



Wind energy expansion scenarios – A spatial sustainability assessment



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ABSTRACT

Wind power plays an integral role in the transition of Germany's energy system. In addition to its positive effects (e.g. reduction in greenhouse gas emissions), wind power can also negatively affect inhabitants and the environment. With this in mind, it is important to identify the best locations for wind turbines (WTs) which take into consideration these different sustainability aspects. This paper proposes a new simplified performance index that compares and combines three key aspects in order to assess the viability of wind expansion. These include environmental impacts (bird collisions), human attitudes (settlement distances) and energy performance (annual electricity production for supply security). The index enables a comparison to be made between the sustainability of different WT spatial distribution scenarios. This index is applied to four wind power expansion scenarios whose aim is to fulfill a certain share of the gross electricity consumption in Germany through standard wind power technologies. Finally, the respective spatial expansion scenarios are compared in terms of their lowest combined impact and their sustainability performance.

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1. Introduction

A key challenge of the 21st century is to mitigate global warming in order to sustain biodiversity and maintain livable conditions for humankind. The transformation of the energy supply system towards renewable resources is seen as one step towards reaching the objectives of the Paris Climate Agreement [1,2]. In Germany, the emission of 158.8 million tons of CO₂ equivalent was avoided in 2016 thanks to renewable energies [3]. In 2016, about 32% of gross power consumption was covered by renewable energy, of which wind power (on- and off-shore) contributed about 40% [4]. Wind power is seen as the most promising renewable power source in Germany because it is a mature technology, producing at comparably low costs [5]. Wind turbines (WT) have been erected in increasing numbers since the early 1990s, with a significant number of these WTs soon reaching the end of their 20-year technical life span [13]. This opens up a window of opportunity to improve

the allocation of WTs. While wind energy has many global and national benefits, it can also negatively impact wildlife and domestic settlements, mainly on a local scale.

Flying vertebrates, such as birds and bats, is the wildlife that is primarily impacted [6–10]. The disturbance or displacement of birds [11,12] as well as collision events causing individual deaths [11,13–15], with probable negative consequences on populations [8] are the most prominently recognized conflicts. The impact on terrestrial wildlife is currently inconclusive, however studies suggest that terrestrial animals are able to adapt to wind turbines [16,17]. The spatial location of the current wind turbines, particularly within proximity to habitats and reserves, has been identified as one of the most important drivers of the outlined negative impacts [18–22].

In terms of the impact on domestic dwellings, wind turbines located in close proximity to domestic dwellings can often cause conflicts with local residents which leads to problems with overall acceptance of WT expansion. Two major causes of aggravation are noise pollution and visual pollution. Noise pollution is mainly caused by the rotating blades [6,23] and visual pollution relates to the landscape being overrun by wind turbines to the point of disturbing landscape aesthetics [24,25]. In a comprehensive review, Zerrhan [26] noted that most studies identified a higher willingness

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Nomenclature

AEP	Annual electricity production
CDDA	Common Database on Designated Areas. Database for officially designated protected areas, such as nature reserves, national parks, protected landscapes in Europe
csv	Comma-separated values
FFH	Directive 92/43/EEC on the conservation of natural habitats and wild fauna and flora, a nature conservation directive of the European Union (EU)
d	Distance
GWh	Gigawatt hours
I _{SPA}	Potential impact on special protected area
I _{Set}	Potential impact on human well-being
I _x	Sustainability index
kW	Kilowatt
MW	Megawatt
m	Meters
m/s	Meters per second
SPA	Special protected areas for bird protection. EU Council Directive 2009/147/EC on the conservation of wild birds
TWh	Terrawatt hours
WT	Wind turbine

to pay for WTs located further away from domestic dwellings [27–30], even if all legal requirements pertaining to emission (noise) protection are met [31–33]. However, an attempt to mitigate negative social acceptance could lead to the expansion of wind turbines into more sensitive natural environments.

For entrepreneurs and wind farm operators, one of the biggest drivers for investing in wind power expansion is maximizing economic profit through cost-efficient power generation. Thus, focusing only on the economic aspects of wind expansion could lead to the use of locations with the best wind resources (i.e. high average wind speeds that remain stable over time). Therefore, WTs might be concentrated in locations with preferable wind resources, but these locations might also be important for wildlife or indeed be vulnerable landscapes (e.g. coastal zones of Germany).

Therefore, all three aspects - environmental, social and economic - have to be taken into account when considering the future renewal and expansion of wind power in Germany. This, however, creates the challenge of optimizing limited land area in order to manage such trade-offs. Appropriate site selection is the most important aspect of sustainable wind power expansion. A combination of spatial representation tools, like geographic information systems (GIS) and multi-criteria decision making, are useful in tackling such spatial optimization issues [34]. Different studies have investigated the trade-offs between the economic, social and environmental aspects when allocating wind power technology (i.e. technology focus) [34–50]. The aim of some studies has been to assess only the overall potential land for wind power (i.e. only wind potential sites, not technologies) [43,45,46], while some focus on particular locations, evaluating the suitability of the identified sites in terms of multiple site-specific aspects [38]. A further study introduced a suitability index to compare the different potential sites. Most of the studies only identify potential sites for wind farms in a particular region and not on a nationwide basis. One aspect not covered by the studies is the political objective for wind power expansion, mostly elaborated on by means of energy scenarios. Most of these energy scenarios provide no spatial orientation [51] and are developed using traditional

energy system models [52,53]. The environmental issues are reduced to greenhouse gas emissions [54]. Another feature of these approaches is their complexity and the time required to develop them. Therefore, there is still a need to identify where future wind turbines should be potentially located on a national level. This site selection needs to be done in a relatively simple, understandable and straightforward manner, while accounting for important sustainability aspects such as environmental impacts (bird collisions), human attitudes (settlement distances) and energy performance (annual energy production for supply security).

Thus, the aim of this paper is to develop an updated approach that identifies suitable wind turbine sites and encompasses a multi-criteria scenario assessment for wind power expansion in order to meet the government's renewable energy objectives. For our study we first considered three scenarios that took three different allocation criteria into consideration: 1) the delivery of cost-efficient wind power (WindPro), 2) environmental protection (EnviPro) and 3) residential friendliness (ResPro). A final fourth scenario was created where all 3 aspects were aggregated to an overall index value, thus helping to investigate the trade-offs between optimizing one criterion alone or all in combination (MultiPro). For each scenario a different spatial distribution of wind turbines across Germany was generated which could fulfill the renewable energy objectives of the German government. The results of all scenarios are then compared using the allocation pattern and potential impacts of actual deployment of WTs in Germany.

2. Study region and data

2.1. Study region

The study region encompasses the Federal Republic of Germany. It has an area of 357,580 square kilometers and a population of approximately 82.18 million people, with an average population density of 230 people per square kilometer. By the end of 2016, 45,384 MW of wind power capacity had been installed, hosted by 27,220 WTs [4].

2.2. Data

The primary data for this analysis are land use/land cover data, wind resource data, WT parameters and the geodata of (inter-) nationally protected areas. The input data are displayed in Table 1.

3. Methodology

The study utilizes a four-stage allocation and assessment approach. First, suitable sites and locations for WTs are identified (cf. Section 3.1) and the annual electricity production per turbine is calculated. In this study the term location refers to an individual WT location, while the term site refers to areas able to support several WTs. Second, the criteria for the WT location are defined according to the objectives of the different scenarios (cf. Section 3.2). Third, the potential impacts are estimated (cf. Section 3.3) and fourth, the scenarios are investigated according to their respective objectives (cf. Section 3.4). These objectives are minimizing potential impacts (i) on nature conservation issues and (ii) human well-being, as well as (iii) minimizing the number of WTs in relation to resource-efficient wind power production. The fourth scenario investigates possible improvements and consequences of a multi-criteria optimization approach. For comparison, a base scenario is used that represents the current state of onshore wind power expansion in Germany in 2016.

The process described here is based on a multi-criteria assessment approach developed by Eichhorn et al., 2017 [20] which was

Table 1
Overview of input data.

Type of data	Source
Land use data	The Authoritative Topographic-Cartographic Information System ATKIS, Working Committee of the Surveying Authorities of the Laender of the Federal Republic of Germany Land cover database DLM-DE 2012 - European Commission program to COoRdinate INformation on the Environment (Corine)
Protected areas	European Environmental Agency: Natura 2000 areas, sites designated under the Birds Directive (Special Protection Areas, (SPA)) and the Habitats Directive (FFH) (Sites of Community Importance, SCIs, and Special Areas of Conservation, SACs). State as of 2016 https://www.eea.europa.eu/data-and-maps/data/natura-8/ European Environmental Agency: Nationally designated areas (CDDA) http://ftp.eea.europa.eu/www/cdda/v15/CDDA_ver15_shapefile.zip
Wind resource data	GWS - Meso Data Weibull- Data AL-PRO GmbH & Co. KG Hub height: 149 m Resolution: 2 km × 2 km
Wind turbine parameters	Enercon E101 [18] (3,050 kW rated power, rotor diameter 101 m and hub height 149 m) ENERCON GmbH Dreerkamp 5, D-26605 Aurich

applied to the eastern part of Germany affiliated with one of the four German transmission grids (50 Hz). The focus of this study was to compare two options for wind power technology. The assessment calculated the linear decrease in potential impacts (i.e. environmental, social, economic) as the distance of WTs to protective areas and settlements increased. The approach presented here has adapted and enhanced the method of calculation. In the updated approach we incorporated thresholds relating to distances to domestic dwellings and nature protection areas which have been politically agreed on nationally in recent years [21,51]. This has enhanced the assessment criteria as it enables the impact scores of the individual WTs to be weighted in a very detailed manner, something which had not been previously done. We applied the approach to Germany to demonstrate its potential for supporting traditional national energy scenarios.

3.1. Identification of suitable WT locations and their calculated annual electricity production

In order to identify suitable WT locations, the national energy potential for wind power is mapped using selection and exclusion approaches. The process is broken down into three steps:

1. Analysis of generally suitable sites: Selecting and excluding sites for wind power deployment uses ATKIS land cover data and digital elevation models and applies physical and legal constraints and distance criteria [18,20,52]. In the first step we determined the areas where WTs can be physically installed. This covers open areas like grassland, arable land, heath, de-vegetated areas, etc. Wind turbines cannot be installed in areas with a gradient over 30%. Areas that are closer to settlements than the minimum distance stipulated by the German Federal Immissions Control Act are also excluded. Typical noise levels of modern wind turbines range from 100 to 106 dB [53]. Given the noise emission levels allowed for housing areas, industrial areas, areas of mixed use, and areas of special functional character (e.g. hospitals), we calculated minimum distances ranging from 1,000 m for housing areas and areas of special functional character, 320 m for mixed areas and 180 m for industrial areas.

2. Identification of potential locations using MaxPlace: The remaining sites (e.g. solid polygons in Fig. 1) were then filled with potential wind turbine locations (orange dots in Fig. 1). By applying a developed software tool described in detail by Masurowski 2016 [54], we distributed a maximum number of potential locations within each site by considering distances to neighboring sites [54,55]. The limiting criteria in this process was the individual distance between the potential WT locations, illustrated by the blue

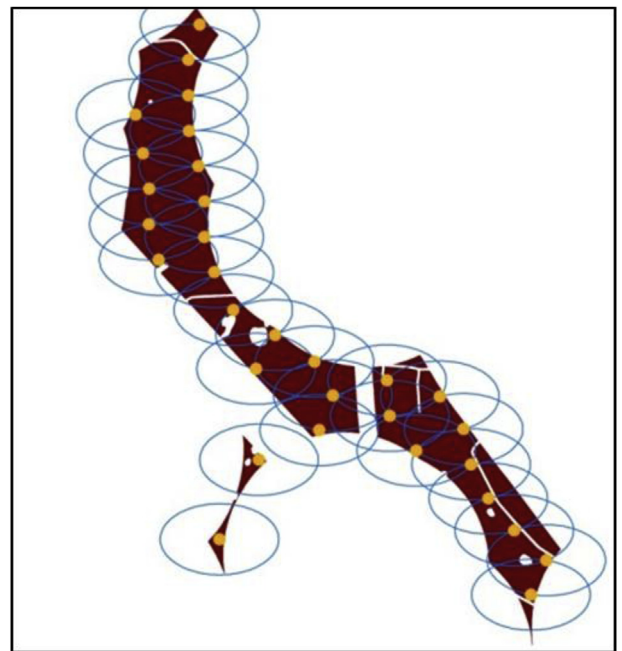


Fig. 1. Distance optimized allocation of wind turbines using MaxPlace [55].

circles in Fig. 1, to avoid the so called “wake effect” (a wind turbine downwind of another receives fewer, and more turbulent currents). The minimum distance between WTs was determined to be five rotor diameters in the main wind direction and three rotor diameters perpendicular to that [56]. As a result, 126,986 potential locations for erecting wind turbines were identified (left panel of Fig. 2).

3. Calculation of the annual energy production using MaxYield: In a final step, the annual electricity production of each potential location is calculated taking into consideration the technological specifications of the respective WT (power curve, power output at a certain wind speed) as well as specific wind data provided by the German Weather Service to assess its individual performance and to estimate how many WTs would be needed to meet the energy objective. A general approach of estimating annual energy production of each potential location is documented e.g. in Eichhorn et al. [18,20]. In this study we applied a further software tool called “MaxYield” to calculate the electricity output. This software is a small desktop application that can calculate annual electricity generation of a specific wind turbine, taking nominal capacity and hub height into consideration. The parameterization

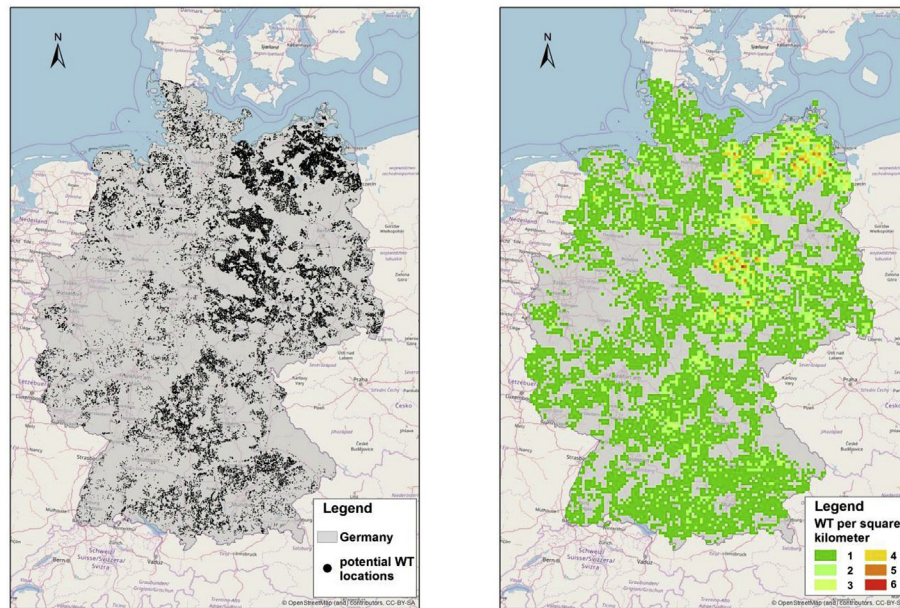


Fig. 2. Left panel: Maximum number (126,986) of legally possible WT locations, right panel density of these WTs per square kilometer.

was done by importing comma-separated value (CSV) files containing the input data (e.g. publicly available Weibull parameters with a spatial resolution of $200\text{ m} \times 200\text{ m}$ and the coordinates of the WT) and the power curve of the respective wind turbine. The different hub heights were also calculated by varying the altitudinal gradients. The tool generates a csv file that includes the input values plus annual electricity generation of the respective turbine at its location.

These calculations produced a theoretical power output of about 1,000 TWh per year for Germany.

3.2. Defining the criteria for WT locations in the different scenarios

The basic assumption of this study is that the potential negative impacts on environment and human well-being decrease as the distance of a WT from protected areas [22–24] and settlement areas increases [12–14], and the total number of WTs decreases. The authors are aware that considering (minimal) distances to protected areas for assessing the impacts of wind turbines on threatened species is not comprehensive from an ecological or ecosystems perspective. However, the special protected areas (SPA) for bird conservation defined by the European Union Natura 2000 framework encompass valuable bird habitats [57,58]. Therefore, estimating the distances between wind turbines and SPAs should act as a meaningful indicator for assessing the risk of negative impacts, even if direct impacts could not be assessed. No such specific protection areas exist for bats. However, some of the Flora Fauna Habitat (FFH) protection areas stipulated by the European Union Natura 2000 framework are also designated for bat protection. In general, “a protected area is a clearly defined geographical space, recognized, dedicated and managed through legal or other effective means, to achieve the long term conservation of nature with associated ecosystem services and cultural values.” (Definition of the International Union for Conservation of Nature and Natural Resources [59].)

Estimating the impact on human beings can be conducted in a similar way. Even if all legal requirements regarding emission protection are fulfilled as described in Section 3.2 [31–33], most people prefer that wind turbines be farther away from their homes

[27–29]. Thus, the distance of a potential WT location to a settlement area is seen as a meaningful criterion.

The total number of installed WTs is the third assessment criteria. Here it is obvious that the fewer wind turbines that have to be installed, the lower the resource consumption, overall costs and the potential negative impacts on the environment and human beings.

Thus, the respective sustainability criteria for the assessment of individual locations and their selection within the different scenarios are (i) the distance of the potential WT to protected areas, (ii) its distance to settlements and (iii) the number of WTs.

The distance between the potential WT location and protected areas is estimated using the near function of a geographic information system. This function allows for the estimation of the distance between a certain point and the closest (polygon) area out of a multiple set of surrounding areas. The CORINE land cover data, the Natura 2000 sites (Special Protection Areas, SPAs for bird protection), the Fauna Flora Habitat direction areas (FFH) and the nationally designated protection areas provided by the European Environmental Agency were employed in the distance analysis. We used this data to cover not only the German territory, but also the neighboring countries. This approach allowed us to increase accuracy by avoiding boundary effects. However, it also meant that accuracy was forfeited with respect to the multitude of protected areas and differentiation of settlement areas. From this general distance-based assessment and selection criteria we were able to establish a more specific potential impact score, improving the assessment quality for the individual locations.

3.3. Potential impact estimation

In the next step, the measured distances (d) of the potential WT locations were converted into a potential impact value (I). The potential impact describes the increasing pressure on the respective protected good through the decreasing distance to the WT. To do this we applied an impact function developed by Eichhorn et al. [18], who modeled the probability $L(d)$ of observing a species of raptor at certain distances from its nest based on observation data [60]. The probability of a raptor being affected by a WT is

proportional to the likelihood of the bird occupying the same physical space as a WT. Therefore, the probability of a bird colliding with a WT located at distance d from the nest is proportional to $L(d)$. The basic findings of a comprehensive literature review by Marques et al. [61] support these assumptions, underlying the impact function with respect to the movement behavior of potentially affected species. This relationship can be expressed as a Gaussian normal distribution, since activities in the vicinity of the nests are more frequent than at distances that are farther away. To overcome the lack of data regarding nest locations, the boundary of a protected area acts as a proxy for the nest locations and, thus, the apex of the normal distribution. This emphasizes that the potential impacts of short distances are more intense than those of larger ones. Here we incorporate real world thresholds recommended by different authorities [21] denoted as k . We modeled the potential severity of an impact (I) at a distance d from a protected area and from a settlement area by applying Equation (1). The benefit of this approach is that these thresholds do not act as exclusion criteria as with buffer zone approaches. Instead they act as weighting factors for smaller distances without excluding certain locations in advance (cf. Equation (1)).

The working group of German Bird Conservancy Observatories recommends a distance of at least 1,200 m to special protected areas that host species prone to collisions with wind turbines. For other protected areas there are no such general recommendations. Therefore, we excluded Flora Fauna Habitat conservation areas (FFH) and the EU's Common Database on Designated Areas (CDDA) from the impact estimation. However, the methodology is open to the inclusion of other protection areas as soon as thresholds become available.

The situation is slightly different for settlement areas. Unlike protected areas, settlement areas have already been buffered during the wind turbine allocation process as a result of legally binding distances of 1,000 m to avoid sound emissions. However, the impairment of the scenic value of the landscape reaches farther than these legal buffers. To consider this effect we included the so-called 10-H rule as a threshold. This regulation prohibits the installation of WTs at distances to settlement areas of less than 10 times the total height of the WT and is based on the Federal Building Act [51]. The selected reference WT has a total height of 195 m, making the value of k 1,950 m. We apply here a similar impact function like in the ecological context. Different studies emphasize a close relationship between the distance of wind turbines to settlements and a willingness to pay for increasing such distances, also expressed by exponential relationships [62].

$$I_j^i(d) = \frac{1}{e^{\left(\frac{d}{k}\right)^{\beta}}}, j \in J, J = \{spa, set\} \quad (1)$$

I_j^i is the individual potential impact of one wind turbine location

based on the distance d_j to the special protected areas ($j = spa$) and to settlement areas ($j = set$). To compare the individual performance of the scenarios, the potential individual impacts, I_{spa}^i and I_{set}^i of each WT are added up individually for each WT ($i = 1, \dots, N$) (cf. Table 3). Finally, the impact values I_{spa}^i and I_{set}^i are aggregated to an also dimensionless sustainability index I_x over all N WTs in the scenarios by adding up the individual potential impacts. A lower Index value I_x outperforms a higher value (cf. Equation (2)). This descriptive-analytical tool is relatively simple. It has a low normative content but acts as a decision support tool.

$$I_x = \sum_{i=1}^N \sum_{j \in J} \frac{I_j^i(d)}{3} \quad (2)$$

3.4. Wind power expansion scenarios

In this study, four wind power expansion scenarios are applied and investigated. The framing conditions for the investigated scenarios are taken from Nitsch et al. [63]. This so-called “lead study” assumes in scenario 2011B that about 279 TWh of wind power will be generated in 2050, of which 141 TWh will be on-shore and 138 TWh off-shore wind power. In this study, 141 TWh of on-shore wind power is set as the energy objective. However, the introduced selection and assessment approach of individual WT locations does not depend on a specific energy objective. Hence, changing energy objectives for on-shore wind power is always a potential alternative.

The scenarios considered in this study represent the positions of different real-world stakeholders. One scenario focuses on business maximum allocations by harvesting maximum energy through a minimal number of WTs and hence minimal investment costs (WindPro scenario). A second scenario emphasizes the interest of residents by maximizing distances to homes, thereby aiming to improve acceptance of wind power projects (ResPro scenario). The aim of the third scenario is to support nature conservation interests by allocating WTs as far away as possible from nature conservation areas (EnviPro scenario). These scenarios are based on mono-criterion optimization techniques. This means that the WT locations are selected based on the performance of only one criterion. A fourth scenario (MultiPro scenario) aims to harmonize the interests of all stakeholders using a multi-criteria approach. For comparison we also assessed the current wind power allocation patterns. Here the assessment approach (cf. Section 3.3) is applied to the WTs already allocated in Germany. This is included to contrast and evaluate the results of the expansion scenarios. An overview of the scenarios is shown in Table 2.

Table 2
Overview of the scenarios.

Type	Conditions
WindPro Scenario Wind turbine minimal allocation	Selecting WTs in descending order of their respective AEP (WT with highest electricity production is the first to be used and so on until the energy objective is fulfilled).
EnviPro Scenario Environmental protection	Selecting WTs in ascending order according to their potential impact on protected areas (WT with largest distance to protected area is the first to be used and so on until the energy objective is fulfilled).
ResPro Scenario Human well-being	Selecting WTs in ascending order according to their potential impact on human well-being (WT with the largest distance to settlement is the first to be used and so one until the energy objective is fulfilled).
MultiPro Scenario Multi-criteria optimization	Selecting WTs in descending order based on the sum of the reclassified distances to protected areas and settlements and reclassified AEP.
Current allocation patterns	Here the existing wind turbines in Germany are assessed.

3.5. Multi-criteria optimization

We applied techniques following the multi-attributes value theory [64,65]. As stated in Section 3.2, a sustainable WT location is characterized by (1) a maximum distance to protected areas, (2) a maximum distance to settlements and (3) the highest possible annual electricity production compared to other potential WT locations in Germany.

To estimate the sustainability of WT locations, the individual scores of annual electricity production, distance to protected areas, and distance to settlements for one WT location are cumulated on an ordinal scale since higher values (greater distance or higher electricity generation) are more favorable than lower values for every criterion. Finally, the suitable WT locations are ranked in descending order. This indicates the best location according to the assessment criteria.

4. Results

4.1. Identification of suitable locations, wind turbine allocation and power production

According to the applied method, 129,896 potential WT locations were identified as theoretically feasible (cf. Fig. 2). Assuming that a circular area consumption of five times the rotor diameter corresponds to minimal distance requirements between turbines (cf. Section 3.1), a total area of about 26,000 square kilometers is required, which corresponds to 7.3% of the area in Germany. These locations fulfil all physical and legal requirements for erecting WTs. The power output per potential WT location ranges from 1.7 GWh to 11 GWh. A total of 1,164 TWh could be generated per year. This corresponds to slightly more than twice the net power consumption of Germany in 2016.

4.2. Wind power expansion scenarios

The three mono-criterion scenarios and the one multi-criteria scenario produce quite different results in terms of the spatial allocation patterns and land consumption of WTs and the resulting potential impacts. Within the scenarios, an area of about 2,365 square kilometers (0.7% of Germany's area) would be used in the WindPro scenario, 3,200 square kilometers in the EnviPro scenario (0.9%), 2,955 square kilometers in the ResPro scenario (0.8%) and about 2,550 square kilometers in the MultiPro scenario (0.7%). A different approach for calculating the area consumption has to be applied for the current allocation of WTs due to a mixed set of WTs. Here we followed the German Energy Agency that assumes an average area consumption of 7 ha per installed MW. Following this approach, the total area consumption of the currently installed WTs is about 3,057 square kilometers (0.85%). Fig. 3a–d illustrate the spatial distribution of WTs according to the different scenarios. Fig. 3e illustrates the spatial allocation and density of the reference scenario. Here the density of the WTs is indicated as the number of WTs per square kilometer.

The results of the scenario assessment in terms of the potential impacts and indexes are illustrated in Table 3.

Table 3

Results of the analysis. Lower values indicate better performance of the scenarios.

	Number of WTs [n]	Pot. impact on special protected areas (I_{spa}) [-]	Pot. impact on human well-being (I_{set}) [-]	Index (I_k) [-]
WindPro scenario	11,805	1,763.49	5,525.72	6,364.74
EnviPro scenario	15,978	0.43	8,567.90	8,182.11
ResPro scenario	14,755	2,870.63	1,269.22	6,298.28
MultiPro scenario	12,733	1,003.23	3,203.99	5,646.74
Current allocation	26,024	2,839.91	15,042.92	14,635.61

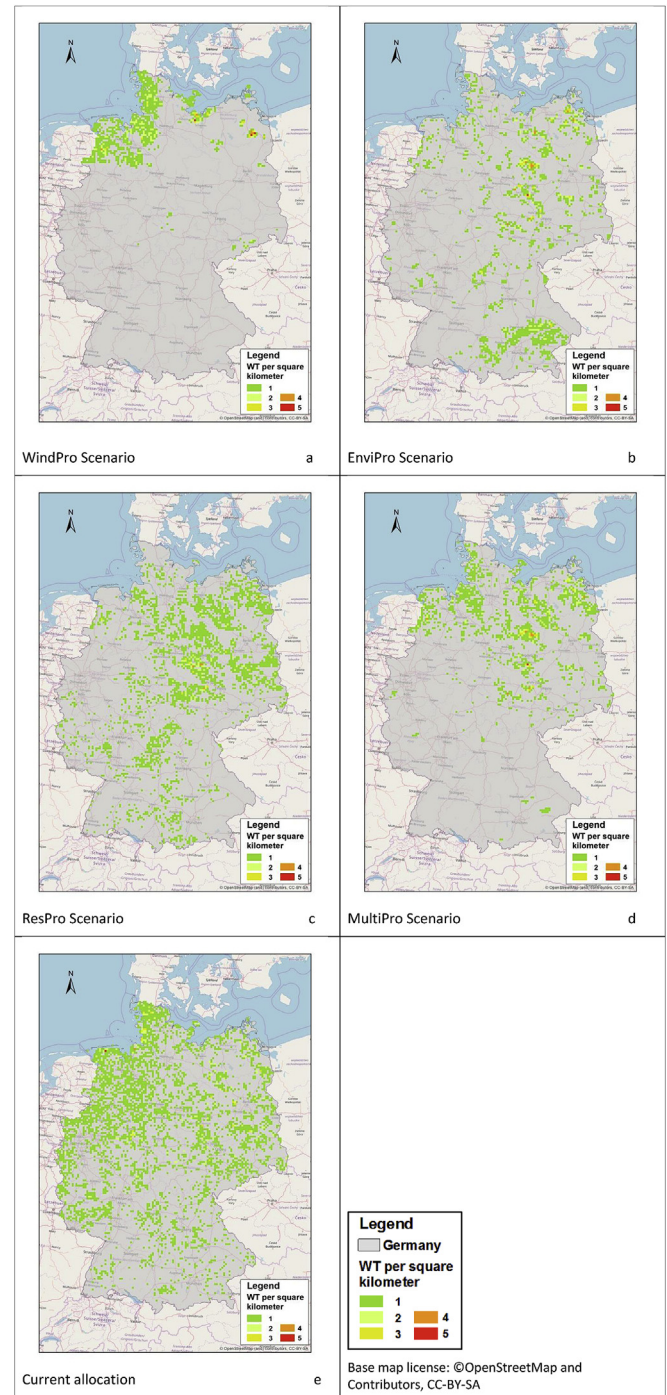


Fig. 3. Spatial distribution of WTs (WTs per square kilometer). 3a WindPro Scenario - minimal allocation wind turbine scenario, 3b EnviPro Scenario - nature conservation scenario, 3c ResPro Scenario - human well-being scenario, 3d MultiPro Scenario - multi-criteria scenario, 3e current allocation.

5. Discussion and conclusion

The objective of this study was to identify WT locations that cause the minimum amount of impact on nature conservation and human well-being, and to save resources by allocating the minimum number of necessary WTs. It demonstrates that simple means allow such locations to be identified while taking into account different trade-offs.

With this study we were able to show that optimizing locations with respect to one objective (WindPro, EnviPro and ResPro scenarios) generates trade-offs in other objectives, hindering a sustainable expansion (see Table 3). The spatial allocation of WTs strongly differs between the scenarios which is a reflection of the spatial distribution of the protected goods and natural resources under consideration. Compared to the current situation, all scenarios were able to provide improvements which supports the efforts of repowering old and currently inefficient WTs and locations.

The WindPro scenario performs best when it comes to the number of WTs. This was expected because only highly productive locations were selected and, thus, a minimal number of WTs were needed to fulfil the energy objective defined in Sections 3.2 and 3.4. However, in this scenario most WTs would be installed in the northwest of Germany with a strong concentration of plants in certain areas. The EnviPro and ResPro scenarios deliver the poorest results. This is due to the fact that the allocation was based on the distance to the protected areas and settlements and the AEP of individual locations was not considered. Therefore, more locations are needed (for the EnviPro scenario 1.3 times and for the ResPro scenario 1.2 times the number of locations than the WindPro scenario) since not only the most productive sites are selected.

The MultiPro scenario offers a compromise. Here 968 more WTs are needed than in the WindPro scenario but 3,245 WTs less than in the EnviPro scenario and 2,022 WTs less than in the ResPro scenario. Since the weighting factors resulting from the distance thresholds are of an exemplary nature and not all protected areas have been considered, the results should not be used for project implementation. However, the applied approach demonstrates that better results could be achieved by considering all stated interests than by optimizing individual objectives.

In terms of the number of WTs needed, all scenarios perform better than what is indicated by the developments of the current allocation patterns. Nearly twice as many WTs are currently installed than in the ResPro scenario, generating only about half of the energy potentially generated in the scenarios. This shows that even with the state-of-the-art technology, improvements could already be achieved. The EnviPro scenario performs best with regard to the potential impact on special protected areas for bird conservation (I_{spa}). This was expected since here the optimization criterion was to maximize the distance to special protected areas and, in so doing, minimize this impact. Likewise, the MultiPro scenario performs second best based on the criterion “number of WTs needed to fulfil the energy objective”. Interestingly the current allocation pattern of WTs performs within the range of the other scenarios. This indicates that nature conservation issues are currently being taken into consideration in the approval procedures. The potential impact on settlements (I_{set}) is lowest for the ResPro scenario, for reasons similar to the potential impact on special protected areas. The MultiPro scenario performs second best and the reference scenario performs worse. I_{set} is nearly double the values of the worse scenarios. This is due to a combination of high settlement density in Germany and the high number of WTs installed.

In the political context, we repeatedly meet the demand to present complex issues as simple key figures. The introduction of the sustainability index is an attempt to meet this demand. It gives

a clearer picture by summarizing the individual values. Assessing the scenarios by applying the sustainability index produces the following results: The MultiPro scenario outperforms all other scenarios. The WindPro scenario performs second best however this is due more to the low total number of wind turbines than to preferable locations. Likewise, the worse total performance of the ResPro and EnviPro scenarios are caused by the total number of WTs required. The current allocation pattern of WTs performs worst because of the high number of turbines and the worse performance of I_{set} . The sustainability index is meant as a communication instrument. However, it should not be used completely independently from the potential impacts. Our results complement the investigations of e.g. Jung et al. [66] and Höfer et al. [40] as they combine technical, social and environmental aspects for the spatial optimization of the construction targets of wind energy and apply this to Germany as a whole.

The approach introduced in this paper deals with the issue of a sustainable transformation of the energy system. The objectives of the energy transition are based on the need to mitigate climate change on a national scale. However, the allocation of wind turbines and, with it, the respective impacts are on a regional and local scale. Thus, the approach described here aims to support both national energy policies, by showing possibilities and consequences of on-shore wind power expansion on a national/international scale (settlements and protected areas from abroad have been considered), and local and regional authorities by providing an easy-to-apply toolset for assessing potential impacts of existing and future wind turbine allocations.

The described approach has some weaknesses, too. These are basically related to the assessment of the impacts on nature conservation issues. From an ecological standpoint, focusing on protected areas in general, and special protected areas in detail, may not be sufficient since most species affected by wind turbines are not limited to protected areas. The better way would be to use specific habitat data. However, detailed and exhaustive data on breeding/feeding areas are scarce. Thus, it has been assumed that protected areas, e.g. the Special Protected Area (SPA) of the European Union Natura 2000 framework, encompass valuable habitats. Therefore, maximizing distances between wind turbines and SPAs should reduce the risk of negative impacts. For the purpose of this study, we chose an ordinal scale for classifying the sustainability of the locations in order to compare different potential wind turbine locations and the respective expansion scenarios. This allows locations to be identified with the least potential impact on the protected goods. A differentiation of “how much better” a location is compared to another one is difficult to make. Here we see the need for further research.

The results of this study can be regarded as an orientation for wind energy expansion planning. Possible consequences of different planning objectives are demonstrated (e.g. the use of only the windiest locations reduce WT numbers but lead to strong concentrations in certain areas). The concrete spatial planning for wind power, including an environmental impact assessment, has to be done on a regional scale. This is the level where ecological complexity and human attitudes have to find a balance. But our results can provide an initial orientation, particularly on the national scale.

In conclusion, a joint consideration of multiple interests of the different stakeholders results in more sustainable solutions for all parties than emphasizing individual interests. The authors are aware that the approach presented in this study is not yet comprehensive. Further research is necessary, particularly in two fields. First, the applied assessment criteria for environmental impact and human well-being have to be further enhanced.

Attention should be given to the applied thresholds and to a more diverse application of protected goods. Second, a stronger integration of variable renewable sources into the power system will lead to new requirements for the spatial configurations and optimal siting of wind turbines [67]. This also has to be integrated into the sustainable expansion of wind power in Germany.

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