

The feasible onshore wind energy potential in Baden-Württemberg: A bottom-up methodology considering socio-economic constraints



Tobias Jäger, Russell McKenna^{*}, Wolf Fichtner

Chair of Energy Economics, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany

ARTICLE INFO

Article history:

Received 14 September 2015

Received in revised form

30 April 2016

Accepted 3 May 2016

Available online 15 May 2016

Index Terms:

Power generation economics

Wind energy

Social barriers

Cost-potential curves

Potential analysis

ABSTRACT

Detailed information about the potential and costs of renewable energies is an important input for energy system models as well as for commercial and political decision-making processes. Especially wind energy with its increasing locally installed capacity and hub heights plays an important role when it comes to meeting climate targets and optimizing electricity networks. Recently however, wind energy has faced more and more social barriers and land use constraints which can negatively impact both political goals and investment decisions. Therefore this work presents a bottom-up methodology to estimate these effects by calculating the feasible potential and the associated costs for the German federal state of Baden-Württemberg as a case study. Landscape aesthetical aspects are considered and an algorithm applied based on graph-theoretical considerations to include spatial planning rules such as separation distances between wind farms. By means of spatially high-resolution land use data and techno-economic parameters, possible wind turbines are placed considering wind direction and variable spacing between turbines. In a further step, possible farm sites are located and assessed, and the result is presented in the form of cost-potential curves. The feasible potential is found to be between a third and a half of the technical potential and is between 11.8 and 29.1 TWh, with costs between 6.7 and 12.6 €/ct/kWh. In addition, a substantial spatial shift in the location of future wind energy production can be observed when wind farm spacing is taken into account. The quality of the algorithm is tested against already existing wind farms and areas that are approved by regional authorities for the use of wind energy, and a very good correlation is observed. The focus in future work should lie on the development of an economic criterion that, unlike the leveled cost of electricity (LCOE), is able to account for the system costs of a widespread wind energy development, including network expansion, balancing power and reserve energy costs. Further, visibility analysis could be implemented using digital elevation models to consider the topography for optimal wind farm spacing.

© 2016 Elsevier Ltd. All rights reserved.

1. Introduction

In the context of European, national and regional energy policies and targets, Germany 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, renewable energy capacities already accounted for 25.6% of the gross electricity production for the whole of Germany, whereby significant regional differences between the sites of the renewable energy sources can be observed [1]. Wind farms can be predominantly found in the north of

^{*} Corresponding author.

E-mail addresses: tobias.jaeger2@kit.edu (T. Jäger), mckenna@kit.edu (R. McKenna).

Germany, which is geographically characterized by the North German Lowlands and, due to the geographic proximity to the North and Baltic Seas, represents the windiest region. In the south of Germany, however, photovoltaic and hydropower is more prevalent due to higher global irradiation and favorable geographical locations respectively. For instance, in the federal state of Baden-Württemberg, situated in the south west of Germany, the generated electricity in 2013 by means of photovoltaic and hydropower was 3.9 TWh (6.4% of the gross power generation) and 5.6 TWh (9.1%) respectively [2]. Electricity produced by wind turbines only amounted to 0.7 TWh (1.1%), generated by 386 turbines with a total installed capacity of 544 MW. This relatively small amount of energy is due to less favorable wind sites and is often associated with a restrictive legislative framework in terms of spatial planning procedures, within which so called Public Planning

Nomenclature of symbols

$\eta_{\text{availability}}$	efficiency to account for downtime of a wind farm, [%]
η_{op}	efficiency to account for suboptimal control systems and misaligned components, [%]
η_{wake}	efficiency to account for losses due to wake effects in a wind farm, [%]
η_{windpark}	efficiency of the whole wind farm, [%]
ϕ_R	Rayleigh distribution, –
ϕ_W	Weibull distribution, –
A	scale factor of the Weibull distribution, –
d	degradation of the energy output of a single wind turbine per year, [%/year]
$E_{t,el}$	annual energy yield of a wind turbine, [kWh]
i	interest rate, [%]
I_0	investment, [€]
k	shape factor of the Weibull distribution, –
$LCOE$	levelized cost of electricity, [€/kWh]
n	economic operational lifetime, –
OC_t	operating costs in year t , [€/year]
$P_j(v)$	power curve of turbine j , [kW]
t	year, –
T	total number of full load hours per year, [h]
v	wind speed, [m/s]
v_m	mean wind speed, [m/s]

Organizations can approve and exclude specific areas for wind energy developments [3]. Table 1 provides an overview of some pertinent data relating to Baden-Württemberg.

In order to foster the expansion of onshore wind energy, the legislative framework in terms of spatial planning was revised in 2012 by the federal state government of Baden-Württemberg. At the time of writing areas cannot be excluded that straightforwardly and local communities can also plan additional areas for wind energy, whereby coordination with the regional Public Planning Organization has to be maintained [3]. Additionally, the federal state parliament enacted a law in 2013 obligating itself to reduce greenhouse gases by 25% and 90% by 2020 and 2050 respectively, in comparison to 1990 [4]. To achieve these goals an action plan was set up, which includes different expansion targets for renewables. Especially the goals for onshore wind energy, with a targeted electricity production of 6.4 TWh in 2020 and 18.1 TWh in 2050, are highly ambitious [5]. These ambitious goals have been accompanied by a continuing debate about the various potential, costs, social acceptance and land use constraints of onshore wind energy in



Fig. 1. Overview of the regional catchment areas of the regional Public Planning Organizations in Baden-Württemberg.

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.

Against the background of the literature review in section 2, the present study develops and applies a bottom-up methodology to estimate the wind potential and the associated costs on a wind farm level, which explicitly considers some of the constraints associated with social acceptance. A geo-referenced database containing information about landscape aesthetic aspects [6] is used and constraints derived from rules of spatial planning are employed. The latter comprises rules that should prevent scattered wind turbines (promote concentration zones with at least three wind turbines) and too many wind turbines at a certain site (spacing between wind farms) to account for landscape aesthetic aspects, amongst other things [7–9]. These rules are considered to be an accurate indicator to anticipate social barriers on a regional

Table 1

Overview of some pertinent data relating to Baden-Württemberg. Values refer to the year 2013 [2,5].

Socio-economic data		Present energy related data		Political goals	
Population total	10.5 Mio.	Power generation in TWh from		Onshore wind energy production in TWh	
Population density	300/km ²	Photovoltaic	3.9	in 2020	6.4
Gross domestic product (GDP)/cap.	38716 EUR	Wind	0.7	in 2030	14.5
		Hydro	5.6	in 2040	17.8
		Biomass	4.2	in 2050	18.1
		Nuclear	20.1		
		Coal	20.0		
		Others	7.0		
		Sum of own generation in TWh	61.6		
		Total electricity demand in TWh	77.9		
		Electricity imports in TWh	16.3		

level (see Fig. 1), since regional Public Planning Organizations in Baden-Württemberg are elected democratically by either district/city councils or directly by the population and also consider public participation to set up their regional plan [10]. Whilst this approach does not take into account social barriers and support on a local level in detail, it is thought to be indicative of a general tendency with some deviations in specific areas.

Furthermore, the methodology includes other novelties like considering prevailing wind directions and variable spacing between wind turbines to enable the use of different wind turbines with different rotor diameters. Wind speed data with a spatial resolution of 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 farms over the operation time which results in a lower energy output and higher costs are also considered. Wind turbines in forests are addressed especially by taking into account a minimum hub height due to turbulences. The method is implemented in the geographical information system ArcGIS and MATLAB®.

The paper is structured as follows: first an overview of relevant literature on the socio-economic aspects of and cost-potentials for wind energy is given in section 2. Then the definition of the term 'potential' is discussed and the methodology to determine the feasible potential is presented in section 3. In section 4, the results are presented and a sensitivity analysis is conducted. Subsequently, these results are discussed in section 5. The paper closes with a conclusion in section 6.

2. Literature review

This section reviews the relevant literature on the socio-economic aspects of onshore wind energy. It begins in subsection 2.1 by examining the different social acceptance effects, before presenting relevant cost-potential studies in subsection 2.2.

2.1. Social acceptance of wind energy

A large and growing body of literature deals with the social acceptance of wind energy projects. Most contributions in this area focus on some or all of three types of effect [11]: visual impacts on the landscape, shade and noise effects on human health, and biodiversity effects. The remainder of this section is primarily concerned with the former type of effect; for a meta-analysis of the effects of wind turbine noise on sleep and quality of life, the reader is referred to [12], and for a review of all types, to [13].

The journal Energy Policy published a Special Section on “Social Acceptance of Renewable Energy Innovation” (2011, 35, 5, pp. 2683–2810), which contains several contributions relating to onshore wind energy (e.g. Refs. [14–16]).

Jobert et al. [14] carried out five case studies in Germany and France in order to identify and analyze the success factors for winning the acceptance of wind parks on a local level. They distinguished between two categories of factors, namely institutional conditions, including incentives and regulations, and site-specific conditions, including local economy and geography, actors and the on-site planning process. Their case studies confirm the key factors affecting social acceptance from the literature, including visual impact, ownership, information and participation. Their insights also stress the importance of a local integration of the developer, the creation of a support network around the project and access for the community to ownership of the park. Finally, they found that barriers are much higher in France than in Germany due to different energy-political support frameworks and legal/

planning restrictions.

Van der Horst [15] identified six variables that “can hamper the comparison between different public perception studies” and concluded that proximity to a proposed renewable energy project has a strong influence on public attitudes, but their nature and extent vary according to the local context and value of the land. Hence communities that feel attached to their local landscape are more likely to exhibit lower social acceptance of proposed projects. This study also highlights the problem of cognitive biases that is often encountered in surveys, whereby amongst other things the expressed responses of the interviewees may be influenced by their ethical judgement of the question and therefore do not necessarily reflect how they would or do act.

Breukers and Wolsink [16] compared experiences in wind power implementation in the Netherlands, England, and the German state of North Rhine Westphalia. The comparison focuses on the conditions that affect the local planning contexts, i.e. the level at which social acceptance (or lack of it) often manifests itself. In all three contexts social acceptance is seen as being problematic and not recognized enough by policymakers or wind project developers. One solution is to facilitate ownership through and involvement of the local community in order to better recognize multiple, partly conflicting interests at the local level. Musall and Kuik [17] took this as a starting point to explore whether such effects can also be demonstrated in a community co-ownership model. They find that, compared to a case without community ownership (or co-ownership) the level of local acceptance in the local community is higher.

Numerous other studies have examined the social acceptance of wind energy plants in case studies of specific regions. For example, Liu et al. [18] used the theory of planned behavior with a logit model to examine the determinants of social acceptance of renewable energy deployment in Shandong Province, China. They found that the probability of a positive attitude towards such projects increases with household income, individual knowledge level and beliefs about the costs of renewable energy, but decreases with age. The small sample size limits the applicability of the results, as the authors themselves state: the three selected villages are quite closely located and have similar economic and geographic backgrounds.

In addition, Jones et al. [19] carried out multiple regression analyses on survey data obtained in a region of the UK (Humberhead Levels) simultaneously subject to nine wind farm proposals. They found that the majority of respondents would endorse some local development, but there was considerable variability in the upper level (of capacity) that was considered acceptable. Prominent predictors include the general attitude, perceived knowledge of wind power, community attachment and environmental values.

The distance from and frequency of encounters with wind turbines seems to play a decisive role in social acceptance. For example, 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 [20]. In addition, peoples' attitudes towards wind turbines depend on the number of turbines they encounter on a daily basis, whilst the negative impact of these sightings does not appear to increase above five each day [21]. Similarly, for the distance from the observer (in terms of residential buildings, landmarks, observation points) there seems to be an upper threshold, above which the negative visual impact of wind turbines disappears: 10 km for the most attractive landscape and 5 km for the least attractive one [22]. The survey in the latter study was carried out solely with students, so the results should be treated with caution.

One of the most relevant contributions in the present case is

that of Drechsler et al. [11], which combines spatially-explicit ecological-economic modelling and choice experiments to determine the welfare-optimal spatial allocation of wind turbines in West Saxony, Germany. The results indicate that the external costs represent about 14% of the overall costs (production plus external) and locating wind turbines purely based on production costs would imply (much) higher external costs. In the study region the distance to settlements (of the turbine) and the impact on a focal species (red kite) are significant externalities, on the other hand the wind park size and the height of turbines are not. This seems to be one of the first studies to combine two distinct research threads on externalities of onshore wind and spatial planning of wind turbines respectively. Some of the weaknesses of this approach, as highlighted by the authors, include for example the lack of consideration of on-site management and wind directions, both of which could change the collision risk for birds. In addition, the interactions between the considered externalities, as well as other externalities, are overlooked, and the sample is socio-demographically different from the population of West Saxony, for which it is taken to be representative. Finally, compared to the present study, Drechsler et al.'s [11] techno-economic modelling of the wind turbines is quite rudimentary: they only consider two turbine types, do not aggregate turbines into wind parks, and overlook wind park losses.

2.2. Cost-potential studies for wind energy

Several studies have examined the technical potential and related costs for onshore wind energy in Baden-Württemberg or for Germany as a whole [23–26]. 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 [23,25,27–32]. 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 [24,26,33]. 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 [25]. The disadvantages are discussed in detail in section 5.2. Table 2 provides an overview of the relevant studies, which mostly analyze the technical potential (often from an economic perspective), as well as the present study.

Hence the present contribution combines two separate areas of research relating to onshore wind energy. The first relates to the social acceptance, in terms of landscape aesthetics, and the second is the area of cost-potential studies, which until now have largely overlooked social aspects. In the next section the methodology is presented.

3. Methodology

This section is subdivided into three subsections. The first subsection gives an overview of the different types of 'potential'. Secondly, the total available area is calculated by using a criteria catalogue to extract unsuitable areas and on basis of that, wind turbines following a LCOE minimization criterion are placed to determine the technical potential. Thirdly, wind farms are located and the feasible potential and associated costs are determined to

derive the cost-potential-curve on a wind farm level.

3.1. The definition of the term 'potential'

In line with [32] and [34] the term 'potential' is broadly distinguished into either four categories, namely, the theoretical, the technical, the economic and the feasible potential, or into five categories if the geographical potential is also considered. These terms can be defined as follows:

- *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 energy in the wind over land in Baden-Württemberg in a year.
- *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.
- *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.
- *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 a 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 [35]. As a consequence, the assessment of the technical potential in terms of the economic feasibility turns into a non-trivial case by case decision.
- *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 local community acceptance of landscape-aesthetical aspects in Baden-Württemberg.

Hence by employing these definitions each successive potential can be interpreted as a subset of the preceding potential¹. Consequently, if social aspects are to be taken into account, the economic potential has to be determined first. To consider the importance of acceptance and reduce the complexity by calculating the economic potential in detail, a few assumptions have to be made to estimate

¹ In some cases the feasible potential may be larger than the economic potential due to market distortions such as economic support for renewables, e.g. in the form of feed-in tariffs.

Table 2

Overview of relevant studies that have analyzed the onshore wind energy potential.

Source	Area analyzed	Potential determined/ analyzed	Method
McKenna et al. [23]	Baden-Württemberg	Technical, economically analyzed	Power densities using single turbine types.
LUBW ^a [24]	Baden-Württemberg	Technical	Wind turbine placing algorithm with a single wind turbine.
McKenna et al. [25]	Germany	Technical, economically analyzed	Power densities using a minimal generation costs criterion and a set of different turbines.
UBA ^b [26]	Germany	Technical-ecological	Wind turbine placing algorithm using a maximum full load hour criterion for two different turbine types.
Schallenberg-Rodríguez and Notario-del Pino [33]	Canary Isles	Technical	Wind turbine placing algorithm using a single wind farm configuration layout for a reference turbine.
Fueyo et al. [27]	Spain	Technical	Power densities using single turbine types.
Gass et al. [28]	Austria	Technical	Power densities using single turbine types.
Siyal et al. [29]	Sweden	Technical	Power generation of a single wind turbine within a cluster of 1 km × 1 km
Nguyen et al. [30]	Vietnam	Technical	Power densities using a single turbine.
McKenna et al. [31]	Europe	Technical, economically analyzed	Power densities using a minimal generation costs criterion for large turbines (>3 MW).
Hoogwijk et al. [32]	Worldwide	Technical, economically analyzed	Power densities using a linear relation between wind speed and full load hours.
Present 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

^a LUBW: Federal State Institute for Environment Measurement and Nature Conservation Baden-Württemberg.^b UBA: Umweltbundesamt [German Federal Environment Agency].

the feasible potential. Firstly, the market design is assumed to be not complex, meaning only one feed-in-tariff exists without any market premiums available. Thus, the trajectory of wind energy can be assumed as mainly driven by only one economic parameter such as the levelized costs of electricity (LCOE). Secondly, as mentioned above, the rules of spatial planning in combination with the landscape-aesthetical aspects are assumed to be a good indicator to anticipate social barriers. Thirdly, it should be noted that the strict definition of the technical potential given above is relaxed slightly in this paper. This is because of the need to define a decision variable, e.g. the LCOE, to place the wind turbines and wind farms. It should therefore be borne in mind that the technical potential is, strictly speaking, additionally assessed economically. This was also done previously for the technical potential in Ref. [25].

3.2. The technical potential

In this subsection, the technical potential, more precisely the technical potential economically assessed, is calculated. The available area is determined in a first step and in a second step the costs and energy yields of the optimal turbine for each site following a LCOE minimization criterion is calculated. In a last step, the wind turbines are placed and the technical potential can be calculated.

3.2.1. Determination of the available area

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) [36]. 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 [37]. 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) [38]. Other animal species that are considered as sensitive to wind turbines according to [39] 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 [40].

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 [41] and areas with a maximum slope of 20° and above are excluded [42]. The calculation of the latter is carried out with the digital elevation model (DGM-25) of the LGL [43] with a spatial resolution of 25 m. An overview of the excluded areas and buffers employed in this study is given in Table 3.

3.2.2. Calculation of the energy yield and the LCOEs

The available area is 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 data for the prevailing wind direction and with a dataset containing information about the land use attribute 'forest'. The wind speeds are derived from the RIPS with a spatial resolution of 50 m and are clustered into 0.25 m/s intervals from '<4.50 m/s', '4.50–4.75 m/s', and so on up to '>7.50 m/s' [37]. 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 [45]. The data for the prevailing wind directions are derived from the anemos Wind Atlas by evaluating wind time series with a time resolution of 10 min and a spatial resolution of 20 km since 1990 [46]. Hence wind roses with sixteen segments are used to evaluate the prevailing wind directions. The data of the land use information 'forest' is derived from Ref. [36]. This extra information is required due to the quality of the wind speed data, which is not complete as effects of local turbulence are not taken into account [47]. As velocity profiles, however, show a sudden move towards higher wind speeds in the height of 100 m in the transition from turbulent to laminar flow in forests, an additional technical constraint such as minimum hub height seems reasonable [48]. According to [49] the minimum hub height is set to 100 m.

On the basis of this data, the optimal wind turbine for each site can be calculated. The procedure starts by calculating the wind speed distributions at the relevant hub heights, as the average wind speeds are given. In general, the wind speed distribution can be

Table 3

List of applied criteria for exclusion and excluded areas within the distance around the area itself in meters (Own illustration based on [44]).

Category	Distance (m)
<i>Urban areas and special buildings</i>	
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 stations	15000
<i>Traffic areas and infrastructure</i>	
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
<i>Mineral planning</i>	
Mining operation, open-pit-mining, quarry	0
<i>Water protection</i>	
Flood zone	0
Water body >6 m and of 1. order	10
Water protection zone I/II	0
Mineral springs	0
<i>Agriculture and forestry</i>	
Avalanche forest and Schonwälder	200
<i>Protected areas</i>	
Biosphere areas – core zone	200
Biosphere areas – cultivation zone	0
Bird protection areas	700
Wood grouse cock (category 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
<i>Not in List</i>	
Nightly military low flying operation routes	–
Civil radio link	–
Recreational forest	–
Special protection areas (e.g. red kite, black kite, bats)	

calculated with the Weibull distribution Φ_W :

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

where k is the shape factor of the Weibull distribution, A the scale factor of the Weibull distribution, and v 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 [45]:

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

where v_m is the mean wind speed [m/s]. As the wind speed distribution is known, the annual electricity generation can be determined by using Eq. (3) [50]:

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

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

The wind farm efficiency is 85% comprising energy losses due to operating losses such as sub-optimal control systems and misaligned components ($\eta_{op} = 98\%$) [45,51], non-availability ($\eta_{availability} = 97\%$) [53–54] and assumed wake effects ($\eta_{wake} = 90\%$). The latter assumption is strongly simplified, neglecting interdependencies between wind farm size and wind farm arrangement as Table 4 exemplarily shows for different wind farm sizes [52,55].

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 between 0.4% and 1.1% per year for newer turbines (commissioned between 2002 and 2007) [56,57]. 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

Table 4

Typical array efficiency for different size and spacing of square arrays (non-directional wind regime) [52].

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

outputs, this can be done with Eq. (4) [58]. 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% [59]. The economic operational lifetime is assumed to be 20 years.

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

where I_0 is the investment expenditures [€], OC_t the operating 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 [59]. 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 accurately calculate the LCOE based on these specific investments according to Eqs. (3) and (4). Instead, a methodology is used which is described in detail in Ref. [25] 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. [59] the operating costs are 2.41 €/Cent/kWh for the first ten years and 2.68 €/Cent/kWh for the next ten years.

On the basis of this data, the optimal turbine (minimal LCOE) can be calculated, resulting in a grid of optimal wind turbines containing all techno-economical parameters as well as information about the prevailing wind direction.

3.2.3. Determination of the technical potential

As all optimal wind turbines are given, the wind turbine placing algorithm can be applied, which can be described in four main steps. As a starting point, the (geographically) leftmost point in the grid of optimal wind turbines with the minimum LCOE is selected (step 1). This grid point is then marked as ‘wind turbine’ (step 2) and, to account for energy losses through wind shadowing from upstream machines, an ellipse around this point is drawn, which is accordingly aligned to the prevailing direction (step 3). The spacing selected here is 8 rotor diameters in the prevailing and 3 rotor diameters in the crosswind direction respectively, which corresponds approximately to the assumed wake losses above. All grid points within this ellipse will then be marked as ‘inactive’ and no wind turbine can be placed (step 4).

The algorithm will then start again with step 1 by searching the next (geographically) leftmost point in the grid with the minimum LCOE, and so on. This procedure is repeated until all grid points are either marked as ‘wind turbine’ or ‘inactive’. The energy that can be produced by all points marked as ‘wind turbine’ is the technical potential economically assessed. A schema of how the wind turbines are placed is shown in Fig. 2.

3.3. The feasible potential

In order to anticipate possible opposition due to landscape aesthetical aspects, landscapes that are considered to be particularly beautiful, unique and/or original are excluded. This is done by using the geo-referenced results of a pilot project for Baden-Württemberg [6] based on a methodology developed in Ref. [60] to compute and assess the landscape-aesthetical potential of larger areas. In a first step, the methodology analyzes all important characteristics of a landscape such as topography, land use, water body, viniculture, high-voltage transmission line, major streets, industrial and commercial area and even woodland borders to evaluate representative areas to be examined. In a second step, photographs of 300 different areas were taken [6], considering inter alia season, image layout and weather conditions such that the character of the photos can be considered to be comparable and neutral. On this basis, a survey with 400 participants was conducted, including a selection of representatives of parliament, experts and average citizens, assessing the photographs in 12 sessions by giving each photo a value between 0 and 10, where a 10 means an extraordinary quality of the landscape. Subsequently, each photograph was evaluated by calculating the arithmetical mean revealing a high level of consistency between the participants. The results could be confirmed by control groups such that they are interpreted as being inter-subjectively valid. In a last step, a regression analysis was carried out between the survey results and the structural characteristics of the areas defined above. The result was a set of parameters and a regression model that can describe what is meant above by a particularly beautiful, unique and/or original landscape. By means of this regression model an analysis across the whole federal state was conducted to assess the landscape aesthetical quality. The result was a geo-referenced map and is available with a spatial resolution of 100 m, with information about the quality of the landscape quantified by values between 0 and 10 (Fig. 3.). On basis of this, outstanding landscapes can now be excluded based on a statistical threshold that is defined by the arithmetical mean plus the standard deviation [6].

After extracting these areas, further – more wind-farm-specific – constraints derived from rules of spatial planning, such as avoiding scattered wind turbines (concentration zones) and too many wind turbines at certain sites are incorporated. Therefore, a minimum and maximum number of wind turbines that can form a wind farm as well as a spacing between wind farms are assumed. The minimum wind farm size according to rules of spatial planning requires in practice mostly three wind turbines [7–9] whereas the maximum wind farm size is assumed to be twenty in the present study. The minimum spacing distance between wind farms is, according to rules of thumb applied by the regional Public Planning Organizations in Baden-Württemberg, between 3000 and 5000 m [7–9]. An expert report given in Ref. [8] recommends a minimum spacing of 5 km, although this can be reduced if special topographic conditions prevent overlapping of the intervisibility of wind farms. These spacing rules can also be found in other federal states in Germany i.a. Mecklenburg-Vorpommern and Niedersachsen as well as e.g. in the region Yorkshire and the Humber in England and Northern Ireland [61–63]. In the latter two cases a spacing of 6 up to 15 km is reported. Hence the methodology is in principle

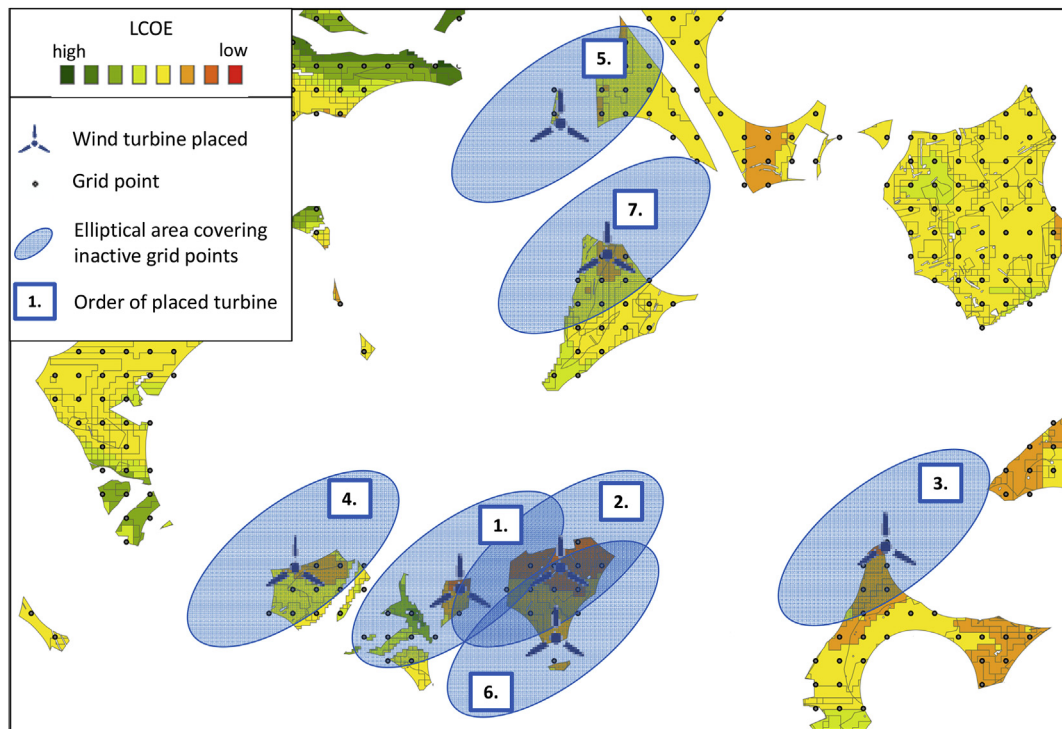


Fig. 2. Schema of how the wind turbines are placed for 7 turbines (Colored areas correspond to the available area).

applicable to other contexts and regions, provided the necessary information about the planning process and aesthetic appreciation is available. In addition, a maximum distance between two possible wind turbines within one wind farm is assumed with 1200 m. This is 10 rotor diameters of a wind turbine with a corresponding rotor diameter of 120 m. To account for the extracted outstanding landscape the algorithm in section 3.2.3 has to be run again.

On the basis of this parameterization, the algorithm begins by clustering wind turbines by their LCOEs, whereby the cluster with the minimum LCOEs is selected first. All wind turbines of this cluster are graph-theoretically interpreted as edges and will then be stored for computational reasons into a separate list, which is called *List_A*. The wind turbines in *List_A* are then interlinked amongst themselves by running a range search with the defined spacing distance between wind farms (3000 m or 5000 m). The result is a list of directed graphs (vertices) that are stored in an extra list, called *List_B*. Then, the algorithm proceeds by selecting the geographically leftmost wind turbine with the lowest LCOE in *List_A* and thereupon, all possible successors by means of *List_B* within the maximum distance between wind turbines (1200 m) are searched. Out of these wind turbines only the wind turbine with the lowest LCOE and distance is selected, and the search resumes as long as further successors can be found or the upper limit of the total number of wind turbines per wind farm is reached. Note that the search for possible successors is done for all wind turbines found so far such that cost-efficiency and compactness of the wind farm can be guaranteed. If the upper limit is not reached, also the total number of selected wind turbines has to be checked, in order to ascertain whether the constraint 'minimum number of wind turbines per wind farm' is met. Depending on this, the wind turbines are either transferred to a *List_C* (if the minimum number of wind turbines is met) or to a *List_D* (if the minimum number of wind turbines is not met). Then, the wind turbines in *List_C* are checked for possible links to wind turbines within the defined spacing of wind farms (3000 m or 5000 m) in *List_B*. If wind

turbines within the wind farm spacing can be found, the corresponding wind turbines in *List_A* are also transferred to *List_D*. Finally, all wind turbines transferred to *List_C* or *List_D* need to be removed from *List_A* to avoid double counting or violating constraints. The procedure will then start again by selecting again the leftmost wind turbine with minimum LCOE in *List_A* as long as there are wind turbines in *List_A* left.

After emptying *List_A*, wind turbines that are within the defined spacing of wind farms have to be deleted. This concerns on the one hand the wind turbines in *List_D* and on the other hand also wind turbines of the next LCOE cluster which are therefore also transferred to *List_D*. Then the wind turbines of *List_C* and *List_D* are interlinked by directed graphs (vertices) within the distance of the defined spacing of wind farms. On the basis of that, all wind turbines within the spacing of two wind farms can be detected and deleted permanently from *List_D*.

The algorithm is then repeated from the beginning, iterating all LCOE clusters as described, but with a slight change. After the range search of *List_A*, the resulting *List_B* needs to be modified by two further lists of vertices. The first list of vertices is a list of links among wind turbines of *List_C* with the maximum distance between wind turbines (1200 m). This assures maintaining already established wind farms in the next iteration step. The second list of vertices is the result of a range search between *List_C* and *List_D* with the spacing of wind farms. This is to prevent wind turbines from being deleted that are already stored in *List_C* in the next iteration step (directed graphs). This has to be done until all LCOE clusters are processed. The result is the feasible potential and the associated costs. Note that the 386 already existing wind turbines in Baden-Württemberg are not considered.

4. Results

The available area in Baden-Württemberg for wind energy is estimated at 4402 km². This is about 600 km² more than in

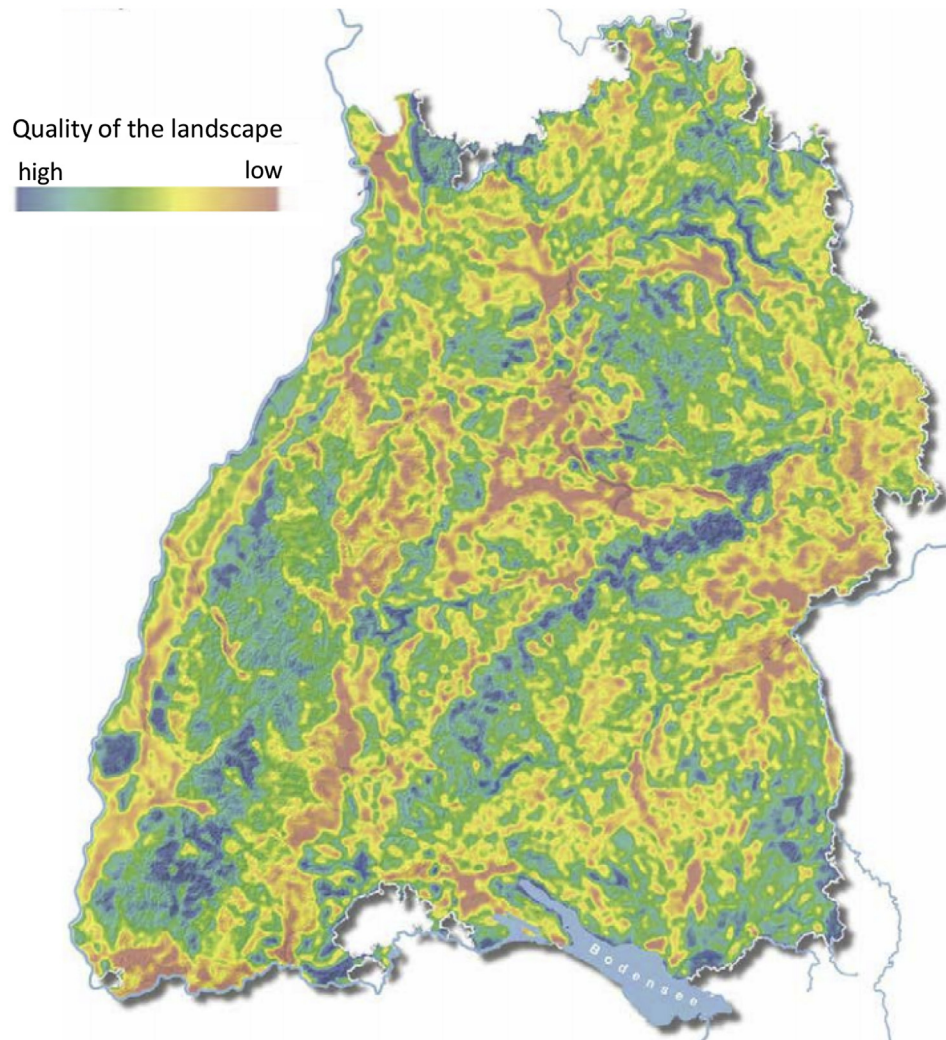


Fig. 3. Quality of the landscape analysis of Baden-Württemberg [6].

previous studies using public databases [25], which is thought to be due to the use of suitability factors in the latter case. The technical potential without considering any constraints is between 60.8 TWh and 127.7 TWh, strongly depending on the area covered by the assumed ellipse to account for the wake losses. This relationship is nonlinear, as shown in Fig. 4. Furthermore it is observed that the geometry of the ellipse also has a small effect.

With an assumed ellipse of $8D \times 3D$ (reference configuration;

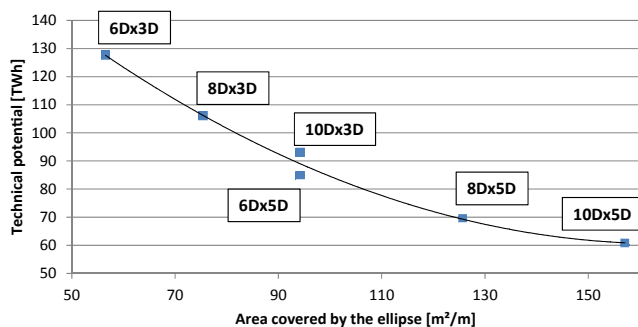


Fig. 4. Technical potential as a function of the area covered by the ellipse expressed in covered area per each meter of the rotor diameter [m²/m].

technical potential: 106.0 TWh), the wind farm placing algorithm is applied. This is done for two different wind farm spacings of 3000 m and 5000 m respectively, alternating the minimum number of wind turbines per wind farm between three, five and seven. The result is shown in Fig. 5. Maintaining a constant wind farm spacing and varying the minimum number of wind turbines per wind park, the feasible potential increases accordingly. It increases from 11.8 TWh for a minimum number of three wind turbines per wind farm to 14.6 TWh and 16.7 TWh with five and seven wind turbines respectively. This has also been done for a wind farm spacing of 3000 m, resulting in a feasible potential for a minimum number of three wind turbines per wind farm of 23.1 TWh. By increasing the minimum number of wind turbines per wind farm from 3 to 5, the feasible potential increases to 26.8 TWh and for a minimum number of seven to 29.1 TWh. Thus, the feasible potential for wind energy in Baden-Württemberg is estimated between 11.8 TWh and 29.1 TWh, as shown in Fig. 5.

Additionally, also the effect on the distribution for the two assumed wind farm spacings is investigated and compared to an approach without any constraints in terms of spatial planning. To compare the results, the distribution of a possible wind energy production in 2020 for Baden-Württemberg according to the 6.4 TWh goal set out by the federal government is investigated [5]. According to the LCOE criteria, only the most economical wind

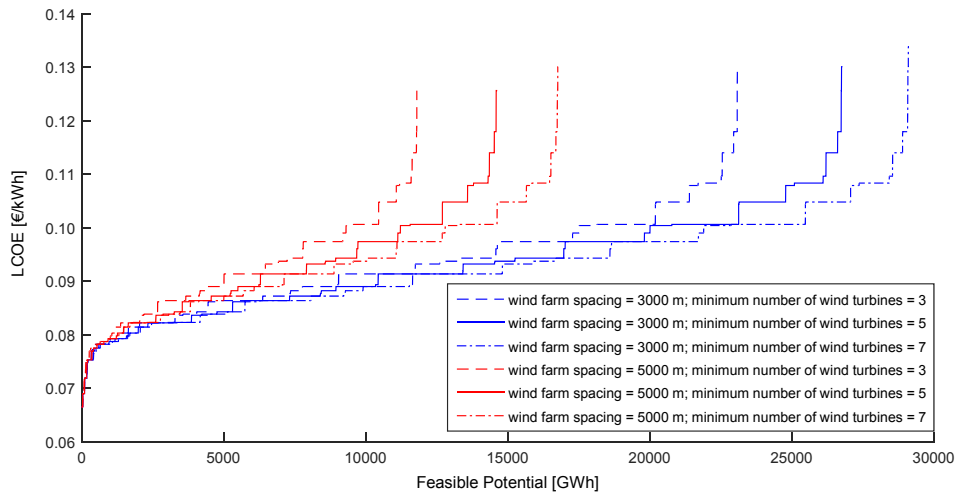


Fig. 5. Cost-potential-curves for wind farm spacing of 3000 and 5000 m and for a different minimum number of wind turbines per wind farm.

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 farms (see section 5 – validation) [2]. Lastly, the order of the calculated LCOEs and technical aspects are assumed to be the same in 2020 as today. The results are shown in Fig. 6.

Without considering any constraints derived from spatial 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 farms in the south and south-east, no wind farm can be found. This changes for a wind farm spacing of 3000 m, when the energy production is a little more widespread and less intensely focused. Simultaneously, in the surroundings of the scattered wind producing communities, further wind farms can be found. This trend is accelerated for a wind farm spacing of 5000 m, leading to an even more widespread energy production across Baden-Württemberg.

5. Discussion

5.1. Discussion of results

In comparison with other studies for Baden-Württemberg, the technical potential found here is partially in agreement with the technical potential found in the literature. McKenna et al. [25] estimated the technical potential at 72.0 TWh, which was found to be 69.6 TWh in the present study for the same assumed spacing between two wind turbines of $8D \times 5D$. The present study, however, uses an ellipse instead of a rhombus, which is more land-intensive due to the geometrical shape. Furthermore, as ellipses have a different packing density (for ellipses this is 0.9069; for rhombus this is 1 [64]) and a degradation of the wind turbines is taken into account, this might explain why the 600 km² larger area does not result in a larger overall potential in the present case. How this affects the shape of the cost-potential curve, however, has not been investigated, but since Ref. [25] uses suitability factors and a wind power density function, this methodology may underestimate very good sites as these areas are usually smaller, whereas less economic sites tend to be overestimated as no areas are excluded due to already existing wind turbines (see Fig. 2 in section 2.2). In another study, the LUBW in 2013 calculated a total technical potential for Baden-Württemberg of 122.4 TWh [23]. LUBW used a

wind turbine placing algorithm with a single type of wind turbine and an ellipse of $5D \times 3D$, and no economic assessment is conducted. The LUBW possesses a better data basis (e.g. nightly military low flying operation routes, civil radio 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 140 m. 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 feasible potential is determined between 11.8 and 29.1 TWh and is therefore less than a third of the technical potential (106.0 TWh) for the reference configuration. 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 2500 most economical wind turbines determined by the algorithm are plotted exemplarily together with existing wind turbines and already planned wind farms in Fig. 7 for two different wind farm spacings of 3000 m and 5000 m for the administrative district Main-Tauber-Kreis. The majority of the wind turbines for a wind farm spacing of 5000 m seem to correspond well to the existing and planned wind turbines and farms, even if not all wind farms are identified. The same can be stated for a buffer of 3000 m, although the quality is difficult to quantify with respect to heavily scattered wind farms.

In terms of the future distribution of wind energy production, wind turbines are distributed more widely across the whole federal state of Baden-Württemberg for the feasible potential than based on the 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 potential in areas that are not, or inversely, correlated.

Furthermore, the sequence of wind turbines added by the wind farm placing algorithm was investigated (Fig. 8). Two sequences for a spacing of 3000 m around the wind farm, 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. 8 shows that the curve of 'sequence b' runs above that of 'sequence a' in the beginning but gets overtaken by 'sequence a' between 2.7 and 4.1 TWh. Moreover, the amplitude of 'sequence b' fluctuates more strongly, which implies that in this case wind farms tend to consist of a

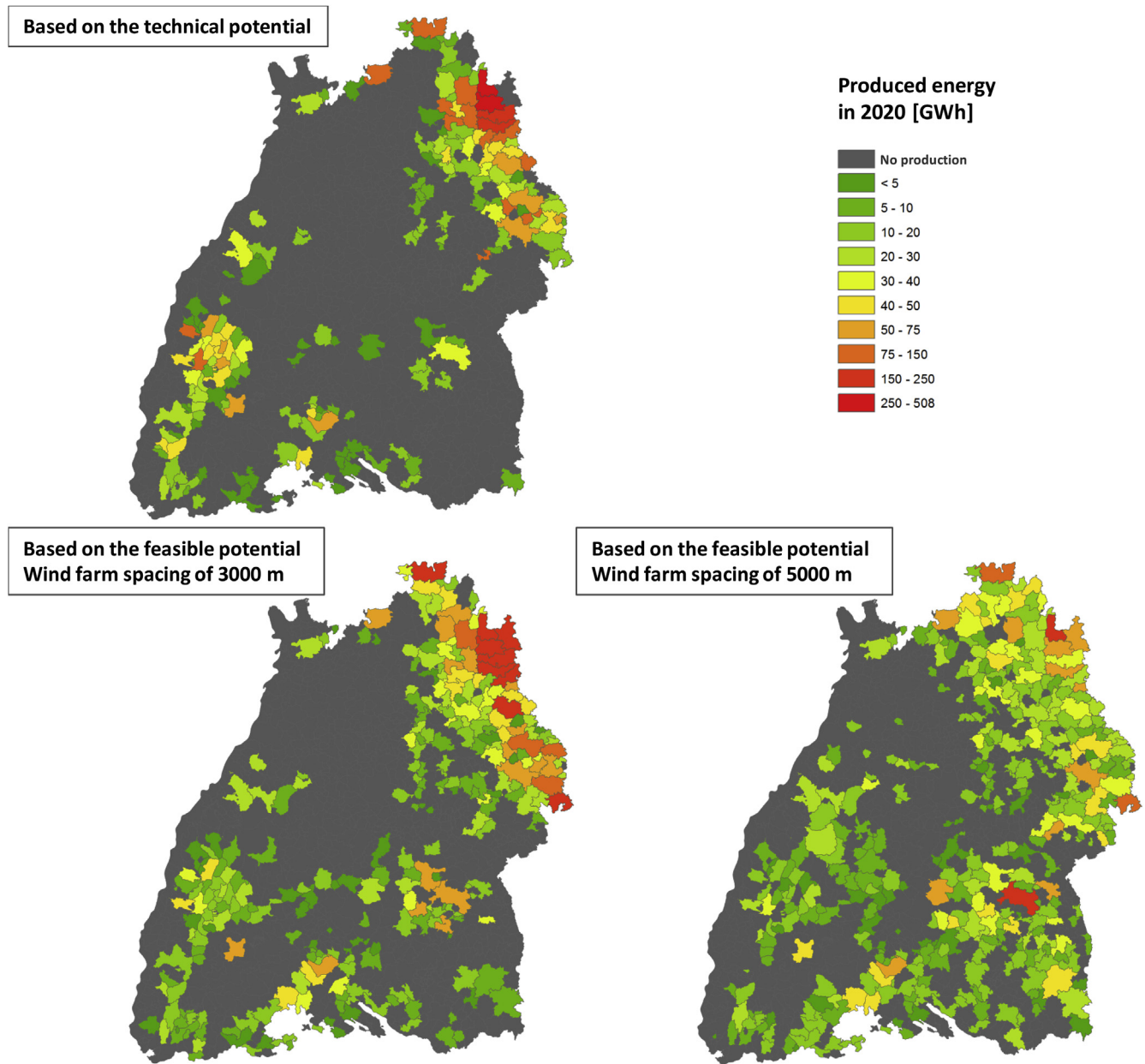


Fig. 6. Produced energy in 2020 [GWh] by communities on most economic sites according to the goal of the federal government of Baden-Württemberg (6354 GWh) for the technical (top) and the feasible potential for different wind farm spacing and an assumed minimum number of wind turbines per wind park of three (below). Existing turbines are not considered (~667 GWh).

mixture of very economical and less economical wind turbines. As market players usually try to maximize their profits, however, the commissioning of such wind farms can be doubted and ‘sequence b’ therefore assumed to be less realistic than ‘sequence a’ which leads to a reduced feasible potential as shown in Fig. 5.

5.2. 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 farms should be addressed. This fact causes errors each time when at least two wind-intensive sites are next to each other, e.g. two hills with enough space for 3 wind turbines each and with 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 the behavior 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 farm may serve as a rough guide. According to that, the feasible potential varies strongly with the number of minimum wind turbines per wind farm: 6.0 TWh for a wind farm spacing of 3000 m and 4.9 TWh for a wind farm spacing of 5000 m.

Another question is the quality of the wind data, which could lead to errors in the results. Besides the incorporated constraint of minimum hub heights in forests to account for incomplete wind speed data in terms of local turbulences in forests [47], another

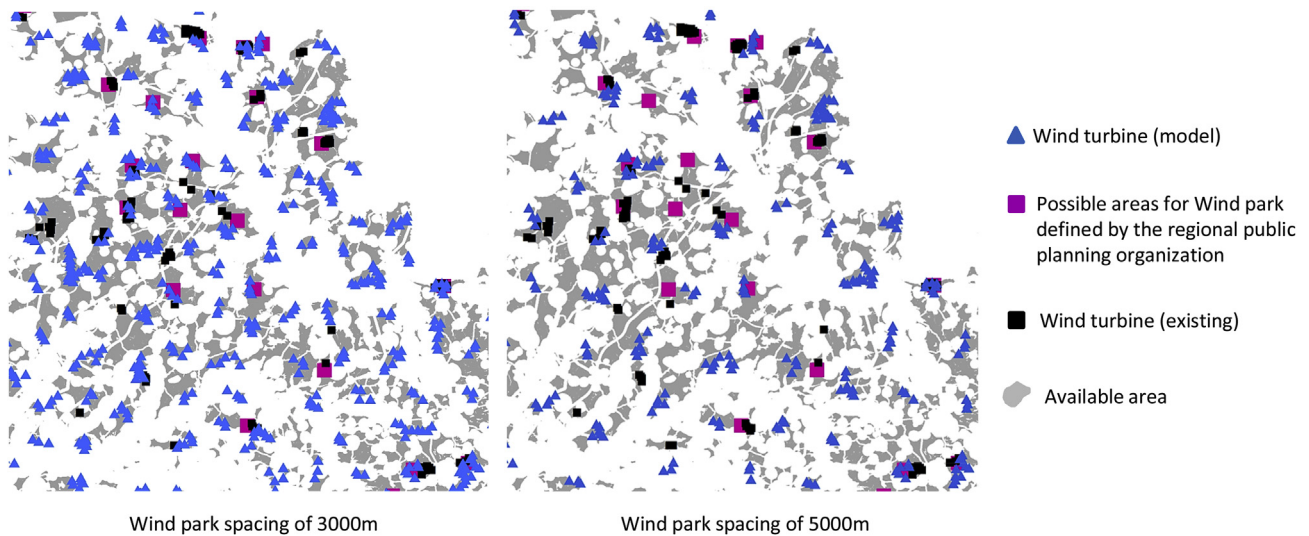


Fig. 7. Wind turbines placed by the algorithm in comparison with existing wind turbines and planned wind farms in the Main-Tauber-Kreis.

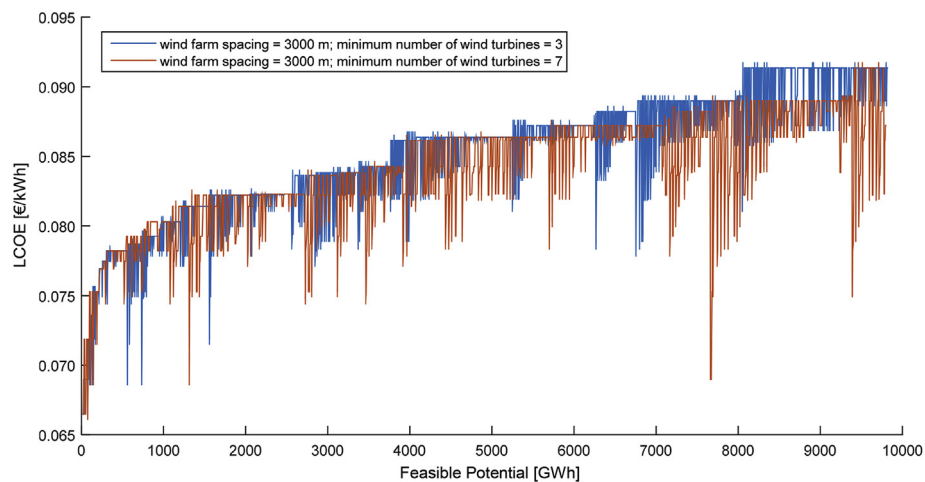


Fig. 8. Wind turbines added by the algorithm for a buffer zone of 3000 m and two different minimum number of wind turbines per wind park.

possible error in this context might be 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 zero. Further, Ref. [47] 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 potential 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 spatial planning constraints are used to exclude areas unsuitable for wind farms. Hence areas that are considered especially beautiful, as well as those where there is resistance to planning processes, are excluded from the potential analysis. Thus these barriers, which result from aesthetic appreciation as well as spatial planning, are taken as a proxy to anticipate social barriers in the definition of the feasible 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 (see section 2), 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 [60], in accounting for social constraints in general.

Finally, the limited consideration of the economic potential should be mentioned. The LCOE criterion 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. When examined from the perspective of the investor other than the “central planner”, the energy-political framework in the form of the German Renewable Energies Act (EEG) in Germany has to be taken into account, possibly leading to other locations than the ones selected here. Secondly, the LCOEs as calculated here (cf. Eq. (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 [65]. Whilst this is not significant for smaller proportions of wind energy in the electricity system, as the penetration 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 may foster the development of such wind farm locations in future. Another possibility to better account for the system costs could be made by considering further constraints such as distances to substations to account for the costs of grid connection or the ownership structure of the land between the wind farm 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 Ref. [27], or the distances can be multiplied with the costs per meter of cable. 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 farms and configurations.

6. Conclusion

Motivated by the lack of attention given to social restrictions in the large-scale assessment of wind energy potential, this paper has proposed a new methodology to locate and assess wind farms based on graphic-theoretical considerations to account for rules of spatial planning. Therefore, wind turbines are placed directly using variable wind directions and variable spacing between wind turbines while considering degradation of wind turbines and wind turbines in forests in detail. Further, a new dataset to exclude areas in terms of landscape aesthetical aspects was employed. The technical potential for Baden-Württemberg was found to be between 60.8 TWh and 127.7 TWh, strongly depending on the area covered by the assumed ellipse to account for the wake losses. For the same ellipse configuration the results seem to be largely in agreement with previous studies, but may result in a change of the cost-potential curve's shape. The feasible potential was estimated between 11.8 TWh and 29.1 TWh at costs between 6.7 and 12.6 €/ct/kWh for the reference configuration, strongly depending on the assumptions related to wind farm size and spacing. In addition, the dependency of the distribution of the future energy production of wind farms on the wind farm spacing 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. In order to test the quality of the wind turbine placing algorithm, already existing and planned areas for wind farms were compared to modeled wind farm locations, and a very good correlation could be observed for a wind farm spacing of 5000 m. 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 farms could help to identify a distribution of locations that, whilst individually partly economically suboptimal, are optimal from a systems perspective. Further, visibility analysis should be implemented using digital elevation models to consider the topography for

optimal local wind farm spacing. In the present study, a generalized assumption for wind farm spacing was assumed, which is correct for flat terrain, but can cause errors on hilly ground, although the windiest sites are mostly on top of hills such that wind turbines can be seen over distances. Notwithstanding these potential improvements to the methodology, the results generated here represent crucial inputs to energy system models and the general energy-political discourse in the region.

Acknowledgment

The authors gratefully acknowledge the funding of the Federal State Ministry for Environment, Climate and Energy Economics Baden-Württemberg for the project BWE13022. The authors would also like to thank the Federal State Institute for Environment Measurement and Nature Conservation [LUBW], Baden-Württemberg, and Frank Roser for the permission to use their geo data for this work, as well as two anonymous reviewers for their comments on an earlier version of this paper. Any errors are the responsibility of the authors.

References

- [1] Ministerium für Wirtschaft und Energie, Zeitreihen zur Entwicklung der erneuerbaren Energien in Deutschland, 2015 [Online] Available: <http://tinyurl.com/k2ajdly>.
- [2] Statistisches Landesamt, Umwelt, Verkehr, Energie – Daten zu Baden-Württemberg, 2015 [Online] Available: <http://tinyurl.com/oga2vsf>.
- [3] Gesetzblatt für Baden-Württemberg, Stuttgart, May 2012, 2015 [Online] Available: <http://tinyurl.com/ocnmvug>.
- [4] Klimaschutzgesetz Baden-Württemberg (KSG BW), January 2015.
- [5] Parlament of Baden-Württemberg, Integriertes Energie- und Klimaschutzkonzept Baden-Württemberg (IEKK), July 2014 [Online]. Available: <http://tinyurl.com/nwh53ou>.
- [6] F. Roser, Entwicklung einer Methode zur großflächigen rechnergestützten Analyse des landschaftsästhetischen Potenzials, Weißensee Verlag, Stuttgart, Germany, Berlin, 2011. Ph.D. dissertation, Dept. Architektur und Stadtplanung, Univ.
- [7] Regionalverband Donau-Iller, Regionalplan – 4. Teilfortschreibung Nutzung der Windkraft, 2009 [Online] Available: <http://tinyurl.com/mmdgea5>.
- [8] Regionalverband Südlicher Oberrhein, Regionalplan Südlicher Oberrhein – Kapitel "Windenergie" 2006, 2011 [Online] Available: <http://tinyurl.com/mtwv4wg>.
- [9] Regionalverband Heilbronn-Franken, Regionalplan Mittlerer Oberrhein 2003, Fortschreibung des Kapitels 4.2.5 Erneuerbare Energien, Plansätze 4.2.5.1 „Allgemeine Grundsätze“ und 4.2.5.2 „Vorranggebiete für regionalbedeutsame Windkraftanlagen“, 2015 [Online] Available: <http://tinyurl.com/prgg8s6>.
- [10] Stefan Köhler, Ulrich Schulze, Volker Wille (Eds.), Landes- und Regionalplanung in Baden-Württemberg – Eine Zwischenbilanz anlässlich der 100. Sitzung der LAG Baden-Württemberg, Akademie für Raumforschung und Landesplanung, Hannover, 2008.
- [11] M. Drechsler, C. Ohl, J. Meyerhoff, M. Eichhorn, J. Monsees, Combining spatial modeling and choice experiments for the optimal spatial allocation of wind turbines, *Energy Policy* 39 (2011) 3845–3854.
- [12] I.J. Onakpoya, J. O'Sullivan, M.J. Thompson, C.J. Heneghan, The effect of wind turbine noise on sleep and quality of life: a systematic review and meta-analysis of observational studies, *Environ. Int.* 82 (2015) 1–9.
- [13] S. Wang, S. Wang, Impacts of wind energy on environment: a review, *Renew. Sustain. Energy Rev.* 49 (2015) 437–443.
- [14] A. Jobert, P. Laborgne, S. Mimler, Local acceptance of wind energy: factors of success identified in French and German case studies, *Energy Policy* 35 (2007) 2751–2760.
- [15] D. van der Horst, NIMBY or not? Exploring the relevance of location and the politics of voiced opinions in renewable energy siting controversies, *Energy Policy* 35 (2007) 2705–2714.
- [16] S. Breukers, M. Wolsink, Wind power implementation in changing institutional landscapes: an international comparison, *Energy Policy* 35 (2007).
- [17] F.D. Musall, O. Kuik, Local acceptance of renewable energy – a case study from southeast Germany, *Energy Policy* 39 (2011) 3252–3260.
- [18] W. Liu, C. Wang, A.P.J. Mol, Rural public acceptance of renewable energy deployment: the case of Shandong in China, *Appl. Energy* 102 (2013) 1187–1196.
- [19] C.R. Jones, B.J. Orr, J.R. Eiser, When is enough enough? Identifying predictors of capacity estimates for onshore wind-power development in a region of the UK, *Energy Policy* 39 (2011) 4563–4577.
- [20] K. Molnarova, P. Sklenicka, J. Stiborek, K. Svobodova, M. Salek, E. Brabec, Visual preferences for wind turbines: location, numbers and respondent characteristics, *Appl. Energy* 92 (April 2012) 269–278.

- [21] J. Ladenburg, J.O. Dahlgaard, Attitudes, threshold levels and cumulative effects of the daily wind-turbine encounters, *Appl. Energy* 98 (2012) 40–46.
- [22] V. Betakova, J. Vojar, P. Sklenicka, Wind turbines location: how many and how far? *Appl. Energy* 151 (2015) 23–31.
- [23] R. McKenna, S. Gantenbein, W. Fichtner, Determination of cost-potential-curves for wind energy in the German federal state of Baden-Württemberg, *Energy Policy* 57 (2013) 194–203.
- [24] Landesanstalt für Umwelt, Messungen und Naturschutz Baden-Württemberg (LUBW), Potenzialanalyse, 2013 [Online] Available: <http://tinyurl.com/kgu6vbk>.
- [25] R. McKenna, S. Hollnaicher, W. Fichtner, Cost-potential curves for onshore wind energy: a high-resolution analysis for Germany, *Appl. Energy* 115 (2014) 103–115.
- [26] Umweltbundesamt (UBA), Potenzial der Windenergie an Land: Studie zur Ermittlung des bundesweiten Flächen- und Leistungspotenzials der Windenergienutzung an Land, UBA, Dessau-Roßlau, June 2013.
- [27] N. Fuyeo, Y. Sanz, M. Rodrigues, C. Montañés, C. Dopazo, The use of cost-generation curves for the analysis of wind electricity costs in Spain, *Appl. Energy* 88 (2011) 733–740.
- [28] V. Gass, J. Schmidt, F. Strauss, E. Schmid, Assessing the economic wind power potential in Austria, *Energy Policy* 53 (2013) 323–330.
- [29] S.H. Siyal, U. Mörtberg, D. Mentis, M. Welsch, I. Babelon, M. Howells, Wind energy assessment considering geographic and environmental restrictions in Sweden: a GIS-based approach, *Energy* 83 (2015) 447–461.
- [30] K. Nguyen, Wind energy in Vietnam: resource assessment, development status and future implications, *Energy Policy* 35 (2007) 1405–1413.
- [31] R. McKenna, S. Hollnaicher, P. Ostman, v. d. Leye, W. Fichtner, Cost-potentials for large onshore wind turbines in Europe, *Energy* 83 (April 2015) 217–229.
- [32] M. Hoogwijk, B. de Vries, W. Turkenberg, Assessment of the global and regional geographical, technical and economic potential of onshore wind energy, *Energy Econ.* 26 (2004) 889–919.
- [33] J. Schallenberg-Rodríguez, J. Notario-del Pino, Evaluation of on-shore wind techno-economical potential in regions and islands, *Appl. Energy* 124 (2014) 117–129.
- [34] M. Kaltschmitt, *Renewable Energy: Technology, Economics and Environment*, 3rd ed., Springer Vieweg, Berlin; Heidelberg, 2007.
- [35] O. Grothe, F. Müsgens, The influence of spatial effects on wind power revenues under direct marketing rules, *Energy Policy* 58 (July 2013) 237–247.
- [36] Landesamt für Geoinformation und Landesentwicklung Baden-Württemberg (LGL), DLM-25 BW ATKIS.
- [37] Landesanstalt für Umwelt, Messungen und Naturschutz Baden-Württemberg (LUBW), Daten aus dem Räumlichen Informations- und Planungssystem (RIPS), 2014 [Online] Available: <http://udo.lubw.baden-wuerttemberg.de/public/>.
- [38] Forest Research Institute of Baden-Württemberg (FVA), Windkraft und Auerhuhn. [Online]. Available: <http://tinyurl.com/mbaem3k>
- [39] Landesanstalt für Umwelt, Messungen und Naturschutz Baden-Württemberg (LUBW), Verbreitungskarten Artenvorkommen, 2014 [Online] Available: <http://tinyurl.com/pf59l65>.
- [40] Landesanstalt für Umwelt, Messungen und Naturschutz Baden-Württemberg (LUBW), Wie werden Vögel und Fledermäuse bei der Planung von Windenergieanlagen geschützt, 2015 [Online] Available: <http://tinyurl.com/o8eydj7>.
- [41] Juwi, Windkraft im Wald, in: 5. Fachkonferenz des Deutschen Städte- und Gemeindebundes, 2012 [Online] Available: <http://tinyurl.com/k87q68b>.
- [42] R. Gasch (Ed.), *Windkraftanlagen – Grundlagen, Entwurf, Planung und Betrieb*, sixth ed., Vieweg + Teubner, Wiesbaden, 2010.
- [43] Landesamt für Geoinformation und Landesentwicklung Baden-Württemberg (LGL), DGM-25.
- [44] Landesanstalt für Umwelt, Messungen und Naturschutz Baden-Württemberg (LUBW), Kriterienliste Windpotenzial, 2011 [Online] Available: <http://tinyurl.com/o8nee5u>.
- [45] E. Hau, *Windkraftanlagen: Grundlagen, Technik, Einsatz, Wirtschaftlichkeit*, fifth ed., Springer Vieweg, Berlin, Heidelberg, 2014, pp. 555–557.
- [46] Anemos Windatlas, “Europe, 20×20 Km², Temporal Resolution of 10 min”.
- [47] Ministerium für Umwelt, Klima und Energiewirtschaft Baden-Württemberg, „Windatlas Baden-Württemberg, June 2011 [Online] Available: <http://tinyurl.com/lgxhk75>.
- [48] P.H. Meier, *Forschungsmast Liefert Vielversprechende Ergebnisse*, vol. 9, BWK das Energiefachmagazin, 2014, pp. 58–61.
- [49] T. Arnold, Bei Waldstandorten für Windenergieanlagen differenzieren, 2012, pp. 60–61. EW Magazin für die Energiewirtschaft, Heft 19 (Jg. 111).
- [50] M.O.L. Hansen, *Aerodynamics of Wind Turbines*, third ed., Taylor & Francis Ltd, London, 2015.
- [51] M. Ali, J. Matevosyan, J.V. Milanović, Probabilistic assessment of wind farm annual energy production, *Electr. Power Syst. Res.* 89 (Issue 1) (2012) 70–79.
- [52] M.J. Grubb, N.I. Meyer, Wind energy: resources, systems and regional strategies, in: T.B. Johansson, H. Kelly, A.K.N. Reddy, R.H. Williams (Eds.), *Renewable Energy-sources for Fuels and Electricity*, Island Press, Washington D.C., 1993, pp. 157–212.
- [53] N. Conroy, J.P. Deane, P. Brian Ó Gallachóir, Wind turbine availability: should it be time or energy based? – a case study in Ireland, *Renew. Energy* 36 (Issue 11) (Nov. 2011) 2967–2971.
- [54] A. Graves, K. Harman, M. Wilkinson, R. Walker, Understanding availability trends of operating wind farms, poster presented at the AWEA Windpower Conference, Houston, June 2008.
- [55] F. González-Longatt, P. Wall, V. Terzija, Wake effect in wind farm performance: steady-state and dynamic behavior, *Renew. Energy* 39 (Issue 1) (March 2012) 329–338.
- [56] I. Staffel, R. Green, How does wind farm performance decline with age? *Renew. Energy* 66 (June 2014) 775–786.
- [57] I. Staffel, R. Green, Supplementary Material to ‘How does wind farm performance decline with age? *Renew. Energy* 66 (June 2014) 775–786.
- [58] P. Konstantin, *Praxisbuch Energiewirtschaft: Energieumwandlung, -transport und -beschaffung im liberalisierten Markt*, second ed., Springer, Berlin, Heidelberg, 2009.
- [59] Deutsche WindGuard, “Kostensituation der Windenergie an Land in Deutschland,” Varel: Deutsche WindGuard, November 2013 [Online] Available: <http://tinyurl.com/ktafln4>.
- [60] F. Roser, Vielfalt, Eigenart und Schönheit – eine landesweite Planungsgrundlage für das Schutzgut Landschaftsbild, *Naturschutz-Info* 1 (2013) 23–29.
- [61] Erneuerbare Energien, Überblick zu den landesplanerischen Abstandsempfehlungen für die Regionalplanung zur Ausweisung von Windenergiegebieten, May 2013 [Online] Available: <http://tinyurl.com/nn6zfer>.
- [62] Government Office for Yorkshire and Humber, and the Yorkshire and Humber Assembly, Final Report, Planning for Renewable Energy Targets in Yorkshire and Humber, Vol. 2, December 2004 [Online] Available: <http://tinyurl.com/qerp7gb>.
- [63] Environment and Heritage Service, Wind energy development in northern ireland’s landscapes draft supplementary planning guidance to accompany planning policy statement 18, *Renew. Energy* (February 2008) [Online] Available: <http://tinyurl.com/ps3y5t3>.
- [64] J.H. Conway, N.J.A. Sloane, *Sphere-packings, Lattices, and Groups*, third ed., Springer, New York, 1987.
- [65] F. Ueckerdt, L. Hirth, G. Luderer, O. Edenhofer, System LCOE: what are the costs of variable renewables? *Energy* 63 (December 2013) 31–75.