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# Spatial-Economic Potential Analysis of Wind Power Plants in Germany

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**Abstract:** Before a new wind farm can be built, politics and regional planning must approve of the respective area as a suitable site. For this purpose, large-scale potential computations were carried out to identify suitable areas. The calculation of wind power plant potential usually focuses on capturing the highest energy potential. In Germany, due to an energy production reimbursement factor defined in the Renewable Energy Sources Act ("Erneuerbare-Energien-Gesetz", EEG) in 2017, the influence of energy quantities on the power plant potential varies, economically and spatially. Therefore, in addition to the calculation of energy potentials, it was also necessary to perform a potential analysis in terms of economic efficiency. This allows, on the one hand, an economic review of the areas tendered by the regional planning and, on the other hand, a spatial-economic analysis that expands the parameters in the search for new areas. In this work, (a) potentials with regard to the levelized cost of electricity (LCOE) were calculated by the example of the electricity market in Germany, which were then (b) spatially and statistically processed on the level of the federal states.

**Keywords:** LCOE; potential analysis; renewable energy; wind energy



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## 1. Introduction

With the aim of making energy production climate-friendly, the expansion of renewable energies is an essential component of worldwide energy policy. In Germany, this was recognized early on and the Act on the Sale of Electricity to the Grid ("Stromeinspeisungsgesetz") which commenced in 1990 was the first step towards a subsidy policy which regulated the mandatory purchase of renewable energies (RE) by the grid operator. Further on, the Renewable Energy Sources Act ("Erneuerbare-Energien-Gesetz", EEG) was introduced in 2000, which gave the starting signal for the specifically aimed energy turnaround ("Energiewende"). The resulting feed-in tariff system has often been used as a template for RE legislation worldwide [1].

The motivation behind the EEG 2000 was to make RE sources competitive as opposed to conventional primary energy sources such as coal, oil, or nuclear energy, and to double the renewable share provided for used energy by 2010. By using a fixed feed-in tariff for wind energy, which was regulated by a nominal degressive annual reduction for 20 years, an economic incentive for expansion was to be created.

RE gained more and more importance in the power supply. According to [2], almost 42% of electricity consumption in Germany is already covered by RE. Wind is one of the most important energy producers and has already replaced lignite in the German electricity mix in 2019.

In order to help RE to become more prevalent, the fixed feed-in tariff was replaced by a procurement system with the 2017 amendment to the EEG. Accordingly, the allowance for the feed-in tariff will now go to the one investor that sets the lowest price (Euro/kWh) for the feed-in reimbursement. Alongside switching to a procurement system and in order to make the less windy German areas more economically interesting in the future, a correction factor was introduced. This correction factor depends on the ratio between the reference yield of the planned turbine (a purely turbine-specific figure) on the one hand and the site yield (a site-specific figure) on the other hand. (For computational information see the technical guidelines issued by FGW e.V. ("Fördergesellschaft Windenergie und andere Dezentrale Energien"), https://wind-fgw.de/shop/technical-guidelines/?lang=en, accessed on 21 January 2021). If the reference yield is higher than the site yield (suggesting a rather low-wind site), the correction factor is higher than 1, and vice versa, it is lower than 1 for sites possessing strong wind. In simple terms, the calculated factor is then, finally, multiplied by the negotiated feed-in compensation.

Despite the success of RE over the last 20 years and the introduction of the EEG in 2017, the expansion of onshore wind energy has recently declined sharply [3]. Reference [4] sees the reasons for this in emission control approvals and lawsuits against already approved projects. Other reasons could be a lack of economic viability or an insufficient number of tendered areas. An important characteristic with regard to economic potentials are the levelized costs of electricity (LCOE), since these may exceed the guaranteed market premium at low-wind sites, making such sites unprofitable. Therefore, the purpose of this paper is to present a nationwide potential analysis based on LCOE. In this article, Germany is used as an example for the following analysis approach, which can however be adapted to other countries and their own political frameworks. For this, the LCOEs are calculated based on local wind properties for a raster dataset covering the entirety of Germany. This encompasses 14.3 million data points. The reference yield relies on results found in a previous study by [5] where for each of these points, best yielding turbine types and hub heights (both of which are variables influenceable by the builder) were found. From this, we compute the correction factor and apply it to the LCOE. The results are then spatial-statistically compared to pure LCOE values and serve as a tool to identify sites with high wind power potential.

Using the LCOE measure allows comparability between countries and their energy policies. The analysis was first performed at the national level and was then disaggregated to and evaluated at the federal state (German "Land") level. Section 2 begins with a technical classification of the topic. Section 3 then discusses the data used and the methodological approach, and Section 4 presents the results. Finally, a brief conclusion is drawn in Section 5.

## 2. Background and Literature Review

In order to be able to further promote the expansion of RE, in particular wind power plants, potential analyses are carried out, which are of great interest for political decision-making [6]. Usually, the focus of these analyses is on the potential energy yield, on the number of plants that can be installed, or on the calculated minimum capacity exploitation, i.e., the number of equivalent full load hours per year. A potential energy yield is calculated on the basis of wind speed data and the performance data of a reference turbine. Afterwards, attractive areas can be filtered out depending on the defined energy threshold and then be used for potential calculation, such as the number of turbines ([7,8]).

In addition to yield filtering, potential sites are also limited by critical construction areas. Depending on the political and legal orientation of the sites, these filters often vary in strength or weakness. However, the general prohibition of construction on areas such as protected areas, airports, and settlement areas is overall valid, which means that these critical areas are often excluded from large-wind energy scale calculations ([7]).

This approach of potential calculation only represents the energetic area. Another important aspect in the realization of a wind farm project, however, is its economic efficiency. Reference [5] combine both approaches and calculate an economically weighted energy yield. For this purpose, a grid dataset with mean wind speeds for the entirety of Germany with a resolution of 200 $\times$ 200 m is used. Based on these data, the site yields of each pixel are calculated for 84 different turbine types (see Figure 1, power curves of 12 selected turbines by way of example) on nine different hub heights (70–150 in 10-m steps) by means of a simulation study. The calculated site yields are then compared to the reference yields, allowing the respective correction factors to be calculated. Thus, it is possible to multiply the correction factor and the site yield, whereby the economically weighted energy yield is determined. These steps are performed for each pixel of the wind grid and each turbine–height combination, whereby, finally, the best turbine–height combination, correction factor, energy yield, and weighted energy yield for each pixel can be determined. Given energy yield and correction factor along with the negotiated feed-in tariff (the procurement bid), revenue can be calculated.

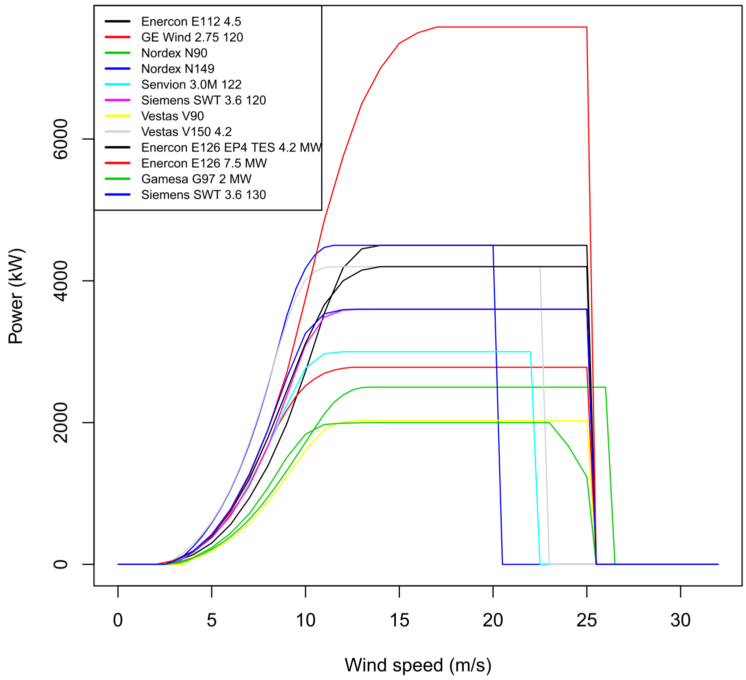


**Figure 1.** Power curves of 12 turbines selected as examples ([5]).

However, for an investor's profit calculation, the LCOE of electricity is required in addition to the revenue. The LCOE is usually adopted as a comparative metric between energy producers. Especially in the RE world, this allows for a more comprehensible representation and analysis of the relationship to conventional generators ([9,10]). LCOE is also widely used among investors for estimates of critical energy prices and thus, as a basis for economic decision-making ([11]).

Over time, various LCOE calculation methods have been established and are summarized by [12]. Reference [13] define the basic formula as:

$$\text{LCOE} = \frac{\text{TLCC}}{\sum_{t=1}^{N} \frac{Q_t}{(1+i)^t}} \tag{1}$$

where TLCC (total life-cycle cost) represents the discounted total costs (capital expenditures, operating costs, maintenance costs, and disposal costs) over the entire utilization period $N$, $Q_t$ denotes the energy production of year $t$, and $i$ is the interest rate.

References [14,15] compare the LCOE to feed-in tariffs in order to verify economic viability. Due to the introduction of the EEG 2017, especially the introduced reverse auction, the LCOE might have gained importance for the economic assessment in Germany as well.

The impact of locational relationships on LCOE as well as territorial divisions can also already be found in the scientific literature. Reference [16] present a comparison of different energy generators at a state level in the United States. Reference [17] use the LCOE to show the potential of tidal generators versus wind energy for specific locations. Reference [18] use GIS (Geographic Information System) and LCOE-based methods to analyze options for energy mitigation for rural communities in Western China. Reference [19], on the other hand, develop two new metrics for RE system planning and optimization based on LCOE.

In summary, LCOE is a tool for the economic comparability of energy producers. In addition, this metric can be used to better assess the economic viability of a project, especially in relation to the prevailing policy in Germany regarding the remuneration of energy quantities fed into the grid.

## 3. Data and Methodology

LCOE is calculated based on energy production and total cost over time $N$. The former depends on the wind speed at the potential sites, which influences the turbine type selection, which, in turn, influences the installation costs. Basic data covering information on wind speeds is provided by the German Weather Service ("Deutscher Wetterdienst", DWD) as a freely available raster dataset. This raster was calculated based on 218 ground stations, taking into account geographic location, elevation, terrain, and land use using the statistical wind field model. (The dataset is available for download at http://wflo.auf.uni-rostock.de/index.html, accessed 21 January 2021). The coverage includes averaged data in the time span from 1 January 1981 to 31 December 2000 ([20]): $n$ = 8,935,733 excluding 5,364,267 missing data; values range from 1.1 to 8.4 m/s, mean 32, median 3.4. Based on this, key figures of the reference turbine(s) are required to calculate the resulting energy yield. For this purpose, the simulation analysis of [5] is used in this work. The methodology is divided into two levels. The first level represents the large-scale calculation of LCOE in relation to the entirety of Germany, the second level is based on that and deals with the calculation of potential areas within the individual federal states, which enables a spatial-statistical evaluation at the federal state level.

### *3.1. LCOE Calculation*

For preparation, a table was generated from the wind data. Since a specific turbine-hub height combination has been determined for each wind speed (cf. [5]), in short, for 84 turbine types and hub heights between 70 and 150 m in steps of 10 m, resulting in nine distinct hub heights, scenarios were computed for each distinct wind speed. From that, they pick the turbine/hub height combination that provides the best (highest) location quality factor as defined by the EEG), it is possible to use the wind speed as the link identifier to the information. Consequently, hub height, turbine type, yield and correction factor can be stored within this single table. In order to additionally analyze the effects of the correction factor on the LCOE, the simple energy yields as well as the correction factor weighted values (henceforward referenced to as ALCOE, "adjusted LCOE") are included. As mandated by the EEG, location yield (annual electricity production, AEP, i.e., the amount of energy a distinct turbine can produce at a specific location within one year) is to be divided by reference yield (potential AEP of this turbine at an average location). This returns the location quality factor, which is then mapped to a correction factor according to the table given by § 36 h EEG. Weighing LCOE by this correction factor yields ALCOE. This makes it possible to perform the LCOE calculations on the basis of both energy yield values (i.e., plain and weighted data).

As discussed in Section 2, to determine the LCOE, the total costs are divided by the total discounted electricity generation in a simplified way. The electricity generation is already given by the existing dataset. Cost components for each year need to be multiplied by the discount factor $(1+i)^{-t}$ for each year t and summed up. The cost calculation, therefore, is at the heart of this calculation and can be done in four steps:

Step 1—Installation costs: In the first step, the installation costs for a turbine are determined. According to [21], they are divided into two groups based on capacity (rated power). Depending on the hub height, the costs increase further, see Table 1. While this may be very simplistic (among other things, in reality, the costs also vary over time, and they are due as well as by manufacturer, groundwork effort, basement effort, and grid connection complexity), it still gives a good first cost approximation. Real costs must of course be computed based on each project's idiosyncrasies individually.

**Table 1.** Installation costs in €/kW installed capacity ([21]).

| Hub Height (HH) | 2 to 3 MW | 3 to 4 MW |
|---|---|---|
| Less than 100 m | 980 € | 990 € |
| 100 to 120 m | 1160 € | 1120 € |
| 120 to 140 m | 1280 € | 1180 € |
| More than 140 m | 1380 € | 1230 € |

For each wind speed, the appropriate installation costs can be added by means of the turbine capacities and hub heights stored in the properties table. The installation ancillary costs (e.g., logistics) are estimated as an average value of 387 € per kWh ([22]), since, e.g., the transport route's length and outlay differs for each project depending on the federal state and the distance to the corresponding turbine manufacturer. This results in the calculation of:

$$a_{total} = (a + a_n) \cdot p \tag{2}$$

where $a_{total}$ represents the total installation costs, $a$ denotes the installation costs per kW (as given by Table 1), $a_n$ depicts the installation ancillary costs, and $p$ covers the installed capacity in kW.

Step 2—Deconstruction costs: In a typical cost calculation, the residual value (RV) reduces the costs. However, since turbines have to be dismantled and disposed of after their lifespan, negative residual sales, i.e., dismantling costs and disposal fees, are to be taken into account as well. According to [23,24], these are to be set at 6.5% of the installation costs ($a_{total}$), i.e., $RV = 0.065 \cdot a_{total}$.

Step 3—Discounted operating costs: For the calculation of the sum of the discounted operating costs (4) of an assumed 20-year term (i.e., $N = 20$), the annual operating costs (3) are required in addition to the interest rate ($i = 3.80\%$, [22], resp. defining $q := 1 + i$, see below) according to:

$$R_D = E \cdot R_{kWh} \tag{3}$$

where $R_D$ represents the annual operating costs of a decade, $E$ is the energy yield in kWh/year, and $R_{kWh}$ denotes the average operating costs in € per generated kWh. According to [21], the operating costs are 0.0241 in the first decade and 0.0268 €/kWh in the second decade, due to increased maintenance of the aged turbine.

Often, operating costs are calculated as a general sum without including depreciation ([25]). In this paper, however, two decades ($R_{D1}$ for the first, and $R_{D2}$ for the second decade, respectively) are assumed and an average of the annual operating costs: $R_t$ is formed from $R_{D1}$ and $R_{D2}$. Finally, the sum of the discounted operating costs ($D$) of all periods $t$ can then be calculated as:

$$D = \sum_{t=1}^{N} R_t \cdot q^{-t} \tag{4}$$

Step 4—Annual average cost: In conclusion, the annual average cost ($AC$) is calculated from the previously obtained results as:

$$AC = \left(a_{total} + RV \cdot q^{-N} + D\right) \cdot AF \tag{5}$$

where $AF$ is the annuity factor, i.e., $AF = \frac{q^N(q-1)}{q^N - 1}$. As can be seen, this is calculated based on the interest rate ($i$ resp. $q$) and the total life extension in years ($N$). By this factor, the sum of the discounted total costs is calculated back to an annual value, taking depreciation into account.

After the cost calculation, the LCOE can be determined by means of:

$$\mathrm{LCOE} = \frac{AC}{E} \tag{6}$$

Finally, for a Germany-wide representation, an LCOE raster with about 14.3 million pixels is created from the DWD wind speed dataset and the calculation results.

### 3.2. Statistical Evaluation

The results are linked back to geodata for statistical evaluation at the state level. For this purpose, the wind speed raster dataset was converted into a vector dataset and saved as an ArcGIS shape file, whereby the raster values, i.e., the wind speeds, were transferred into the vector dataset. The LCOE results table can thus be linked to the geometries by means of wind speeds, whereby all generated information can be bundled within the shape file for further analyses.

In order to obtain an overview of the potential areas, the dataset had to be filtered through economically viable areas. Since according to [26], an average market premium of 0.088 €/kWh is predicted for the year 2021, a prudent threshold value of 0.06 €/kWh was assumed for this purpose in order to guarantee a profit in (almost) all cases. All areas possessing costs lower than this threshold are considered economically attractive or profitable. For the further statistical analysis, the resulting areas are then split by the federal states using the administrative boundaries. The statistical analysis is divided into a descriptive and a spatial-statistical analysis.

In the descriptive analysis, the federal states are examined with regard to the following values in relation to the calculated LCOE: minimum, maximum, mean value, median, standard deviation, skewness, kurtosis, and population $M$ (the number of areas). The spatial-statistical analysis focuses on the economically attractive areas within the total area of each federal state. For this purpose, the percentage shares of the respective total areas are related to each other.

### 3.3. Spatial Analysis

The spatial analysis was intended to examine the areal coverage of attractive, unfragmented regions within each state, since wind farms (consisting of several turbines) are only feasible above a certain extension, as there are (legally) mandatory minimum distances between turbines. For this purpose, a minimum size of 25 hectares was assumed. Thus, four turbines on an area of 500 × 500 m, with a minimum distance between the turbines of 500 m, were the smallest assumed wind farm. The assumptions here were very conservative. Minimum distances of three to five rotor diameters are often recommended ([7]), but a higher minimum distance compensates for the geometric deviations of the calculated areas from an optimal area.

Besides the pure size of an area, the geometry was also decisive for its real usability. For example, a rather "tube-shaped" oblong area is rather unsuitable for the construction of a wind farm. Since the park layout, then, would be limited to wind turbines arranged in a row, wind direction-dependent wake effects within the layout might occur and could not be taken into account by a more suitable (i.e., wake avoiding) turbine arrangement within the farm. However, exactly this kind of shape is often found in the created dataset (Figure 2). In parts, this can be explained by topography: As reliefs and valleys (mountain regions in general) tend to influence perceived wind speeds (and also, wind directions), longish areas of comparably high wind speeds may occur in those regions. However, due to rough terrain, installing wind turbines may be impractical in those areas. In addition to the above-mentioned turbine arrangement argument (minimum distances between turbines), this may also be a reason for the desire to exclude those regions from further investigation.

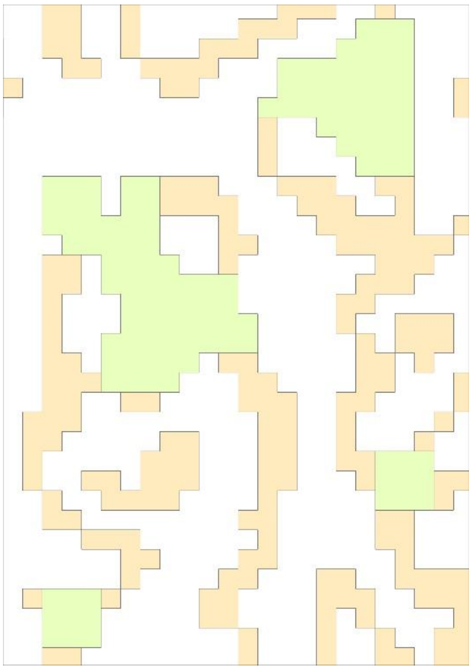

**Figure 2.** Tube shapes of the economically potential areas.

An example zoom can be seen in Figure 2. The figure presents a raster map in which white areas are excluded by the algorithm for wind energy usage, whereas only the areas marked green would be usable. The orange tube-like areas would be not merely because of their geometric shape. In order to being able to establish a comparability with regard to practical feasibility, key figures are required. Landscape structure metrics offer an answer to this. They are used to describe a landscape and its geometric form mathematically. The description of the complexity of an area, also called "patch" in this field of research, is also addressed. Since the above-mentioned tube shapes connect several surfaces with each other (Figure 2), complex surfaces are created, which can be determined or described with precise reference to these measures.

One of the complexity measures is the shape index ([27,28]) according to:

$$SI_j = \frac{0.25p_{i,j}}{\sqrt{a_{i,j}}} \tag{7}$$

where $p_{i,j}$ is the perimeter of patch $i$ in federal state $j$, and $a_{i,j}$ represents the corresponding area. This measure describes the difference of the perimeter's shape to that of a standard shape with the same area. The reference value of one is valid when related to a square (7), or to a circle (8), following:

$$SI_j = \frac{p_{i,j}}{2 \cdot \sqrt{\pi \cdot a_{i,j}}} \tag{8}$$

The shape index is not dependent on size and can easily be applied to the problem presented here. In particular, the comparison with a square is an ideal measure in our case, since with an area of 25 ha on a square, the largest possible number of plants can be built. Other landscape structure metrics, however, include, e.g., the total edge, edge density, fractal dimension, area-weighted mean shape index, or double log fractal dimension (see [28,29]).

The calculations were performed on the basis of the vector dataset. All areas characterized with an LCOE below the above-mentioned threshold of 0.06 €/kWh were controlled for their size. If an area was smaller than 25 ha, it was removed for future calculations. In the further process, the perimeter was calculated afterwards. The sums of the areas and perimeters of the patches within the federal states are finally used as values for the calculation of the shape index in order to make an overall statement.

## 4. Results and Discussion

Since the base dataset as well as the calculations of energy yields and weighted energy yields were separated, a comparison between both values could be drawn to illustrate the effects of the introduced correction factor (cf. [5]). Figure 3 shows the LCOE (left) and the adjusted LCOE (ALCOE) (right) in map form. The value ranges were divided into five classes. They span from less than or equal to 0.06 € (green) to 2.60 € (red). The unweighted results immediately show a preference for the northern, coastal states. This is naturally due to the favorable wind conditions prevailing there, which results in a high energy yield. However, the rest of Germany is strongly disadvantaged in this respect; in particular, the south has a very low number of economically potential areas.

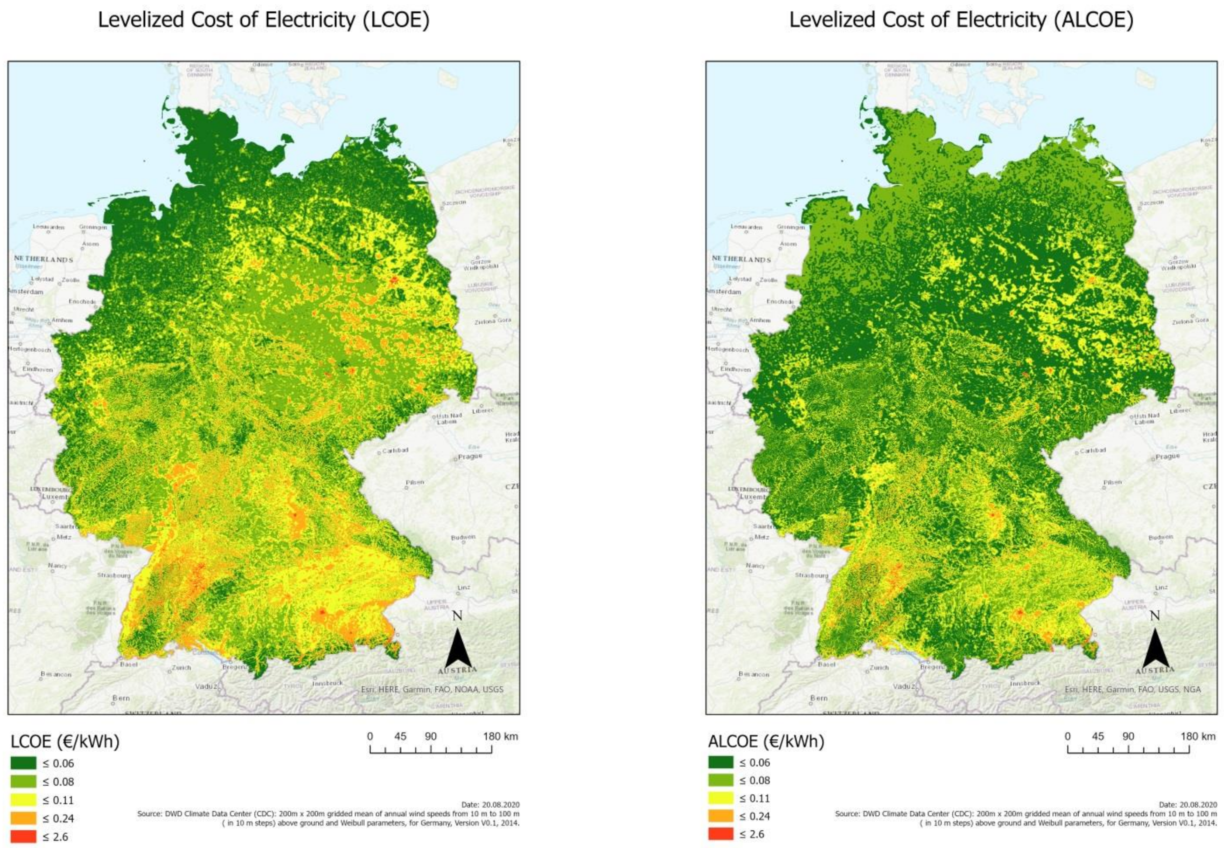


**Figure 3.** LCOE and ALCOE maps for Germany.

The weighted results, in contrast, showed a very different picture. Applying the correction factor reduces the heterogeneity of the LCOE and thus causes a widening of attractive areas extended to the entirety of Germany. The Northern German regions lose relative attractiveness. However, expansion has been stagnating there for years anyway, as many suitable areas have already been built on ([3]). Central Germany, on the other hand, benefits from the correction factor, which means that areas in North Rhine-Westphalia, Lower Saxony, and Saxony-Anhalt in particular are being promoted.

In its entirety, the dispersion of LCOE within Germany was reduced. However, there are still strong differences within the federal states. In order to be able to examine these differences in greater detail, a look at the level of the federal states is required.

The descriptive analysis of the weighted ALCOE showed the above changes in numbers (Table 2). Special attention is being paid to Schleswig-Holstein (SH), Saxony-Anhalt (ST), and North Rhine-Westphalia (NW). In these federal states, the influence of economic weighting was most pronounced. On average, SH still seems to be favored. However, since the ALCOE values differ greatly, especially in the case of ST, the average is not very meaningful. The median, in contrast, somewhat compensates for outliers and distinguishes ST as the more attractive state with a value of 0.0559 €/kWh in contrast to SH with 0.0631 €/kWh. In addition, this value indicates that in the case of NW (0.0560 €/kWh) and ST, at least 50% of the total area are indeed below the above set critical ALCOE value of 0.06 €/kWh.

**Table 2.** Descriptive analysis of ALCOE by state (*M* = number of samples per state).

| State | Min | Mean | Max | Median | SD | Skewness | Kurtosis | M |
|---|---|---|---|---|---|---|---|---|
| Baden-Wuerttemberg | 0.0481 | 0.0833 | 2.0233 | 0.0761 | 0.0398 | 7.7112 | 151.2408 | 892,435 |
| Bavaria | 0.0475 | 0.0775 | 0.7664 | 0.0758 | 0.0275 | 8.949 | 180.8449 | 1,760,482 |
| Berlin | 0.0541 | 0.0868 | 0.208 | 0.0812 | 0.0331 | 2.6511 | 9.8326 | 22,349 |
| Brandenburg | 0.0541 | 0.0663 | 0.2471 | 0.0578 | 0.0138 | 1.4902 | 7.4002 | 742,211 |
| Bremen | 0.0517 | 0.0617 | 0.0814 | 0.0607 | 0.0071 | 0.859 | 3.0493 | 10,518 |
| Hamburg | 0.0499 | 0.0653 | 0.1099 | 0.0631 | 0.0104 | 0.6249 | 2.3215 | 18,827 |
| Hesse | 0.0499 | 0.0702 | 0.9466 | 0.0607 | 0.02 | 5.2926 | 134.2796 | 527,947 |
| Mecklenburg-Western Pomerania | 0.0499 | 0.0611 | 0.1218 | 0.0631 | 0.0059 | 1.2735 | 5.0887 | 581,538 |
| Lower Saxony | 0.0493 | 0.0618 | 0.2471 | 0.0578 | 0.009 | 2.5168 | 18.8112 | 1,193,176 |
| North Rhine-Westphalia | 0.0531 | 0.0625 | 0.7664 | 0.056 | 0.0153 | 17.8221 | 723.2602 | 851,400 |
| Rhineland-Palatinate | 0.0536 | 0.0682 | 0.2471 | 0.0607 | 0.0183 | 2.0389 | 7.9481 | 496,157 |
| Saarland | 0.0541 | 0.0689 | 0.1781 | 0.0607 | 0.0156 | 1.3041 | 5.1145 | 64,012 |
| Saxony | 0.0478 | 0.0657 | 0.7664 | 0.0578 | 0.0193 | 8.666 | 194.8548 | 460,352 |
| Saxony-Anhalt | 0.0471 | 0.0661 | 1.5322 | 0.0559 | 0.0263 | 14.6607 | 396.9082 | 514,291 |
| Schleswig-Holstein | 0.0475 | 0.0612 | 0.1099 | 0.0631 | 0.0047 | −0.0813 | 6.3198 | 395,301 |
| Thuringia | 0.0536 | 0.0678 | 0.6306 | 0.0578 | 0.0197 | 5.0664 | 88.9488 | 405,311 |

This idea is further broken down in the spatial-statistical analysis. In Figure 4, the percentage of the total area of the German states below an (unweighted) LCOE value of 0.06 €/kWh is shown. In this case, over 80% of SH's area was below the threshold. NW and ST, on the other hand, were below 30% and below 10%, respectively.

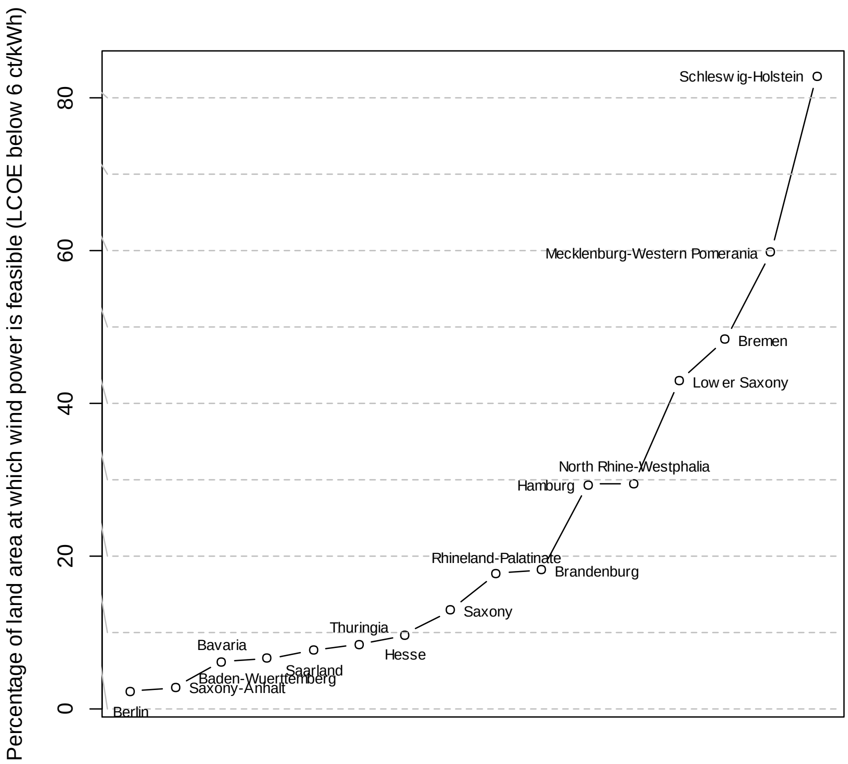


**Figure 4.** Percentage of German states' area of economically feasible land (LCOE).

However, inspecting the ALCOE areas (Figure 5), we observed a strong increase, especially in ST. Here, NW and ST seem to be leading in Germany in terms of the percentage of economically feasible areas. The number of attractive areas in the northern states, such as SH, drops drastically by roughly 50 percentage points compared to the simple LCOE. In addition, however, it can be seen that the federal states are moving closer together overall (see the different scaling of the ordinates in the two figures) and that the majority of states settled at 40% to 50% of usable area, and while for LCOE, only two states were above the 50% mark, for ALCOE, they became six. Based on these results, the complexity of the identified patches should also be investigated. Table 3 breaks down the measures of complexity analysis, again on a state level.

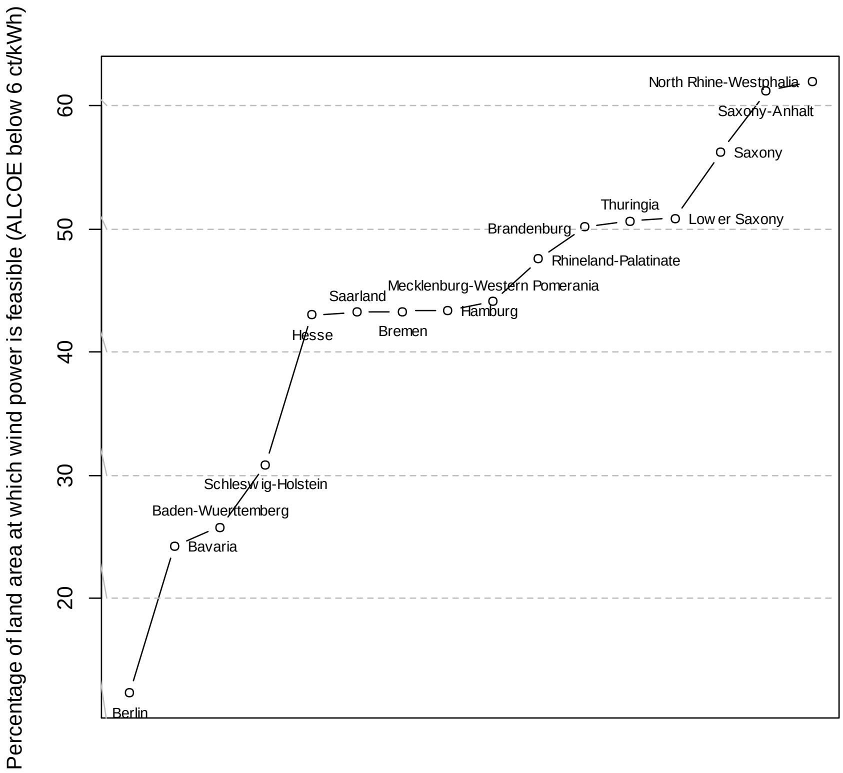


**Figure 5.** Percentage of German states' area of economically feasible land (ALCOE).

**Table 3.** Results of the complexity analysis using shape index.

| State | Number of Patches | Perimeter (km) | Area ($km^2$) | Shape Index |
|---|---|---|---|---|
| Baden-Wuerttemberg | 3524 | 31,114 | 9216 | 81.03 |
| Bavaria | 5944 | 52,635 | 17,103 | 100.62 |
| Berlin | 42 | 309 | 110 | 7.35 |
| Brandenburg | 451 | 12,920 | 14,895 | 26.47 |
| Bremen | 19 | 362 | 182 | 6.7 |
| Hamburg | 36 | 570 | 327 | 7.88 |
| Hesse | 1728 | 25,594 | 9089 | 67.11 |
| Lower Saxony | 722 | 24,126 | 24,278 | 38.71 |
| Mecklenburg-Western Pomerania | 504 | 13,538 | 10,260 | 33.41 |
| North Rhine-Westphalia | 1375 | 32,300 | 21,125 | 55.56 |
| Rhineland-Palatinate | 1175 | 28,073 | 9445 | 72.21 |
| Saarland | 171 | 2612 | 1107 | 19.62 |
| Saxony | 502 | 14,696 | 10,362 | 36.09 |
| Saxony-Anhalt | 415 | 10,348 | 12,596 | 23.05 |
| Schleswig-Holstein | 392 | 7289 | 4882 | 26.08 |
| Thuringia | 1293 | 19,139 | 8218 | 52.78 |

The complexity of the economically potential areas could not be more different. Here, the city states (Bremen, Berlin, and Hamburg) left only little headroom for the complexity of a patch due to their very small base area. The comparably large state of Bavaria (BY) instead shows the highest complexity of the patches with a shape index of 100.62, which can be explained to a high degree by the alpine regions, since in the respective part of this federal state only small, isolated patches are usable. Initially, the number of patches and the total area size seem to be decisive for the high complexity. With regard to the total area size, however, the example of NW showed that this assumption is of rather secondary importance. The number of areas, on the other hand, was at first glance a greater influencing factor. The example of Hesse (HE) with 1728 areas having a shape index of 67.11 in comparison to Rhineland-Palatinate (RP) with 1175 areas and a shape index of 72.21 with similar total perimeter as well as area values suggests that even several smaller areas can lead to a lower shape index.

The German states examined in the above analysis span the midfield. It can be seen here that NW, with a shape index of 55.56, had a value twice as high as ST and SH. ST with a value of 23.05 was still ahead of SH (26.08). Therefore, ST's areas have not only become more attractive, but also in many cases even turned out to be actually usable. The total area of the filtered potential suitability areas was also almost three times that of Schleswig-Holstein.

It is worth mentioning that not all of the areas that are potentially economically viable are actually usable. Nevertheless, this analysis shows the strong impact of the correction factor. Therefore, a potential analysis in terms of energy yield does not necessarily reflect the distribution of the economic potential. This results in a benefit for the search for new potential areas and the associated tendering of new suitability areas, in addition to the economic analysis of the areas tendered by the policy. Due to the strong influence of the correction factor described above, areas become interesting which are rather considered to be less windy and therefore not necessarily perceived as suitable areas by the regional planning. Thus, by a spatial-economic analysis on the part of the state's energy policy, their own new adoptable tool, namely the "correction factor", could indeed help in the processes of finding further suitable areas.

## 5. Conclusions and Policy Implications

This paper shows how much the RE potentials evaluation can change through the use of policy tools such as the correction factor. In 2020, the debate on the minimum distance rules made clear how differently the governments of the federal states act with regard to the acceptance and willingness for the expansion of RE on the part of politics.

Besides the pure energy potential analysis, it is also important to shed light on the economic background, otherwise misunderstandings may arise between business and politics. Increasing ALCOE increase the lower bid limit for investors for the reverse auction system usually employed to allocate energy amounts. This could make projects more difficult to realize sometimes because then they may not be financially viable. However, the plannability can be increased performing an economic potential analysis by means of ALCOE.

In addition, a spatial-economic analysis can filter out not only wind-rich areas in the search for new suitability areas, but also wind-poor areas that are nevertheless economically profitable. This would increase the amount of politically tendered areas, which would further increase the expansion of onshore wind energy.

Nevertheless, it should be noted that the use of the correction factor does achieve its intended effect. The economic attractiveness of the entire Federal Republic of Germany is increasing, which should further promote an expansion of wind power, at least from an economic perspective. A slightly increasing expansion in 2020 (1431 MW in additionally installed capacity compared to 1078 MW in 2019) seems to confirm this assumption (see [30,31]). In particular, the frontrunners NW and ST, which can be deducted from Figure 4 on the right, indeed show an increasing expansion and move up in the expansion ranking (NW from third to first place and ST from sixth to fourth place, see [31]). This suggests that practitioners already identified the impact of the correction factor on the attractive areas we discussed in this paper. Other states worldwide may therefore, again, follow the German example and increase the economic incentive for expansion, if regionally necessary.

The results, in this case at the federal state level, can be further refined by including settlement areas, protected areas, airports, and others. A cooperation with the regional planning of the individual states would further be beneficial, since the exclusion factors are different for each state.

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