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MAPPING WIND POTENTIAL AREAS IN BAVARIA, GERMANY

Martin Stengel, Matthias Mitterhofer

Abstract: The federal Onshore Wind Energy Act requires Bavaria to designate 1.8 % of its area for wind energy by the end of 2032. To identify feasible solutions, we conduct geospatial eligibility analyses with varying distances to residential buildings, different degrees of forest use and economic constraints. Our results indicate that feasible distances to residential buildings range from 700 meters (no forest use) to slightly below 1 200 meters (with restricted forest use), depending on the degree of forest use and almost regardless of economic constraints. Designating currently protected forest areas could enable distances up to approximately 1 300 to 1 400 meters to residential buildings.

Keywords: Renewable energy sources, wind energy, potential analysis, land eligibility

KARTIERUNG VON WINDPOTENZIALGEBIETEN IN BAYERN

Zusammenfassung: Das Windenergieflächenbedarfsgesetz verpflichtet Bayern, bis Ende 2032 1,8 % seiner Fläche für Windenergie auszuweisen. Wir führen räumliche Analysen mit steigenden Abständen zu Wohnbebauung, unterschiedlicher Waldnutzung und wirtschaftlichen Randbedingungen durch, um geeignete Flächen zu finden. Unsere Ergebnisse zeigen, dass abhängig vom Grad der Waldnutzung und fast unabhängig davon, ob wirtschaftliche Randbedingungen berücksichtigt werden, Abstände zwischen 700 Metern (ohne Waldnutzung) und knapp unter 1 200 Metern (mit eingeschränkter Waldnutzung) zu Wohnbebauung im Rahmen des Gesetzes realisierbar sind. Die Ausweisung derzeit geschützter Waldgebiete könnte maximale Abstände zwischen 1 300 und 1 400 Metern zu Wohnbebauung ermöglichen.

Schlüsselwörter: Erneuerbare Energiequellen, Windenergie, Potenzialanalyse, Landeignung

1 INTRODUCTION AND RELATED WORK

While wind energy is a safe and cost-effective alternative to fossil fuels, wind turbines require space (Koldrack et al. 2014) and are criticised for their visual appearance or noise emissions (Langer et al. 2016). To moderate the resulting land use conflicts, legislators often regulate the expansion of wind energy, e. g., by stipulating that wind turbines may only be constructed at a certain distance from residential buildings (Masurowski et al. 2016). A corresponding regulation, the so-called 10 H regulation in Bavaria, Germany, has been the subject of frequent debates since its introduction in 2014: It states that the distance between a residential building and a planned wind turbine must be at least ten times the turbine's total height. While the 10 H regulation has provided legal guidance regarding the distance to residential buildings, it has been criticised for slowing down wind energy expansion in Bavaria (Stede & May 2020, Langer et al. 2016). The geospatial eligibility analysis of Risch et al. (2022) identified 0.4 % of the Bavarian area as eligible for wind energy projects, assuming the 10 H regulation, unrestricted forest use and no economic constraints (Scenario S1). While the 10 H regulation was relaxed in 2022 to allow a minimal distance of 1 000 meters or even 800 meters to residential buildings under certain circumstances (Gesetz zur Änderung der Bayerischen Bauordnung 2022, Karakislak & Schneider 2023), in 2023 the federal Onshore Wind Energy Act was introduced, requiring Bavaria to designate 1.1 % of its area by the end of 2027 and 1.8 % by the end of 2032 for wind energy (Gesetz zur Festlegung von Flächenbedarfen für Windenergieanlagen an Land 2022).

The results of Risch et al. (2022) raise the question of how these requirements can be met, especially when considering the

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following limitations. Langer et al. (2016) and Langer et al. (2017) suggest that relaxing distance regulations might reduce the acceptance of wind energy projects. While a literature review was inconclusive, interviews with various stakeholders (Langer et al. 2016) and an online survey (Langer et al. 2017) suggest that respondents prefer larger distances between wind turbines and their place of residence. Further, while wind energy projects in forests are generally permitted in Bavaria, specific types of forests defined in the forest function mapping (in German: Waldfunktionskartierung), e. g., forests used for soil or noise protection, natural forest reserves, or recreational forests, cannot be used for wind energy projects (Bunzel et al. 2019). Lastly, low wind speeds impede economic wind power projects in parts of Bavaria. Therefore, in this paper, we address the following research questions:

1. What is the maximum feasible distance to residential buildings to fulfil the requirements of the Onshore Wind Energy Act in Bavaria?
2. How do results vary when considering different degrees of forest use and economic constraints, such as wind speed?

While there is an extensive body of related research, the above questions have not been addressed in detail. Related work has presented tools for geospatial eligibility analysis (Ryberg et al. 2020, Neumayer et al. in print) and used these tools to assess the potential of wind energy in Germany (Risch et al. 2022, Navigant & Fraunhofer IEE 2019) and common constraints in Europe (Ryberg et al. 2018). However, these analyses typically examine a limited number of scenarios regarding distance to residential buildings or forest use and elaborate on the specific situation in Bavaria only briefly (Risch et al. 2022, Navigant & Fraunhofer IEE 2019). Risch et al. (2022) explicitly leave analysing the sensitivities of forest use and distance to buildings as future work. Ryberg et al. (2018) identified, classified, and evaluated the influence of widespread constraints regarding land eligibility for wind energy projects. However, the sensitivity of exclusion criteria in Bavaria remains to be investigated. Hennecke & Croonenbroeck (2021) perform a spatial analysis of economic wind energy potentials in Germany by estimating the levelized cost of electricity in a 200 × 200 meters raster. The authors report the levelized cost of electricity with and without weighing in correction factors given by the Renewable Energy Sources Act to make low-wind sites more attractive. In Masurowski et al. (2016), the authors divide Germany into raster cells of 20 × 20 kilometers and estimate the wind energy potential under varying distances to residential buildings. While the authors note that in Bavaria, the energy potential is highly sensitive towards an increased distance to residential buildings due to scattered settlements, an analysis of the eligible areas in Bavaria is missing. Furthermore, all of the above studies were conducted before the implementation of the Onshore Wind Energy Act; therefore, results are not discussed in the context of the new regulatory framework.

2 DATA AND METHODS

To address these shortcomings and answer our research questions, we extend the analysis conducted by Risch et al. (2022), focusing on Bavaria. We acquire the required geodata, preprocess it, map constrained areas, and perform several eligibility analyses. In contrast to the fixed distance to residential buildings and simplified consideration of forests in Risch et al. (2022), we increase the distance to residential buildings from 0 to 2000 meters (approx. 10 H assuming a hub height of 120 and a rotor radius of 155 meters) in three scenarios of forest use (unrestricted forest use, restricted forest use according to the forest function mapping, no forest use). Each scenario is considered with and without the exclusion of low-wind areas, which presents another enhancement compared to Risch et al. (2022). As further extensions, we acquire geodata and exclude areas of the Alpine plan and adapt the model to new guidelines from the German air navigation service provider. Afterwards, we discuss the resulting eligible areas in the context of the current legal framework of the Onshore Wind Energy Act and the previous strict 10 H regulation. Finally, we review the limitations of our study and derive opportunities for further research.

2.1 DATA ACQUISITION

We acquired data following the supplementary materials of Risch et al. (2022). Additionally, we acquired geodata regarding the Alpine Plan, protected forests in Bavaria, and regions with an average wind speed of 4.5 meters per second or lower at a height of 120 meters. See Table 1 for an overview of the used data and the replication package for further details.

2.2 MAPPING CONSTRAINED AREAS

To understand the spatial distribution of constraints and their interaction, we map the constrained areas based on the acquired geodata. First, we classify the acquired geodata into four categories (social political, physical, conservation and technical economic constraints) according to Ryberg et al. (2018). Then, we input, filter and buffer it using GLAES (Ryberg et al. 2017, 2018)

Used data	Data source	License/ Terms of use
Administrative boundaries	https://geodaten.bayern.de	CC BY 4.0
Buildings	https://geodaten.bayern.de	CC BY 4.0
Land use	https://geodaten.bayern.de	CC BY 4.0
Forest function mapping	https://geoportal.bayern.de	CC BY 4.0
Nature conservation	https://gdk.gdi-de.org	custom
Water protection	https://geoportal.bafg.de	custom
Biosphere	https://geodienste.bfn.de	custom
Alpine plan	https://geoportal.bayern.de	CC BY-ND 4.0
EU-DEM	https://ec.europa.eu	custom
Historical areas and streams	https://download.geofabrik.de	ODbL
(Doppler) very high frequency omnidirectional range stations	OpenStreetMap	ODbL
Borders	https://gdz.bkg.bund.de	DL-DE->BY-2.0
Wind speeds	https://www.lfu.bayern.de	CC BY 4.0

Table 1: Used data sources alongside their licenses or terms of use

according to the specifications of Scenario S1 in Risch et al. (2022), which reflects the regulations applicable at that time and using a raster size of 10 × 10 meters. For each of the four categories, we create a map and report the constrained area as a percentage of Bavaria's area. Note that residential areas and forests are not included in the maps as their influence is analysed in greater detail in the following eligibility analysis.

2.3 ELIGIBILITY ANALYSIS

Based on the mapping of constrained areas and the aforementioned parameters, we perform eligibility analyses again based on Scenario S1 in Risch et al. (2022) for Bavaria with the following modifications: Following new guidelines from the German air navigation service provider (in German: Deutsche Flugsicherung GmbH), we reduced the distances to Doppler very high frequency omnidirectional range stations from 10 to 7 kilometers. Additionally, we exclude areas classified as zone C in the Alpine Plan. The distance to residential areas, data on forest use and regions with low wind speeds are handled as follows.

First, the unrestricted forest use scenario is calculated without considering economic constraints: To do so, all excludes except residential, forested areas and areas with low wind speeds are excluded. Then, in a loop that increases the buffer size from 0 to 2000 meters in steps of 100 meters, residential buildings are buffered and excluded. Subsequently, these initial results are loaded to calculate the other scenarios, e.g., by also excluding different degrees of forest use or economic constraints. For each calculation, the eligible area is collected as raster cells and as a percentage of Bavaria's land area. For all implementation details, refer to the open source replication package available on GitHub (https://github.com/EWeQua/ByWind).

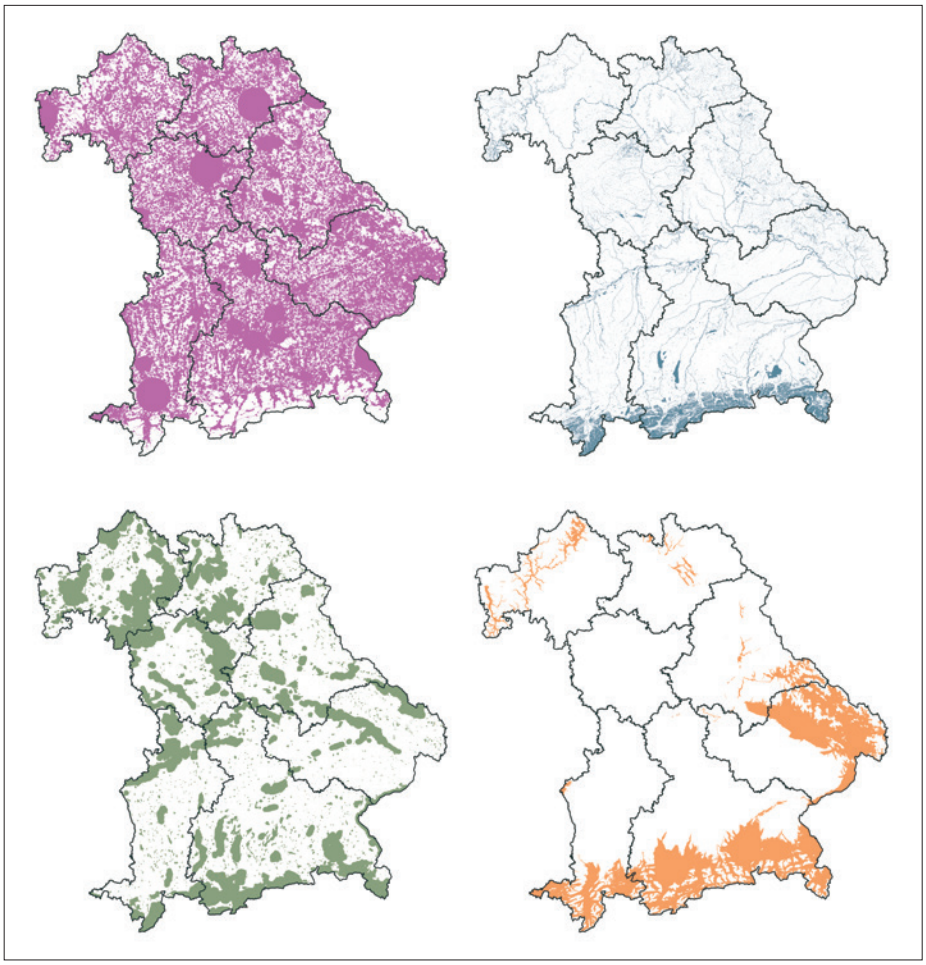

Figure 1: Constrained areas overlaid on Bavaria's governmental districts: Social political (purple), physical (blue), conservation (green) and technical economic constraints (orange)

3 RESULTS

3.1 MAPPING CONSTRAINED AREAS

The results of mapping constrained areas are shown in Figure 1. Social political constraints are shown in purple at the top left, physical constraints are shown in blue at the top right, conservation constraints are shown in green at the bottom left, and technical economic constraints are shown in orange at the bottom right.

Social and political constraints are scattered over Bavaria, following settlements and covering about 62 % of its area, except for a few mostly mountainous areas. The large buffers around very high frequency omnidirectional range stations stand out visually. In contrast, physically constrained areas are located in mountainous regions in the south due to their steep slope and around water bodies such as lakes or rivers, covering about 10 % of Bavaria. In larger contiguous areas, conservation constraints are spread across Bavaria, oftentimes surrounding water bodies or mountainous regions, covering close to 30 %. Lastly, technically and economically constrained areas are typically located at the foot of mountains or in other low-lying areas, e.g., surrounding rivers. They cover nearly 18 % of Bavaria.

3.2 ELIGIBILITY ANALYSIS

The results of our eligibility analyses are presented as a plot of eligible land for wind turbines against the distance to residential buildings in Figure 2. While the graph on the left shows the results without considering economic constraints, the graph on the right provides the results after excluding low-wind areas. Both figures highlight the requirements of the Onshore Wind Energy Act for 2027 and 2032 as dotted and dashed horizontal lines.

Unrestricted forest use yields the highest percentage of eligible land, starting at about 14.68 %, respectively 13.58 % of the Bavarian area, at a 500-meter distance from residential buildings. As the distance to residential buildings increases, the percentage of eligible areas drops quickly, plateauing at 0.4 %, respectively 0.37 % given a 2000-meter distance. The restricted forest use scenario resembles the unrestricted forest use scenario; however, it yields slightly less eligible land, starting at approximately 11 %, respectively 10.23 % at a 500-meter distance and decreasing to 0.22 %, respectively 0.21 % at a 2000-meter distance to

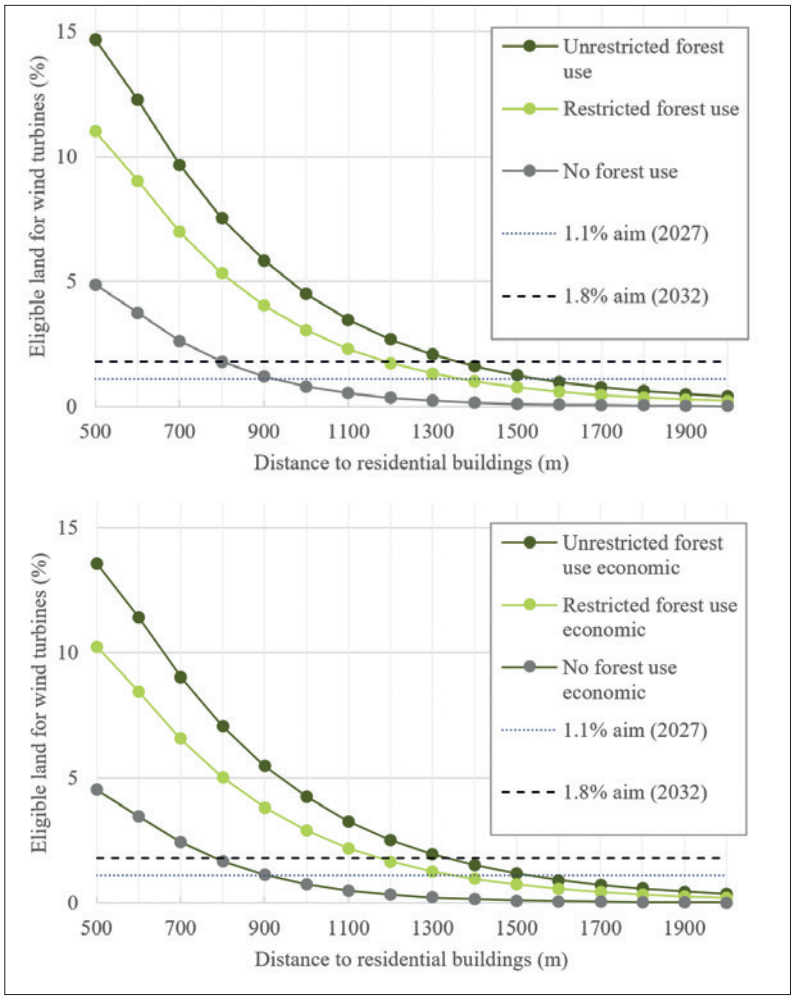

Figure 2: Percentage of eligible land for wind turbines with increasing distance to residential buildings in the different scenarios, without (top) and with economic constraints (bottom)

residential buildings. No forest use yields the lowest percentage of eligible land, with about 4.87 %, respectively 4.51 % at a 500-meter distance, flattening out faster than the other scenarios and reaching 0.02 % at a 2000-meter distance to residential buildings.

The change in the influence of economic constraints and forest use as the distance to residential buildings increases is noteworthy: While for smaller distances to residential buildings, designating forested or economically constrained areas allows for a considerable increase in eligible areas, we see diminishing returns as the distance to residential buildings increases. These effects can be attributed to the fact that the buffers around residential areas increasingly overlap with forested and economically constrained areas as the distance to residential buildings increases, making the distances to residential buildings the decisive factor.

Focusing on the 1.8 % aim of the Onshore Wind Energy Act and assuming unrestricted forest use, the maximum feasible distance to residential buildings lies between 1 300 and 1 400 meters. Assuming current restrictions on forest use, the maximum feasible distance drops to slightly below 1 200 meters. Lastly, if forests shouldn't be designated at all, distances lower than 800 meters are required to reach the 1.8 % aim. Our results also indicate that the 1.8 % aim and the previous strict 10 H regulation are incompatible. Under the assumptions made, a distance of 2 000 meters (approximately 10 H assuming a wind turbine height of 197.5 meters) leaves less than 0.4 % of the Bavarian area eligible for wind energy, even with unrestricted forest use and disregarding economic constraints. In this regard, our results align with those presented by Risch et al. (2022).

4 DISCUSSION AND CONCLUSION

The Onshore Wind Energy Act mandates Bavaria to designate 1.8 % of its state area for wind energy by the end of 2032. To find compliant solutions and feasible distances to residential buildings, we perform geospatial eligibility analyses with varying distances to residential areas in different scenarios of forest use and economic constraints.

To meet the requirements of the Onshore Wind Energy Act while excluding protected forests, a distance of slightly below 1 200 meters to residential buildings is achievable. Designating protected forest areas would allow the distance to residential buildings to be increased to nearly 1 400 meters. If no forests are designated, the achievable distance to residential buildings drops between 700 and 800 meters. In conclusion, assuming restrictions on forest use are not relaxed, feasible distances to residential buildings for the 1.8 % aim range from 700 to slightly below 1 200 meters, depending on the degree of forest use and almost regardless of whether economic constraints are considered. While economic constraints reduce eligible areas at lower distances to residential buildings, their effect diminishes as distances to residential buildings increase, making the distance to residential buildings the decisive factor.

Since wind potential areas in Bavaria depends heavily on the distance to residential areas and the relationship is not linear, a reliable data foundation for policymakers is essential. The results presented in this paper can serve as a point of reference. Furthermore, the presented open source implementation can be adapted to the state of the debate and facilitate further analysis.

While this article advances the understanding of wind potential areas in Bavaria, several limitations remain. We argue that building upon the methodology of Risch et al. (2022) is a suitable choice, given its transparent use of open data and detailed representation of individual residential buildings. However, the economic viability is hardly addressed in the original model and our extension, excluding low-wind areas, represents only a simplified assessment. Future work could model economic restrictions in greater detail through additional constraints, such as distance to roads or the power grid (Ryberg et al. 2018) or a comprehensive cost calculation (Hennecke & Croonenbroeck 2021).

Similarly, existing wind turbines and already designated areas are not accounted for in our analysis and should be part of future work. Combining an economic assessment with further land-use-focused constraints and existing infrastructure presents a promising opportunity for future work.

Second, the data used in our assessment were acquired from different sources at different times. Therefore, data quality may vary both between and within datasets. As a detailed analysis is beyond the scope of this work, we follow best practices, e. g., reported in Risch et al. (2022), and assume that the geodata used is of sufficient quality and consistency. Future work could analyse the data quality to strengthen our results or identify problems, such as inconsistencies between the different data sets.

Finally, the public's acceptance of forest-based projects warrants further investigation. While the general public acceptance of wind energy projects has been subject to considerable research, the acceptance of projects in forests has received less attention. Further research could address this issue and clarify the extent to which the scenarios presented here are socially acceptable to derive evidence-based policy advice.

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