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Onshore wind energy in Baden-Württemberg: a bottom-up economic assessment of the socio-technical potential

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***Index Terms*—Power generation economics, wind energy, social barriers, cost-potential curves, potential analysis.**

1. Introduction

The German energy transition towards a more sustainable energy system is well under way. In the context of European, national and regional energy policies and targets, the country has experienced very rapid developments in renewable energies in recent years, due mainly to political support in the form of a feed-in tariff. In 2013, the federal state government of Baden-Württemberg enacted a law obligating itself to reduce greenhouse gases by 25% and 90% by 2020 and 2050 respectively, in comparison to 1990 [1]. To achieve these goals, a strategy paper was published in 2014 specifying aims for each sector (e.g. energy) and setting up an action plan [2].

In this strategy paper, renewable energies play an important role on the way into a decarbonized future energy system. For onshore wind energy this means targets in the region of 6.4 TWh in 2020 and 18.0 TWh in 2050 [2]. This is despite their relatively modest development to date in Baden-Württemberg, especially in terms of onshore wind energy when compared to other federal states in the north of Germany. In 2013, for example, the amount of electricity produced by onshore wind capacities in Baden-Wuerttemberg was around 0.7 TWh, which is approximately 1.1 % of the gross power generation, compared to 8.5 % for the whole of Germany [3, 4]. In order to catch up on the backlog there has been a recent continuing debate about the various potentials, costs, social acceptance and land use constraints of onshore wind energy in this region. The latter two aspects are especially related to the increasing locally-installed turbine capacity and hub heights, which may negatively affect the aesthetic quality of the landscape.

Several studies have examined the technical potentials and related costs for onshore wind energy in Baden-Württemberg in particular as well as Germany as a whole [5]-[6][8]-[9]. The most common approach is to exclude unsuitable areas, e.g. protection and settlement areas, using geographical information systems (GIS) in combination with wind power density functions and/or suitability factors to account for further constraints [5][8][10]-[14]. This approach is usually applied for larger geographical areas (e.g. worldwide or countries), is easy to implement and fast in computation. However, for more detailed local insights, this approach can be too rough and in terms of suitability factors somewhat arbitrary. This can be avoided by placing wind turbines directly, for example by using an algorithm. This bottom-up-approach is commonly used on a regional level although it is also applicable for larger regions such as countries [6]-[7][9]. The advantage of this method is a higher accuracy, particularly when it comes to handling smaller areas (less than 0.05 km²) where the wind power density approach can significantly underestimate the technical potential [8].

Table 1 – Overview of relevant studies that have analyzed onshore wind energy potentials

Source	**Area analyzed**	**Potential determined/ analyzed**	**Method**
McKenna et al. [5]	Baden-Württemberg	Technical, economically analyzed	Power densities using single turbine types.
LUBW [6]	Baden-Württemberg	Technical	Wind turbine placing algorithm with a single wind turbine.
Schallenberg-Rodríguez and Notario-del Pino [7]	Canary Isles	Technical	Wind turbine placing algorithm using a single wind farm configuration layout for a reference turbine.
McKenna et al. [8]	Germany	Technical, economically analyzed	Power densities using a minimal generation costs criterion and a set of different turbines.
UBA [9]	Germany	Technical-ecological	Wind turbine placing algorithm using a maximum full load hour criterion for two different turbine types.
Fueyo et al. [10]	Spain	Technical	Power densities using single turbine types.
Gass et al. [11]	Austria	Technical	Power densities using single turbine types.
Nguyen et al. [12]	Vietnam	Technical	Power densities using a single turbine.
McKenna et al. [13]	Europe	Technical, economically analyzed	Power densities using a minimal generation costs criterion for large turbines (> 3 MW).
Hoogwijk et al. [14]	Worldwide	Technical, economically analyzed	Power densities using a linear relation between wind speed and full load hours.
This study	Baden-Württemberg	Socio-technical, economically analyzed	Wind turbine and wind farm placing algorithm using a minimum generation costs criterion and a set of different wind turbines

Whilst these contributions provide valuable insights for energy system models as well as for commercial and political decision-making, they partly overlook some of the “softer” socio-economic factors relating to the development of wind energy. Some of these factors, such as the attitudes of the local population towards wind turbines and parks, are arguably equally as if not more important than purely technical or economic ones. The degree to which wind turbines are perceived to negatively affect the visual quality of the landscape depends on several factors, most importantly landscape attributes and the siting of turbines [15]. In order to obtain a more realistic estimation of that fraction of the technical and economic potentials that might be achieved in practice, these and related aspects must be considered in detail.

Against this background, this study develops and applies a bottom-up method for wind turbine and park placement, which explicitly considers some of the constraints associated with social acceptance and land use planning. Therefore, a geo-referenced database containing information about landscape aesthetic aspects [16] as well as constraints derived from rules of land use planning is employed. The latter comprises rules that should prevent too many wind turbines at a certain site (landscape aesthetic aspects) and scattered wind turbines (promote concentration zones), amongst other things [17]-

[18]. Since these rules are specified by regional public planning organizations, they can be considered to be an accurate reflection of local social acceptance of wind energy. In other words, the local land use planning rules can be taken as a proxy for public acceptance. Furthermore, the methodology includes other novelties like the implementation of a rotation matrix in order to consider prevailing wind directions and variable rotor diameters. Wind speed data (resolution 50 m x 50 m) is used at 5 different hub heights (80 m – 160 m), which allows wind profiles to be created by interpolation for each raster, to reduce further uncertainty arising from the commonly used logarithmic law. Additionally, to improve the accuracy further, a possible degradation of wind parks over the operation time which results in a lower energy output and higher costs are also considered. The method is implemented in the geographical information system ArcGIS and MATLAB®.

The paper is structured as follows: first the definition of the term 'potential' is discussed and the methodology to determine the socio-technical potential is presented in Section 2. In Section 3, the results are presented and a sensitivity analysis is conducted. Subsequently, these results are discussed and the methodology is critically scrutinized in section 4. The conclusion is in section 5.

2. METHODOLOGY

This section is subdivided into three subsections. The first subsection gives an overview of the term 'potential' and defines more clearly what is meant by the 'socio-technical potential' employed in this paper. Secondly, the technical potential is estimated by applying a land use planning module using a criteria catalogue to calculate the total available area (geographical potential) and an algorithm to place wind turbines with the lowest cost of electricity (LCOE). Third, the socio-technical potential and the associated costs are determined to derive the cost-potential-curve on a wind farm level.

2.1 The definition of the term 'potential'

In line with Ref. [14] and [19] the term 'potential' is broadly distinguished in four categories, namely, the theoretical, the technical, the economic and the feasible potential. The potentials can be defined as follows:

- the *theoretical potential*: the physically usable amount of energy within a certain region and time. In the present case of onshore wind, the theoretical potential would be the total power/energy in the wind over land in Baden-Württemberg.
- the *geographical potential*: the area that is available for the generation of energy from the wind, accounting for restrictions such as nature reservation areas and other land uses such as urban fabric and traffic routes. In the present case the geographical potential is the total amount of area available in Baden-Württemberg, whilst considering these restrictions.
- the *technical potential*: the usable amount of energy under technical constraints within a certain region and time. In this case the technical potential is the amount of energy generated by wind turbines installed within the available area in Baden-Württemberg, whilst accounting for technical specifications such as conversion efficiencies, spacing requirements and wake effects.
- the *economic potential*: the technical potential that can be realized economically within a certain region and time. This strongly depends on the perspective taken, i.e. whether assessed from a private investor's or society's perspective, which manifests itself for example in the employed discount rate, as well as the economic criteria employed, i.e. whether payback period, net present value, internal rate of return etc. In addition, the determination of the economic potential can be difficult for markets with a more complex market design. In Germany, for example, fixed feed-in tariffs (FITs) as well as market premiums exist. The latter is a function of the wholesale electricity market price, the overall amount of wind energy produced within a month and the amount of energy produced by wind turbine at a certain site within this month. Therefore, as wind turbines are more likely to be situated in the north of Germany, the option of direct marketing for non-correlated wind turbines on other sites can be more profitable. This is especially the case for wind turbines in Baden-Württemberg in the south of Germany [20]. As a consequence the assessment of the technical potential in terms of the economic feasibility turns into a case by case decision and cannot be done easily.
- the *feasible potential*: the actual achievable economic potential, whilst accounting for market, organizational and social barriers, which mean that in practice the economic potential is not realized. In the present case the focus is on the socio-economic constraints resulting from landscape-aesthetical aspects and acceptance within the local community in Baden-Württemberg.

Hence by employing these definitions each successive potential can be interpreted as a subset of the preceding potential (see Fig. 1). Consequently, if social aspects are to be taken into account, the economic potential has to be determined first. Calculating the economic potential for markets with a more complex market design as mentioned above however, can be tough challenge. Furthermore, there is no evidence for the economic constraints to be more important than constraints due to social acceptance.

Thus, to emphasize the importance of acceptance as well as to avoid calculating the economic potential in detail, the term 'socio-technical potential' is introduced and is defined as follows:

- the *socio-technical potential*: the actual achievable technical potential under constraints such as landscape aesthetical aspects and acceptance within the local community.

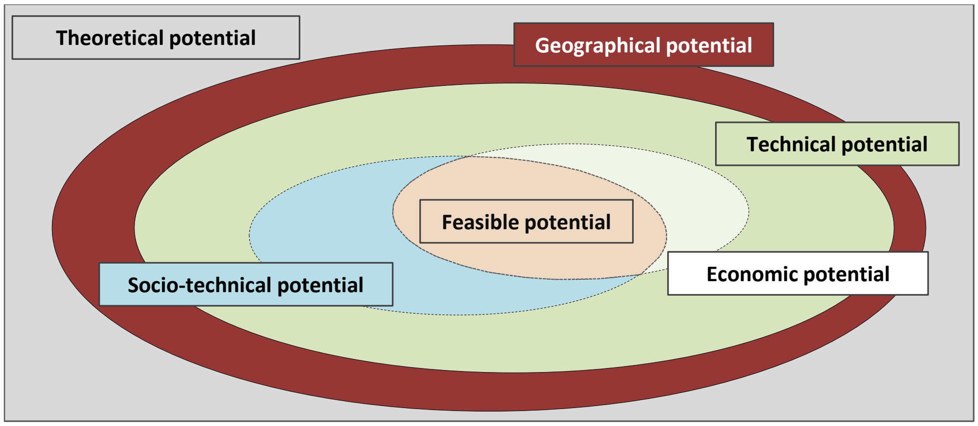

Figure 1. Overview of the different potentials (loosely based on [9])

The need to define more diversified potentials is not a novelty and was done by other authors before. Ref. [9] differentiates between a technical potential and a techno-ecological potential to account especially for detrimental impacts for human beings and animals whereas Ref. [14] differentiates between a technical and a geographical potential to emphasize land use constraints. However, the introduction of a new potential term also leads to a change of the above mentioned hierarchy of potential terms. The socio-technical potential can be classified into the hierarchy level next to the economic potential such that the feasible potential can be calculated by simply permute the order of the constraints (here social and economic).

Finally, it should be noted that the strict definitions of the potential terms given above are relaxed slightly in this paper. This is because of the need to define a decision variable to place the wind turbines and wind parks. As a decision variable the levelized cost of electricity (LCOE) is used whereas a minimization LCOE criterion is applied. It should therefore be borne in mind that the technical and the socio-technical potential are, strictly speaking, only "assessed economically". A determination of the economic potential would require a consideration of further economic constraints such as FIT or market designs, which is not carried out here as also done previously for the technical potential [8].

2.2 The technical potential

In this subsection, the technical potential, more precisely the technical potential economically assessed, is calculated. Therefore, the geographical potential is determined in a first step. Secondly, the costs and energy yields are calculated. In a last step, the optimal wind turbines for a certain place following a LCOE minimization criterion are placed.

a) Determination of the geographical potential

First, to determine the available land, unsuitable areas like settlement areas, protection areas and corresponding buffer zones due to noise control for human beings and for certain birds as well as possible bird strikes are excluded. The database for the land use data is the digital land use model 'DLM-25 BW (ATKIS)' of the State Agency for Spatial Information and Rural Development Baden-Württemberg (LGL) [21]. As a database for the protection areas the 'Räumliches Informations- und Planungssystem (RIPS)' [Spatial Information and Planning System] of the Federal State Institute for Environment Measurement and Nature Conservation Baden-Württemberg (LUBW) is employed [22]. As a regional peculiarity, breeding ground and living space of the wood grouse cock is also accounted for, with data derived from the Forest Research Institute of Baden-Württemberg (FVA) [23]. Other animal species that are considered as sensitive to wind turbines according to [24] such as black and red kite, bats or peregrines are not considered due to local case-by-case decisions if avoidance and compensatory measures are taken into account [25].

Furthermore, isolated areas with a total size smaller than 0.2 ha, which is considered as the minimum size for placing a wind turbine, are also erased [26] and areas with a maximum slope of 20° and above are excluded [27]. The calculation of the latter is carried out with the digital elevation model (DGM-25) of the LGL [28]. The spatial resolution of the databases is 25 m. An overview of the exclusion and buffers employed in this study is given in Tab. 1.

Table 1: List of applied criteria for exclusion and buffer. (Own based on [29])

Category	buffer (m)
Urban areas and special buildings	
Areas of special functional character	1000
Residential areas	700
Areas with mixed use	450
Industry and commercial areas	250
Special areas, areas for public facilities, green and recreational areas	0
Observatory	3000
Weather station	15000
Traffic areas and infrastructure	
Federal motorways	160
Federal roads and state roads	100
District roads	90
Railways	110
Electricity lines ≥ 110 kV	160
Airports (aircraft traffic areas, special purpose airfields, gliding airfields)	1000
Mineral planning	
Mining operation, open-pit-mining, quarry	0
Water protection	
Flood zone	0
Water body > 6m and of 1. order	10
Water protection zone I/II	0
Mineral springs	0
Agriculture and forestry	
Avalanche forest and Schonwälder	200
Protected areas	
Biosphere areas - core zone	200
Biosphere areas - cultivation zone	0
Bird protection areas	700
Wood grouse cock (categorie 1-3)	0
Flora Fauna habitats (FFH-area)	0
National park	200
Natural monuments	0
Nature reserve	200
Landscape protection areas	0
Protected biotopes	0
Mineral springs	0
Not in List	
Nightly military low flying operation routes	-
Civil radio link	-
Recreational forest	-
Special protection areas (e.g. red kite, black kite, bats)	-

b) *Calculation of the energy yield and the LCOEs*

The resulting areas are then intersected with the wind speed data comprising average wind speeds for five different hub heights (80 m, 100 m, 120 m, 140 m and 160 m). The wind speeds are derived from the RIPS with a spatial resolution of 50 m and are clustered in 0.25 m/s intervals from '< 4.50 m/s', '4.50 – 4.75', and so on up to '> 7.50 m/s' [22]. The wind profiles are then calculated by linear interpolation between the hub heights, thus avoiding the application of the commonly used logarithmic law which is usually valid only for altitudes of 30-50 m, in neutrally stratified atmosphere and flat terrain [30].

As the average wind speeds are known, the wind speed distribution at hub height can now be derived. In general, the wind speed distribution can be calculated with the Weibull distribution Φ_W:

$$\Phi_W = \frac{k}{A} \cdot \left(\frac{v}{A}\right)^{k-1} \cdot \exp\left[-\left(\frac{v}{A}\right)^k\right] \qquad (1)$$

where k is the shape factor of the Weibull distribution, A the scale factor of the Weibull distribution, and v is the wind speed [m/s].

Typical values for k range between 1.5 for offshore and 2.5 for onshore sites with a high surface roughness. As the wind speeds in this study, however, are lower than 7.5 m/s and the change of the total energy produced seems to be less sensitive to the shape factor for these wind speeds, the shape factor k is assumed to be 2, and thus it can be approximated by the Rayleigh distribution Φ_R [30]:

$$\Phi_R = \frac{\pi}{2} \cdot \frac{v}{v_m^2} \cdot \exp\left[-\frac{\pi}{4} \cdot \left(\frac{v}{v_m}\right)^2\right], \qquad (2)$$

where v_m means wind speed [m/s]. As the wind speed distribution is known, the annual electricity generation can now be obtained by using Eq. 3:

$$E_{t,el} = T \cdot \eta_{windpark} \cdot (1-d)^t \cdot \int_0^{\infty} \left(\Phi_R(v) \cdot P_i(v)\right) dv, \qquad (3)$$

where $E_{t,el}$ is the annual yield [kWh], T the total number of full load hours per year [h], $\eta_{windpark}$ the wind park efficiency [%], d the degradation of energy output [%/year], t is the year and $P_i(v)$ the power curve of turbine i [kW].

The wind park efficiency is 85% comprising energy losses due to operating losses such as sub-optimal control systems and misaligned components (η_{op}=98%) [30]-[31], non-availability ($\eta_{availability}$=97%) [32]-[33] and wake effects (η_{wake}=90%). The latter assumption is strongly simplified, neglecting interdependencies between wind park size and wind park arrangement as Tab. 2 for different wind park sizes exemplarily shows [34]-[35].

Table 2: Typical array efficiency for different size and spacings of square arrays (non-directional wind regime) [34].

	Turbine spacing					
	4D	**5D**	**6D**	**7D**	**8D**	**9D**
	Array efficiency (compared to equivalent number of machines with no interference)					
Array size	*percent*					
2 x 2	81	87	91	93	95	96
4 x 4	65	76	82	87	90	92
6 x 6	57	70	78	83	87	90
8 x 8	52	66	75	81	85	88
10 x 10	49	63	73	79	84	87

The degradation, caused by, inter alia, fouling of blades, gradual reduction in component efficiency and the fact that the availability declines with age due to more frequently occurring failures of turbines, is for newer turbines (commissioned between 2002 – 2007) between 0.4% and 1.1% per year [36]-[37]. In this study, this value is assumed to be 0.7% per year.

Finally, the LCOEs are calculated. Based on the costs linked to the investment, the operating costs and the sum of the yearly energy outputs this can be done with Eq. 4 [38]. The interest rate to discount the cash flows is the usual capital costs on the market (weighted average costs of capital, WACC) and is assumed to be 7.9%. The equity contribution is 22% at 9% discount rate and the debt contribution is 78% with 3.8% [39]. The economic operational lifetime is assumed to be 20 years.

$$LCOE = \frac{I_0 + \sum_{t=1}^{n} \frac{A_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{E_{t,el}}{(1+i)^t}}, \qquad (4)$$

where I_0 is the investment expenditures [€], A_t the annual total costs in year t [€/year], n the economic operational lifetime [years], i the interest rate [%], and t the year (1,2,…n).

The investment for a wind turbine usually is given in Euro per kW and for onshore wind turbines in Germany is between approximately 1400 and 1700 €/kW (including ancillary costs) for nominal powers between 2.0 and 3.5 MW in 2013 [39]. However, as the investment is not directly linked to a specific wind turbine and for this reason neither to a specific power curve, it is not possible to calculate accurately the LCOE according to Eq. 3 and Eq. 4. Instead, a methodology is used which is described in detail in Ref. [8] based on simple mass-based cost components. The specific investment corresponds to a range of 1100 – 2200 €/kW.

The operating costs can either be expressed as costs per kWh or costs per kW. As costs increase with operational lifetime, costs per kWh are favored. According to Ref. [39] the operating costs are 2.41 €Cent/kWh for the first ten years and 2.68 €Cent/kWh for the next ten years.

c) Placing the wind turbines

On the basis of this data, the optimal turbine (minimal LCOE) for a specific site can be calculated and the wind turbine placing algorithm applied. As seed, the leftmost wind turbine with the minimum LCOE, within the matrix of all possible turbine locations, is selected. This turbine is placed, an ellipse with e.g. 8D (eight rotor diameters) in prevailing and e.g. 3D in cross wind direction drawn, and a rotation matrix to consider the prevailing wind direction applied. Within this ellipse no other wind turbine can be placed. This step is repeated until all possible wind turbines are placed.

2.3 The socio-technical potential

To account for landscape aesthetic aspects, landscapes that are considered to be particularly beautiful, unique and/or original are excluded. Ref. [16] analyzed in a first step all structural sizes of the landscape in Baden-Württemberg such as relief energy, land use or woodland borders. In a second step, 300 photos of representative sites were taken considering i.a. season, image layout and weather conditions. On this basis, a survey was conducted in which around 400 participants assessed these photos. The survey revealed a high level of consistency between the participants, which is seen as an intersubjective validation. In a final step, a regression analysis was carried out between the survey results and the structural sizes. The result was a map with a spatial resolution of 100 m with information about the quality of the landscape quantified by values between 0 and 10, where a 10 means an extraordinary quality. Outstanding landscapes can now be extracted by a statistical threshold that is defined by the arithmetical mean plus the standard deviation [40].

In order to account for constraints derived from rules of land use planning, such as landscape aesthetic aspects and concentration zones, the following steps are undertaken. A minimum and maximum number of wind turbines that can form a wind park and a maximum distance between two possible wind turbines within a wind park are implemented. Then, a buffer zone around the wind parks is defined, where no other wind park can be commissioned. The minimum wind park size is assumed to be three wind turbines and the maximum wind park size is twenty. The buffer range is between 3000 and 5000 meters [17][18]. For the minimum distance between two different wind turbines 1200 meters, which is approximately 10 rotor diameters with 120 m, is assumed.

The algorithm begins by building clusters of wind turbines with equal LCOEs and the cluster with minimum LCOEs is selected first (see Figure 3). Thereupon, a range search for this LCOE-cluster is run. Then, starting with the first turbine in the list, all possible successors in the list are searched and the turbine with the lowest LCOE and distance to this turbine is selected. If a successor can be found, the search resumes, and so on. It is quite similar to the nearest neighbor algorithm but

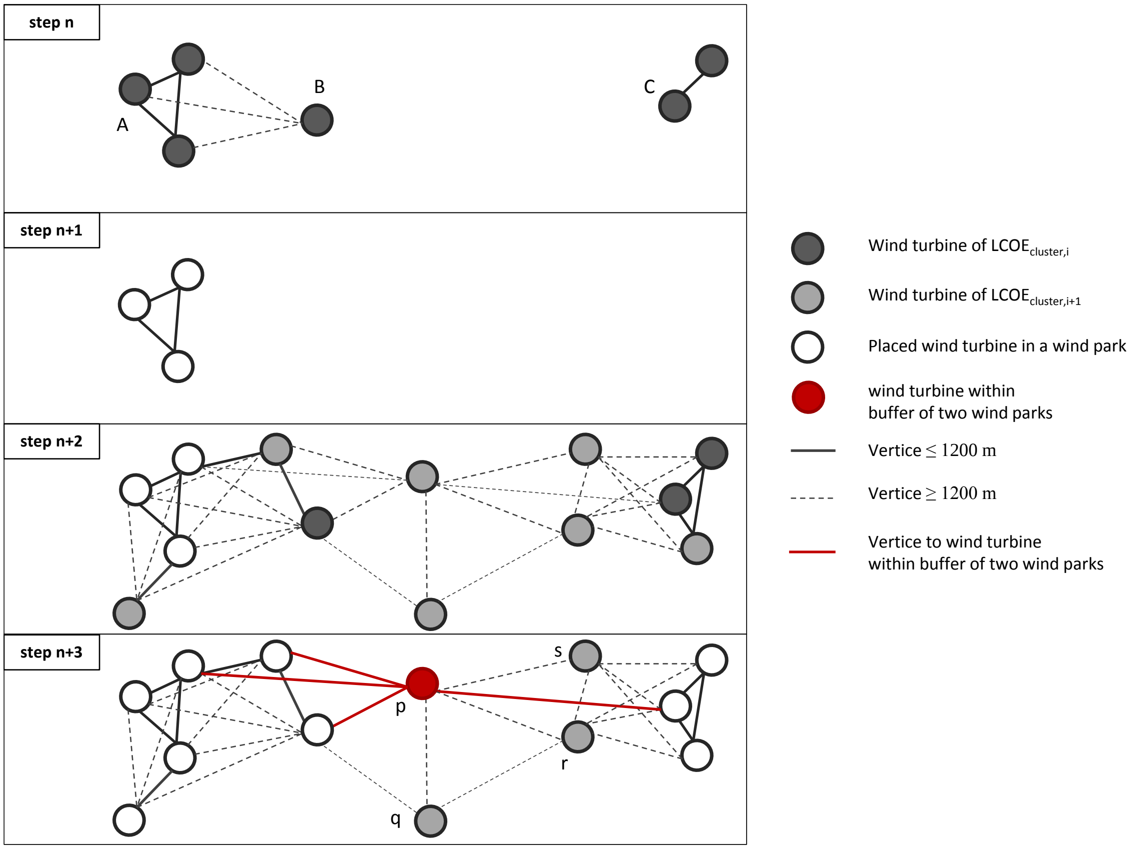

Figure 2: Algorithm to place wind parks.

the predecessors are not excluded and the LCOE is accounted for as well. This can be compared to crystal growth where constraints such as the minimum and maximum number of atoms must be met. In Fig. 2 in ‘step n’ only the wind park A meets these requirements whereas wind park B and C are too small. Thus, wind park A is marked as a placed wind park (see step n+1 in Fig. 2), the wind turbines in wind park B and C, however, are transferred into a temporary list but not yet deleted. These wind turbines can possibly be connected with another wind turbine of the next LCOE-turbine-cluster (see ‘step n+2’ in Fig. 2) as long as the wind turbine is not located within the buffer zone of two different wind parks. Otherwise, the wind turbine has to be deleted (see Fig. 2, the wind turbine ‘p’ in ‘step n+3’. The wind turbines ‘q’, ‘r’ and ‘s’ are transferred into the temporary list).

3. RESULTS

The available suitable area in Baden-Württemberg for wind energy is estimated at 4.402 km². This is about 600 km² more than in previous studies using public databases [8], which is thought to be due to the use of suitability factors. The technical potential without considering any constraints is between 50.9 TWh and 132.1 TWh, strongly depending on the area covered by the ellipse surrounding individual turbines. This relationship is nonlinear, as shown in Fig. 3. Furthermore it is observed that the geometry of the ellipse also has a small effect.

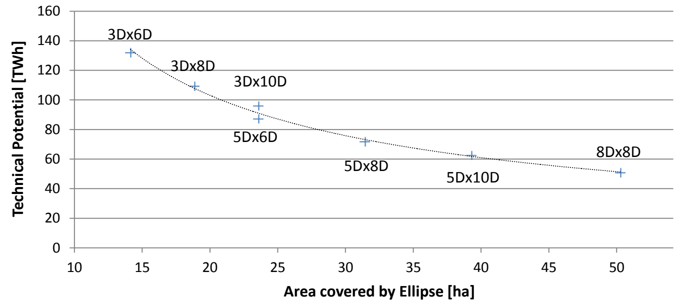

Figure 3. Technical potential as a function of the applied ellipse.

With a reference ellipse of 3D x 8D, which is chosen as the reference configuration, the wind park placing algorithm is applied. With a buffer zone of 3000 m around the wind park and a minimum number of wind turbines of three per wind park, the socio-technical potential and the associated costs are calculated. Furthermore, a sensitivity analysis is conducted, varying the buffer zone and the minimum number of wind turbines per wind park. The results are shown in Fig. 4, which shows that the socio-technical potential of 23.0 TWh is very sensitive to these factors. Firstly, the minimum number of wind turbines per wind park is varied. In doing so, the socio-technical potential increases from 23.0 TWh for a minimum of three wind turbines to 27.0 TWh for five, and reaches 29.4 TWh for seven wind turbines. In a next step, the buffer zone is varied. For a minimum of three turbines and a buffer zone of 5 km the socio-technical potential almost halves to 11.8 TWh, but increases again with the number of minimum turbines, and is 14.8 TWh for a minimum of five, and 16.9 TWh

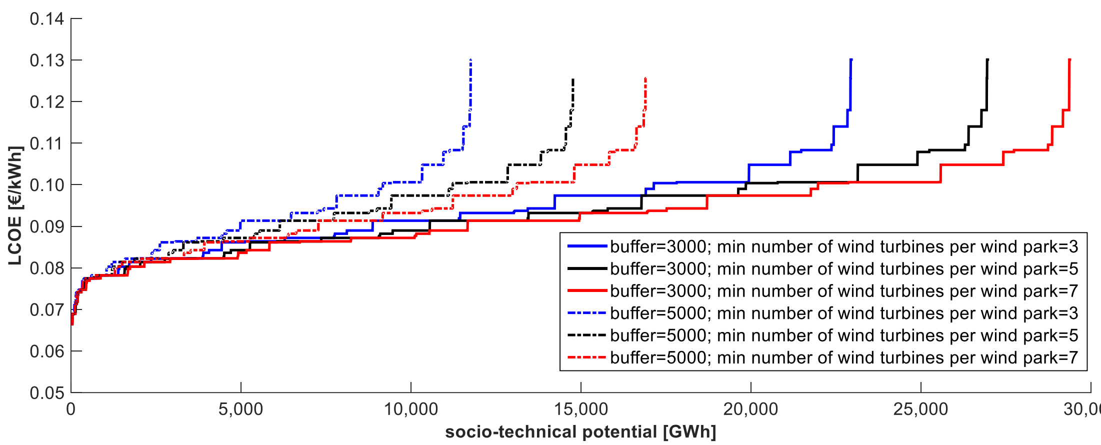

Figure 4. Cost-potential-curves for different buffer zones around the wind park and for different number of wind turbines per wind park.

for a minimum of seven wind turbines. Thus, a socio-technical potential for wind energy in Baden-Württemberg between 11.8 TWh and 29.4 TWh is obtained.

In addition, also the effect on the distribution for the two assumed buffer zones is investigated and compared to an approach without any constraints in terms of land use planning. To compare the results, the distribution of a possible wind energy production in 2020 for Baden-Württemberg according to the goals set out by the federal government with 6.4 TWh is investigated [2]. According to the LCOE criteria, only the most economical wind turbines are chosen to fulfill this goal. Existing wind turbines are neglected as their energy production today is small (0.667 TWh in 2013) and as the model seems to identify well the existing wind parks (see chapter 4 - validation) [3]. Lastly, the order of the calculated LCOEs and technical aspects are assumed to be constant for 2020 as it is today. The results are shown in Fig. 5.

Without considering any constraints derived from land use planning, the whole energy production is strongly focused in two regions: one in the north-east of Baden-Württemberg and the other in the south-west. In the remaining regions of Baden-Württemberg, besides a few scattered wind parks in the south and south-east, no wind park can be found. This changes for a buffer of 3000 m. The energy production is now a little bit more widespread and less intense focused. Simultaneously, in the surroundings of the scattered wind producing communities, further wind parks can be found. This trend is going to accelerate for a buffer of 5000 m, leading to an even more widespread energy production across Baden-Württemberg.

4. Discussion

4.1 Discussion of results

In comparison with other studies for Baden-Württemberg, the technical potential found here is partially according to the technical potentials found in literature. McKenna et al. [8] estimate the technical potential in 2014 at 72.0 TWh, which was found to be 71.9 TWh in this study for the same size of ellipse but with an additional 600 km² of available land. Ref. [8] uses suitability factors and a wind power density function with an assumed ellipse of 5D x 8D. In another study, the

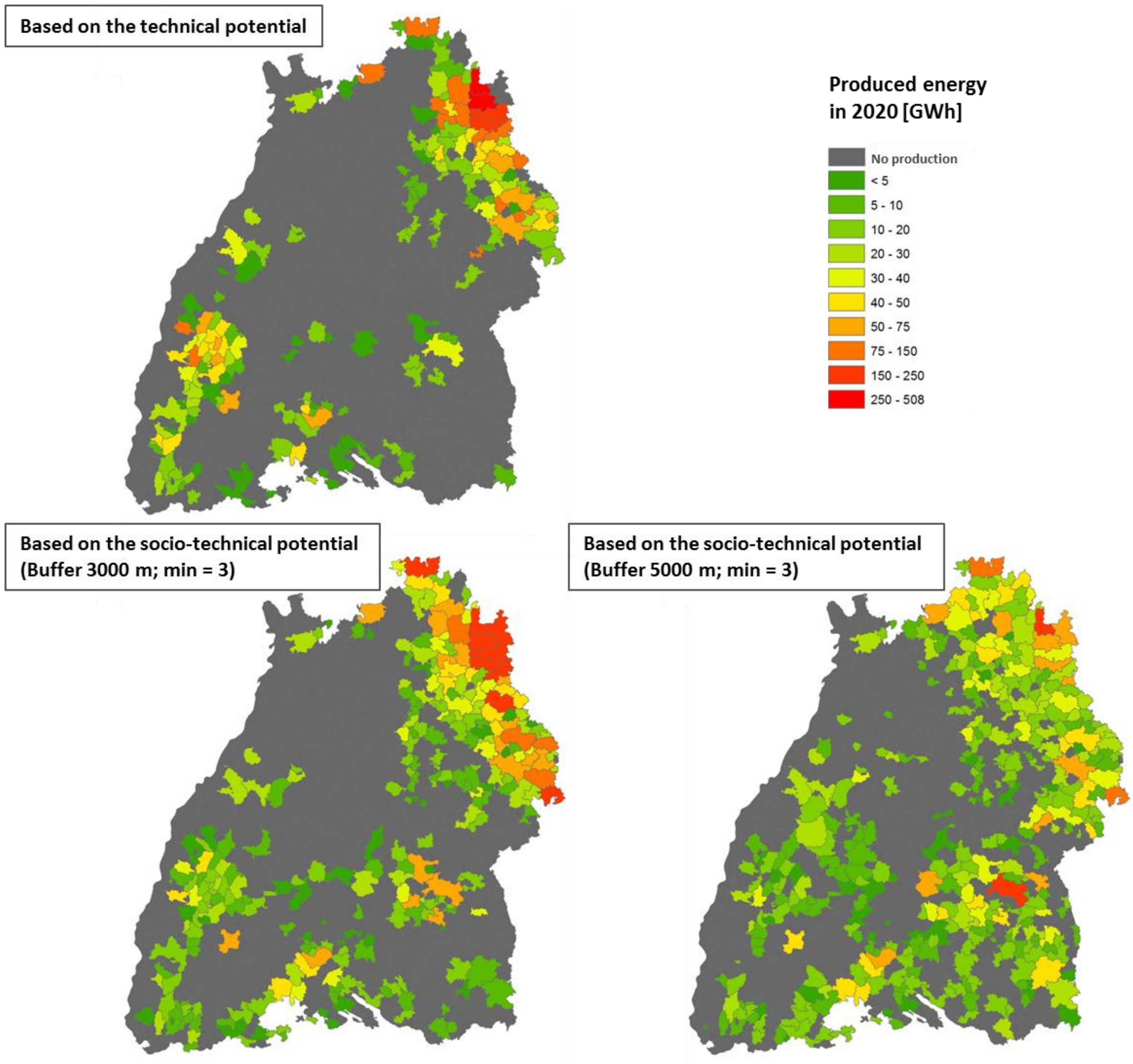

Figure 5. Produced energy in 2020 [GWh] by communities on most economic sites according to the goal of the federal government of Baden-Württemberg (6354 GWh) for the technical (top) and the socio-technical potential (below). Existing turbines are not considered (~ 667 GWh).

LUBW in 2013 calculates a total technical potential for Baden-Württemberg of 122.4 TWh [6]. LUBW uses a wind turbine placing algorithm with an ellipse of 3D x 5D without considering any constraints in terms of land use planning. The LUBW possess a better data basis (e.g. nightly military low flying operation routes, civil links), uses smaller and constant rotor diameters (100 m) with a nominal power of 3 MW and excludes areas with wind speeds less than 5.5 m/s at 140m. Hence, as the LUBW determines solely the technical potential based on different assumptions, a comparison with the current methodology is difficult.

After considering the social constraints, the socio-technical potential is determined between 11.8 and 29.4 TWh and therefore less than the half of the technical potential. Since land use constraints are land-consuming and eliminate a lot of available area, this result seems plausible but is not yet validated. To do so, the 2.500 most economical wind turbines determined by the algorithm are plotted exemplarily together with existing wind turbines and already planned wind parks in Fig. 6 for two different buffer zones of 3000 m and 5000 m for the administrative district Main-Tauber-Kreis. The majority of the wind turbines for a buffer of 5000 m seems to correspond well to the existing wind turbines and planned wind parks, even if not all wind parks are identified. The same can be stated for a buffer of 3000 m, although the quality is difficult to tell with respect to heavily scattered wind parks.

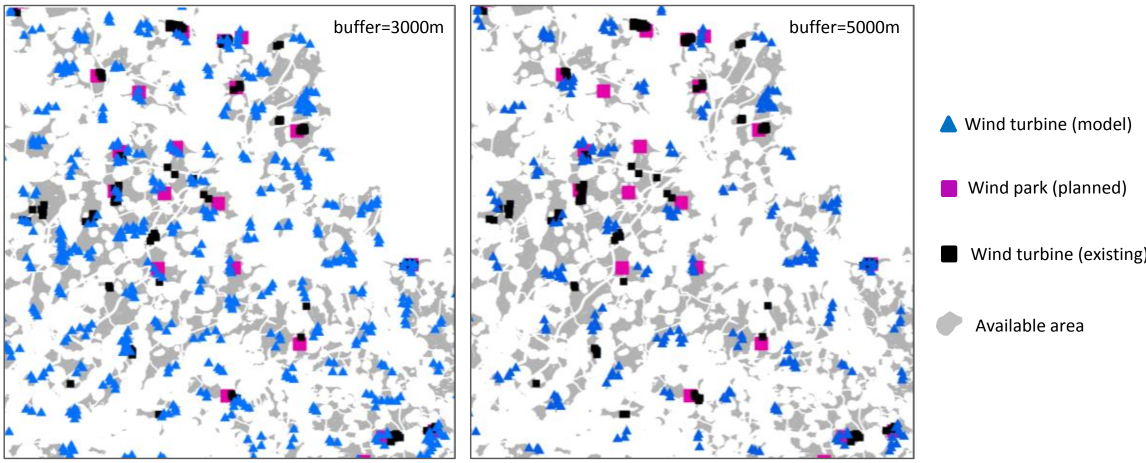

Figure 6. Wind turbines placed by the algorithm in comparison with existing wind turbines and planned wind parks in the Main-Tauber-Kreis.

Wind turbines are distributed more widely across the whole federal state of Baden-Württemberg for cost-potential curves based on the socio-technical potential than based on the purely technical potential. For grid extension planners and energy system modelers this is an important factor, since future occurring overproduction of wind energy is less concentrated in one region and additionally wind regimes of different administrative districts are not 100% correlated with each other. This may result in a more smoothed energy production, by exploiting the wind potentials in areas that are not, or inversely, correlated.

Furthermore, the sequence of wind turbines added by the wind park placing algorithm was investigated (Fig. 7). Two sequences for a buffer of 3000 m around the wind park, one with a minimum number of 3 (sequence a) and the other with a minimum number of 7 wind turbines (sequence b) are compared. Fig. 7 shows, that the curve of ‘sequence b’ runs above

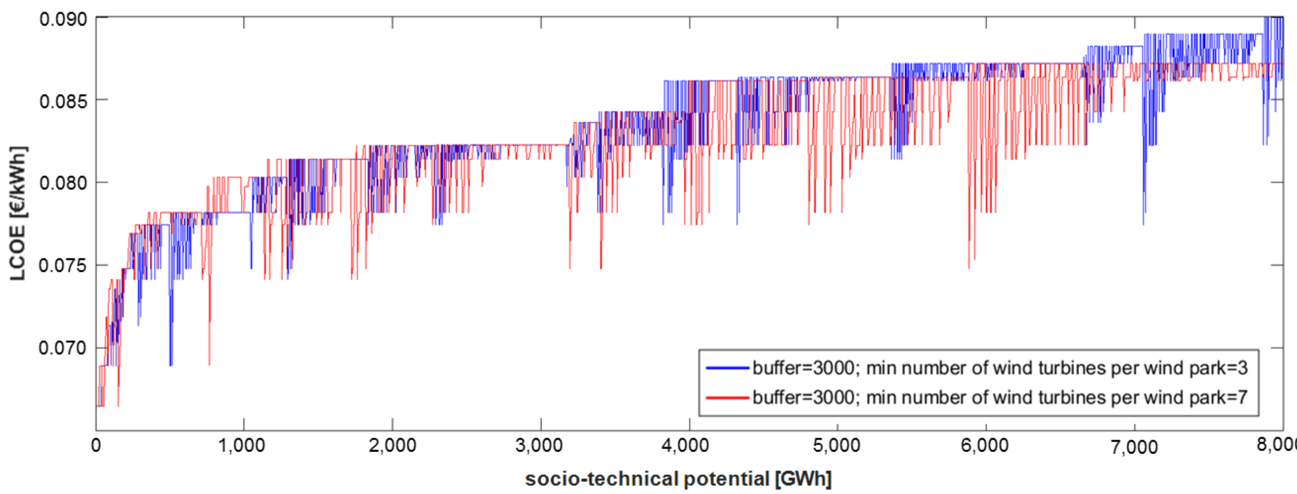

Figure 7. Wind turbines added by the algorithm for a buffer zone of 3000 m and two different minimum number of wind turbines per wind park.

the ‘sequence a’ in the beginning but gets overtaken by ‘sequence a’ between 3 and 4 TWh. Moreover, the amplitude of ‘sequence b’ fluctuates more strongly, which implies that in this case wind parks tend to consist of a mixture of very economical and less economical wind turbines. As market players usually try to maximize their profits, however, the commissioning of such wind parks can be doubted and ‘sequence b’ therefore assumed to be less realistic than ‘sequence a’ which leads to a reduced socio-technical potential.

4.2 Discussion of methodology

In this section, the developed and employed methodology is critically discussed and potential improvements are highlighted. First, the possibility to incorporate merging wind parks should be addressed. This fact causes errors each time when at least two wind-intensive sites are next to each other (see Fig. 2 in previous section), e.g. two hills with enough space for 3 wind turbines each and a distance between them of 3 km, whereas to merge would be more economical than to develop separately. In reality, however, this can also be interpreted as an acting of two competing market players or two market players with limited funds. In order to quantify this error, the conducted sensitivity analysis in terms of the minimum number of wind turbines per wind park may serve as a rough guide. According to that, the socio-technical potential varies strongly with the number of minimum wind turbines per wind park: 6.4 TWh for a buffer of 3000 m and 5.1 TWh for a buffer of 5000 m.

Another question is the quality of the wind data. The previously mentioned problem with wind turbines in the forest can also arise from incomplete wind speed data as the effect of turbulence is not taken into account [43]. A recent study, however, shows a velocity profile with a sudden move towards higher wind speeds in the height of 100 m in the transition from turbulent to laminar flow whose consideration could make an additional constraint such as minimum hub height obsolete [44]. Another possible error in this context is the wind speed resolution of 0.25 m/s. If the wind speed e.g. in 80 m and 100 m is the same, the gradient of the wind velocity profile is flat. Further, Ref. [43] indicates that the uncertainty in complex terrain structures can amount up to ± 0.25 m/s at 100 m and ± 0.40 m/s at 140 m.

Further issues with the methodology relate to the types of potentials assessed and the criteria employed to do so. One main novelty of this work lies in the application of quantitative data relating to the visual sensitivity of the general population, which alongside land use planning constraints are used to exclude areas unsuitable for wind parks. Hence areas that are considered especially beautiful, as well as those where there is resistance to planning processes, are excluded from the potential analysis. Hence these barriers, which result from aesthetic appreciation as well as land use planning, are taken as a proxy for social acceptance in the definition of the socio-technical potential. Whilst these criteria are thought to be indicative of a general tendency it is likely that there are deviations from this in specific areas. There are more aspects to social acceptance than aesthetics, so whilst this study represents a first attempt at accounting for social acceptance in large scale wind potential analysis, the limitations of this dataset should be borne in mind. Future work should therefore attempt to understand the representativeness of this dataset, derived from 300 photos and a questionnaire of 400 people [16], in accounting for social constraints in general.

Finally, the limited consideration of the economic potential, i.e. only the economical *assessment* of the socio-technical potential, should be mentioned. The LCOE criteria employed here is problematic for several reasons. Firstly, it takes the macro-economic perspective, that is, it does not aim at profit-maximization as in the case of most real-world wind projects. Instead, the LCOE method focused on cost-minimization and therefore does not account for the energy-political framework in the form of the EEG in Germany. When examined from the perspective of the investor other than the “central planner”, therefore, other locations would be favoured than the ones selected here. Secondly, the LCOEs as calculated here (cf. equation 4) do not consider all costs relevant to generation and integration of electricity from onshore wind, collectively known as the system costs and including cost positions such as grid, balancing and profile costs [41]. Whilst this is not significant for smaller proportions of wind in the electricity system, as the penetration becomes increases so too does the significance of these system costs. Thirdly, and related to this second point, is the fact that the LCOE approach takes no consideration of the respective location of wind energy generators with respect to one another. Hence the potential reduction of the system costs for the whole electricity/energy system, in this case Baden-Württemberg, e.g. through an exploitation of locations with a minimum or negative correlation of wind power, is not considered with this approach. Relatively recent changes in the German Renewable Energies Act (EEG), whereby direct marketing of electricity from wind is now an option, thus achieving higher revenues if the wind power is not highly correlated with the wholesale electricity market price. Another possibility to better account for the system costs could be made by considering further constraints such as distances to substations to account for costs of grid connection or the ownership structure of the land between the wind park and the grid connection point. This can be considered for example by excluding all available areas with a distance more than 10 km from a grid line or a substation, which was already proposed by [10], or the distances can be multiplied with the costs per meter of the cable. Fourthly, also the implementation of a further technical constraint regarding wind turbines in forests should be considered. Wind turbines in forests usually need higher hub heights to avoid turbulent flow conditions [42], but the application of just one economic decision parameter, in the form of the minimum LCOE, was not sufficient to regard this technical constraint. These are all aspects that should be addressed in future work, perhaps starting with an analysis of the generation profiles from a scenario set of possible wind parks and configurations.

5. CONCLUSION

Motivated by the lack of attention given to social restrictions in the large-scale assessment of wind energy potentials, this paper has proposed a new methodology to place wind parks based on graphic-theoretical considerations to account for rules of land use planning. In doing so, the term socio-technical potential was introduced to emphasize the importance of acceptance and bring the methodology into accordance with the existing definitions. The technical potential for Baden-Württemberg in this paper was found to be 71.9 TWh, which is largely in agreement with previous studies, whereas the socio-technical potential was estimated between 11.8 TWh and 29.4 TWh at costs between 7 and 14 €ct/kWh, strongly depending on the assumptions relating to wind park size and spacing. In addition, the dependency of the distribution of the future energy production of wind parks on the size of buffer zones was investigated and compared to the distribution of a future energy production on the basis of a purely technical potential. This resulted in a substantial spatial shift in the location of wind energy production, which is especially relevant in order to break the federal state target for wind energy down to the communal level. The results generated here thus represent crucial inputs to energy system models and the general energy-political discourse in the region. In order to test the quality of the wind turbine placing algorithm, already existing and planned wind parks were compared to modeled wind park locations, and a very good correlation could be observed. The bottom-up methodology is therefore considered to be appropriate for the present purpose but could be improved in future work to consider more technical, economic and social constraints. In particular, the focus should lie on the development of an economic criterion, which unlike the LCOE is able to account for the system costs of a widespread wind energy development, including network expansion, balancing power and reserve energy costs. To this end a better understanding of the (non-)correlation between potential sites for wind parks could help to identify a distribution of locations that, whilst individually partly economically suboptimal, are optimal from a systems perspective.

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REFERENCES

[1] *Klimaschutzgesetz Baden-Württemberg (KSG BW)*, January 2015.
[2] Parliament of Baden-Württemberg, “Integriertes Energie- und Klimaschutzkonzept Baden-Württemberg (IEKK),” [Online]. Available: http://tinyurl.com/nwh53ou, July 2014.
[3] Statistisches Landesamt, “Bruttostromerzeugung aus erneuerbaren Energieträgern,” [Online] Available: http://tinyurl.com/q3fejzf, 2015.
[4] Ministerium für Wirtschaft und Energie, “Zeitreihen zur Entwicklung der erneuerbaren Energien in Deutschland,” [Online] Available: http://tinyurl.com/k2ajdly, 2015.
[5] R. McKenna, S. Gantenbein, W. Fichtner, “Determination of cost-potential-curves for wind energy in the German federal state of Baden-Württemberg,” Energy Policy, vol. 57, pp. 194-203, 2013.
[6] Landesanstalt für Umwelt, Messungen und Naturschutz Baden-Württemberg (LUBW). “Potenzialanalyse,” [Online] Available: http://tinyurl.com/kgu6vbk, 2013.
[7] J. Schallenberg-Rodríguez, J. Notario-del Pino, “Evaluation of on-shore wind techno-economical potential in regions and islands,” Applied Energy, vol. 124, pp. 117-129, 2014.
[8] R. McKenna, S. Hollnaicher, W. Fichtner, “Cost-potential curves for onshore wind energy: A high-resolution analysis for Germany,” Applied Energy, vol. 115, pp.103-115, 2014.
[9] Umweltbundesamt (UBA), “Potenzial der Windenergie an Land: Studie zur Ermittlung des bundesweiten Flächen- und Leistungspotenzials der Windenergienutzung an Land,” UBA, Dessau-Roßlau, June 2013.
[10] N. Fueyo, Y. Sanz, M. Rodrigues, C. Montañés, C. Dopazo, “The use of cost-generation curves for the analysis of wind electricity costs in Spain,” Applied Energy, vol. 88, pp. 733-740, 2011.
[11] V. Gass, J. Schmidt, F. Strauss, E. Schmid, “Assessing the economic wind power potential in Austria,” Energy Policy, vol. 53, pp. 323-330, 2013.
[12] K. Nguyen, “Wind energy in Vietnam: Resource assessment, development status and future implications,” Energy Policy, vol. 35, pp. 1405-1413, 2007.
[13] R. McKenna, S. Hollnaicher, P. Ostman v. d. Leye, W. Fichtner, “Cost-potentials for large onshore wind turbines in Europe,” Energy, vol. 83, pp. 217-229, April 2015.
[14] M. Hoogwijk, B. de Vries, W. Turkenberg, “Assessment of the global and regional geographical, technical and aconomic potential of onshore wind energy,” Energy Economics, vol. 26, pp. 889-919, 2004.
[15] K. Molnarova, P. Sklenicka, J. Stiborek, K. Svobodova, M. Salek, E. Brabec, “Visual preferences for wind turbines: Location, numbers and respondent characteristics,” Applied Energy, vol. 92, pp. 269–278, April 2012.
[16] F. Roser, “Entwicklung einer Methode zur großflächigen rechnergestützten Analyse des landschaftsästhetischen Potenzials,” Ph.D. dissertation, Dept. Architektur und Stadtplanung, Univ. Stuttgart, Germany, Berlin: Weißensee Verlag, 2011.
[17] Regionalverband Donau-Iller, “Regionalplan – 4. Teilfortschreibung Nutzung der Windkraft,” [Online] Available: http://tinyurl.com/mmdgea5, 2009.
[18] Regionalverband Südlicher Oberrhein, “Regionalplan Südlicher Oberrhein – Kapitel “Windenergie” 2006,” [Online] Available: http://tinyurl.com/mtwv4wg, 2011.
[19] M. Kaltschmitt, *Erneuerbare Energien: Systemtechnik, Wirtschaftlichkeit, Umweltaspekte*, 5th ed., Ed. Berlin, Berlin: Springer Vieweg, 2013.
[20] O. Grothe, F. Müsgens, „The influence of spatial effects on wind power revenues under direct marketing rules,“ Energy Policy, vol 58, pp. 237-247, July 2013.

[21] Landesamt für Geoinformation und Landesentwicklung Baden-Württemberg (LGL). DLM-25 BW ATKIS.
[22] Landesanstalt für Umwelt, Messungen und Naturschutz Baden-Württemberg (LUBW). Daten aus dem Räumlichen Informations- und Planungssystem (RIPS). [Online] Available: http://udo.lubw.baden-wuerttemberg.de/public/. 2014.
[23] Forest Research Institute of Baden-Württemberg (FVA). Windkraft und Auerhuhn. [Online]. Available: http://tinyurl.com/mbaem3k,
[24] Landesanstalt für Umwelt, Messungen und Naturschutz Baden-Württemberg (LUBW). Verbreitungskarten Artenvorkommen. [Online] Available: http://tinyurl.com/pf59l65, 2014 .
[25] Landesanstalt für Umwelt, Messungen und Naturschutz Baden-Württemberg (LUBW). Wie werden Vögel und Fledermäuse bei der Planung von Windenergieanlagen geschützt. [Online] Available http://tinyurl.com/o8eydj7, 2015.
[26] Juwi, „Windkraft im Wald," 5. Fachkonferenz des Deutschen Städte- und Gemeindebundes, [Online] Available: http://tinyurl.com/k87q68b, 2012.
[27] R. Gasch (ed.), *Windkraftanlagen – Grundlagen, Entwurf, Planung und Betrieb*, 6th ed., Ed. Wiesbaden, Wiesbaden: Vieweg + Teubner, 2010.
[28] Landesamt für Geoinformation und Landesentwicklung Baden-Württemberg (LGL). DGM-25.
[29] Landesanstalt für Umwelt, Messungen und Naturschutz Baden-Württemberg (LUBW). Kriterienliste Windpotenzial. [Online] Available http://tinyurl.com/o8nee5u, 2011.
[30] E. Hau, *Windkraftanlagen: Grundlagen, Technik, Einsatz, Wirtschaftlichkeit,* 5th ed., Ed. Berlin, Heidelberg: Springer Vieweg, 2014, pp. 555-557.
[31] M. Ali, J. Matevosyan, J.V. Milanović, "Probabilistic assessment of wind farm annual energy production," Electric Power Systems Research, vol. 89, Issue 1, pp. 70–79, 2012.
[32] N. Conroy, JP Deane, P. Brian Ó Gallachóir, "Wind turbine availability: Should it be time or energy based? – A case study in Ireland," Renewable Energy, vol. 36, Issue 11, pp.2967–2971, Nov. 2011.
[33] A. Graves, K. Harman, M. Wilkinson, R. Walker, "Understanding availability trends of operating wind farms," unpublished, presented at the AWEA Windpower Conference, Housten, June 2008. [Online]. Available: http://www.gl-garradhassan.com/assets/downloads/AvailabilityTrends_AWEA2008(2).pdf.
[34] M.J. Grubb and N.I. Meyer, "Wind energy: Resources, systems and regional strategies," in: T.B. Johansson, H. Kelly, A.K.N. Reddy, R.H. Williamds (eds.), Renewable Energy-Sources for Fuels and Electricity, Washington D.C.: Island Press, pp. 157-212, 1993.
[35] F. González-Longatt, P. Wall, V. Terzija, "Wake effect in wind farm performance: Steady-state and dynamic behavior," Renewable Energy, vol. 39, Issue 1, pp. 329-338, March 2012.
[36] I. Staffel, R. Green, "How does wind farm performance decline with age?," Renewable Energy, vol. 66, pp. 775–786, June 2014.
[37] I. Staffel, R. Green, "Supplementary Material to 'How does wind farm performance decline with age?'," Renewable Energy, vol. 66, pp. 775–786, June 2014.
[38] P. Konstantin, *Praxisbuch Energiewirtschaft: Energieumwandlung, -transport und -beschaffung im liberalisierten Markt*, 2nd ed. Ed. Berlin, Heidelberg: Springer, 2009.
[39] Deutsche WindGuard, "Kostensituation der Windenergie an Land in Deutschland," Varel: Deutsche WindGuard, [Online] Available: http://tinyurl.com/ktafln4, November 2013.
[40] F. Roser, "Vielfalt, Eigenart und Schönheit – eine landesweite Planungsgrundlage für das Schutzgut Landschaftsbild," *Naturschutz-Info*, vol. 1, pp. 23-29, 2013.
[41] F. Ueckerdt, L. Hirth, G. Luderer, O. Edenhofer, "System LCOE: *What are the costs of variable renewables?*," Energy, vol. 63, pp. 31-75, December 2013.
[42] T. Arnold, „Bei Waldstandorten für Windenergieanlagen differenzieren," EW Magazin für die Energiewirtschaft, Heft 19 (Jg. 111), pp.60-61, 2012.
[43] Ministerium für Umwelt, Klima und Energiewirtschaft Baden-Württemberg, „Windatlas Baden-Württemberg," [Online] Available http://tinyurl.com/lgxhk75, June 2011.
[44] P.H. Meier, "Forschungsmast liefert vielversprechende Ergebnisse," in BWK das Energiefachmagazin, vol. 9, pp. 58-61, 2014.

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