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Short communication

A spatially explicit assessment of the wind energy potential in response to an increased distance between wind turbines and settlements in Germany

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HIGHLIGHTS

- Distance between wind turbines and settlements is an important policy criterion.
- We predict the impact of varying the distance on the regional energy potential.
- The impact can be explained from the settlement structure.
- The impact varies by region and German Federal state.

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ABSTRACT

Setting a minimum distance between wind turbines and settlements is an important policy to mitigate the conflict between renewable energy production and the well-being of residents. We present a novel approach to assess the impact of varying minimum distances on the wind energy potential of a region, state or country. We show that this impact can be predicted from the spatial structure of the settlements. Applying this approach to Germany, we identify those regions where the energy potential very sensitively reacts to a change in the minimum distance. In relative terms the reduction of the energy potential is maximal in the north-west and the south-east of Germany. In absolute terms it is maximal in the north. This information helps deciding in which regions the minimum distance may be increased without large losses in the energy potential.

1. Introduction

Wind power is one of the most important resources for renewable electricity production in Europe. Furthermore, at least in Germany, onshore wind power plants are the most cost-effective renewable energy source (ISE 2003), i.e. they have the lowest production cost per kWh. In terms of production cost onshore wind power can even compete with fossil fuels. These facts, the excellent climate balance and the political promotion are the reason for the rapid expansion of wind and solar power in Germany (Knopf et al., 2015).

However, even though their expansion represents a key approach to climate protection, renewable energies are not free from negative side effects. Since the energy density (electricity produced per unit area of land) of renewable power plants is lower than that of fossil power plants more space is required which leads to conflicts with the environment. Wind turbines, for instance, negatively affect biodiversity, especially birds and bats (e.g., Hötker et al., 2006; Bright et al., 2008). Human health can be affected by moving shades and noise (e.g., Hau, 2006, Rogers et al., 2006). Therefore wind turbines are subjected to various restrictions. For instance, they are not allowed in nature protection zones ("taboo areas") and must have a minimum distance to settlements (Bund-Länder-Initiative Windenergie, 2013).

Minimum distances to settlements are one of the main instruments of German legislation to mediate the external effects of wind power on humans. Two sources for these minimum distances exist in Germany. First, there is the Bundes-Immisionsschutzgesetz (German Federal Immission Control Act) that limits the noise immissions in settlements. Since noise levels decline with increasing distance between wind turbines and

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settlements, this implies that wind turbines must have a certain minimum distance to settlements. This minimum distance depends among others on the type of wind turbine because noise levels at the turbine are technology-dependent. The minimum distance also depends on the type of settlement, because allowed immission levels in housing areas are lower than in industrial zones.

Beyond these restrictions, the different Federal states in Germany have defined their own minimum distances which vary strongly between states (Bund-Länder-Initiative Windenergie, 2013). These minimum distances are an important policy instrument that helps to balance renewable energy production with the demand of society for an undisturbed environment.

Recently, the state of Bavaria increased its minimum distance by demanding that wind turbines must have a minimum distance to housing areas that equals ten times the height of the turbines. For the modern technologies with heights of 200 m this implies values of 2000 m. In a densely populated country such as Germany the question arises how minimum distances of this magnitude affect the national wind energy potential. By wind energy potential we mean the amount of wind energy that can be produced at maximum, given physical and legal constraints.

A first answer to this question was provided by the Umweltbundesamt (Federal Environmental Protection Agency) in its publication in 2014 (UBA, 2014). For three compartments of Germany, (north, central, south) the authors analysed how the wind energy potential changes if minimum distances are increased from 600 m to 2000 m. They found that the wind energy potential for the whole country reduces to 3% with highest reductions in the south of the country.

Two questions remain. First, the distinction into north, central and south is too coarse and the question, which regions in Germany are most sensitive to increases in the minimum distances has not yet been answered. Second, an explanation is missing why some regions are more sensitive than others. Is it possible to predict the reduction in the energy potential from geographical properties of the region?

The existing literature offers only little to answer these questions. There are many wind energy potential analyses, ranging from regional scales (e.g., McKenna et al., 2013) to the scale of the whole world (e.g., Lu et al., 2009) which assess the wind energy potential in a spatially explicit manner, so that for each spatial unit of the study region the wind energy potential can be identified. Generally however, these studies, consider only a single landscape with fixed policy constraints. Next to UBA (2014), an exception is the analysis of the impact of nature protection zones on the regional wind energy potential (Krewitt and Nitsch, 2003) which however does not provide spatially explicit results.

To our knowledge the present study is the first that assesses the impact of the minimum distance between wind turbines and settlements on the spatially differentiated wind energy potential on both regional and national scales and further explains this impact from regional geographical conditions.

Our approach consists of the following steps. We started with the analysis of the wind energy potential as a function of the minimum distance on a fine scale. Then the wind energy potential was related to geographical properties such as the share and spatial distribution of settlements. We fitted regression equations to these data that allow predicting the reduction in the wind energy potential when the minimum distance is increased. With the help of these equations we built maps that predict the magnitude of that reduction for each region in Germany. The results can be used to inform policy making by setting appropriate minimum distances. Policy implications are discussed.

2. Methods

2.1. Analysis of the wind energy potential

In the first step we determined the areas where wind turbines can be physically installed. This includes open areas such as grassland, arable land, heath, devegetated areas, etc. In some Federal states of Germany wind turbines may be installed in forests so we considered this possibility as well. We further considered that wind turbines cannot be installed in areas with slope larger than 30%.

In the next step, we excluded areas that are closer to settlements than the minimum distance deduced from the German Federal Immissions Control Act. We considered the noise levels of an Enercon E101 turbine which is a widely used technology and for which technological data are available. This wind turbine belongs to the largest wind turbines currently installed and has a hub height of 149 m and a rotor diameter of 101 m. Given the immission levels allowed for housing areas, industrial areas, areas of mixed use, and areas of special functional character (e.g. hospitals) we deduced the following minimum distances: 1000 m, 180 m, 320 m and 1000 m, respectively.

The remaining “suitability areas” (polygons) were then filled with wind turbine sites. The aim in this step was to distribute a maximum of potential sites within each suitability area. To avoid the “wake effect” (a wind turbine downwind of another receives less, and more turbulent, current), we considered the technical recommendation that the wind turbines have minimum distances between each other of five respectively three rotor diameters in the main wind direction respectively perpendicular to that (DWIA, 2003).

For each (potential) wind turbine site we next determined the potential energy yield. We assumed the installation of Enercon E 101 turbines. The wind turbine type has a sigmoid power curve $P(v)$ which tells us how much energy can be produced at a given wind speed. From a professional supplier we purchased wind speed data on a 1 km by 1 km resolution as Weibull parameters of the local distribution of wind speeds. These data allowed us to establish a wind speed frequency distribution $f(v)$ for each potential wind turbine site. The energy produced by the wind turbine per year is obtained by

$$E = 8760 \int f(v)P(v)\ dv$$

where 8760 is the number of hours per year.

2.2. Definition of grid cells and distance scenarios

We laid a grid with grid cell size 20 by 20 km^2 over the whole country, determined for each grid cell the abovementioned energy potential (or potential wind energy yield) and plotted the results for all grid cells in a map. Then we randomly selected 100 grid cells which contained at least one potential wind turbine site. For these grid cells we increased the minimum distances by a total of 1000 m in steps of 50 m. We considered two scenarios: in the first scenario we increased the minimum distances for all of the four settlement types (housing areas, industrial areas, areas of mixed use, and areas with special functional character) simultaneously; and in the second scenario, we only increased the minimum distances to housing areas where the expected conflict between wind turbines and humans is highest.

2.3. Spatial characteristics of the grid cells

Next we analysed the grid cells with regard to geographical features that might have an influence on the response of the

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