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# Nature conservation as a driver in wind energy scenarios



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## Abstract

**Background:** Germany has set ambitious goals for the reduction of greenhouse gases. The decarbonisation of the energy system has been in focus. An important means to achieve this is the increased utilisation of wind energy. The growth of wind power entails changes not only in the electrical system but also in the landscape and environment. Prospectively, scenarios will have to consider a wide range of aspects, not only economics and technology but also nature conservation and social affairs. The authors are participating in the research study “Szenarien für den Ausbau der erneuerbaren Energien aus Naturschutzsicht”, funded by the Federal Agency for Nature Conservation, which examines the possibilities of integrating nature conservation into the development of scenarios.

**Methods:** For aspects of nature conservation to be taken into account in scenario development, a multi-stage methodology has been developed to assess the conflict risk of wind energy and nature conservation throughout Germany. To ensure comparability of the scenarios, all of them are based on the same general framework consisting of fixed excluded areas, the same method of detail allocation and the same overall expected energy output. The “nature conservation” driver is integrated in the form of a nationwide comparative assessment of risk levels. The mapping of spatially differentiated risk levels for wind energy has been achieved in a GIS-based and discursive process.

**Results:** The results show that nature conservation can be addressed properly in scenario-building. Here, the method of multi-criterion scenario-building itself, with its focus on including nature conservation as one of several drivers determining the spatial distribution of wind turbines, is a major result. The authors have developed specific scenarios that mainly address questions of landscape and nature conservation. Out of the four generic scenarios presented for the year 2035, two have nature conservation as their main driver, whereas the other two consider energy-economic drivers only. Examining these scenarios provides insight into the influence of each driver. For example, adding nature conservation as the main driver (highest priority) reduces the specific conflict risk by 26.1%, while at the same time only a relatively small increase in wind turbines is required (+12.5% in numbers, +2.3% in installed power capacity).

**Conclusion:** The methods developed here provide a driver for allocating wind power plants to reduce conflicts in high-risk areas. Furthermore, using the same spatial distribution of risk levels makes it possible to subsequently rate the scenarios from a conservation perspective. The method developed here provides the means to analyse trade-offs between relevant drivers. The “nature conservation” scenarios show a relatively small additional demand for wind turbines but a greater amount of avoided conflict risk.

**Keywords:** Wind energy, Scenario-building, Nature conservation, Rating conflict risk, Spatial distribution, Spatial planning, Drivers, Energy consumption covered by wind energy

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## Background

The transition of the energy sector, also known as *Energiewende*, aims at today's foremost ecological goals. Among other activities like energy saving, changing to renewable energies is the most central aspect to fulfilling international climate goals. In Germany, the *Energiewende* is a goal broadly accepted by the public [1, 2]. At the same time, it is not without consequences for nature conservation [3, 4].

This paper builds on the research study "Szenarien für den Ausbau der erneuerbaren Energien aus Naturschutzsicht", funded by the Federal Agency for Nature Conservation. It describes a method designed to better take into account the consequences for nature and landscape associated with the energy transition in decision-making on a strategic level. The conflicts associated with renewable energies in the context of the expansion of onshore wind energy are particularly striking. Not only is this the type of energy generation with the biggest contribution to the current production of renewable energies [5] but also with the largest potential for expansion (cf. scenario framework 2030 NEP [6]). At the same time, the expansion of onshore wind energy is in conflict with nature and landscape conservation concerns, especially compared to other renewable energies [1, 7].

The state of the art thus concerns the various subject areas, in particular comparative assessments of conflict risks in relation to nature conservation, scenario development and placement of wind turbines according to specific criteria, and also the combination of these two areas. In the following, existing work relevant to the context but also its delimitation with this paper will be mentioned.

Several authors have shown that certain legally protected environmental goods are particularly affected, most of all the ecosystems and habitats of avifauna and bats as well as the beauty, diversity, singularity and the recreational value of nature and landscape [8, 9]. These findings have led to the growing importance of spatial planning and consideration of environmental and social impacts. Some research projects are concerned with the optimisation of wind farms and the visualisation of wind turbines and their effects on ecosystems and nature conservation [10]. However, those approaches must not be confused with broad-based scenario-building and the inclusion of nature conservation as a criterion. Still, wind energy scenarios usually consider economic and technical factors only.

The aim of the study was, therefore, to devise a method for assessing the risk that conflicts occur (conflict risk) and to integrate nature conservation into multi-criterion scenarios. While multi-criterion scenario-building is often used to evaluate the spatial distribution of renewable energy sectors, e.g. by WWF

and Agora [11, 12], only a few studies on the national level have taken nature conservation into account, e.g. Federal Agency for Nature Conservation [13]. At the subnational level, more studies included nature conservation, if not as a legitimate driver, at least as an exclusion criterion [14, 15]. Proposals for the methodological inclusion of bird strike have been made by Drechsler et al. [16] but concern a rather narrow area of nature conservation. Lately, there have been calls for recognising ecological aspects beyond exclusion criteria in nationwide energy scenarios, e.g. Naegler [17]. At this point, we should mention a study on the national level on the topic of wind energy and nature conservation by Cowell [18]. However, it focuses on "efforts of the Welsh Assembly Government to develop a spatial planning framework for wind energy" and, with this focus on concrete project planning for wind farms planning for a specific area, is not transferable to a general scenario perspective.

In a broader sense, research on ideal distances between turbines in wind farms [19] and the optimisation of wind farm placement [20, 21] are also related to the subject of this paper. However, they are only concerned with the classification of a specific sub-step of the presented methodology, namely the selection of possible sites.

This study is necessary to fill gaps in the literature and current methodology. It can support policy advice to investigate possible levers from different spatial distributions of energy production to nature conservation aspects.

## Methods

The overall approach is divided into the following methods and steps:

- Method for determining nature conservation as a driver
- Methods for determining other drivers
- Selection of scenario settings
- Placement algorithm for potential locations of wind turbines
- Technical methods for the development of scenarios and their evaluation

To establish *nature conservation as a driver* for spatial allocation in wind energy scenarios, a complex method was devised. It aims at a spatially differentiated assessment of nature and landscape conservation issues at the federal level. Here, the small scale only allows conflict risks to be addressed. The mapping of risk levels for wind energy was achieved in a combined geographic information system (GIS)-based and discursive process. At first, considering the typical effects of wind turbines,

potential conflicts were identified—for example, with avifauna, bats or recreational functions of the environment [22, 23]. Based on knowledge about possible conflicts, spatial information on sensitive areas was gathered. For example, datasets about Nature 2000 sites were suitable. Overall, there is limited homogenous data on the federal level. Available data include information about protected areas, land use, topography (elevation model, visibility model) and occurrence of species. Each of these datasets contains multiple categories, see Table 1. Protected areas, for example, include nature reserves, landscape conservation areas, biosphere reserves, Nature 2000 sites and others. These categories can be used to determine the spatial distribution of sensitive areas where conflicts may arise.

However, none of the geodata contains the precise information necessary to pinpoint specific conflicts. Therefore, an assessment of conflict risks with consideration to impact, vulnerability and the normative meaning of the information used, as well as the accuracy of the geodata, is necessary. Concerning these characteristics, the

assessment is carried out by leading ecologists, environmental, conservation and spatial planning experts from the federal government, universities and consulting firms. The list of categories is presented to the group of experts in the form of a modified Delphi survey [33]. Within the development and testing of the method, the number of experts is limited to 15. For the implementation, a nationwide participation of all experts is recommended. The respondents have an opportunity to assess each category in two rounds. From the second round onwards, feedback is given on how other experts have responded. The main objective is to differentiate between lower and higher conflict risks with nature and landscape conservation on a five-point scale for each category and protected good (fauna, flora, biodiversity, soil, water, air, landscape and recreation). The outcome of the Delphi survey in the first round showed that some categories were assessed unanimously while other categories were assessed differently. The differences mainly result from the specific views of the experts and could be eliminated in the second round by a consensus for

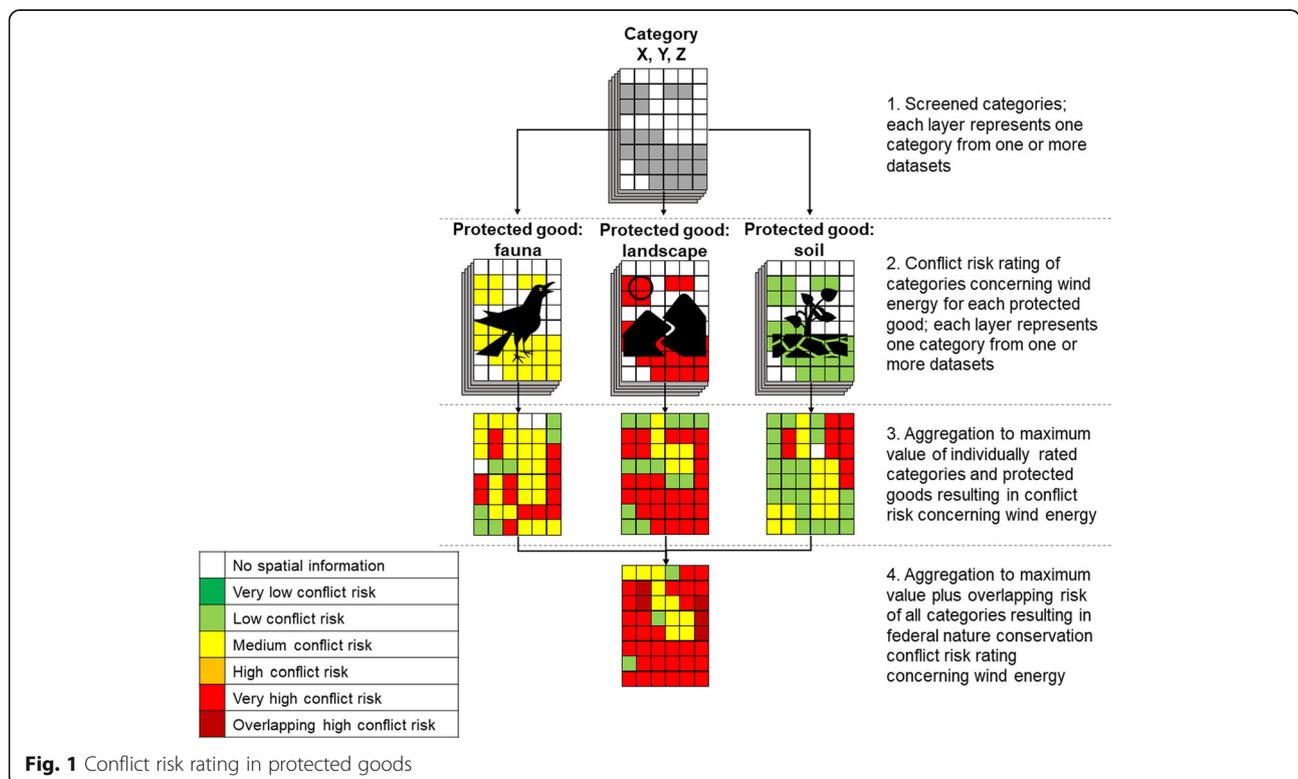
**Table 1** List of datasets and included categories

Dataset	Category
Protected areas Source: Federal Agency for Nature Conservation [24, 25]	<ul style="list-style-type: none"> <li>• Nature reserves</li> <li>• Landscape conservation areas</li> <li>• Biosphere reserves (zone III)</li> <li>• Ramsar areas and adjacent areas at a distance of 0–1000 m</li> <li>• Nature 2000 sites:               <ul style="list-style-type: none"> <li>◦ Special protection area with/without the occurrence of bird species sensitive to wind energy</li> <li>◦ Areas adjacent to special protection areas with occurrences of bird species sensitive to wind energy at a distance of 1000–2000 m and 2000–3000 m</li> <li>◦ FFH areas without occurrences of bird or bat species sensitive against wind energy</li> <li>◦ Areas adjacent to FFH areas with occurrences of bird or bat species sensitive to wind energy at a distance of 0–1000 m, 1000–2000 m and 2000–3000 m</li> </ul> </li> <li>• Areas adjacent to national parks at a distance of 0–1000 m</li> <li>• Areas adjacent to nature conservation areas at a distance of 0–1000 m</li> <li>• Areas for the biotope network of wetland, dry and forest habitats as well as habitat networks with international significance</li> <li>• Areas of the Grünes Band Deutschland</li> </ul>
Important Bird Area Source: NABU [26]	<ul style="list-style-type: none"> <li>• Important Bird Areas (IBA) of categories A1–3, A4 (iv), B1 (iv), B2, C1 and 2, C5 and 6 outside Nature 2000 sites and adjacent areas at a distance of 0–1000 m</li> </ul>
Water conservation Source: Federal Institute of Hydrology (BfG) [27, 28]	<ul style="list-style-type: none"> <li>• Water conservation areas</li> <li>• Medicinal-spring protection areas both already established and in planning</li> </ul>
Land use Source: Federal Agency for Cartography and Geodesy (BKG) [29] and DDA [30]	<ul style="list-style-type: none"> <li>• Habitats of bird species of the Helgoländer Papier sensitive to wind energy with mortality index A, B and C outside protected areas</li> </ul>
Land use Source: Federal Agency for Cartography and Geodesy (BKG) ATKIS-AAA-Basis-DLM [29]	<ul style="list-style-type: none"> <li>• Deciduous, coniferous, mixed-forest and adjacent areas at a distance of 0–200 m</li> <li>• Farmland</li> <li>• Pastures/permanent grassland</li> <li>• Open land outside agricultural land</li> <li>• 250-m corridors along large water axes and adjacent areas at a distance of 250–1000 m</li> </ul>
Historic forest sites of Germany Source: Federal Agency for Nature Conservation [31]	<ul style="list-style-type: none"> <li>• Historic forest sites and adjacent areas at a distance of 0–200 m</li> </ul>
River floodplains of Germany Source: Federal Agency for Nature Conservation [32]	<ul style="list-style-type: none"> <li>• River floodplains</li> </ul>

the federal level. To generate a federal nature conservation conflict risk rating, the partially overlapping geodata are aggregated within the GIS based on rules. The conflict risk for each cell of the grid (25 × 25 m) associated with the protected good is first determined using the maximum-value principle per protected good. Later, the conflict risk concerning all protection goods is determined for each cell, also using the maximum-value principle, see step 3 in Fig. 1. For example, conflicts with bird presence are mapped by several different categories. Since the conflict indicated by all categories is the same, the highest conflict risk remains, which avoids double evaluations of categories that represent the same conflict. However, it should be taken into account that several different conflicts can occur in a single cell. If the overlapping categories represent various protected goods and, therefore, different potential conflicts, the conflict risk will increase due to an increased probability of occurrence, see step 4 in Fig. 1. Thus, in addition to the maximum conflict risk value, the model also calculates the density of conflicts. For the overlapping risk value, the original value of the cell is increased by one based on rules if it has a high conflict risk class (CRC > 3) and more than three different protected goods are affected. This should also be done if a cell with the highest conflict risk class to date has a higher conflict risk according to the extended aggregation rule. Therefore, the additional conflict risk class with the value “overlapping

high conflict risk” is introduced in the result of the evaluation. In total, there are six CRCs. The result is a map that can be used as a driver to allocate wind power plants in such a way as to reduce conflicts in high-risk areas, see Fig. 1.

In addition to nature conservation, *two other drivers* are used for scenario development. “Wind resources” is used as the basic driver for all scenarios. The calculation is based on mesoscale models for wind speed. In multicriterion scenarios, a comparison of possible electricity yields is useful for achieving a correct evaluation of the advantages and disadvantages of the locations despite the high non-linearity of the wind energy amounts in relation to wind speed. An existing wind energy yield model from Fraunhofer IEE is used to generate the *wind power* produced in 1 year. The method is described in Arbach et al. [34]. Model development has made strides, particularly in the area of underlying weather models and calibration factors: the numerical weather prediction model Cosmo-DE [35] has been used here. The second driver, “energy consumption ratio”, i.e. the share of the *power consumed that is wind generated*, has been specifically developed for the purpose of this study. Just like wind suitability, the driver “energy consumption ratio” should reflect the view of energy economics, in contrast to the criterion addressing nature conservation discussed later. This driver is concerned with the question of how much energy can be generated in the location where it is



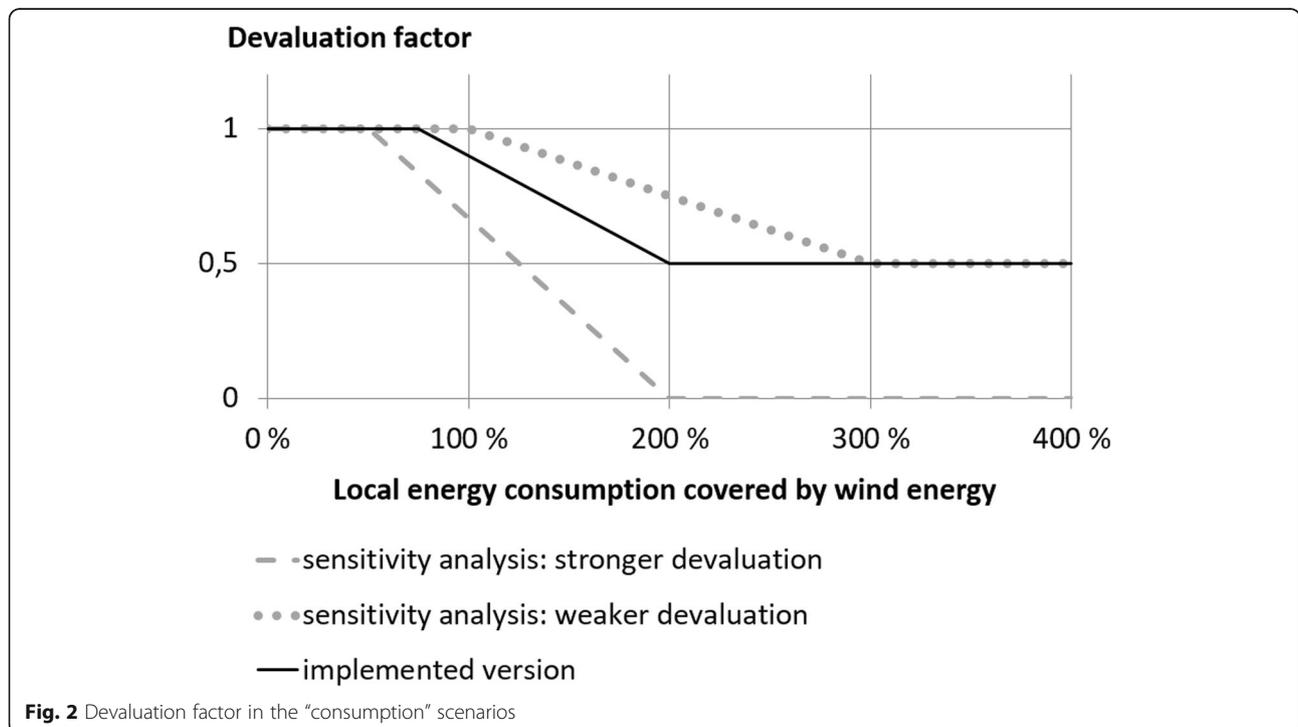
**Fig. 1** Conflict risk rating in protected goods

also consumed. One input variable is local electrical load, the other installed wind power, which is determined in the allocation process. The methodology for determining area-related load in municipalities is an output of an existing Fraunhofer model and is described in Härtel et al. [36]. The existing model uses top-down energy consumption (at different levels) and bottom-up distribution variables to model loads at hectare resolution. In the context of the research described here, the load is assumed to be area wide over communities. The temporal resolution is not taken into account, i.e. the energy quantity is compared, but not the temporal simultaneity values of the energy generation load. Considering that no grid calculations have been carried out within the framework of the project, the assessment of the “consumption” scenarios can only be understood as an indicator for the subject at hand. The driver is deliberately formed independently of the electricity grid’s actual supply areas. In contrast to wind suitability, “energy consumption ratio” is not a value that is independent of the expansion in the scenarios but a quantity that is determined iteratively. During the site-selection process, the ratio of the wind power generated and the local consumption within the surrounding area (diameter of 50 km) is checked after each site selection. If production exceeds 75% of consumption (which includes the industrial consumptions), locations in the vicinity will receive a malus. The limits for the increase of the malus are not defined from a technical point of view. They are the result of discussions in the project team to adequately

reflect the influence of the load. Nevertheless, they are to be regarded as estimated values and are, therefore, integrated into the model as variable input variables. In contrast to the other drivers, “energy consumption ratio” is, therefore, not a value that can be assigned to each location from the outset but a value that results from the iterative allocation process and changes with each wind turbine placed. Figure 2 shows the devaluation factor used in the project for different shares of energy consumption covered by wind energy.

The course of the function was worked out by the project team. For the analysis of the robustness, the function course was varied in a sensitivity analysis. On the one hand, a stronger devaluation was made on the basis of an earlier and stronger reduction. On the other hand, a weaker devaluation was achieved by a later starting and slower reduction. As expected, a stronger devaluation factor leads to a stronger redistribution compared to the “efficiency” scenario and thus a higher number of installations and vice versa. However, the changes are relatively small, the change in the number of installations varies only +2.9% (to 21,880) and -1.9% (to 20,850). Here, the framework numbers at the federal state level and the general methodology of the devaluation factor appear to have a stronger influence than the very precise functional course, which can, therefore, be regarded as relatively robust.

Within the wide range of possibilities for scenario-building, the authors decided to simulate generic scenarios describing the influences of different drivers on



allocation patterns. Considering existing wind turbines or annual repowering would not help but, on the contrary, complicate scenario evaluation. In consequence, plant distributions are based on a greenfield approach with a fixed target energy quantity. The basis for the distribution is the total area of Germany minus the pre-excluded areas. All legally inadmissible sites, e.g. in national parks, are initially excluded in advance. Furthermore, all sites that are predominantly excluded by law in individual cases, e.g. within a distance of less than 1000 m from residential buildings, as well as sites that are unsuitable from a technical point of view, e.g. steep areas (gradient over 30%).

The resulting scenarios are well suited to identify the influences of several drivers but must not be mistaken for scenarios that likely represent the future accurately. Wind suitability serves as the basic criterion, and “wind power” is the only driver in the first scenario. The other scenarios include every combination of the other two drivers (“energy consumption ratio” and “nature conservation”). Figure 3 shows an overview of the drivers.

The allocation process has two steps and uses a specific placement algorithm. In the first step, the grid cells are scanned and the next free cell is identified. In the second step, the possible location is marked and an elliptical buffer zone is drawn. This ellipse describes the necessary distance from the closest wind turbine, defining all pixels contained as occupied. The minimum distance between turbines depends on the main wind direction. It is commonly assumed that, in the main wind direction, a distance of five times the rotor diameter must be maintained. In the secondary wind direction, three times is sufficient [37, 38] (see Fig. 4). The assumed rotor diameter is 135 m. It should be mentioned that although rotor diameter is fixed regardless of location, site-specific requirements are taken into account by selecting three types of turbines. They differ in hub height (160 m, 135 m, 110 m), power density (220 W/m<sup>2</sup>, 285 W/m<sup>2</sup>,

350 W/m<sup>2</sup>) and the resulting rated power (3.15 MW, 4.08 MW, 5.01 MW). The three types represent a realistic plant mix for the year 2035, according to analyses of previous plant development [39]. While in reality a different rotor diameter seems realistic for these different turbine types, a uniform diameter is useful for the modelling since a continuous placement algorithm (most resource-intensive part of the model) can be used, and at the same time a changed rotor diameter does not represent a generally changed land consumption since all three variables (apart from form factor influences) are generally linearly related: energy quantity/rotor area/area consumption. Therefore, a uniform rotor diameter seems appropriate and at the same time acceptable as an assumption. However, the three turbine types have not been chosen to reject the diversity of turbine types used in reality but to provide a good basis for comparability in the context of the greenfield approach described above.

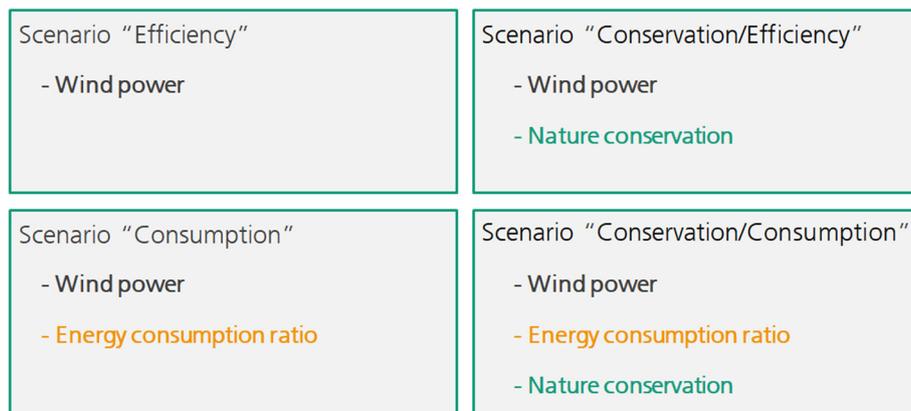
Thus, a good utilisation of the potential areas calculated in the scenarios is achieved using the described algorithm (see Fig. 4).

The best locations are used for scenario-building, with the evaluation depending on the combination of drivers in each scenario. For scenarios that do not take consumption into account, the evaluation for each location is unique. Considering the share of load covered by wind energy turns the allocation process into an iterative process as described above.

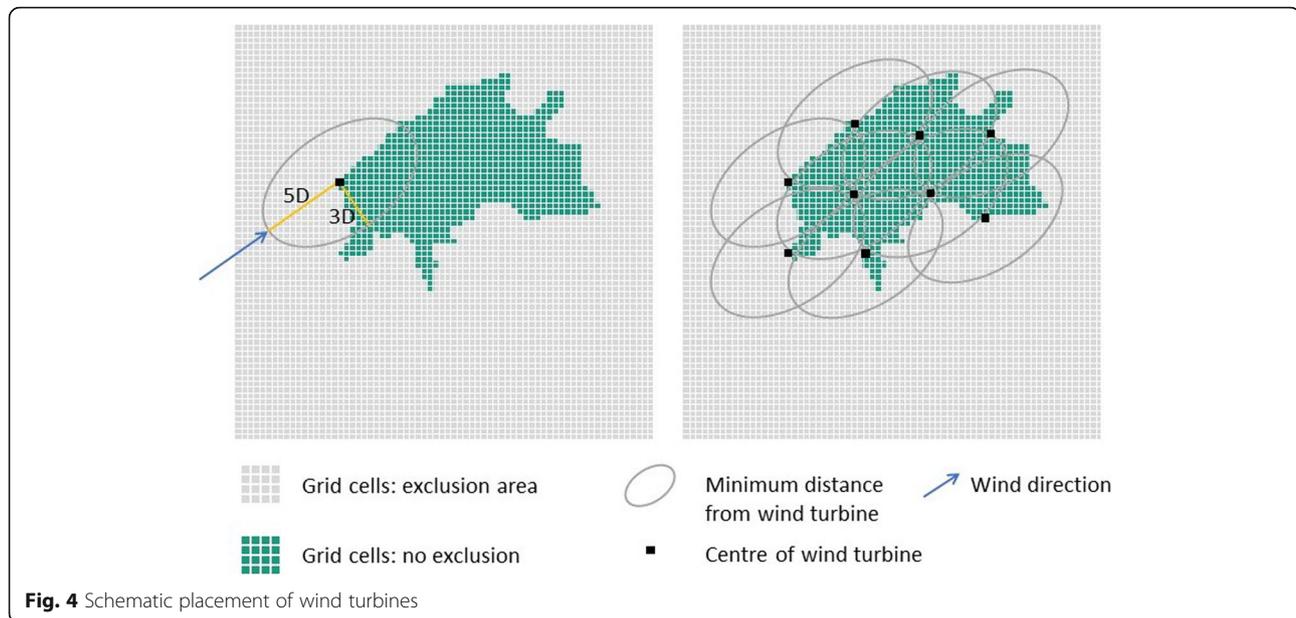
**Results**

The following two results best describe the main research findings:

- Nationwide “nature conservation” conflict risk map
- Methodology and numerical examples for multi-criterion scenarios



**Fig. 3** Different drivers in the four scenarios



A major result is the nationwide mapping of nature vulnerability against wind energy. Further insight into how the map was generated is provided in “Methods”. It is based on available data, e.g. Nature 2000 sites and information about habitat and species protection. Overall, the model considers all concerns of nature conservation such as flora and fauna, biodiversity, water, soil, air and climate as well as landscape and recreation. Risk levels on a six-point scale describe the compatibility of nature conservation and wind energy. A low level indicates an area where sustainable usage is predominantly possible, and a high level an unsustainable area. The risk level is the result of a comparative assessment. The numerical output of the methodology developed here is a grid-shaped and high-resolution assessment of vulnerability in terms of nature conservation. With this high-resolution map, conventional wind energy scenarios can be evaluated from a nature conservation perspective. The evaluation unit of total conflict risk is physically undefined and results from the sum of claimed conflict risk levels. At the same time, the conflict risk rating can also be used—this is the second important result of the study—as a key driver in multi-criterion scenario-building. Both options, the assessment of existing scenarios and the implementation of nature conservation as an input for scenario-building, are schematically presented in Fig. 5.

The other major results are four multi-criterion scenarios which demonstrate the influence of nature conservation aspects on the potential spatial distribution of wind turbines. In addition to the analyses of impacts on nature conservation, the scenarios are also evaluated with consideration to energy management issues. The

generic scenarios are not meant as a future prognosis but to describe the influences of several drivers. For this reason, existing wind turbines and annual repowering were deliberately disregarded. The scenarios are based on a greenfield approach for a fixed target energy quantity. Each placement of a wind turbine depends on the respective driver combination in each scenario. While all scenarios contain a driver regarding the wind conditions, the “consumption” and “nature conservation” drivers are combined differently in each scenario.

All four scenarios have the same amount of produced wind energy (269 TWh per year). The amount of wind energy results from an analogous consideration of wind energy rated power as in [12], which was supplemented by more recent figures from updated sources of grid development plans [6]. This rated power results—for the specific turbine distribution from the “Efficiency” scenario—in an energy quantity that is also used as a target value for all other scenarios. These differ in the number of installed wind turbines, their spatial distribution and the total conflict risk (without physical unit, see above for derivation). The results of the four scenarios are shown below. The “energy consumption ratio” driver has the greatest influence on spatial distribution, cf. Fig. 6. However, the influence of the “nature conservation” driver on the distribution must not be neglected. The comparison of the scenarios “Efficiency” and “Conservation/Efficiency” shows that only a small increase in the number of wind turbines placed (+12.5% in numbers, +2.3% in installed power capacity) is needed to generate the same amount of energy, while a strong reduction in total conflict risk is achieved (−26.4%). Figure 7 shows the relative (plant-related) conflict risk and the total

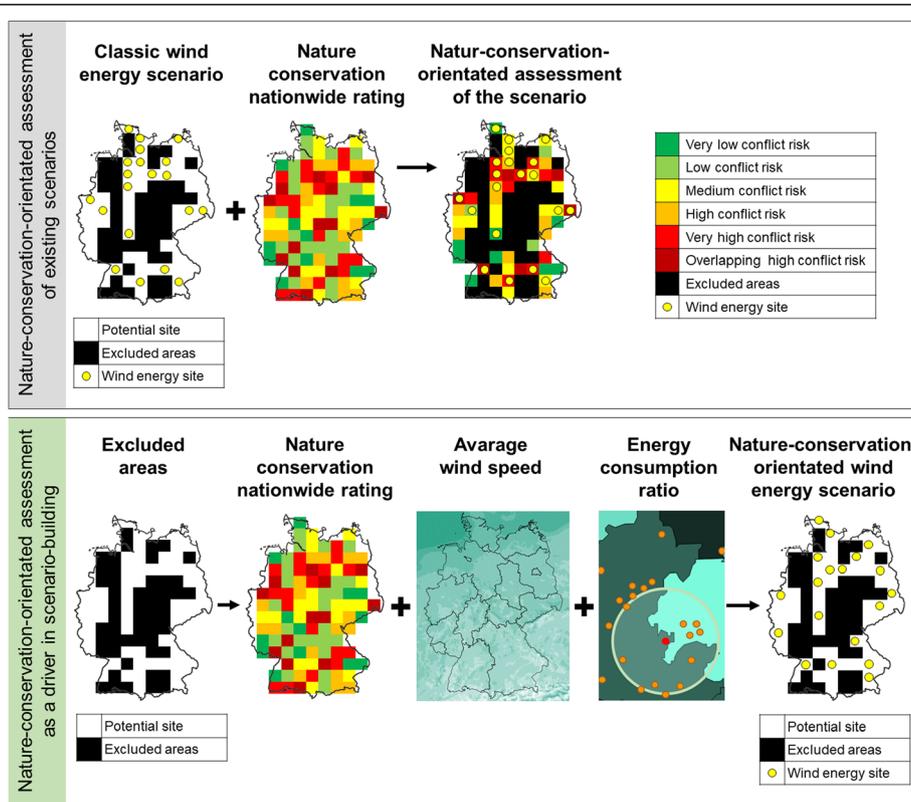


Fig. 5 Possible applications of the conflict risk rating in scenario assessment and development

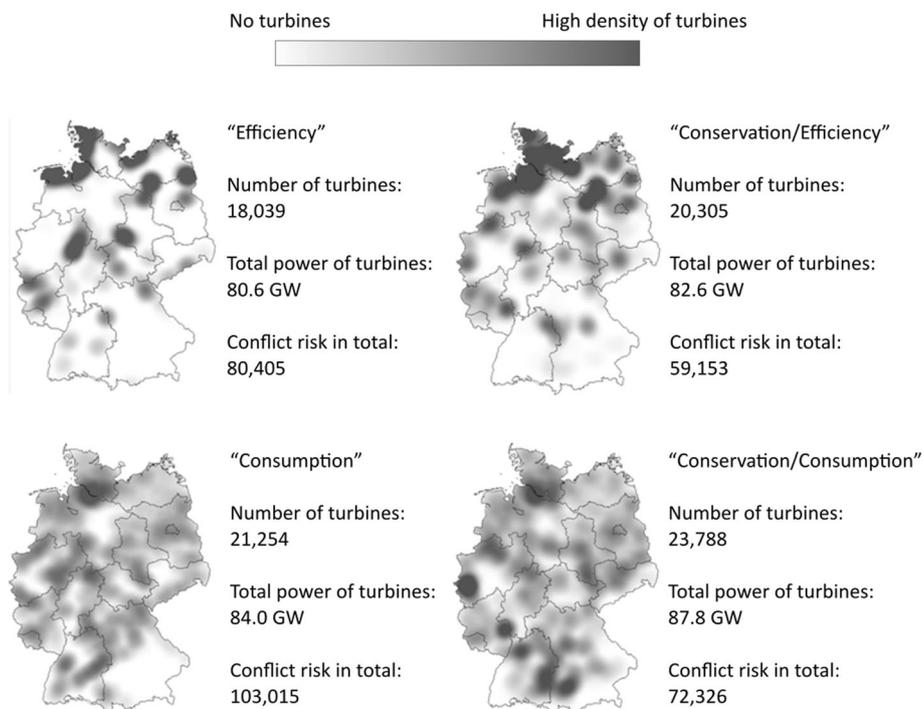
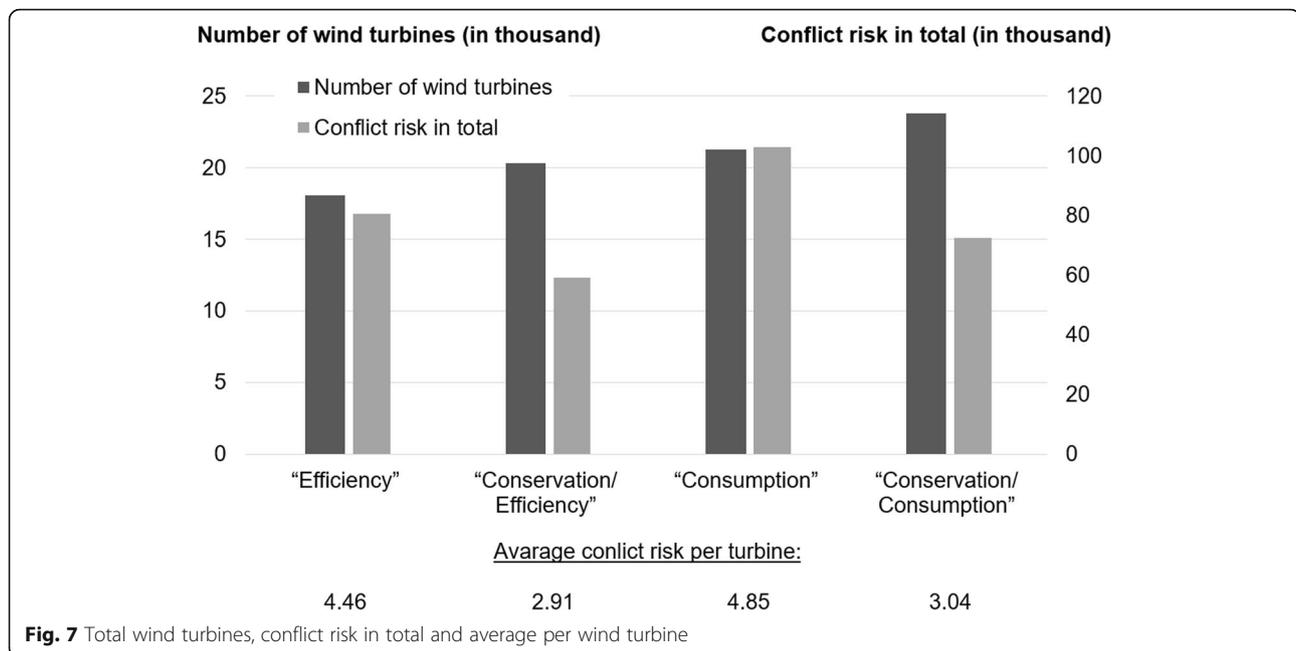


Fig. 6 Heat maps of the four scenarios



conflict risk for each scenario with respect to the total number of wind turbines used. It becomes clear that the low plant-related conflict risk of the “Conservation” scenarios significantly reduces the overall conflict risk despite the greater amount of investments (see Figs. 6 and 7). As for the methodology, these results show that the acquired driver “nature conservation” is very well suited to adequately take into account nature and landscape concerns in the scenarios.

The influence of the drivers on the spatial distribution of wind turbines is mostly contrary. The highest degree of efficiency is achieved through the central allocation of wind turbines in windy regions. In contrast, an expansion close to where the energy is consumed requires a decentralised distribution, with few exceptions. At the same time, particularly windy regions are often prone to conflict from a nature conservation point of view. In conclusion, targets in one area can only be achieved at the expense of other targets. The methodology presented can be used to illustrate these effects and to support decision-making with respect to the necessity of weighing and balancing contradictory goals.

## Discussion

The described research shows how nature conservation conflict risk can be mapped nationwide and used as a driver for scenario-building. Naturally, under the assumption that the same amount of energy is generated, the addition of drivers leads to an increased turbine requirement. An interesting finding is that the results of the “nature conservation” scenarios show a relatively small additional demand for wind turbines but a greater

amount of avoided conflict risk, as seen in the results, e.g. Fig. 7.

To evaluate these results, it is essential to fully comprehend what is behind the multi-stage procedure of assessing nature conservation. The strength of the procedure—a broad database and comprehensive involvement of experts in assessing different categories—has also proved to be a hurdle: over the course of the research work, the inclusion of a great number of expert opinions proved difficult on several occasions. This was mainly due to three major issues: the necessity to comprehensively clarify (1) the used terminology, (2) the complexity of the multi-stage assessment procedure and (3) the required data quality. While it is rather easy to provide a glossary defining all terms in need of clarification, it became apparent that a longer period of time is required for experts to get accustomed to the assessment procedure and to apply coherent benchmarks. Concerning the use of nationwide data, it was challenging to convey the utilisation of general area information (e.g. Nature 2000 sites) to address a certain conflict (e.g. disturbance or collision of birds). Experts proposed to consider regional data, which possess a greater level of detail (e.g. detailed mapping of bird occurrences in a region). Although there is a justified interest in using more precise data, a nationwide comparable assessment first of all requires homogeneous data. Nonetheless, it became obvious that the existing federal data leave room for improvement.

Eichhorn et al. [40] also come to this conclusion—also for the level of the federal states [41]. They limit the consideration of nature conservation concerns to certain

protected areas in which species sensitive to wind energy are protected. The spatial differentiation of the scenarios is less pronounced than the approach presented. In contrast to the intended simple determination of scenarios for the expansion of wind energy according to Eichhorn et al. [40], particular importance is attached here to the consideration of all nature conservation concerns. Especially possible conflicts outside the relevant protected areas (SPA and FFH) are taken into account to get a step closer to reality.

In fact, here are numerous other projects concerned with the building of wind energy expansion scenarios based on placement algorithms and location evaluations or weightings, such as Braun et al. [42] and Jetter et al. [43], to name two important study reports for Germany. In some scientific papers, some highly detailed criteria were included to arrive at GIS-supported wind energy distributions [44, 45]. Similar to some of the studies mentioned above, this study uses an algorithm with elliptical minimum-distance areas around the wind turbines and includes a subsequent selection of potential locations. In contrast to most of the other studies, where site selection is mainly based on an energy-economic evaluation, this paper focusses on nature conservation as a driver. It should not be forgotten that the numerical results have been compiled in generic scenarios in which wind turbines are distributed over available areas until an annual power generation quantity is reached without taking into account the number of existing turbines or simulating an annual extension. They should, therefore, not be mistaken for scenarios that likely represent the future accurately. Nevertheless, our findings offer opportunities to support policy advice decisively and close a gap in scenario-building.

The adaptable structure of multi-criterion scenario-building also allows for supplementary future research work. While various complementary research activities are conceivable, the consideration and quantification of the required network expansion for the various scenarios are particularly important. As numerous network development studies of the grid extension conduct a cost assessment only, a consideration of conflict risks concerning nature conservation would be extremely helpful. First of all, a possible scenario would have to include a similar assessment of nature conservation conflict risks concerning grid extension. Furthermore, a reasonable consequence would be to add comprehensive overall energy simulation (which includes all energy producers and consumers connected to the grid) and grid calculation, which, taken together, would result in more realistic scenarios. This would particularly improve the evaluation of the “consumption” scenarios. A first intermediate step could be the implementation and consideration of a current consideration of the actual momentary correspondence

between load and wind energy generation, whereby it can be questioned whether this—as long as a grid calculation does not take place—actually represents a qualitative added value compared to the currently used methodology with annual energy consumption. In combination with existing methods of network calculation, the method presented here constitutes a suitable building block for this. However, a more holistic methodology encompassing all elements yet needs to be developed.

## Conclusion

This study aimed to implement nature conservation as a valid driver in scenario-building. For this purpose, adaptable methods for a nationwide rating of nature conservation conflict risk and modelling of multi-criterion scenarios with high-resolution site selection were developed. It turned out that a suitable driver could be found that could easily be integrated into the multi-criterion scenario-building method. As far as the necessity of such a driver is concerned, it could be shown, based on the generic scenarios, that nature conservation has a significant impact on scenario results. Furthermore, it became clear that prioritising any of the three drivers would lead to significantly deteriorated achievement of objectives in the other areas. This negative correlation between the main drivers “efficiency”, “consumption” and “nature conservation” makes it particularly important to consider them equally. It must be concluded that a planning process that takes all drivers into account is to be recommended. Last but not least, this requirement also leads to the necessity of weighting the drivers. The discussion showed that these issues must be resolved in political and social debates concerning the future expansion of wind energy. The subject is of increasing importance against the background of the declining number of new wind turbines being built. The expansion of wind energy fell by about 50% in 2018 compared to 2017. Surely, this is not in the spirit of the *Energiewende*. In conclusion, it can be stated that the presented methodology can greatly contribute to answering the question of how and where an expansion of onshore wind energy should proceed.

## Abbreviations

NEP: Netzentwicklungsplan Strom (network development plan); GIS: Geographic information system; CRC: Conflict risk class

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## Authors' contributions

The methodology of nature conservation assessment and the derivation of a uniform “nature conservation” driver have been developed and described by SchS. PG has developed and described the methodology of multi-criterion scenarios in general, the consideration of individual criteria in particular and the selection of sites. CP has developed the geometric investigation of potential wind turbine sites. The methodological approach for considering

local energy consumption covered by wind energy as a driver has been developed by CP and PG. The presentation preceding the paper on the same topic at the UFZ Energy Days was given by PG. SchS and PG have contributed equally to the writing, and an additional revision of the manuscript has been provided by CP. All authors read and approved the final manuscript.

#### Authors' information

##### About the authors

Philip Gauglitz studied mechanical engineering at the RWTH Aachen University, majoring in energy technology. As a project manager and research associate at Fraunhofer IEE, he works on and leads research projects in the field of regionalisation of energy producers (e.g. wind turbines) and energy consumers (e.g. electric vehicles) in scenarios.

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#### Availability of data and materials

The nationwide data used for nature conservation assessment have been collected in the context of the research project "Szenarien für den Ausbau der erneuerbaren Energien aus Naturschutzsicht" and made available by the Federal Ministry for Nature Conservation, among others. Unfortunately, it is not publicly available. A more comprehensive list of the data and map materials will follow with the final report of the research project mentioned above, which will be published shortly.

#### Ethics approval and consent to participate

Not applicable.

#### Consent for publication

Not applicable.

#### Competing interests

The authors strive for neutral and open-ended research. The methods developed here can be used as a tool in policy consulting. It is not possible and not in the authors' intention to use the methodology to evaluate individual locations in a way that would constitute a conflict of interest. At the present stage of research, the authors declare that they have no competing interests, particularly because the focus is on a single energy source (onshore wind energy).

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