight height, based on empirically determined flight height distribution.
Flight through rotor probability (p_{rsa})	Probability that the raptor flies through the rotor swept area and did not pass around.
Physical collision probability (p_{BAND})	Probability of a bird being hit by a rotor blade if passing orthogonal to rotor swapped area.
Collision avoidance probability (p_{av})	The likelihood of a red kite actively avoiding collision with a WT.
Probability of circling and flying forward, (p_f)	Controls flight behavior during the search flight (cf. Fig. 2). The variable p_f indicates the probability of flying forward. The probability of performing a left respectively a right full circle is $(1-p_f)/2$.
Maximum residence time on cell, (*T*)	Determines how long the agent occupies the same cell, if all neighboring cells are of lower habitat quality.
Wind turbine	
Coordinates	Determine the position of the WT in the model landscape.
Hub height (*hh*)	Height of the rotor center: 78 m.
Rotor blade length (*r*)	Half of the rotor diameter: ½ of 82 m=41 m.

Process overview and scheduling

The ABM is based on three movement processes *(random flight, directed flight and flight forward)* and two event processes (*collision-event* and *catch-the-prey*). At the beginning of each model step the bird samples the habitat conditions of the occupied and the neighboring cells. Three conditions are possible:

A) The occupied cell is of the worst habitat quality, initiating the *flight forward* procedure, where the agent moves one cell (100 m) forward;

B) The occupied and all neighboring cells are of the same and not of the worst habitat quality, leading to the *random-flight* procedure. Here the agent moves one cell forward and then decides with a certain probability (1-p_f)/2 to fly a right or a left full circle, respectively; and

C) The neighboring cells differ in habitat quality, leading to the *directed flight* procedure. Here, the agent moves forward to one of the cells with the best habitat quality and decides with a probability of (1-p_f)/2 to fly a right or a left full circle, respectively.

Within these procedures the two event processes were executed: the *collision-event* procedure and the *catch-the-prey* procedure. The *collision-event* procedure determines on what conditions collisions occur between the red kite and the WT. Different circumstances have to coincide for a collision to occur: the raptor has to occupy a cell where a wind turbine is located, it has to fly at a height at which the rotor blades operate, and it has to move through the part of the cell affected by the rotor blades. If the raptor crosses the area of risk spanned by the WT rotor, and does no active attempt to avoid the strike it will be hit by a blade. These circumstances are incorporated into the ABM through the determination of the respective probabilities:

(i) The basic condition for a collision to occur is that the raptor reaches an area (cell) where a WT is located.

(ii) The probability that the red kite ranges at a height swathed by a WT rotor (p_{fh}). Taking a WT with hub height *hh*=78 m and rotor length *r*=41 m and using empirical data from Mammen (2010) we estimate a probability of p_{fh}=0.34.

(iii) The probability of the raptor passing the area affected by the rotor. To derive a simple estimation we assume that the raptor flies horizontally to the land surface and orthogonally to the plane swept by the rotor. Given that the raptor flies within the height interval determined by the WT's hub height (*hh*) plus/minus one rotor blade length (*r*). The area of concern has a size of 2r times the width w=100 m of the cell.

The area affected by the rotor blades equals' πr^2. So, the probability that the raptor flies through the rotor swept area equals:

$$p_{rsa} = \frac{\pi * r^2}{2r * w} = 0.65 \quad (1)$$

(iv) The probability of a bird being hit, when flying through the rotor (p_{BAND}) is calculated using stage 2 of the Band Collision Risk Model (Band et al. 2007). The Scottish Natural Heritage provides a template that is used to calculate the collision risk for the red kite according to the regarded WT (SNH 2010). Depending on the pitch angel of the rotor blades, the p_{BAND} ranges between 0.144 and 0.205.

(v) The probability that the raptor recognizes the threat and actively avoids collision (p_{av}).

In most cases raptors discern their surroundings and do actively avoid collisions with infrastructure. This behavior is summarized by the avoidance probability p_{av}. The estimation of the avoidance probability is a challenging task (Chamberlain et al. 2006, Whitfield and Madders (2006a), Whitfield 2009). Smales and Muir (2005) use three arbitrary avoidance probabilities of 95, 98 and 99 % for collision risk modeling in Australia. Using data of several predatory birds at 13 wind farms in northern Spain, Whitfield and Madders (2006b) empirically estimated avoidance probabilities between 98 and 100 % with a probable value of 99 % for the red kite. In the present study we consider four possible levels for p_{av}: 98, 98.5, 99 and 99.5 %.

Summing up, if the modeled red kite occupies the same cell as a WT, its probability of colliding with the WT is

$$p_{col} = p_{fh} * p_{rsa} * P_{BAND} * (1 - p_{av}) \quad (2)$$

The *catch-the-prey* procedure determines the point in time when the red kite catches a prey and returns to its aerie before it starts the next foraging flight. This procedure is parameterized using the frequency distribution of absence times from the aerie provided by Nachtigall (2008), taking into account that ca. 50 % of the absence time is used for flying (cf. subsection State Variables and Scales). This frequency distribution of flight times is discrete by providing the probability of observing a flight time within a particular interval. We assume that within each of these time intervals the flight times are equally distributed to obtain a continuous probability density function of flight times (Fig. 1). A flow chart of the ABM with the described procedures is given in figure 2.

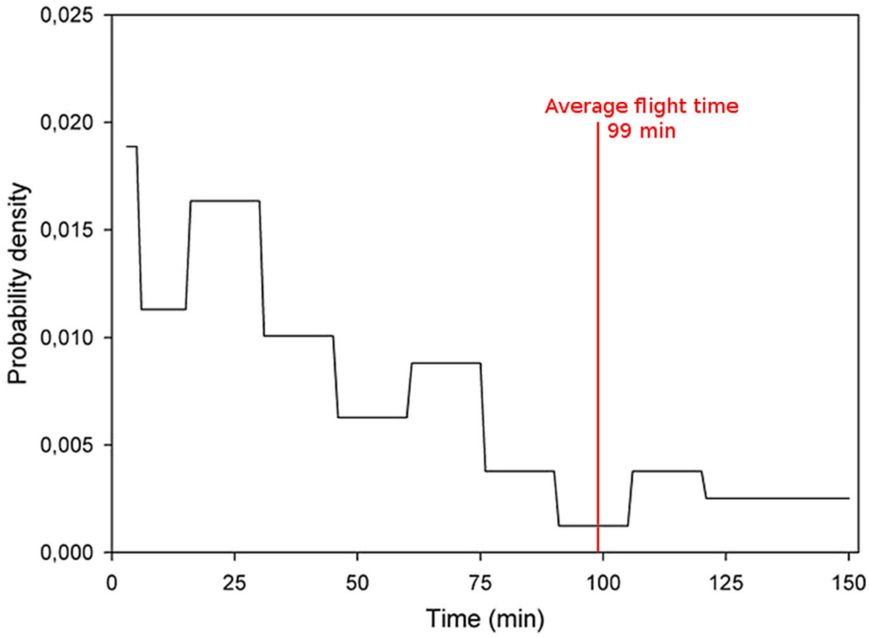

Figure 7.1: Probability density function of flight duration based on Nachtigall (2008).

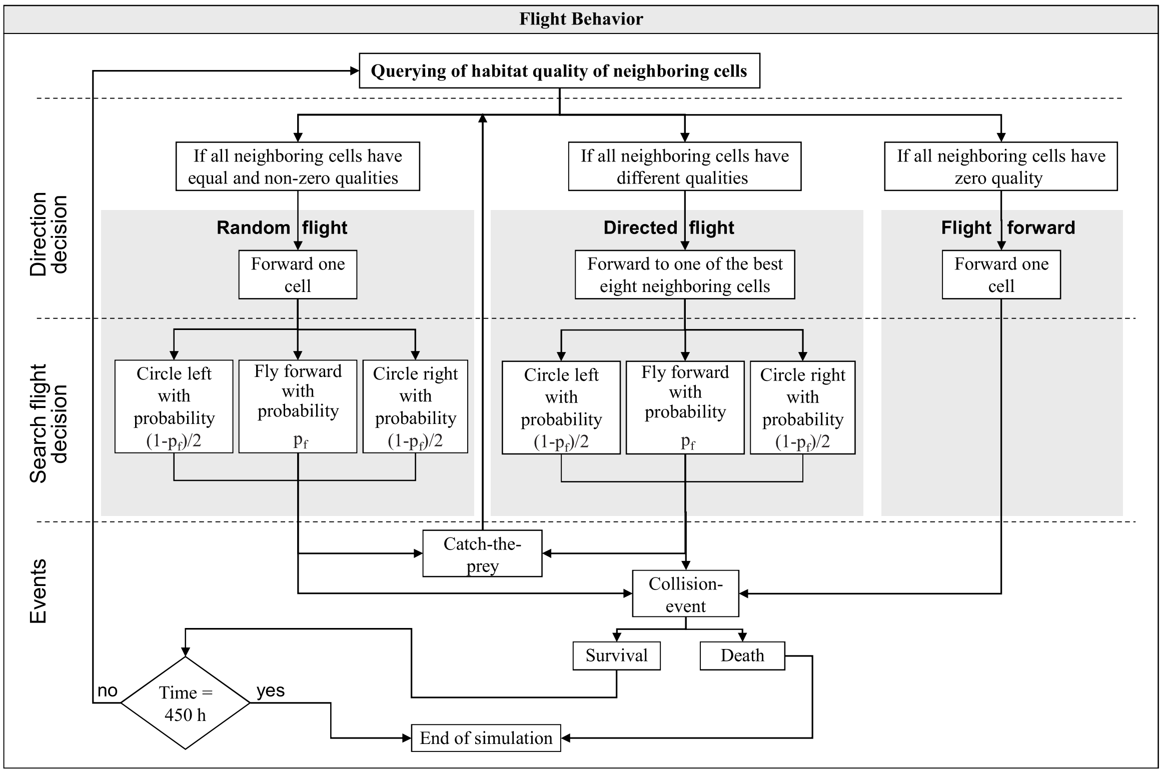

Figure 7.2: Process overview.

Relevant design concept

Stochasticity

The virtual landscape is generated randomly, assuming fixed shares of the different habitat types. Further, the behavioral decisions of the raptor during its flight are largely stochastic and, among others, depend on the probability p_f of flying forward and the probability density function of the flight duration (Fig. 1). The model was run 10,000 times and relevant variables were statistically analyzed.

Initialization

The model landscape is initialized by creating a random landscape for each simulation run. The number of cells with a particular habitat quality (*hq*=0, 1, 2, 3) is fixed and based on the landscape structure in the region of West Saxony. The red kite agent is initialized at the aerie placed in the center of the model world. The WT entity is initialized at a randomly chosen location limited by two constraints. First, it can only be located on suitable habitat cells, so for example forest (*hq*=0) is excluded. Second, it is located at a specified distance to the aerie, which is varied between 100 m and 500 m in steps of 200 m and from 500 to 5,000 m in steps of 500 m.

Input

Input data are used for two procedures. First, the proportions of land use types, observed in our reference region West Saxony, are used to generate a virtual landscape. The region is characterized by a high proportion of open agriculture land and a small proportion of forest areas. The different land use types extracted from real land cover data (The Authoritative Topographic-Cartographic Information System ATKIS (2007) ATKIS®-DGM25. License number: 3219/07, Ordnance Survey Saxony, Dresden) are summarized into four classes with different habitat quality levels. Grassland and pasture have the highest habitat quality (*hq*=3) and comprise about 11 % of West Saxony, habitat quality *hq*=2 (e.g. croplands) comprises about 55%, habitat quality *hq*=1 (e.g. settlements) about 4% while forest areas have the lowest quality (*hq*=0) and comprise about 17 % of the landscape.

Interaction

The red kite agent interacts with the surrounding landscape whereby the quality of the landscape influences the flight behavior of the agent. A second interaction takes place between the red kite and the WT. If certain conditions are fulfilled the red kite collides with the WT (cf. section Process Overview and Scheduling).

Model validation

We validated the model by comparing its output to empirical behavior data of the red kite in the field. Detailed field data of the behavior of the focal species are rare. For the red kite the residence frequencies of the raptor in a certain distance class to the aerie and its maximum distance to the aerie were determined by Nachtigall (2008). These data were taken as reference values.

Strategies

There are two model parameters, which predominantly control the flight behavior of the red kite agent: the probability p_f of flying forward and the maximum residence time T. Due to their uncertainties, plausible values are estimated by pattern-oriented modeling (Grimm et al. 2005). The probability p_f ranges from 0 to 1 and the residence time T ranges from 1.2 min to 12 min (pers. Communication Nachtigall 2009). Varying p_f in steps of 0.1 and T in steps of 1.2 min, and systematically combining p_f and T for all values leads to 110 parameter combinations, henceforth termed *strategies*.

Determination of best strategies

To determine which of these strategies leads to the best fit between modeled and empirical behavior we ran the model 10,000 times for each strategy and recorded the residence frequencies x_i of the raptor in four different distance classes (i=1,...,4) from the aerie: between 0 and 1 km (i=1), between 1 and 2 km (i=2), between 2 and 3 km (i=3) and greater than 3 km (i=4). Nachtigall (2008) determines frequencies for these distance classes of: y_1=0.6, y_2=0.2, y_3=0.15 and y_4=0.05 for male red kites. Besides the distance classes we compared the modeled maximum distance from the aerie (denoted as k) with the value l_{max}=4,500 m observed in the field by Nachtigall (2008).

The relative deviation (σ_i) of x_i from the empirical data y_i for each distance class (i) was calculated by

$$\sigma_i = \frac{|x_i - y_i|}{y_i} \; for\ i=1,2 \ldots 4 \qquad (3)$$

and the mean relative deviation over all distance classes $\sigma_{distclas}$ by

$$\sigma_{distclass} = \frac{1}{4}\sum_{i=1}^{4}\sigma_i \qquad (4)$$

The relative deviation $\sigma_{maxdist}$ with regard to the maximum distance was calculated by

$$\sigma_{maxdist} = \frac{|k - l_{max}|}{l_{max}} \qquad (5)$$

By using these equations we identified the strategies that minimize $\sigma_{distclass}$ and $\sigma_{maxdist}$, respectively.

Collision risk analysis

For the strategies that provide the best model fit to the empirical data we determined the collision risk for a set of scenarios. Each scenario is defined by a combination of aerie - WT distances and the avoidance probability p_{av}, the only variable value of the *collision event procedure* (cf. subsection Process Overview and Scheduling). The aerie - WT distance ranges in eleven steps from 100 to 5,000 m and the avoidance probability p_{av} in three steps from 0.98 to 0.995 (cf. subsection Process Overview and Scheduling) leading to a total of 48 scenarios.

For the best strategies and the 48 scenarios we ran the model 10,000 times. For every model run, a random landscape with the same proportions of habitat types as in the study region was generated, the WT was placed randomly at the specified distance from the aerie and we recorded whether a collision occurred or not. The collision risk was then calculated for each scenario by dividing the number of collision events by the number of model runs. Since each model run covers one year (450 flight hours), the calculated collision risk represents the annual risk, i.e. the annual probability that the raptor collides with the WT.

7.4 Results

Model validation

The flight behavior in the model is characterized by flying forward probability and residence time on a cell. For 110 different strategies, each defined by a combination of the probability of flying forward p_f and the maximum residence time T, the relative deviations between modeled and empirical data (Nachtigall 2008) for $\sigma_{distclass}$ and $\sigma_{maxdist}$, were calculated according to the section METHODS/ Model Validation.

Figure 3 shows the results of the sensitivity analysis for frequencies the raptor is observed in different distance classes ($\sigma_{distclass}$) as a function of p_f and T. It strongly varies for p_f but depends only weakly on T. The minimum relative deviation $\sigma_{distclass}$ of 0.17 is found for strategy p_f =0.4, T=12 min.

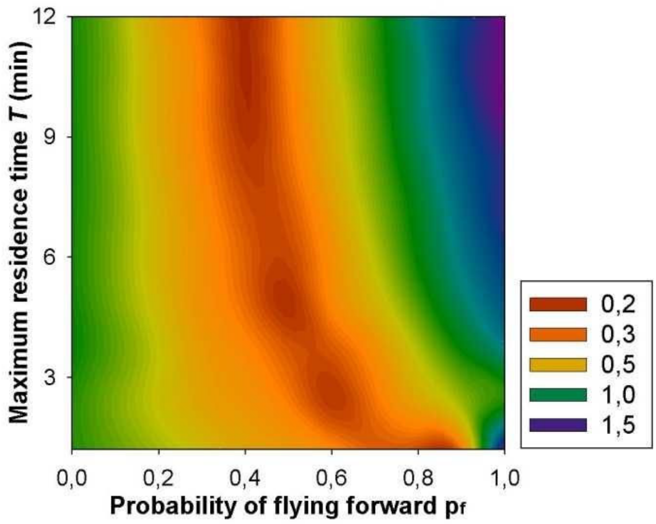

Figure 7.3: Relative deviation $\sigma_{distclass}$ between model output and empirical data as a function of the model parameters p_f and T (for details see text). The level of $\sigma_{distclass}$ is represented by color.

Figure 4 shows the results of the sensitivity analysis for maximum flight distance to the aerie ($\sigma_{maxdist}$) as a function of p_f and T. Similar to $\sigma_{distclass}$ in figure 3, $\sigma_{maxdist}$ strongly varies for p_f but depends only weakly on T. The minimum relative deviation $\sigma_{maxdist}$ of 0.01 is obtained for strategy p_f=0.3 and T=3.6 min.

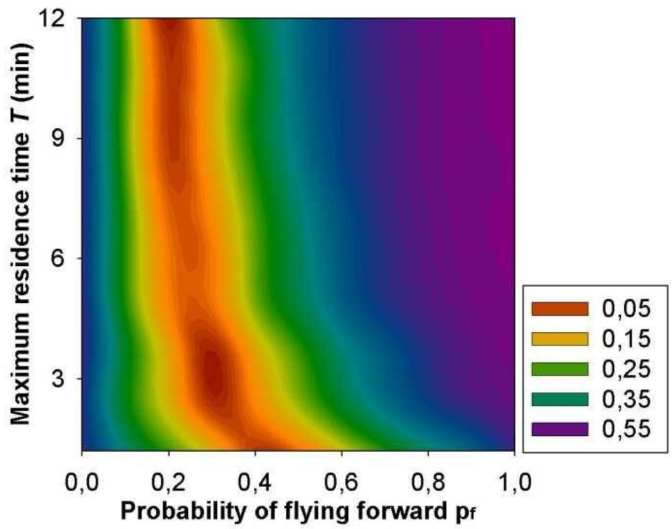

Figure 7.4: Relative deviation $\sigma_{maxdist}$ between model output and empirical data as a function of the model parameters p_f and T (for details see text). The level of $\sigma_{maxdist}$ is represented by color.

The two strategies derived from figures 3 and 4 (p_f =0.4, T=12 min and p_f =0.3, T=3.6 min) represent similar levels for p_f (0.4 vs. 0.3) and differ considerably in T (12 min vs. 3.6 min). However, as noted above, the level of T only weakly determines the deviation between model output and field observations. Therefore both strategies provide a satisfactory model fit with relative deviations below 20 %. Since strategy p_f =0.4, T=12 min performs slightly better with regard to $\sigma_{distclass}$ while strategy (p_f=0.3 and T=3.6 min) performs better for $\sigma_{maxdist}$ we consider both in the analysis of the collision risk.

Collision risk analysis

Our sensitivity analysis of flight behavior revealed two strategies which correspond to observed field data. For these strategies (p_f =0.4, T=12 min, Fig. 5b, d and p_f =0.3 and T=3.6 min, Fig. 5a, c) the collision risk analysis was performed and the impact function was derived.

Figure 5 shows the annual collision risk as a function of aerie - WT distances for four avoidance probabilities p_{av} and two different physical collision probabilities p_{BAND}. As expected, the collision risk decreases with increasing aerie – WT distance. The curves have an exponential shape so that the collision risk declines rapidly nearby the aerie and more slowly at larger distances. This is compiled as our impact function. The flight behavior with the shorter residence time has a higher probability for a WT collision. Consequently, the longer the residence time of the red kite on a cell the lower is the mortality rate.

Decreasing the avoidance probability increases the collision risk. At short aerie - WT distances (< 1500m) the collision risk strongly depends on the level of the avoidance probability. It varies up to 0.4 in mortality rate for p_{av} between 0.98 and 0.995. In contrast, at longer distances (> 1500m) the impact of avoidance probabilities p_{av} on the collision risk is marginal.

We varied p_{BAND} to incorporate different wind speeds (Fig. 5a,b versus Fig. 5c,d). An increase in p_{BAND} displays a higher probability for the raptor to be hit by the rotor blade, due to geometrical changes in the WT rotor blades in adaption to higher wind speeds.

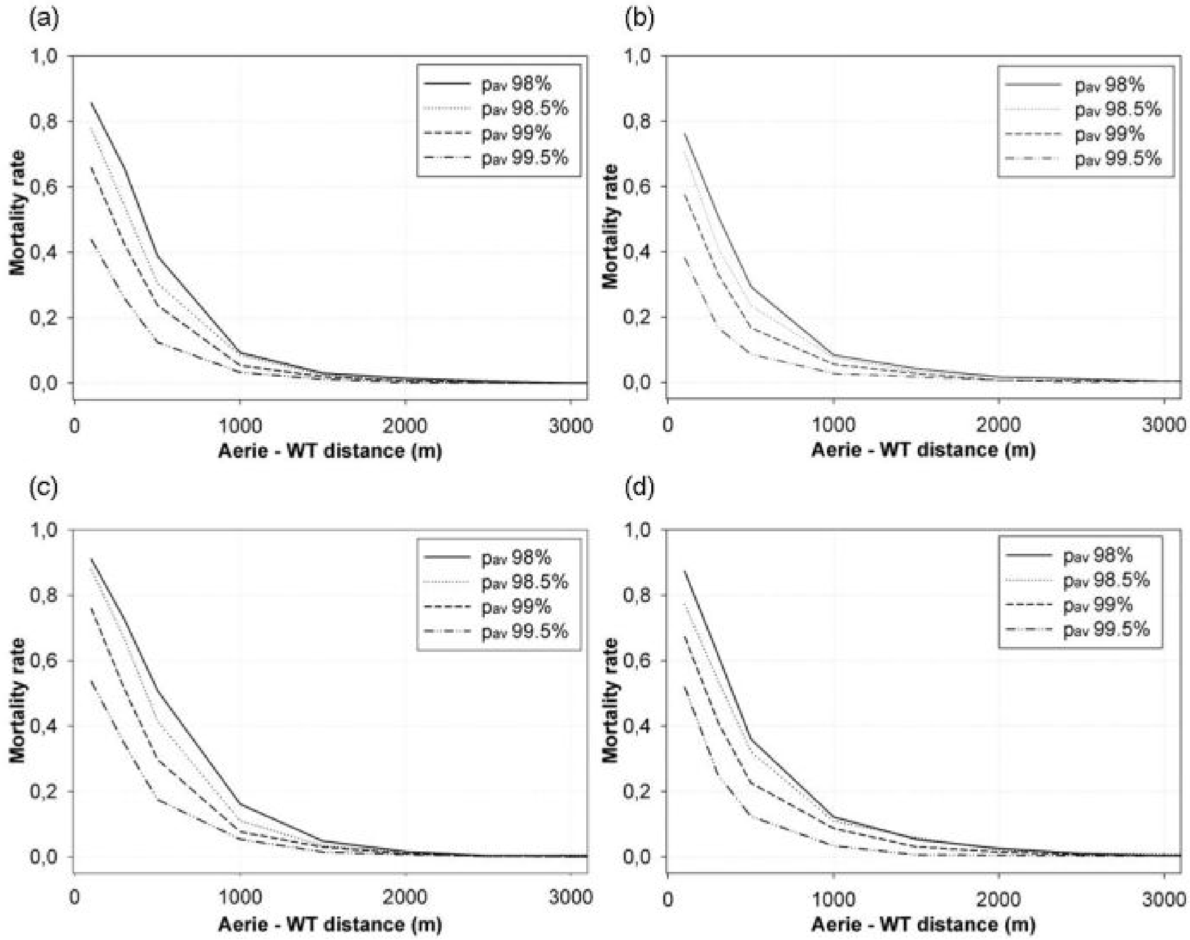

Figure 7.5: Annual collision risk (mortality rate) as a function of the distance between aerie and WT for different collision avoidance probabilities. Panel (a) is obtained for strategy (p_f = 0.3 and T = 3.6 min) with p_{BAND} = 0.144, panel (b) for strategy (p_f = 0.4, T = 12 min) with p_{BAND} = 0.144, panel (c) for strategy (p_f = 0.3 and T = 3.6 min) with p_{BAND} = 0.205 and panel (d) for strategy (p_f = 0.4, T = 12 min) with p_{BAND} = 0.205.

7.5 Discussion

For predicting the biological impact of wind turbines (WTs) quantitative predictions of bird collision risks as a function of the distance between aerie and WT are essential. Up to now, such predictions have been impossible due to the lack of suitable models. We developed an agent-based model of a foraging predatory bird during the breeding season in a spatially structured landscape. To simulate red kite’s foraging flights in response to landscape structure the model is based on the knowledge of the behavior of the red kite. Such an agent-based approach generally allows the assessment of species-specific vulnerability to particular temporal and/or spatial landscape attributes (e.g. Verboom et al. 1991, Johst et al. 2001, Wichmann et al. 2004, Rodríguez et al. 2006, Bauer et al. 2008). The attribute of concern for a central place forager like the red kite is the location of a WT in the surrounding of the aerie. The vulnerability is represented by the collision risk of the raptor with this WT. We apply this modeling approach to predict the impact of a WT on the red kite in the region of West Saxony.

The agent-based model was validated by comparing model output to field data Therefore, the frequency of a bird observed in particular distance classes was analyzed. The relative deviation between modeled and observed frequencies was found to be below 20 %. The best fit was obtained by varying some uncertain parameters. It is to note, that residence within certain distance classes only partly characterizes the movement pattern of a raptor around its aerie. In the present model the movement of the red kite depends on the actual environmental conditions including a random component, but not memory. In reality, certain sectors around the aerie are preferred than others, because raptors are able to remember good hunting areas. This could not be considered in the model. However, more detailed behavioral rules could be integrated into the model if adequate empirical data become available.

A possible experimental approach to gain better knowledge about movement behavior is for example GPS satellite telemetry. Solar-powered lightweight GPS transmitters have been used for the telemetry for migratory flights of an adult red and a black kite since 2007 (Meyburg and Pfeiffer 2009). Such data could be incorporated into the present model. The chosen agent-based modeling approach is flexible enough to implement more realistic movement rules and produce more reliable collision risk estimations.

A critical parameter revealed by our model is the avoidance probability that specifies the likelihood of a bird actively avoiding to be hit by a rotor blade. Estimations of this probability are mainly based on assumptions, and leads to uncertainty in the predicted collision risks, which have to be considered. Still, a model-based approach like the present one displays a valuable tool for collision risk scenarios. Moreover, it can be extended to other bird species with similar behavior like the red kite.

In the present model analysis, the simulation runs comprise 450 hours of flight time corresponding to one breeding season or, since collisions occur mainly during this time, one year. Therefore, the collision risk analysis yields to the annual collision probability of a red kite with a WT located at a certain distance from its aerie. For the first time we derived a relationship between raptor collision rates and aerie - WT distances for certain flight behaviors and different physical collision probabilities. This is given as an impact function in figure 5 for four avoidance probabilities.

For the validation of our mortality rates as a function of aerie – WT distances, two main references for raptor collisions were considered. These are based on field data, reflecting the number of dead birds per turbine per year. However, the relationship of the mortality and the aerie – WT distance was not investigated. Hötker et al. (2006) compiled results from different research projects and found collision rates of 0.012-8 raptors per turbine per year in Europe and North America. The median of raptor collisions per turbine per year for all studies is 0.03 and the average is 0.6. Furthermore, Hötker et al. (2006) estimated that 100 red kites are killed by WTs in Germany per year. Presuming an equal distribution of bird strike over all German WT (16,500 WT (BWE 2010)) results in 0.006 collisions per turbine in 2004. Using our impact function, the collision rate derived from Hötker et al. (2006) corresponds to an aerie – WT distances of 2,000 m and 2,500 m. Hence, the modeled aerie – WT distances predict reliable collision risks, since these distances are present in the region and belong to typical flight distances of the red kite.

Dürr (2009) used records from the German Federal State of Brandenburg, a nearby region to West Saxony. Here, the collisions of red kites with WT were recorded between 2001 and 2009. From these records a rate of 0.028 birds per turbine per year was estimated. Interpreting this value as an annual collision risk, it is comparable with the annual mortalities in figure 5 assuming an aerie- WT distances of 1,300 m and 1,500 m in our impact function. Thus, also these aerie – WT distances are observed in the region, meaning our impact function predicts reliable collision risks

The slight variations in the collision risks for the two references and deduced distances can be related to the different stages of development of the wind power projects on which both investigations were based on. Hötker et al. (2006) takes into account the development up to 2004, whereas Dürr (2009) up to 2009. During these 5 years the number of WTs has almost doubled up in Germany. Thereby, a shift of WT locations closer to breeding habitats could be observed, due to less available space and other land use demands, which is reflected by the decline in the aerie – WT distances in the model.

The agreement between predicted and observed collision risks provides confidence in the model. Hence, it can also be used to assess the effect of wind farms with several WTs. If there are several WTs, the probability of not colliding with any of these is the product of the probabilities of not colliding with each individual WT. The individual collision probabilities are obtained by performing the present analysis separately for each WT. Alternatively, the model could be run with several WTs in the model landscape.

The investigation of the population dynamic consequences of collision risk is also of interest. The question is: Do the additional mortalities caused by the WTs lead to a population decline or do they only compensate density dependent population regulation? Unfortunately, we cannot answer this question with our model alone, yet. Hötker et al. (2006) gives a promising approach. Using the simulation software package VORTEX (Version 9) and empirical data for the red kite, they show a clear tendency to a population decline for scenarios including mortalities due to WTs. However, Hötker et al. 2006 demanded the need of more information on individual collision risk of the relevant species for reliable population viability analyses. Our agent based model can deliver this information. The combination of both models would therefore give a satisfying answer of the question. Furthermore, our model can be used to define minimum buffer zones for a given landscape, if an acceptable collision mortality is defined.

The analysis of our agent-based modeling approach reveals that the synergistic effects of foraging behavior and landscape structure can be captured by an aggregated function of collision risk decreasing with aerie - WT distance. This shows that the approach of a simple impact function used by Eichhorn and Drechsler (2010) is generally suitable for assessing the impacts of WT on the red kite. However, the present model analysis shows that an exponential dependency (exp(-distance)) is more appropriate, than the bell-shaped (exp(-distance^2)) impact function of the previous study.

The present study displays that the collision risk and its dependency on the aerie – WT distance is influenced by the flight behavior of the red kite. Moreover, the detailed shape of the impact function depends on the considered species. Likewise, the landscape composition affects the shape of the impact function. Therefore, it would be interesting to compare the impact functions obtained for different species and different landscape compositions in further studies.

A great advantage of the derived impact function is that it allows an easy and rapid impact assessment of existing and planned WT. Therefore our approach of deriving impact functions through agent-based modeling provides a helpful tool in landscape planning for wind power development and helps to meet renewable energy targets in a sustainable manner.

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Chapter 8

Discussion and Conclusion

Onshore wind power generation is a well-established renewable energy source and one of the most cost-efficient sources available (ISE 2010). The expansion of this renewable energy source is viewed as an appropriate way to support the achievement of national and international climate protection goals. Furthermore, wind power generation contributes to building a more sustainable and import-independent energy supply system. Wind farm operators have an interest in erecting wind turbines (WT) at sites where high energy output is possible and hence assuring high monetary profit. Moreover, they have to use sites where a WT achieves a minimum of 60 % of a pre-defined reference yield to get reimbursed in accordance with the Renewable Energy Sources Act, Sec. 29 (EEG 2009).

However, these high energy sites favored by WT operators are not always economically optimal, since wind power generation may have negative external effects. The impairment of the landscape, sound and shadow emissions, and the endangerment of birds and bats are the most predominant effects (see Chapters 1, 6, 7). Such negative externalities affect human health and well-being and nature conservation. Hence, wind power is a controversial issue with conflicts of interest between economic demands made by wind farm operators, energy and climate policy, environmental concerns for an undisturbed landscape, human health and nature conservation. In this context, this PhD thesis has pursued the goal of contributing to the minimization of such land-use conflicts by investigating selected and relevant controversial issues.

The present work considered three essential research topics (Section 1.4) which are discussed below. Firstly, the current planning practice and the limitations of the current designated priority and suitability areas for wind power were investigated for two study regions. In addition, potential areas and measures for future development of wind power were identified (Chapters 4, 5).

Secondly, a methodology for identifying optimal sites for wind power plants was developed taking energetic and ecological aspects into account (Chapter 6). Based on this methodology, a measure was devised to evaluate the severity of the conflict between energy output and bird conservation objectives.

Third and lastly, an agent-based simulation model was developed to investigate predatory bird – wind turbine interactions by performing virtual experiments. Finally, the practical relevance of some of the findings of this PhD thesis is highlighted.

8.1. Analysis of the current planning practice and investigation of measures for future wind power developments in the two study regions

The economic development of wind energy began in Germany with the "Stromeinspeisegesetz" (*Electricity feed-in Act,* (StromEinspG 1991)) and the amendment to the "Baugesetzbuch" (*Town and Country Planning Code,* (BauGB 1996)). The StromEinspG obligated energy supply companies to ensure that renewable energies have access to their grids and are guaranteed reimbursement for the power generated. The amendment to the BauGB has favored wind turbine (WT) installations in the outer area[1] over other types of land use (Koeck and Bovet 2008). During this time period, experience with negative externalities of wind power generation was very limited. Acting in combination, these factors encouraged wind farm operators to randomly allocate WTs at all available sites without adequate planning, leading to a disordered expansion of wind power with widely dispersed wind turbines in Germany.

In response to this development, regional planning authorities began to control the development of wind power in their region. They designated either priority areas (*Vorranggebiete*) or suitability areas (*Eignungsgebiete*) or a combination of both - priority areas with the impact of suitability areas referred to as VE areas (*Vorrang- und Eignungsgebiete*). Within priority areas, the installation and operation of wind turbines is favored over other types of land use. In contrast, within suitability areas, wind power generation is not prioritized, although these areas are considered "suitable" for it.

[1] Term taken from zoning law that defines all parcels of a community area that are not designated by a binding zoning plan and do not belong to a built-up area.

Furthermore, the designation of suitability areas excludes all other sites in the planning region from having wind power developments. The combination of priority and suitability areas assures that wind farming is given priority over other land use, while, at the same time, preventing all other sites in the planning region from being used for wind farming (Koeck and Bovet 2008). This resulted in the planning authorities having a high degree of responsibility for the future development of wind power.

Therefore the question arose as to whether the current planning practice for wind power project development fostered the efficient expansion of wind power generation in order to achieve climate protection objectives. If not, what measures could improve this situation? These questions were investigated in two study regions: ‘West Saxony’ and ‘North Hesse’. Both represent typical German inland regions so that the findings are transferable to other regions. The two study regions are explained in detail in Chapter 2 of this thesis and in Monsees and Eichhorn (2010).

In an initial step the allocation of current WTs as well as the occupancy rate for the existing VE areas was estimated. At the time of the investigation (2007/2008) West Saxony was home to a total of 221 WTs. Of these, 138 WTs were distributed over 21 VE areas encompassing a total of 1,142 hectares. In North Hesse a quite similar number of WTs was installed - in total 223. Here, 141 WTs were allocated within 18 existing VE areas totaling 1,073 hectares. In addition, 1,025 hectares of VE areas labeled “not yet operating” are scheduled to be designated when the new Regional Plan comes into force. The available space at the VE areas in both study regions is almost used to capacity. Furthermore about 43 % of all VE areas in North Hesse are impacted by distance recommendations for a military radar range which nearly increases the area needed per turbine tenfold. Hence, two main problems arise: i) an additional installation of WTs is hardly possible in existing VE areas and ii) a significant number of turbines are allocated outside the existing VE areas. This means that after reaching their life span, these turbines will have to be dismantled and won’t be replaced. Consequently, wind power generation would decrease at least in West Saxony over the next twenty years.

To prevent such a development, alternatives have to be found which would enable wind power to increase within the VE areas and have the capacity to compensate for the WT dismantling outside. One possibility is the so-called repowering of WTs inside the VE areas. This means the replacement of older, low-performing WTs by new, higher performing ones. Thus, the installed capacity, and with it, the energy yield would increase despite a decreasing number of turbines, over-compensating even the dismantling of WTs outside VE areas.

However, the WTs to be installed would be larger than the older ones and may have different energetic performance and external effects. The following would have to be taken into consideration.

(1) Distance to settlement increases

The required minimum distance to settlement areas would increase since the sound emissions would have a greater range. However, as most VE areas were established based on the technical standards prevalent at that time, the increase in turbine size would imply that existing settlement distances are not sufficient.

(2) Reference energy yield criterion has to be achieved

In 2004, the concept of a specific reference energy yield criterion was introduced, which has to be fulfilled by all WT in order to get reimbursed. Since most VE areas were designated before 2004, the reference energy yield criterion was not considered in the designation process. As a result, the allocation of new turbines in these VE areas may not achieve the reference energy yield criterion in all instances.

(3) Collision risk of predatory birds

This topic is considered and discussed in detail in Section 8.2.

The effects described in (1) und (2) are taken into account single and in combination. To investigate whether repowering inside existing VE areas is an option to further extend wind power generation in the two study regions, an initial repowering scenario is assumed using a larger type of wind turbine. Based on the different legal or regional planning provisions, references, and fact sheets including technical parameters, the following set of criteria was derived:

- Requirements of the respective regional plan (height limitation, minimum distance to settlement areas and their combination)
- Technical parameters of wind turbines (land requirement for a WT, hub height, nominal capacity, annual energy yield)
- Requirements of the EEG (60 % performance level)
- Legal restrictions (BImSchG[2], TA LÄRM[3])
- Wind energetic performance (Deutscher Wetterdienst DWD (2007)).

[2] BImSchG – Bundesimmissionsschutzgesetz *Federal Emission Protection Act*

[3] TA Lärm. 1998. Technische Anleitung zum Schutz gegen Lärm [neue Fassung] Sechste Allgemeine Verwaltungsvorschrift zum Bundes-Immissionsschutzgesetz (TA Lärm) vom 26. August 1998 (GMBl. Nr. 26 vom 28.08.1998 S. 503).

These criteria have to be fulfilled in order to receive permission to erect a WT at a certain site. The turbine in question for the repowering scenario is a state-of-the-art WT hereafter referred to as WT I, with a 2 megawatt nominal capacity, 82 m rotor diameter and total height of 121 m. The resulting repowering scenario for the West Saxony planning region was explained in Chapter 4. Here, the currently designated 1,200 hectares of VE area for wind power development are widely insufficient for repowering. The distance to settlement areas, the height limitations and the EEG reference yield criterion were identified as limiting factors. Only about 214 hectares of VE area are suitable for WT I, with respect to the required distance to settlement areas and height limitations, and only an area of 1 hectare would altogether be suitable for repowering when taking the EEG reference yield criterion into consideration.

For the second study region, North Hesse (Chapter 5), the wind energy conditions are more suitable for wind power generation. Beyond that, the regional plan (RVN 2009) does not define distance and height regulations and their combination. Hence, a repowering is feasible in the entire study region. However, a more serious limitation arises out of a distance recommendation between individual turbines for a military radar range in North Rhine Westphalia. This affects 43 % of the VE areas. Thus, the land requirement for a turbine increases from 4.6 hectares to 44 hectares. Therefore, instead of the 166 WT I theoretically possible in the case of unrestricted use, only around 20 WT I could be erected inside the VE areas.

It was shown, that the definitions of the regional plan of the particular study region is the most limiting factor for repowering. The general methodology of designating VE areas for wind power generation is quite similar in both study regions. However, both regions have different environmental factors (average wind speed, population and settlement density) that make the identification of sites for VE areas more difficult in West Saxony than in North Hesse. To understand why regional plans are the limiting factor it is important to consider that regional planning is a long-term process with a long-term validity of ten years on average. It deals with several different land use demands and is influenced by higher level planning and political guidelines. The VE areas were first selected in the early 1990s. They were in accordance with prevailing technical standards and near-future prospects of wind turbine technology (total heights of around 100 m and a nominal capacity of 0.6 megawatt (MW)). However wind power technology underwent rapid development. In ten years (1995 to 2005) the total height of turbines increased to around 150 to 200 m with nominal capacities of 1.5 to 3 MW (Fig. 8.1).

This seems to be the reason why West Saxony VE areas are insufficiently suited for repowering especially taking into account the higher population density (lower availability of space).

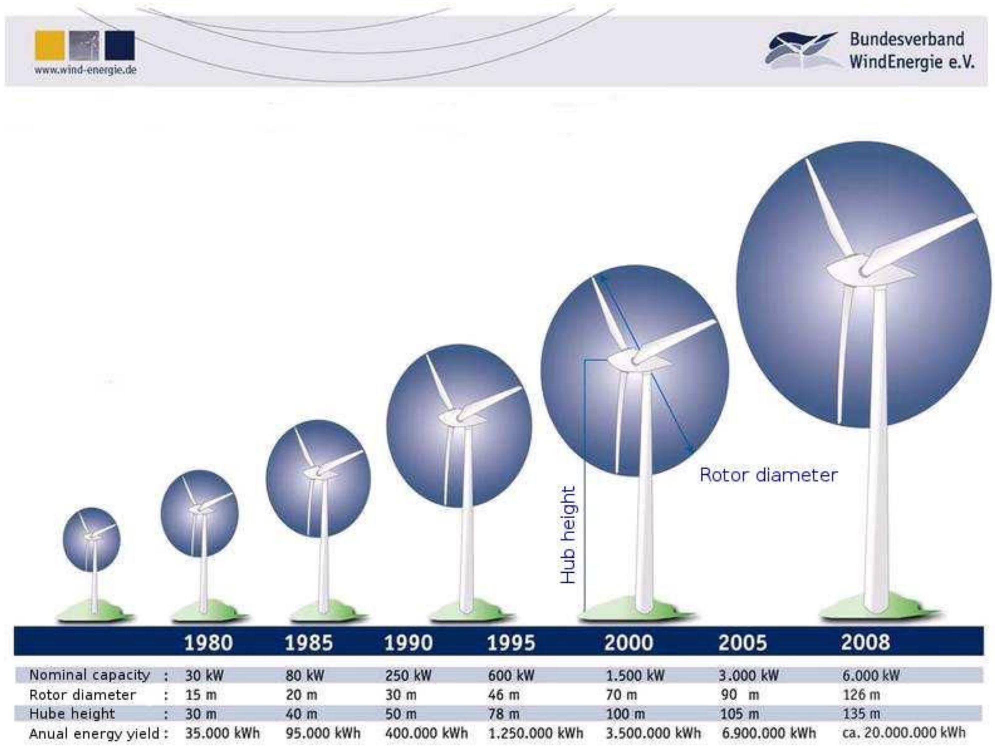

Figure 8.1: Development of wind turbines in terms of power and size in the last 20 years. (Source: Homepage of the German Wind Energy Association (BWE), edited).

In summary, repowering with WT I within the VE areas is possible for both regions. However, in West Saxony the percentage of VE area is negligible (just 1 hectare). In North Hesse about half of the VE areas also have a restricted repowering potential. This is the motivation for exploring two other possibilities: (1) to increase the amount of installed capacity by altering the turbine type under given constraints or (2) to alter these constraints by altering the location of the VE areas. These two options will now be discussed in detail.

(1) Altering the turbine type

A second repowering scenario was investigated, similar to the first, but applying another WT, the WT II, with an increased hub height of 105 m, a rotor diameter of 90 m and a nominal capacity of 3 MW. However, the larger height of the WT II requires larger minimum distances to settlements. This means that only 47 hectares instead of 214 hectares (WT I) are potentially suitable in West Saxony.

Nevertheless, there would be an increase in area that fulfills the EEG reference yield criterion: 23 hectares for WT II are available instead of only 1 hectare for the WT I.
In North Hesse, the repowering scenario using the WT II is quite similar to that of WT I. In all VE areas, the EEG reference yield criterion can be achieved by repowering in order to obtain reimbursement. However, the WT II is also affected by the distance recommendations of the military radar range. Therefore, instead of 97 WT II that would theoretically be possible, only around 20 WT II could be erected in the affected areas. Eventually, the larger area demand of WT II (7.1 hectares instead of 4.6 hectares) would lead to a quite similar amount of installed capacity (around 560 MW) compared to WT I.
For both study regions, repowering with WT II would be possible but would constitute an improvement of the situation mainly for West Saxony.

(2) Reallocation of VE areas

The reallocation of VE areas for wind power development was investigated, prioritizing the energy output of potential areas (Chapters 4 and 5). Reallocation sites with the highest energy output for both state-of-the-art technologies (WT I and WT II) were determined which met the necessary settlement distances to avoid sound emissions and achieved the EEG reference yield criterion.
For West Saxony only a reallocation of VE areas utilizing WT II yields a significant increase in energy output and CO_2 emissions avoidance. In detail, the potential VE areas are 926 hectares for WT II, with an energy output of 546 GWh per year, compared to the current 345 GWh per year (Chapters 4 and 5).
For a reallocation of VE areas in North Hesse, the requirements of the legal assessment criteria were considered and the military radar range was avoided.
The analysis identified such areas with a possible space for 129 WT II with a total energy output of 970 GWh per year without an increase in total demand of land designated for wind farming. For WT I, in principle, the same sectors of the study region can be considered for reallocation. Here, 199 WT I can be installed, with a total energy output of 1,270 GWh per year. The difference in the energy output is due to the different minimum distance between turbines, so more WT I can be installed on the same area.

Concerning the research question 1 found in Section 1.4., it has been shown that the energy output can be increased significantly by the reallocation of VE areas in both study regions.

However, for West Saxony the WT II is the turbine of choice, while for North Hesse the WT I should be preferred to meet energetic objectives.
It could be shown that an alteration in technology (repowering) and the reallocation of VE areas are promising ways to encourage wind power development. The greatest potential for a significant increase in energy output in both study regions was displayed by a combination of reallocation and repowering. In future, it will be necessary to provide suitable data for regional planners to enable them to consider the EEG reference yield criterion or even the potential energy output for an efficient allocation of VE areas. Furthermore, additional research into legal issues is necessary because the reallocation of VE areas affects the property rights of the landowners. For instance, should landowners be compensated for loss in revenue if a WT is dismantled on their site and erected elsewhere?
The analysis of the potential wind power development of the two study regions has so far only been examined from a regional planning and energy output aspect. So far, the ecological impact of reallocation has not been accounted for. The next two sections investigate a species that is endangered, cannot be protected by conservation areas because of its mobility, and which is found close to wind farms.

8.2 Identifying Optimal Sites for Wind Power Generation under Energetic and Ecological Aspects

The reallocation areas identified for West Saxony (Chapters 4 and 5) fulfill legal requirements and enable higher energy yields than currently possible. However, a neglected aspect is the impact of wind power generation on species which cannot be protected by conservation areas because of their mobility. Such species are mainly birds and bats (Hoetker et al. 2006). Predatory birds are notably affected as they frequently die of collision fatalities (Chapters 6 and 7). Therefore, the question arose as to how suitable sites for wind turbines (WTs) can be identified taking into account the aim of increasing wind energy production without overly increasing the ecological impact on raptors.
The occurrence of collision fatalities depends on both the behavioral properties of the species under consideration and the allocation of WTs within the landscape. There are two general ways birds collide with WTs. Some species collide during daily or yearly migratory flights; others collide during foraging flights. A comprehensive review of literature concerning the conflict between wind power generation and possible and observed effects on birds and bats is provided by Hoetker et al. (2006).

However, an integrated assessment of this conflict remains a challenging task. A multi-criteria approach is presented within this PhD thesis which analyzes this conflict. It integrates expert knowledge about the ecological impact of wind power production and data concerning energy productivity of individual WT sites in a spatially explicit ecological - economic optimization framework.

West Saxony currently has a low amount of installed wind power capacity. However, favorable land use patterns and meteorological parameters may support further extension of wind power. However, West Saxony borders on the red kite's (*Milvus milvus*) core habitat which has the highest density of this species worldwide. The red kite is an endangered predatory bird (BirdLife 2009) that is prone to collide with WTs (Duerr 2010). Thus, a substantial conflict between wind power production and red kite protection may arise and solutions to this conflict are urgently needed. Therefore, a new method was developed that enables reallocation areas to be evaluated and compared with one another and with existing VE areas, taking both the potential threat to red kites and the potential energy output into consideration (Chapter 6). The objective was to identify the WT sites that maximize energy output for a given impact on the red kite, hereafter termed ecological impact.

The potential threat for the red kite is described by the collision risk as a function of the WT-aerie distance (impact function). The ecological impact of an individual WT is, then, the sum of its impacts on each aerie. Aggregating the impact of all potential WT sites gives the total ecological impact in a landscape. This approach allows the WT sites to be ranked by the ratio of energy output versus ecological impact. This ranking, again, is the basis for deriving an efficiency frontier and for identifying pareto optimal solutions to determine the best energy output at a given risk to the red kite.

This has allowed an easy-to-apply tool to be designed for planning efforts that have the following criteria:

1. Installed WTs can be evaluated with respect to Pareto optimal allocation. If not allocated optimally, their energy output/ecological impact ratio can be optimized by an appropriate reallocation of WTs in the region.
2. Additional WT sites can be selected using the efficiency frontier.
3. A comparison of proposed wind farms is possible with regard to the severity of the conflict. This is given by the area under the curve (AUC): the higher the AUC the lower the conflict between wind power and ecological impact.

Beyond the conflict described, an effect of social constraints, i.e. the increase of the settlement distance (the minimum distance of WT to settlements), was also identified. The total number of suitable sites declines with increasing settlement distance. Hence, the settlement distance influences the efficiency frontier and the severity of the conflict. For a given ecological impact, energy output decreases significantly with increasing WT settlement distances. This indicates that a trade-off exists between the energy output, ecological impact and settlement distance - intensifying the overall conflict.

In conclusion, the developed method allows for a more efficient identification of optimal sites for WTs by using existing information such as species distribution maps and wind speed data. It analyzes the advantages and disadvantages of different WT sites, taking climate protection goals and species conservation into consideration. Moreover, the presented method is an easy-to-use tool, which can be employed in the formal decision making frameworks of regional planning authorities. The presented method evaluates the ecological impact qualitatively but not quantitatively. For a quantitative assessment, the ecological impact has to be translated into a measureable parameter such as “annual bird mortality” or “annual population decline”. This requires the use of a behavioral model that simulates the foraging behavior of the species and quantitatively predicts the probability of a bird colliding with a WT at a particular location relative to the bird’s aerie.

8.3 Model-based Estimation of Collision Risks of Predatory Birds with Wind Turbines

To quantitatively evaluate the ecological impact, it is necessary to derive a functional relationship between WT-aerie distance and collision risk. Here, agent-based simulation models (ABM) are a suitable approach as they allow the behavior of individuals to be simulated in response to temporal and/or spatial landscape attributes and thus to conduct virtual experiments in virtual landscapes. The agent-based approach enables species-specific vulnerability to be assessed for a variety of landscape scenarios unrealizable in nature (Verboom et al. 1991, Johst et al. 2001, Wichmann et al. 2004, Rodríguez et al. 2006, Bauer et al. 2008).
The ABM/IBM was developed in two steps (Chapter 7). In the first stage a simple foraging behavior model was designed. This was validated using the approach of pattern-oriented modeling with field data.

These empirical data include a frequency distribution of flight distances and flight times of the bird and its maximum observed distance to the aerie. The underlying landscape, although artificially generated, ensures area-wise distribution of the land use classes similar to the West Saxony study region.

The second stage of the model comprises the implementation of the collision event. Whether a collision occurs or not depends on a set of circumstances (Chapter 7). These are incorporated into the ABM by the determination of their respective probabilities. Virtual experiments were performed by placing a WT in different predefined distances to the red kite aerie within the artificial landscape. Four levels of collision avoidance probability, two physical collision probabilities and two movement strategies were applied (Chapter 7).

As a result, the collision probability for a particular WT-aerie distance was obtained and displayed as an array of curves for different scenarios of bird foraging behavior. The effects of the movement strategies and the physical collision probabilities are comparatively weak, but the avoidance probabilities (if a bird hits a WT site during its movement) reveal a strong impact. The validation of the movement behavior turns out to be complicated due to a lack of field data. Considering the derived relationships between collision risk and WT-aerie distance, the corresponding field-data-based collision rates would match WT-aerie distances of 1,300 m to 2,500 m. These are consistent with the observed WT-aerie distances in the study region and the typical flight distances of the red kite. This supports the resulting estimations of the collision risk of the ABM presented.

In relation to the third research question (Section 1.4) it can be concluded that using an ABM gives a broader understanding of the underlying processes leading to the collision of birds with WTs. This allows for the mechanistic derivation of the functional relationship between WT-aerie distances and bird collision risk. The accuracy of the ‘impact function’, which was used to identify pareto optimal sites for wind turbines (Chapter 6), was confirmed and improved by the ABM. Therefore, agent-based ecological modeling represents a method for quantitative analysis for species conservation planning efforts. Beyond this, with slight modifications, GIS based landscapes can be incorporated or the model can be parameterized and analyzed for different species with similar behavior.

The combination of virtual experiments using ABMs and the method of determining pareto optimal sites under wind energetic and ecological aspects (see Section 8.2) supports an efficient impact assessment of potential WT sites that encourages wind power development onshore in order to achieve energy security and CO_2 reductions.

8.4 Relevance of selected results for practical applications

Wind power is a pioneer in the field of the current renewable energy technologies. Nevertheless, its development occasionally encounters resistance in the private as well as the administrative sector. The starting point of this work was to analyze current planning practices and investigate possibilities of extending onshore wind power sites. The aim was to determine optimal locations with respect to economy, ecology and society within the framework of an ecological economic modeling procedure. To do this it looked at the two most relevant conflicts planning authorities are facing: ecological sustainability and energy suitability. Throughout the entire research project, which this thesis is part of, the basic approaches and outcomes were shared with stakeholders at workshops to find relevant and feasible solutions for the planning practices. Attention was turned to the development of methods which can be easily applied by non-experts.

The analysis of the current planning practice and the existing wind farms in the two study regions leads to the following recommendations: A repowering in North Hesse with the WT I and the WT II to achieve the EEG reference yield criterion is possible in all VE areas. A reallocation of the VE areas would lead to a further increase in wind power generation. Here, analysis revealed that the WT I should be selected due to its lower minimum distance requirement to other WTs and to settlements, resulting in a larger total nominal capacity.

In West Saxony, it was shown that in light of the EEG reference yield criterion, repowering is only feasible with WT II although on a small proportion of the VE area. To achieve the EEG reference yield criterion, a reallocation of VE areas in combination with the use of WT IIs is recommended.

For the designation of VE areas, the potential threat to the red kite is a knock-out criterion against the construction of a WT (e.g. VG Koblenz, 24.07.2008, Az.: 1 K 1971/07.KO). Therefore, the goal of producing energy efficiently has to be reconciled with ecological objectives. Against this backdrop a new method was developed as part of this PhD thesis which can support regional planners in the process of designating VE areas taking into account both energetic and ecological aspects. In this method (i) an impact function was derived to determine the threat to the red kite.

(ii) The energetic output of the potential WT was calculated by its nominal capacity and the annual wind speed distribution of the site. (iii) A ratio of impact function and energy output was used for identifying pareto optimal sites for wind power plants. From this analysis, the severity of the conflict between wind energy and species conservation can be derived making it possible to compare different regions. Thus, this method can easily be applied for any VE site analysis and results in a fast, qualitative determination of favorable sites, taking economic and ecologic objectives into account.

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Selbstständigkeitserklärung

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