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Cost-potential curves for onshore wind energy: A high-resolution analysis for Germany

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HIGHLIGHTS

- Cost potential curves for onshore wind energy in Germany.
- Turbine matched to land use and wind speed classes.
- Costs estimated based on a cost model.
- 860 TWh potential at costs of 5–15 €ct/kWh.
- Main uncertainties relate to small areas.

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ABSTRACT

Germany has set itself some very ambitious targets for energy supply from renewable sources, including 80% of electricity by 2050. The favourable economic political framework for renewable technologies has led to the rapid expansion of onshore wind and other renewables in the past years. Motivated by the lack of recent studies dealing with this issue, this paper determines the current potentials and costs for onshore wind in Germany. The developed methodology allocates a wind turbine to a specific location based on the prevailing wind conditions and the surface roughness, compared to previous studies, which assume that one or two turbines is/are installed overall. Cost-potential curves for wind energy are thus generated on a highly disaggregated level (at least 1 km^2) based on various discount rates. The technical potential is around 860 TWh/a and the associated generation costs lie in the range from 5 to 15 €ct/kWh, depending upon the degree of risk-adversity and cost of capital. This implies a currently economic potential of 400–800 TWh/a. The main uncertainties lie in the effect of small areas on the total potential. Further work should therefore focus on developing a clustering method for these small areas, considering the exact location of installed turbines and attempting to account for social barriers (and therefore social costs) to the development of wind energy.

1. Introduction

The European Commission has set an ambitious target for 20% primary energy demand from renewable sources by 2020 [1], which is nationally implemented through the Member States' Renewable Energy National Allocation Plans (RE-NAPs). The RE-NAPs were submitted to the Commission in 2010 and, after being approved following some modifications, are now being implemented. The RE-NAPs stipulate the planned expansion of renewable energies in each Member State until 2020, whereby the national target may be significantly different to the overall 20% goal, the reasoning being that the framework conditions in each country – that is, the renewable resources, political and economic conditions – differ greatly and the target-setting should reflect this.

Within this context Germany has set itself the goal of a 18% renewable energy share in final energy demand by 2020, but for electricity generation alone the target is 35%, increasing to 50% in 2030, and 80% by 2050. In recent years astonishing progress towards these goals has been made, including a rapid increase in capacity and electricity generation from renewable sources. In 2012 the share of renewables was around 13% of final energy demand and 23% of gross electricity consumption [2]. Around 34% or 45 TWh/a of this renewable electricity is generated from the approaching 31 GW of onshore wind turbines installed in Germany. These figures are even more impressive if one considers that in 2000 a mere 5 GW of total wind capacity was installed. The rapid expansion in wind energy as well as other technologies has been motivated by the Renewable Energy Law, which sets the legal

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framework, including feed-in tariffs and marketing mechanisms, for renewables on a national level.

Against this background there is an ongoing discussion about the potential and costs for wind energy, given the continued role it is likely to, or indeed will have to, play in the attainment of the above goals. Several studies have examined the potential for wind energy in Germany or regions thereof, including international studies [3,4], which apply an aggregated methodology to determine potentials for large geographical areas, and therefore inherently employ relatively low spatial resolutions. Held [3] developed cost-potential curves for wind energy in individual countries within the then EU27, although this was not the focus of her dissertation. Due to the large scope, the available land is derived by employing suitability factors on land use categories, with only natural protection areas and mountainous areas excluded directly. EEA [4] carried out a similar analysis of the technical potential in each country according to land cover categories and electricity generation costs. For Germany, the results indicated a technical potential of 4000 TWh/a, with estimates of 258 TWh/a and 384 TWh/a relating to "competitive" and "most likely competitive" scenarios respectively.

National or regional studies have the advantage of a higher spatial resolution, but often simplifying assumptions are made in other respects, such as relating to the type of turbine to be installed in a particular location or the costs for different turbines. For example, the German Association for wind energy [5] recently carried out a study to determine the potential for wind energy in Germany, with a particular focus on the available and required areas for its continued expansion, but did not consider the associated costs. For the German federal state of Baden-Württemberg, McKenna et al. [6] developed cost-potential curves with a similar methodology as employed in Held [3]. The technical potential derived in that study lies between 29 and 41 GW at costs of 6–21 €ct/kWh. More recently, in June 2013, the German Federal Environment Agency (Umweltbundesamt, UBA) published a study of the onshore potential for wind energy in Germany [7]. The focus was thereby placed on determining the technical–ecological potential, which does not consider economic or other constraints, and explains why the resulting 2900 TWh/a potential is relatively high. In addition, in a study considering biomass, onshore wind and photovoltaic, Hoogwijk [7] calculated generation costs and potentials worldwide. Finally, in two related studies, Fueyo et al. explored the potential of onshore wind energy in Spain, calculating the technical potential [8] and developing cost-potential curves [9] based on a 200 m raster. The resulting technical potential is 1100 TWh/a at generation costs between 4 and 30 €ct/kWh. The results of these studies are summarised in Table 1.

What these previous studies all have in common is their abstraction from reality by assuming that only one or two reference turbines are installed, irrespective of the prevailing wind conditions. Held [3] thus employed a linear regression of full load hours against average wind speed based on the Vestas V80 turbine and the EEA [4] based their analysis on a generic 2 MW turbine, assuming that the rated power of turbines "will level off at 2 MW". This has not been the vase in last few years, however, with many turbines in the 5–6 MW range. Fueyo et al. used a reference wind farm of 2 MW turbines as well, though evaluated the effect of different turbine sizes [9]. Given the low wind speeds, the higher 3 MW turbine leads to higher costs. The effect of different turbines with equal capacity, but different size and therefore different suitability for different mean wind speeds, is thus generally not explored. But UBA [7] did employ two turbines for weak and strong wind regimes with 3.2 MW and 3.4 MW, hub heights of 100 m and 140 m, and rotor diameters of 104 m and 114 m respectively.

Against this background, this paper determines current potentials and costs for onshore wind energy in Germany. The developed methodology employs a high spatial resolution and selects the most suitable wind turbine for a given location, based on a comparison of the electricity generation costs for the prevailing wind speed and surface roughness. Hence cost-potential-curves are developed for wind energy on a highly disaggregated level. The paper is structured as follows: Section 2 presents an overview of the methodology, including the criteria catalogue, suitability factors, and the matching of suitable wind turbines to specific wind speed and land use categories; at the end of Section 2 the economic data and calculations are presented; Section 3 contains the main results and Section 4 discussion, comparison with other studies, and an analysis of critical uncertainties; finally, Section 5 summarises and concludes.

2. Methodology

The employed methodology consists of four main steps, as shown in Fig. 1. First, the total available land is calculated based on the criteria catalogue shown in Table 2 and the suitability factors in Table 3. In a second step, the available areas are united with the wind speed data. In a third step the energy yield and generation costs for each polygon are calculated and aggregated into the technical potential and cost-potential curves. These calculations in step 3 are first done for each combination of wind speed and land use category and the results are saved in a matrix. Afterwards, each area is assigned the values of its respective field in the matrix and the specific energy yield and generation costs are calculated with the area of each polygon and aggregated into cost-potential curves.

2.1. Criteria catalogue and suitability factors

In a first step, the total available area for wind energy in Germany is determined. Unsuitable areas, as defined in the criteria catalogue shown in Table 2, are thereby excluded with the geoprocessing software ESRI ArcGIS, before suitability factors are subsequently applied to the remaining areas. Most types of unsuitable area further entail a buffer zone around them, which has likewise been removed from the available land. Since there are no nationwide rules for the planning and building of wind farms, the buffer distances are estimated based on a range of regional planning catalogues published between 2009 and 2012, which outline the criteria for the planning and construction of wind farms in the respective regions. The employed buffer distances are displayed in Table 2. In addition to the criteria in this table, gradients steeper than 20° are excluded, because due to technical and fluid-mechanical reasons they are less suitable for wind turbines [11]. The resulting area represents a technically available area for wind energy, without consideration of other social factors such as acceptance.

The database for the land use data is the European CORINE project (CLC), which on the basis of satellite images provides land use data, divided into 44 categories, whereby the latest data available is for the year 2006 [12]. The minimum spatial resolution of this dataset is 25 ha. In addition the data relating to natural conservation areas are taken from the Federal Office for Natural Conservation [13]. Transport infrastructure such as roads and railways are taken from the Open Street Maps project, which provides data covering all major transport infrastructure down to the local street level [14]. The basis for the calculation of the gradients is the freely available SRTM[1] elevation data in 90 m resolution [15]. Due to limitations on the accuracy of the CORINE data, it is not possible to consider all real exclusion criteria in detail. Especially single buildings

[1] Shuttle Radar Topography Mission (SRTM).