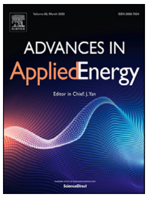
Advances in Applied Energy 7 (2022) 100102

Contents lists available at ScienceDirect

Advances in Applied Energy

journal homepage: www.elsevier.com/locate/adapen



Exploring the trilemma of cost-efficiency, landscape impact and regional equality in onshore wind expansion planning

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ARTICLE INFO

Keywords:
Onshore wind siting
Multi-objective optimization
German energy transition
Landscape scenicness
Trade-off analysis
Social acceptance

ABSTRACT

Onshore wind development has historically focused on cost-efficiency, which may lead to uneven turbine distributions and public resistance due to landscape impacts. Using a multi-criteria planning approach, we show how onshore wind capacity targets can be achieved by 2050 in a cost-efficient, visually unobtrusive and evenly distributed way. For the case study of Germany, we build on the existing turbine stock and use open data on technically feasible turbine locations and data on scenicness of landscapes to plan the optimal expansion. The analysis shows that while the trade-off between optimizing either cost-efficiency or landscape impact of the turbines is rather weak with about 15% higher costs or scenicness, an even distribution has a large impact on these criteria. However, a more evenly distributed expansion is necessary for the achievement of the targeted *south quota*, a policy target that calls for more wind turbine additions in southern Germany. Our analysis assists stakeholders in resolving the onshore wind expansion trilemma.

1. Introduction

As the first legally binding global climate change agreement, the Paris Agreement commits approximately 190 parties to preventing climate change and limiting global warming to below 2 °C [1]. Some parties, such as Canada, Japan and the European Union, are aiming for climate neutrality by 2050 [2,3]. Reducing greenhouse gases through the diffusion of renewable energy technologies can contribute significantly to achieving these objectives [4]. One of the most important renewable energy sources is wind energy with a share of 2.1% in global primary energy consumption [5], which has increased by about 300% between 2010 and 2019 [6] and is the highest among renewable energies after hydro power [5]. The already low cost of wind energy is expected to further decrease significantly by 2050 [7,8].

While energy system planning predominantly focuses on costs [9], the decentralized nature of renewable energy technologies requires more criteria to be considered. On the one hand, pure cost considerations overlook other opportunities, such as job creation or economic benefits for local communities [10]. For the global power sector, a large increase in jobs is expected through the deployment of renewables by 2050 [11]. To ensure that all regions may benefit, an even distribution of renewable energy plants is required. This could also benefit the energy system in general, as it could lead to less curtailment and less need for transmission grid expansion. For onshore wind energy, the focus of this paper, despite general approval local stakeholders increasingly oppose their construction [12,13], especially if they are not involved in the planning process [14,15]. One of the main reasons for this opposition is the visual impact on the landscape [16], as shown in studies for Switzerland [17], the US [18], or Europe [19]. Especially the placement of wind turbines in landscapes with high aesthetic quality is seen critically, while the placement in unattractive landscapes is more accepted [20]. The opposition due to landscape impacts could be one reason for the fact that onshore wind expansion is not accelerating despite declining costs [21]. This is especially evident in Germany, the country with the third largest onshore wind capacity [22] (around 55 GW in 2019 [23]) and the fourth largest share of onshore wind in power generation worldwide [24] (about 26%). After record years in 2014 and 2017 with 4.8 GW and 5.3 GW onshore capacity expansions respectively, only 1.0 GW and 1.4 GW new capacity was added in 2019 and 2020 [25]. The rapid spread and development of onshore wind turbines has sparked an increase in local protest movements and lawsuits across the country [26,27]. Along with hurdles for new installations introduced by lawmakers, this raises doubts about whether the government's expansion

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https://doi.org/10.1016/j.adapen.2022.100102
Received 28 June 2022; Received in revised form 13 July 2022; Accepted 17 July 2022

target of an additional 50 GW by 2050 is feasible [23,26]. A planning approach that addresses the key target criteria of cost-efficiency, landscape impact and regional equality [28] could underpin the achievement of this target and accelerate the expansion again.

Since the relative weighting of different target criteria is challenging, explorative analyses are needed to compare different spatial optimizations according to individual sustainability criteria [29]. In the literature on national onshore wind site planning, the focus has been mainly on techno-economic criteria. Quantitative analyses that take into account social criteria such as social or political acceptance [30,31] or interregional equality (studied for Switzerland [32], Germany [33] and Central Europe [34]) are still relatively scarce. A comprehensive review of relevant studies can be found in the Appendix. None of the previous studies have examined the trade-offs between all three criteria cost-efficiency, landscape impact and regional equality in onshore wind expansion planning.

The objective of this study is to determine optimal locations for onshore wind turbines in 2050. To ensure the lowest possible opposition while maintaining a cost-efficient and regionally even onshore wind expansion, we consider all three dimensions of this onshore wind expansion planning trilemma in a multi-objective approach and thereby show the trade-offs between the criteria. The onshore wind expansion in Germany serves as a case study for the approach. Prior to the actual optimization, we also examine the existing turbine population to show the relevance of the target criteria considered here. A key challenge for science and practice lies in quantifying public acceptance for onshore wind projects, whose approval depends to a large extent on the scenicness of surrounding landscapes[24]. The democratically legetimated goal of the German Nature Conservation Act shows, that scenic beauty has to be protected from uniformization of landscapes by technical infrastructure [35]. Therefore, we employ the scenicness of landscapes as a proxy for the landscape impact, itself a significant part of public acceptance of wind installations. Since electricity networks have an impact on both cost-efficiency [36] and landscape (and thus public acceptance [12]), the length of the necessary additional network is also measured as the distance to the nearest transformer. We measure regional equality or a regionally even distribution using the share of the municipal population in the total German population multiplied by the German capacity target. The municipality level was chosen as most renewable energy plants in Germany are owned by farmers, private individuals or local communities [37]. Therefore, this level is often where the decision to support or resist the installation of wind turbines originates [38]. This also allows all communities to participate equally in the economic benefits and regional opportunities such as equal employment, which could foster the implementation success of renewable targets. In addition to the scenario with a capacity expansion by 50 GW (German government's 2050 target), we consider an ambitious scenario with an expansion by 145 GW, in line with the call of the German Wind Association for an annual addition of at least 4.7 GW to meet climate targets [39].

2. Methods

In a study of the Federal Ministry for Economic Affairs and Energy [40] the onshore wind capacity in Germany until 2050 is defined to 60 GW in 2030 and 93 GW in 2050, based on the Renewable Energy Sources Act 2017. The draft of the Renewable Energy Sources Act 2021 now already calls for a capacity of 71 GW onshore wind in 2030 [23]. This study therefore assumes about 105 GW onshore wind capacity in 2050. For the planning of the future onshore wind locations a brownfield approach is chosen, assuming that the locations and capacities of today's existing onshore wind turbines will not change. This means that with a current capacity of about 55 GW [23], 50 GW would have to be added by 2050. The methodology of this study explores what an expansion might look like under different possible objectives. It draws on a range of publicly available datasets to ensure reproducibility of the approach. First, we describe the datasets used, before we present the multi-criteria planning approach developed.

2.1. Data sets

This study makes use of several mainly publicly available data sets. The data sets on the future onshore wind turbine potential (section 2.1.1), on the existing turbines and transformers (2.1.2) and on the scenicness quality values (2.1.3) are described below.

2.1.1. Wind turbine potential

In Ryberg et al. [41], the future onshore wind energy potential throughout Europe was determined, with the turbines being placed at exact locations throughout Europe. According to Ryberg et al. [41], approximately 160,000 turbines with a capacity of 620 GW and an annual energy yield of 1330 TWh can be placed in Germany. The results of the study are freely available [42] and are suitable for the present study, as future-oriented assumptions on turbine cost and design for 2050 are made. The data includes capacity, full-load hours and LCOEs for each turbine. In the present study, the mean full load hours from all considered weather years are used.

2.1.2. Existing turbines and transformers

For determining the locations of existing wind turbines and transformers in Germany, OpenStreetMap is used: 28,477 wind turbines are recorded (Fig. 1), which corresponds to 97% of the real stock number of about 29,500 turbines [43]. These existing wind turbines are used to exclude turbine locations from the onshore wind potential of the greenfield study by Ryberg et al. [41]. As in Ryberg et al. [41], regardless of the rotor diameter (which is unfortunately unknown), minimum distance buffers are drawn around the existing wind turbines, with a diameter of 1088 m. All wind turbines from the study by Ryberg et al. [41] which are located within the ellipses of existing turbines are excluded from this analysis. This leads to the exclusion of 13.9% of turbines, 14.4% of capacity and 15.7% of energy yield of the onshore wind potential in Ryberg et al. [41].

The connection of wind turbines in Germany is mainly in the medium and high voltage levels with 96% of all turbines [44]. In the power plant database of the Federal Network Agency [45], the voltage levels of the connections are specified. Supplementary Figure S13 presents a violin plot showing which wind plants are connected to which voltage level depending on the nominal power. Most wind plants are connected to 20 kV (40%, capacity between 2.0 MW and 32.0 MW) and 110 kV (45%, capacity between 2.3 MW and 119.6 MW). Therefore, only the transformers of these two voltage levels are obtained via OpenStreetMap. The length of the power lines connecting each wind turbine to the nearest transformer was determined using the straight line. The queries to obtain turbines and transformers from OpenStreetMap can be found in the Appendix.

2.1.3. Public acceptance and scenicness

We define the concept of public acceptance based on the framework of Wüstenhagen et al. [46] with subject, object, and context of acceptance according to Lucke [47] and by the definition of acceptance according to Schweizer-Ries [48]. We apply landscape scenicness to represent the public's (subject) appreciation of the landscape. Onshore wind energy (object) in Germany (context) forms the focus of this study. Regarding the dimensions investigated, we primarily consider community acceptance as we do not have a representative sample of the population to derive insights on their preferences. Market acceptance is also addressed, but only indirectly in the sense that local opposition to planned wind farms may lead to them not being built.

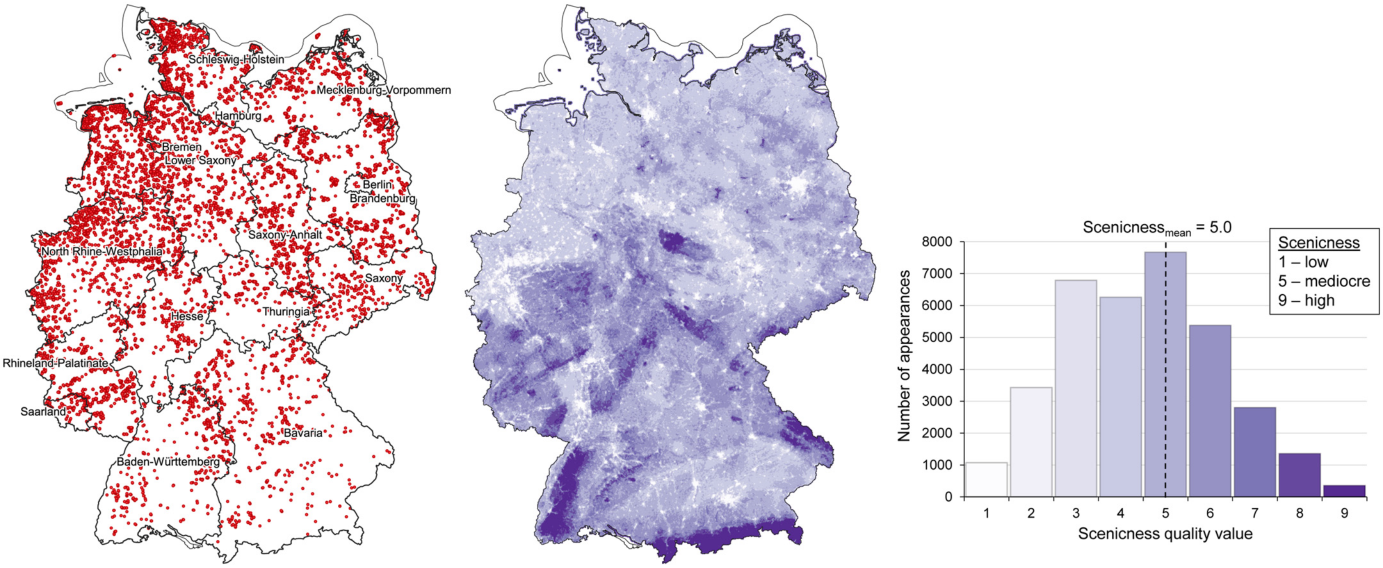

Fig. 1. Existing wind turbines in Germany and scenicness values distributed among the German territory. In the left map of Germany, the existing turbines (about 28,500) are shown as red dots. The color of the scenicness values on the right map of Germany correspond to the colours in the histogram showing the distribution and mean of these values.

In Roth et al. [49], for the first time scenicness quality values, i.e. values for assessing the beauty of landscapes, were determined for the whole territory of a country (Germany). The applied statistical model was based on roughly 45,000 photo-assessments of 3500 participants, which were representatively distributed over Germany. The model explains about 64% of the variance of perceived scenicness by objectively measurable parameters and indicators such as landscape elements and land uses. Infrastructures, such as the density of wind turbines, were also included in the landscape images and the regression. To have German-wide input data for the model, standardized geo-data was used. Please see the Appendix for further information on the landscape images, the sampling procedure or the online questionnaire.

The scenicness values range from 1 (low scenicness) to 9 (high scenicness) and are distributed heterogeneously across the German territory (Fig. 1). The highest scenicness in Germany is found in areas with steep terrain, natural landscapes and low presence of human interference [49]. These areas include the Black Forest in the southwest, the Bavarian Forest in the southeast and the Alps in the south. Areas with high human interference such as cities, on the other hand, show low scenicness. The scenicness data is the only data set not (yet) publicly available that is used in this study. However, as in the present study, the data set can be provided for scientific studies by the German Federal Agency for Nature Conservation.

2.2. Multi-objective optimization

In the multi-objective optimization model developed in this study, the optimal turbine locations are selected depending on various target criteria, based on the technically feasible turbine locations for 2050 identified in Ryberg et al. [41]. Three different target criteria are taken into account in the optimization in order to show different possible expansion strategies:

1) *cost-efficiency*, as it is usually the main objective in energy system plannings [9],
2) *landscape impact*, a significant part of public acceptance, as the plans of the energy transition are affected by a growing number of conflicts around onshore wind [12],
3) *distance to nearest transformer*, as the length of the electricity network is associated with high additional costs [36] and the necessary network could also lead through areas with high scenicness, hence affecting the landscape impact of the wind onshore project [12].

The above-mentioned criteria are highly relevant for planners of national energy systems. However, a centralized expansion of onshore wind would overlook the relative costs and opportunities, which could emerge for local regions by installing and operating wind turbines [9]. Therefore, the analysis is additionally conducted for scenarios with a regionally even onshore wind expansion, in which the wind turbines are distributed as evenly as possible among the different municipalities.

In the analysis we investigate scenarios, in which the above-mentioned target criteria are considered. As described above, based on the current targets of the German government, an expansion of onshore wind capacity of 50 GW for 2050 is planned in this study. However, the German Wind Association calls for an annual addition of at least 4.7 GW to meet climate targets [39]. Extrapolating this figure to 2050 results in a capacity of about 200 GW, i.e., 145 GW would have to be added. Therefore, besides the scenario with an addition of 50 GW (“Base” scenario), we also investigate a scenario with an expansion of 145 GW (“High” scenario) to assess whether an early increase in policy targets could have a large impact on the planning flexibility.

The following sections first discuss the general multi-objective optimization problem (2.2.1), then the extension for regionally even expansion (2.2.2) and finally the methodology for considering all objective criteria in a single optimization (2.2.3).

2.2.1. General model

The parameters and variables of the multi-objective optimization model are shown in Table 1. As can be seen, the problem contains only one kind of variable, a binary variable ($b_{inst,i,j}$) for selecting the different possible turbine locations (i) in the various municipalities (j).

$$\min z = \sum_{i=1}^{N} \sum_{j=1}^{M} b_{inst,i,j} \cdot \left(w_c \cdot C_{i,j} + w_s \cdot S_{i,j} + w_l \cdot L_{i,j} \right) \tag{1}$$

subject to

$$Cap_{obj} \leq \sum_{i=1}^{N} \sum_{j=1}^{M} b_{inst,i,j} \cdot Cap_{i,j} \tag{2}$$

$$\sum_{i=1}^{N} \sum_{j=1}^{M} b_{inst,i,j} \cdot C_{i,j} \leq M_c \tag{3}$$

Table 1

Variables and parameters of the multi-objective optimization model, as well as their definitions. In the supplementary material to this article there are two data tables. The file "1-s2.0-S2666792422000208-mmc2" contains the existing turbines in Germany retrieved from OpenStreetMap together with an assignment to the corresponding municipality and its population. The file "1-s2.0-S2666792422000208-mmc3" contains the potentially additionally placeable turbines [42], together with LCOEs, energy yield, distance to nearest substation as well as assigned to municipalities.

Variable / parameter	Description
$\boldsymbol{b_{inst,i,j}}$	Decides if wind turbine i is installed for municipality j (binary variable)
$\boldsymbol{C_{i,j}}$	LCOE of wind turbine i in municipality j (parameter)
$\boldsymbol{Cap_{i,j}}$	Capacity of wind turbine i in municipality j (parameter)
$\boldsymbol{Cap_{obj}}$	Onshore wind capacity target by 2050 (parameter)
$\boldsymbol{Cap_{obj,j}}$	Onshore wind capacity target in municipality j by 2050 (parameter)
$\boldsymbol{L_{i,j}}$	Length of electricity network to connect wind turbine i in municipality j with nearest transformer (parameter)
$\boldsymbol{M}$	Total number of municipalities (parameter)
$\boldsymbol{M_c}$	Maximum allowed total LCOE (parameter)
$\boldsymbol{M_l}$	Maximum allowed total length of electricity network (parameter)
$\boldsymbol{M_s}$	Maximum allowed total scenicness (parameter)
$\boldsymbol{N}$	Total number of possible turbine installations (parameter)
$\boldsymbol{S_{i,j}}$	Scenicness at location of wind turbine i in municipality j (parameter)
$\boldsymbol{w_c}$	Weighting factor for LCOE objective (parameter)
$\boldsymbol{w_l}$	Weighting factor for length of electricity network objective (parameter)
$\boldsymbol{w_s}$	Weighting factor for scenicness objective (parameter)

$$\sum_{i=1}^{N}\sum_{j=1}^{M} b_{inst,i,j} \cdot S_{i,j} \leq M_s \tag{4}$$

$$\sum_{i=1}^{N}\sum_{j=1}^{M} b_{inst,i,j} \cdot L_{i,j} \leq M_l \tag{5}$$

$$b_{inst,i,j} \in \{0, 1\} \tag{6}$$

In the objective function (Eq. (1)), the LCOEs ($C_{i,j}$), the scenicness ($S_{i,j}$) and/or the length of the electricity network ($L_{i,j}$) are minimized. Different weights between 0 and 1 can be assigned to the target criteria using w_c, w_s and w_l to determine the relative importance of the criteria. In the analysis conducted in this article, only the values 0 or 1 are used. For an assessment of which target criterion should be given a higher/lower weight compared to the others, expert elicitations and multi-criteria decision analyses would be helpful for future analyses (see discussion section).

Eq. (2) ensures that the targeted capacity expansion (Cap_{obj}) is achieved by installing turbines in the various German municipalities. In Eqs. (3)-(5), the maximum permitted total values for LCOEs (M_c), scenicness (M_s) or network length (M_l) can be defined. This enables the determination of pareto curves, in which the changes of the individual objective values are shown in dependence on each other.

2.2.2. Including regional equality

Eq. (7) is introduced to consider a regionally even expansion of the turbines. The capacity $Cap_{obj,j}$ represents the onshore wind capacity that should at least be added in a municipality j to achieve as much equality as possible. This capacity is calculated by multiplying the share of the population of a municipality in the total German population by the capacity target for Germany. The capacity of the existing turbines in a municipality is subtracted from the result. If the potential in a municipality is not sufficient to be greater than $Cap_{obj,j}$, then $Cap_{obj,j}$ is reduced to the maximum achievable value. Otherwise, the optimization problem would not be solvable.

$$Cap_{obj,j} \leq \sum_{i=1}^{N} b_{inst,i,j} \cdot Cap_{i,j} \; \forall j = 1, \ldots, M \tag{7}$$

As in recent studies [32–34], we use the Gini index [50] to measure regional equality, i.e. how even the wind turbines are distributed. We adopt the formulation of Sasse and Trutnevyte [34], who adapted the Gini index as follows:

$$Regional\ equality = 1 - Gini\ index = 1 - \frac{\sum_{j=1}^{M}\sum_{k=1}^{M}\left|x_j - x_k\right|}{2 \cdot M^2 \cdot \bar{x}} \tag{8}$$

In this case, 100% means the highest and 0% the lowest regional equality score. Thereby, x is the capacity of wind turbines per inhabitant in municipality j or k, and M represents the total number of municipalities.

To estimate the influence of the spatial scale in the measurement, we also calculate the regional equality of the wind turbines at the NUTS-3 level (counties). In contrast to the municipality level, electricity consumption estimates for 2050 covering all sectors are available for the NUTS-3 level [51], which are used instead of population to distribute turbines, as has been standard practice in previous studies [32–34]. The results of this alternative approach are elucidated in the discussion section.

2.2.3. Optimizing all criteria

As described above, expert assessments would be necessary to assign appropriate weights to the target criteria. Nevertheless, this study also considers a scenario in which all target criteria are considered simultaneously. For this purpose, an attempt is made to weight the target criteria equally. For this purpose, the values for LCOEs, scenicness and network length (x) are scaled to the value z on the basis of their minimum values x_{min} and maximum values x_{max} [37]:

$$z = \frac{x - x_{min}}{x_{max} - x_{min}} \tag{9}$$

However, even with such an approach, the distributions of the individual target criteria could deviate greatly from one another, if, for example, outliers cause most of the scaled values of a target criterion to be very low and thus not to be significant in the optimization. Therefore, the distributions of all target criteria were subsequently adjusted with a scaling factor so that all distributions have the same mean value. The resulting scaled value distributions of all target criteria are shown in a histogram in Supplementary Figure S14.

3. Results

3.1. Costs and scenicness define turbine locations

The share of already existing turbines as a fraction of the technical German onshore wind potential generally decreases as levelized cost of electricity (LCOEs), scenicness of landscapes, or network length increase (Fig. 2), which emphasizes the relevance of these planning criteria. The technical potential corresponds to the wind power generated within an available area for wind turbines. It considers constraints such as wind turbine characteristics, wind farm array losses and electrical conversion losses [52]. Fig. 2 further shows that much of this potential is still available at favorable locations. The technical potential in Germany in 2050 includes approximately 160,000 onshore wind turbines [41]. About 29,000 turbines have already been installed and are in operation today (about 55 GW in 2019 [23], Fig. 1 in the method section).

The intensified consideration of the LCOEs, scenicness and networks has led to an uneven distribution of existing turbines across Germany. The turbines are mainly located in the northern federal states Lower Saxony (22%, 15.1 turbines per 1000 km^2, Fig. 3), Brandenburg (14%, 14.3 turbines per 1000 km^2), North Rhine-Westphalia (13%, 14.0 turbines per 100 km^2) and Schleswig Holstein (11%, 22.7 turbines per 1000 km^2), which show the highest capacity factors in Germany [53]. The associated lower cost of wind electricity supply is one reason for the high wind diffusion in the north. Furthermore, the scenicness is lower there than in the southern federal states like Bavaria and Baden-Württemberg

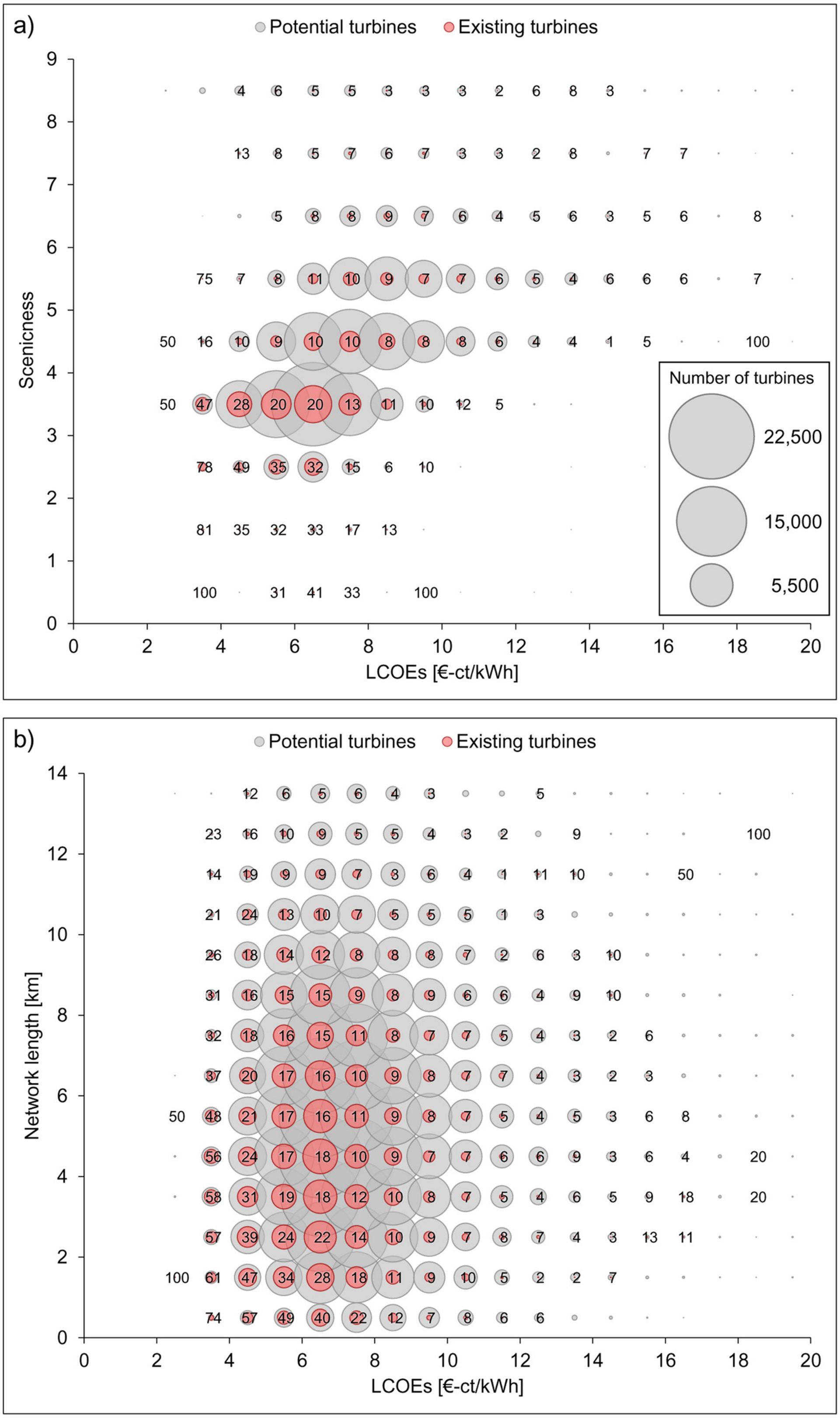

Fig. 2. Number of turbines that could potentially be placed in Germany in 2050 (gray bubbles) and the associated ranges of LCOEs (a and b), scenicness (a) and network length (b). The red bubbles show the number of turbines already installed in Germany and the numbers in the center of the bubbles show their share in the potential, i.e. 100 means that the potential has already been fully exploited. Each bubble applies to an interval, i.e. a bubble between the values 1 and 2 shows the number of turbines at the range (1;2]. We show the number of turbines here and not the capacity, as the latter is not known for individual existing turbines.

(Fig. 3), which could indicate a lower resistance towards onshore wind [54]. Except for the sea coast, the lake districts in north-eastern Germany and some local "hot-spots" like the Lueneburg Heath, northern Germany tends to be an area of low to medium scenicness [49].

The existing wind turbines in Germany are located at sites with a mean scenicness of 4.25 (on a scale of 1 (low scenciness) to 9 (high)), which is below the German average of 5.0 (Fig. 1). Most turbines are located at sites with a scenicness of 3 (15%), 4 (57%) or 5 (16%) (Fig. 2). At sites with a scenicness of 1 and 2, as well as 8 and 9, the smallest

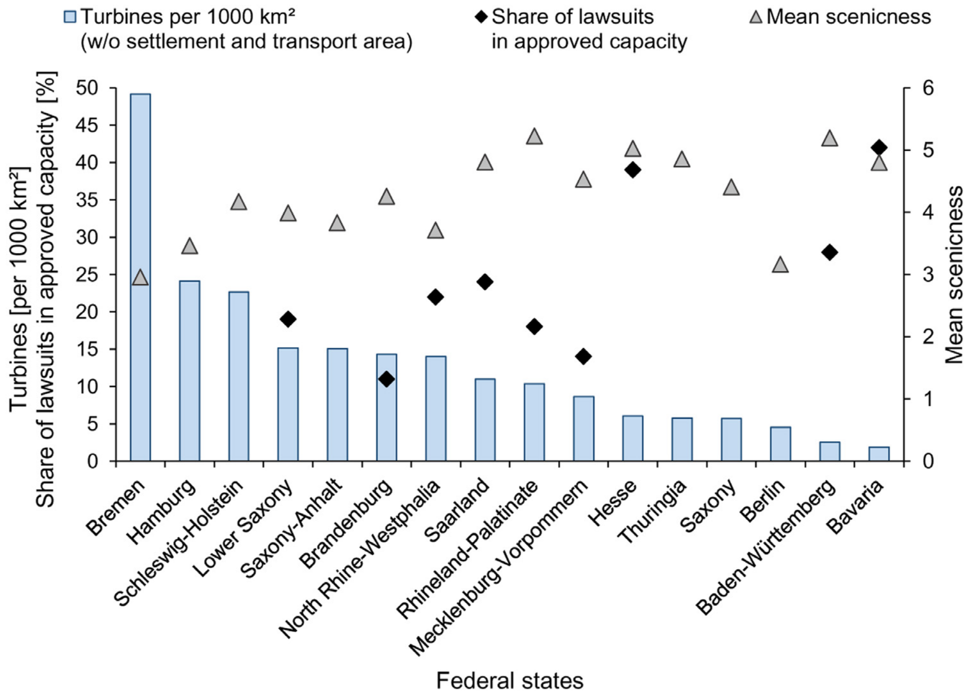

Fig. 3. Specific number of turbines, share of wind turbines in total licensed capacity subject to lawsuits, and mean scenicness of landscapes in the sixteen German federal states. The federal states are ordered from the highest specific number of turbines (Bremen) to the lowest (Bavaria). The share of wind turbines in total licensed capacity subject to lawsuits has been determined by a survey with 89 companies in 14 of the sixteen federal states [55]. However, lawsuits have not been reported for all federal states [55].

proportion of turbines is located (<1%). On the one hand this could be due to the exclusion of these areas (cities) because of minimum distance restrictions, and on the other hand because of the low incidence and the high beauty of these areas. At the same time, the highest average share of existing turbines shows that the potential in areas with a scenicness of 1 and 2 has been exploited the most so far (Fig. 2).

Probably due to lower capacity factors and higher scenicness, the onshore wind diffusion is lowest in the southern federal states Bavaria (1.9 turbines per 1000 km^2, Fig. 3) and Baden-Württemberg (2.6 turbines per 1000 km^2). In general, the mean scenicness in all federal states seems to correlate with the existing specific capacity per km^2 (Fig. 3, Pearson correlation coefficient: −0.66, p-value: 0.0059; Spearman: −0.57, 0.0240; Kendall: −0.42; 0.0255). At the same time, the share of lawsuits against wind turbines [55] (measured in terms of total approved capacity) is higher in the southern federal states than in the northern ones (Fig. 3). The high differences in the specific number of turbines indicate that there has not yet been an even distribution of wind turbines in Germany. In fact, our analysis shows that the regional equality of existing wind capacity per inhabitant measured with the Gini index [50] has a value of only 6.4%, with 100% being a completely even distribution.

The remaining technical onshore wind potential in Germany, which could be added to the existing capacity, shows the lowest LCOEs in landscapes with a scenicness of 3 (up to a capacity of about 15 GW), 4 or 5 (Supplementary Figure S9). Since the existing turbines are mainly located in these landscapes with rather low scenicness, it is evident that cost-efficiency and scenicness could have been the most important factors in siting so far. The greatest onshore wind potential can be realized in landscapes with a scenicness of 4, 5 or 6. In some landscapes with scenicness below average, significantly higher LCOEs have to be expected.

3.2. Weak trade-off between cost-efficiency and landscape impact

The trade-offs that emerge between optimal cost-efficiency and landscape impact are rather weak. The expansion of onshore wind turbines with a total capacity of about 50 GW would be associated with mean LCOEs of at least 4.7 €-ct/kWh (scenario Base_LCOE, Table 2), a mean scenicness of at least 3.6 (scenario Base_Scenic) or a mean length of power cables of at least 1.5 km (scenario Base_Network). If the turbines are placed in areas with minimal scenicness, the average LCOEs would only increase by 13%, and in the case of optimal cost-efficiency, the average scenicness would only increase by 17%. As can be seen in Fig. 4, the turbine locations in the two cases a) and b) do not differ much either, with around 60% of the locations being “no-regret” sites. “No-regret” site means, that a turbine at a specific location is installed under both optimization criteria [29]. However, in the cost-optimal case, for example, many turbines would be placed in the south in the less steep areas near the Alps, which have very high scenicness. This would change in the case with minimal scenicness; here, more turbines would be placed in central Germany instead.

The required mean length of the electricity network to connect the wind turbines with transformers is relatively high in scenarios Base_LCOE and Base_Scenic with 6.1 km and 5.2 km, respectively, which would affect both the cost-efficiency and the scenery of the landscape. If the distance to the nearest transformer is minimized (scenario Base_Network), the mean LCOEs of the turbines (+64%) and the scenicness of the locations (+31%) change significantly. However, the distribution of turbines in this case would be more regionally even: while in the first two cases turbine expansion still occurs mainly in the north of Germany, in the case with minimum distance to the transformers we now see a much more even expansion across the German territory (Fig. 4c). Compared to the Base_LCOE and Base_Scenic scenarios, only about 6% of the turbines would be installed at "no-regret" sites. At the same time, the mean network length decreases by up to 75% (Table 2).

These previously described trade-offs would behave similarly even with a higher target capacity of 200 GW instead of 105 GW in 2050 (scenarios High_LCOE, High_Scenic and High_Network, Table 2). However, the minimum mean LCOEs, scenicness and network lengths would increase by 15%, 8% and 7%, respectively. Furthermore, in High_LCOE and High_Scenic, significantly more turbines would no longer be located only in the north of Germany as in Base_LCOE and Base_Scenic, which would increase regional equality (Supplementary Figure S10a-b).

Beside these trade-offs, the annual generations of the newly installed wind turbines in the respective scenarios deviate significantly (Table 2), despite having the same capacity target. In the scenarios in which the turbines are mainly installed in the north (Base_LCOE and Base_Scenic), the generation expansion is highest, while in the other scenarios with

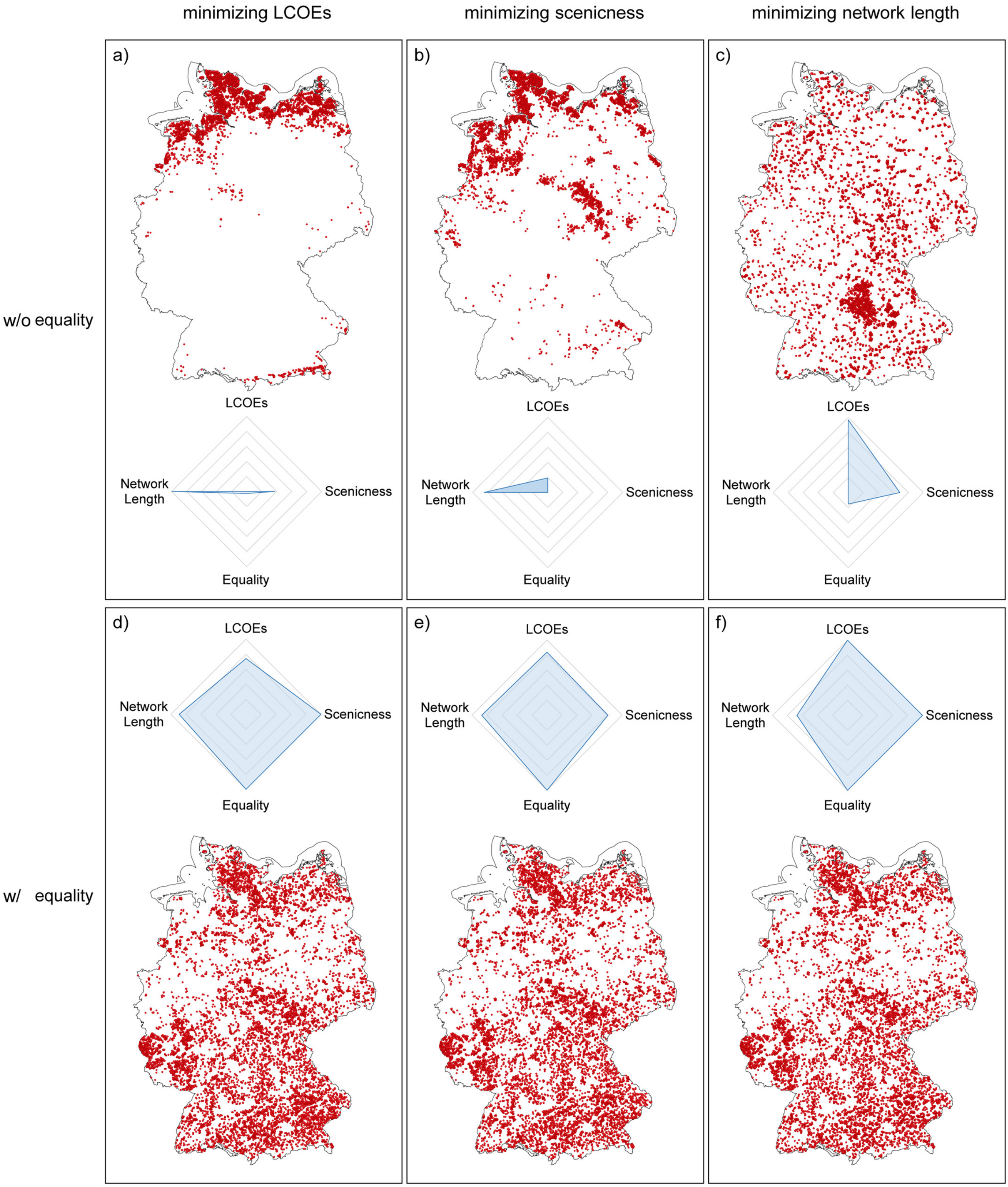

Fig. 4. Optimal locations of onshore wind turbines to be added by 2050 for different target criteria. Turbines are shown as red dots. Around 50 GW of capacity is added in each case. a) – c) show the optimal locations when minimizing LCOEs (scenario Base_LCOE), scenicness (Base_Scenic) or network length (Base_Network), respectively. In d) – f) the same target criteria are used, but in these cases with the constraint, that the capacity expansion has to be regionally even (Base_LCOE_E, Base_Scenic_E and Base_Network_E). The values in the spider charts are scaled based on the minimum and maximum values among the "Base" scenarios, in order to make the charts comparable. For example, in the Base_LCOE scenario (a), there is no amplitude in the chart for LCOE because this scenario has the lowest mean LCOEs (4.7 €-ct/kWh), while the Base_Network_E scenario (f) has the highest LCOEs (7.8 €-ct/kWh) and thus the largest amplitude. For the other scenarios, the amplitude is then scaled based on these two values. As the turbines that are exclusively installed in d)-f) are hardly visible, Figure S11 shows these. "w/" = with; "w/o" = without.

Table 2
Overview of the 14 scenarios considered and their results for mean LCOES, mean scenicness and mean network length as well as regional equality. The scenarios are distinguished by their target criteria (minimization criteria), the capacity target for onshore wind in 2050 and whether the expansion has to be regionally even or not. The last column shows the annual generation of the newly installed wind turbines.

Scenario	Minimization criteria	Regional equality included?	Onshore wind capacity [GW_{2050}]	Mean LCOEs [€-ct/kWh]	Mean Scenicness	Mean network length [km^2]	Regional equality [%]	Annual generation expansion [TWh]
Base_LCOE	LCOEs	×	105	4.7	4.2	6.1	7.5	148
Base_Scenic	Scenicness	×	105	5.3	3.6	5.4	7.1	136
Base_Network	Network length	×	105	7.7	4.7	1.5	9.2	102
Base_all	All criteria	×	105	5.5	3.8	3.1	7.3	132
Base_LCOE_E	LCOEs	yes	105	7.0	5.2	5.6	20.5	132
Base_Scenic_E	Scenicness	yes	105	7.3	4.9	5.5	20.5	121
Base_Network_E	Network length	yes	105	7.8	5.2	4.6	20.5	121
Base_all_E	All criteria	yes	105	7.2	5.1	4.8	20.5	127
High_LCOE	LCOEs	×	200	5.4	4.3	6.1	10.2	386
High_Scenic	Scenicness	×	200	5.9	3.9	5.9	8.5	363
High_Network	Network length	×	200	7.5	4.8	2.6	11.5	308
High_LCOE_E	LCOEs	yes	200	6.3	4.8	5.8	16.1	362
High_Scenic_E	Scenicness	yes	200	6.8	4.5	5.6	16.2	341
High_Network_E	Network length	yes	200	7.6	4.9	3.7	18.1	303

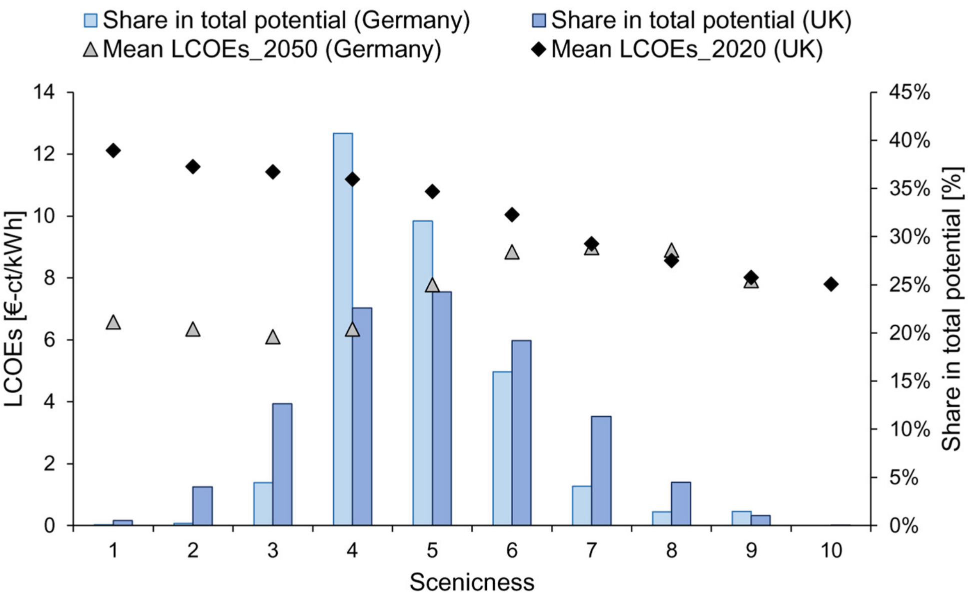

Fig. 5. Mean LCOEs and shares in total onshore wind potential for different scenicness classes of landscapes in Great Britain and Germany. For the scenicness dataset of Great Britain, the ratings range from 1 (low) to 10 (high), for Germany from 1 (low) to 9 (high).

many turbines also in the south with worse wind conditions, the added generation is lower (up to −30% when comparing Base_Network with Base_LCOE). Since generation is the decisive factor in meeting electricity demand, the trade-offs described above could be higher or lower if generation targets would have to be met, as more turbines would be needed in the latter scenarios.

3.3. Inconsistent relationships between windy and scenic locations

The weak trade-off between cost-efficiency and scenicness found in Germany is not observed in other regions. This is particularly interesting when compared with a recent study, which economically assesses the technical onshore wind potential of Great Britain (GB) as a function of scenicness [36]. Whilst for Germany, the scenicness data covers for the entire land area [49], for GB the data exist on a 1 km squared grid distributed throughout the country [56]. This allows comparison to the technical potential data we use for Germany in the present analysis (Fig. 5). The common feature of both GB and Germany is the distribution of the largest potentials among the mean scenicness values 4, 5 and 6. However, in contrast to Germany, the LCOEs of wind turbines decrease almost linearly as a function of scenicness in GB. While in Germany the beautiful landscapes in the south – except for the very beautiful ones with scenicness 9, e.g. in the foothills of the Alps – have higher LCOEs than the windy but less beautiful north, in GB the highest scenicness is mainly in the north of Scotland with beautiful landscapes and high capacity factors [36]. In the German context, this relationship is favourable, because it implies a complementarity (rather than competition) between windy and scenic locations.

However, we demonstrate below that in some German regions (e.g. Bavaria) the trade-off between cost-efficiency and scenic locations is indeed rather strong. Also, the top six locations with the best wind resources and thus lowest LCOEs in Germany are found at a scenicness value of 9. Furthermore, among all scenicness categories, the share of LCOEs smaller than 5 €-cent/kWh is highest for the scenicness category 9 (17%).

3.4. Regional equality significantly constrains planning options

The Pareto curves in Fig. 6 relate two of the target criteria to each other and show only a rather weak trade-off between LCOEs and scenicness in the case without regional equality. If the network length is included, as already described, there is a large influence on LCOEs

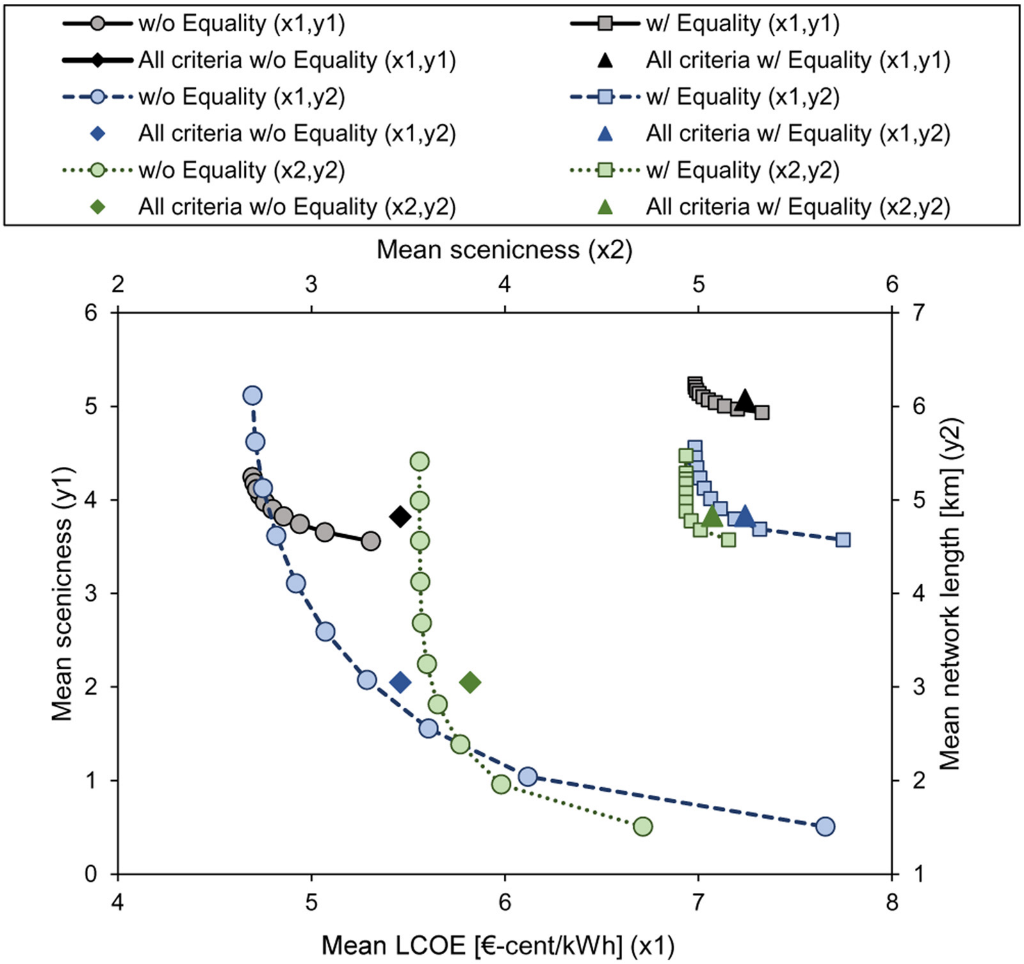

Fig. 6. Pareto fronts between different target criteria. The curves and points each relate to two axes indicated in the legend. The gray curves represent the pareto fronts between scenario Base_LCOE and Base_Scenic, and between Base_LCOE_E and Base_Scenic_E, the blue curves between Base_LCOE and Base_Network, and between Base_LCOE_E and Base_Network_E, and the green curves between Base_Scenic and Base_Network, and between Base_Scenic_E and Base_Network_E. The minimum target values of the criterion to be achieved on the y-axis were decreased by 10% in each optimization, and then the minimum value of the criterion on the x-axis was determined. The diamonds and triangles show the optimum with simultaneous minimization of all target criteria in the case without and with regional equality, respectively. "w/" = with; "w/o" = without.

or scenicness. It is interesting to note that the network length can be reduced significantly without a considerable increase in the mean scenicness. On the other hand, since the areas near substations are often densely populated and not very scenic or windy [36,57], the LCOEs and the scenicness deteriorate significantly at the last improvements in network length. Therefore, the mean LCOEs are similar in the "Base_Networkȁ and "High_Network" scenarios with and without equality (cf. Table 2 and Fig. 6). In general, these curves illustrate that small losses in one target criterion can result in significant improvements in another.

In the case of regionally even expansion planning, these effects do not appear. While the slopes of the Pareto curves in Fig. 6 are similar to the cases without equality, the range in the target criteria values is now significantly smaller: the mean LCOEs can now only change by up to 11% instead of 64%, the mean scenicness by up to 6% instead of 31%, and the mean network length by up to 22% instead of 306%. Hence including equality leads to a significantly smaller planning flexibility. The locations of the turbines would therefore be practically fixed as the comparison of Fig. 4d-f further demonstrates (Figure S11 shows the turbines that are exclusively installed in the respective scenarios). Whilst mean LCOEs, scenicness and network length increase significantly in the scenarios Base_LCOE_E, Base_Scenic_E and Base_Network_E in comparison to the scenarios without equality by up to about 50%, 35% or 205%, respectively, the turbines are now distributed much more even: compared to the current distribution of the existing turbine stock, regional equality increases by about 220%. However, the equality reaches a maximum value of only up to 20.5% as due to the current uneven distribution of existing turbines and low or lacking potentials in many regions, an equality value of 100% among municipalities is far from achievable with only onshore wind. This is further demonstrated by the scenarios High_LCOE_E, High_Scenic_E and High_network_E, which show lower equality values between 16% and 18% despite almost twice as much capacity. In these scenarios the potential maximum capacity is reached in many regions and therefore more capacity has to be installed in regions that already have a high capacity. However, due to the increased capacity, the planning flexibility is higher (Supplementary Figure S10d-f), and mean LCOEs, scenicness, and network length can change by as much as 21%, 9%, and 57%, respectively, at different target weights.

When all criteria are simultaneously optimized with equal weightings rather than just one criterion, the locations of scenarios Base_all and Base_all_E in Fig. 7 result. Base_all includes turbines from all three scenarios Base_LCOE, Base_Scenic and Base_Network: some cost-efficient turbines in landscapes with low scenicness in the north; further turbines in central Germany, which were chosen mainly when minimizing scenicness; and a few turbines in southern Germany, which were chosen when minimizing the required network length. Except for the Pareto

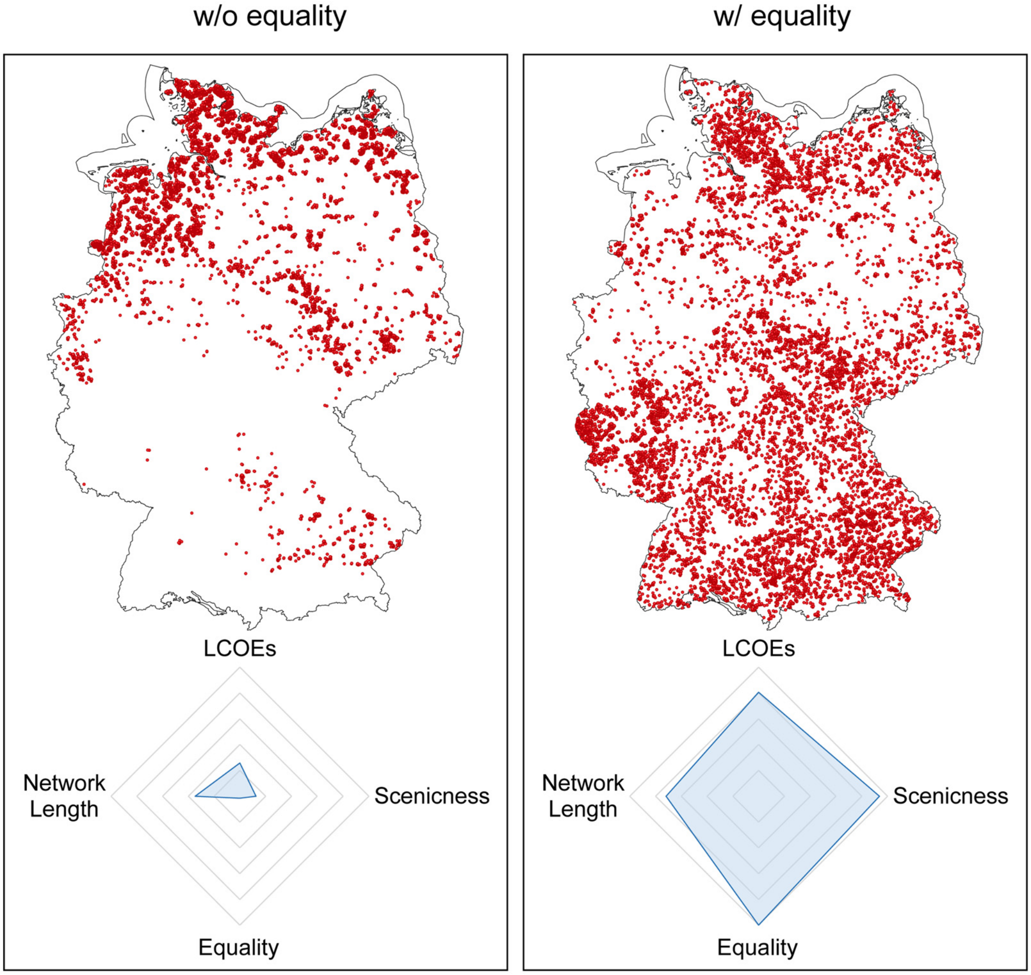

Fig. 7. Optimal locations of onshore wind turbines to be added by 2050 if all three target criteria are considered. Turbines are shown as red dots. Around 50 GW of capacity is added in each case. The left part shows the optimal locations without considering equality (Base_all), the right part with considering equality (Base_all_E). The values in the spider charts are scaled based on the minimum and maximum values among the “Base” scenarios. “w/” = with; “w/o” = without.

curve for scenario Base_LCOE and Base_Scenic, the optimum of Base_all lies pretty much in the middle of all Pareto curves (Fig. 6). Compared to the minima in scenarios Base_LCOE, Base_Scenic and Base_Network, the mean LCOEs would increase by 17%, the mean scenicness by 6%, and the mean network length by 107%. Therefore, when minimizing all criteria, the trade-offs between the objective criteria are lower except for cost-efficiency, which increases less from scenario Base_LCOE to Base_Scenic (+13% instead of +17%).

As already seen in Base_LCOE, Base_Scenic and Base_Network, also in Base_all the mean objective values increase significantly if a regionally even distribution should be achieved. When comparing the LCOEs, scenicness and network length at the locations where the new turbines are placed in Base_all and Base_all_E (Supplementary Figure S12), it is obvious that the most advantageous locations are no longer exploited in Base_all_E. However, the trade-offs in Base_all_E are smaller: compared to the minimum values in Base_LCOE_E, Base_Scenic_E and Base_Network_E, the mean LCOEs, scenicness and network length increase only by 3%, 4% and 4%, respectively. However, this is also related to the low planning flexibility in the scenarios with equality.

3.5. Subordinate political targets only achievable with regional equality

While the policy target for onshore wind capacity in 2050 can be met in any scenario, subordinate targets such as the “south quota” can only be achieved in scenarios that involve a more even distribution of turbines. In recent years, the northern-focused expansion of onshore wind resulted in high and increasing amounts of curtailed electricity, with more than 5 TWh in 2019 [58]. Curtailment means the deliberate reduction of output power below the level that could be generated to balance energy supply and demand or due to transmission constraints [59]. In the Renewable Energy Sources Act 2021, a minimum south quota of 15–20% of new wind development over 2021–2024 will be established to address this issue [60]. Currently, the south quota is about 10% and would further reduce in most scenarios without equality since, as has been shown, the cost-optimal turbine locations would still be in the less beautiful landscapes in the north of Germany (Fig. 8). However, in the scenario Base_Network, as well as all scenarios with a regionally even expansion, the south quota could be increased to a value of about 50%. Therefore, apart from higher costs and lower planning flexibility, the equality scenarios could lower further curtailment.

Onshore wind expansion in the equality scenarios would be largely in the states of Baden-Württemberg and Bavaria, where the fewest wind turbines relative to the area have been built to date (Fig. 3) and which face particularly strong opposition to onshore wind [54]. We have shown above a generally weak trade-off between cost-efficiency and scenicness in Germany, and thus a rather low opposition to onshore wind should be expected in a national planning context. However, the weak trade-off does not apply to Bavaria and Baden-Württemberg: the mean scenicness in these states deviates by 66% with 8.7 (Base_LCOE) and 2.9 (Base_Scenic). In the two scenarios with equality, the difference

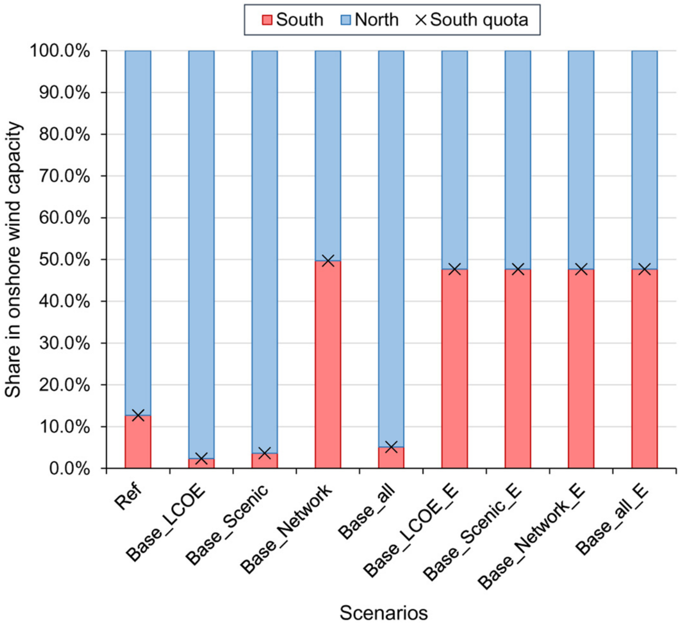

Fig. 8. Shares of southern and northern Germany in onshore wind capacity in 2020 and in eight scenarios for 2050. "Ref" shows the shares of existing capacity, the other scenarios show only the shares of added capacity by 2050. The German districts, which are included in the south quota can be found in the Renewable Energy Sources Act [61].

would be only 6% with 5.6 (Base_LCOE_E) and 5.2 (Base_Scenic_E). All in all, it could be feasible to achieve the south quota – especially in the scenario Base_Scenic_E, in which the turbines are placed in less beautiful landscapes in Bavaria and Baden-Württemberg.

4. Discussion

4.1. Limitations

In our analysis, several assumptions may partly affect the results. Firstly, the general applicability of results for Germany may itself be questioned: whilst we showed strong differences to Great Britain [36], lacking scenicness data and similar studies for other countries makes wider generalisations challenging. We considered only onshore wind, which means that we neglected the opportunity costs of the required land. In addition, other renewable technologies like solar energy, which could be more affordable in the southern regions of Germany, were neglected. However, the German government has specific plans for onshore wind expansion, also regarding its geographic locations (south quota), as demonstrated above. Also, the focus on wind turbine LCOEs neglects the energy system integration costs, which consist of costs related to meeting the residual load with the dispatchable generation (profiling costs), related to the deviation between forecast and actual non-dispatchable generation (balancing costs) as well as related to required grid reinforcements and extension (grid costs) [62,63]. These grid extensions could then again lead to increased public opposition [12]. Moreover, the connection of onshore wind farms to power grids usually requires extensive studies including power flow analyses to assess the technical feasibility [64], which has been neglected in the present study. However, these grid extension analyses, in combination with site optimization, are mostly performed on a local scale (e.g. [65]), as the complexity of these combinatorial optimization problems makes analyses for larger regions or countries impractical [66]. In future grid analyses, the sites identified in this study could be used as input to test their technical feasibility as well as to determine necessary extensions, reinforcements and/or curtailments.

Furthermore, our analysis is static. First, this means we ignored the deployment process for the turbines. Second, we only considered capacity and not hourly generation and its volatility since the onshore wind targets are formulated as capacities by the government. Third, repowering is expected to become increasingly important for the wind industry in the future [67]. We neglected repowering of existing wind farms, despite turbines probably having a capacity of more than 5 MW in 2050 instead of the current mean of about 2.5 MW [8]. Since the higher performance turbines would also require greater minimum distances and thus more land area, this effect was evaluated as remaining constant.

We considered only the straight-line distance for connecting the wind turbines with transformers, which is common practice in electricity network planning. Often, a detour factor is used, to account for locations, in which the straight line route is not feasible [68].

In addition, we define a regionally even distribution of wind turbines by using population size. This is connected to our choice of the municipal level and the limited data availability associated with it. Although the population size correlates with other relevant factors (e.g. the number of industrial companies, unemployment or municipal area [69] – see Appendix for more information), future studies should also include the ratio between wind energy potential and actual generation [33], direct employment for electricity generation and storage [34], or direct land use per total area [34]. Since public acceptance is also relevant in the present study, a distribution of capacity based on population size is assumed to be regionally equal. If other criteria such as average income are used, then poorer regions that do not aspire to have wind turbines in their vicinity might be disadvantaged. Also, we model the non-linear expression of regional equality as a constraint in our optimization model rather than a target criterion. Even though important insights have already been generated this way, future studies should try to improve this approach.

4.2. Key findings

In the following, the key findings of the analysis for the German case study are discussed. **First**, our analysis of the existing turbine stock shows that the criteria used in our planning tool are of high relevance in reality. With increasing LCOEs, scenic beauty of the landscape or required network length, the share of existing turbines in the onshore wind potential (at the respective locations) decreases. However, this also means that a regionally even expansion has been mostly neglected so far, see below.

Second, the trade-off between cost-efficiency and beauty of the landscapes in which the turbines would be placed, and thus landscape impact, turns out to be rather weak in Germany. Considering these target criteria, in both cases the turbines would be installed mainly in the northern federal states Lower Saxony, Mecklenburg-Vorpommern and Schleswig-Holstein (Base_LCOE and Base_Scenic in Fig. 8). These are the same states that already account for the largest share of existing capacity (Ref in Fig. 8), meaning that cost-efficiency and landscape impact were apparently priorities for historical wind farm developments. In other words, taking these target criteria into account alone would reinforce the uneven onshore wind distribution between North and South.

Third, whilst Germany does not show a general competition between windy and scenic locations, other studies [36,70] for Great Britain showed just the opposite. But there are also individual regions in Germany, such as the federal states Bavaria and Baden-Wuerttemberg, which very well show a higher trade-off between cost-efficiency and scenicness in potential wind sites. On the one hand, this shows that general conclusions cannot be drawn from analyses on the relationship between LCOEs and scenicness for one country. Instead, quantitative bases for scenciness in other countries must also be determined. On the other hand, this assessment of the trade-off between cost-efficiency and scenicness of onshore wind strongly depends on the considered system boundaries.

Although the quality of the scenicness assessment model is high and a validation approach with external data has confirmed the validity of the scenicness dataset [71], other factors have an influence on perceived scenicness and thus on the resistance towards wind turbine deployment. Subjective feelings and preferences, as well as place-attachment [72] and local identities also play an important role for landscape appreciation and could evolve over time, but could not be incorporated into the scenicness model. On an individual level, the acceptability of fitting turbines into landscapes could be measured to investigate how residents perceive the mix of landscape with turbines [72,73]. At the large-scale planning level we apply, however, the share of individual aspects is not the relevant part, but the large share (in our case around 2/3) that can be determined intersubjectively. Furthermore, empirical research has shown that there is a large agreement on scenic landscape quality across individuals, even across cultures. To account for transformation processes, the landscape photographs along with our regression model for measuring scenicness also included wind turbines [49]. Other models for the German-wide assessment of scenic attractiveness give a higher relative weight to water features [130], which leads to higher scenicness values in the north-German plains. As the distribution of optimal locations for wind turbines is sensitive to a modified spatial distribution of scenicness values, different scenicness datasets could lead to a shift of optimal locations for wind turbines towards the south.

Furthermore, landscapes with similar scenicness values may have different sensitivities to impacts caused by wind turbines. Thus, other factors such as intervisibility and visual openness should also be considered as proxies for visual landscape sensitivity to wind energy [74,75]. In addition to perceived scenic quality of landscapes, social acceptance of wind turbines is also affected by the recreation potential of landscapes [76]. Finally, while wind turbines and transmission grid infrastructure have a negative influence on perceived scenicness [49], younger generations hardly consider wind turbines to be a general landscape annoyance [77]. This is not true – at least not to the same degree – for transmission lines [78,79]. Thus, the interrelation of network length and scenic landscape quality requires a careful weighing in for future research.

Whilst the landscape impact is arguably most important for public acceptance of onshore wind [16,18–20], public concern is reduced when the affected individuals have prior experience with wind energy [80] (shown for the Upper Rhine region [81], Germany [82] or the US [83]) or live farther from turbines [16,84]. The latter, however, is not universally the case, as a recent national survey of existing U.S. wind project neighbours demonstrates [85]. The quantification of these aspects would also be pertinent to future energy system analyses.

Fourth, a regionally even expansion is associated with significantly higher turbine costs and higher scenicness at the wind turbine sites as well as a low planning flexibility. The question that arises from our analysis is whether benefits such as regional economic stimulation can outweigh the higher costs, presumably greater public opposition, and lower planning flexibility.

As our analysis further shows, an expansion of onshore wind could only achieve a maximum regional equality of about 20%. This is partly because we apply a brown field approach and take into account the existing turbine stock, which shows an equality of only about 6%. Furthermore, in many German regions there is no or only very limited onshore wind potential due to minimum distance restrictions or technical constraints. However, other technologies could also measure equality: for example, a regionally even and cost-efficient distribution may involve onshore wind turbines in the north and photovoltaic panels in the south (mainly in Bavaria and Baden-Württemberg) [33]. But considering that solar photovoltaics has a lower impact on landscapes [86] and leads to less public opposition than onshore wind (as shown for Switzerland [87], Germany [88] and other European countries [89]), this capacity-based equality with various technologies is not necessarily socially equitable. Even in the north of Germany, where the onshore wind turbines are currently mainly located, local citizens may be concerned that wind turbines might put off tourists and thus negatively affect local incomes [26]. Also, since the south quota only applies to onshore wind and biomass [60], a distribution with photovoltaic in the south would not meet this German policy target. Whilst multi-technology approaches are valuable to consider the interactions of different technologies and criteria, the exclusive focus on onshore wind here is the strength of this study, which adds to the discussion about onshore wind development. However, the social acceptance of solar photovoltaics should also be studied further, as studies increasingly indicate that wind could be preferred over photovoltaics in specific regions, for example in the U.S. [83].

At this point it should also be mentioned that the low planning flexibility is also related to our methodology for measuring regional equality. As already mentioned above, the low administrative level of German municipalities was chosen, as this is where decisions for or resistance against the installation of wind turbines often originate. Due to the high number of municipalities (about 11,000) that have to reach certain capacities in our methodology, this reduces flexibility. If the regional equality of the existing turbines is measured on NUTS-3 level, for example, the regional equality increases from 6% to about 25%. Using this approach, the equality could even increase to about 43% in the expansion planning instead of about 20%. This high dependence on the spatial scale suggests that targets for regional equality should probably be formulated at a higher administrative level, as already studied for the county [34] (NUTS-3) or federal state [33] (NUTS-1) level, in order to maintain a higher degree of planning flexibility - even though not all municipalities may participate equally in the opportunities then.

Fifth, some subordinate targets, such as the south quota of wind turbines in Germany, can only be met in the expansion scenarios with a more even distribution of turbines. This target is necessary to reduce curtailment and transmission grid expansion necessitated by overcapacity in the north. Historically, the diffusion of wind turbines in the south of Germany has been slowed down by local opposition [54]. Here, in particular, the scenarios we have shown for placing wind turbines in less beautiful landscapes could reduce opposition.

Sixth, small reductions in one target criterion could result in significant improvements in another. For example, the mean network length required to connect the turbines to transformers can be greatly reduced if the mean scenicness is slightly increased. In general, however, when minimizing turbine LCOEs or scenicness, the mean network length is high. Previous analyses have shown that the networks have a strong influence on total LCOEs (which would double on average if network costs are included [36]) and also on the landscape scenery and thus public acceptance [12]. In this study, the impact of network cables on LCOEs and scenicness was not quantified, in order to determine the optimal turbine locations with a limited number of assumptions. When considering network costs in the LCOEs, wind turbines would have to be clustered into wind farms with heuristics [36], requiring only one connection to the transformers. In the case of scenicness, the impact of the cables on the landscape scenery compared to the turbines would have to be weighted first. However, an improvement to the equally weighted consideration of the target criteria through expert elicitation weights faces high hurdles: whilst stakeholders consider interregional equality an important criterion for allocation, agreement on uniform weightings of various criteria for onshore wind expansion by experts appears to be practically impossible [29]. Our scenarios with one target criterion do at least indicate how the target values and turbine locations would change if one target criterion were weighted differently.

Lastly, the rapid spread and development of onshore wind in the past has sparked an increase in local protest movements and lawsuits across the country [26,27]. Our approach, which includes scenicness of landscapes and equality, can assist in moderating such protests. In addition to this, the introduction of the new "Investment Acceleration Act", which ensures that pending lawsuits will no longer halt the planning or construction of onshore wind farms [90], could also accelerate the German onshore wind expansion. However, these efforts to accelerate wind energy approvals could backfire by galvanizing opposition, when communities feel they were excluded from decision-making – as was the case for the Green Energy Act in Ontario, Canada [91].

Furthermore, policy makers could consider more ambitious targets for onshore wind expansion as in our “High” scenario with a capacity of 200 GW by 2050. In the past, long-term onshore wind capacity targets have been repeatedly increased in response to developments in the energy sector. In addition, many experts see the achievement of climate protection targets at risk if the current targets of the Renewable Energies Act 2021 are maintained [39]. A recent study has shown that an early and steady decarbonisation of the European energy system would be more cost-effective than a late and rapid path [92]. Also, for onshore wind, an early commitment to higher capacities would enhance planning security, prevent conflicts that may arise in the future, and create more planning flexibility as shown by our analysis – even in scenarios with a regionally even approach. In any case, an urgent need would be to set the annual electricity generation as the long-term target, and not the capacity. As our analysis shows, despite the same capacity, generation could differ greatly depending on the scenario.

5. Conclusion

The targeted onshore wind expansion to achieve the German 2050 climate targets will face a number of obstacles. Three relevant criteria for the successful diffusion of turbines form a trilemma in onshore wind expansion planning: cost-efficiency, landscape impact and regional equality. We combined a variety of open data sets, a Geographic Information System, and a multi-criteria optimization to determine the trade-offs between these three objectives within an optimal onshore wind expansion plan. As a necessary condition for the implementation of the expansion in reality, a significant part of public acceptance was quantified for the first time in an expansion planning framework: for this, the scenicness of landscapes was used since the impact on landscapes is one of the most prominent motivations for the opposition towards onshore wind.

We show that, historically, onshore wind development has focused on cost-efficiency in Germany. While the trade-off between optimizing either cost-efficiency or landscape impact of the future turbine fleet is rather weak with about 15% higher costs or scenicness, an even distribution has a large impact on these criteria. For the achievement of the German policy target that calls for more wind turbine additions in southern Germany (*south quota*), however, an evenly distributed expansion is necessary. Consequently, the south quota cannot be addressed by siting decisions alone. Procedural and financial participation in municipalities may help reducing public opposition and improve regional equality in the distribution of benefits and costs. The approach presented in this study is also relevant for wind development planning in other countries. While the turbine data used is available for the whole of Europe, to our knowledge nationwide scenicness data only exist for Great Britain and Germany.

Author contributions

Conceptualization, J.W., R.M.; Methodology, J.W., R.M.; Formal Analysis, J.W.; Data Curation, J.W.; Writing – Original Draft, J.W., R.M., H.H., and M.R.; Writing – Review and Editing, J.W., R.M.; Writing – Interactive Feedback, R.M., H.H., M.R., D.S., and W.F.; Visualization, J.W.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This work was supported by the Helmholtz Association under the program "Energy System Design".

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.adapen.2022.100102.

Appendix

Literature review

Within this literature review we identified studies which analysed the potential of onshore wind energy with a multi-criteria approach. Special emphasis was given to those studies including social aspects as in the present article. In Web of Science we used a search query, which results in roughly 200 studies: TITLE-ABS-KEY OR CONTENT (("multi-object*" OR "multicrit*" OR "multiobj*" OR "multi-crit*") AND ("wind turbine" OR "onshore wind") AND ("potential" OR "location" OR "placement" OR “expansion*” OR “capacity*”)). Subsequently, we added relevant studies mentioned in the literature reviews of the initially identified articles.

Many studies using multi-criteria approaches optimize onshore turbine locations in terms of integration into the power system or grid [93–98], applying techno-economic, legal or environmental criteria [99–103] or focussing on wind turbine selection and wind farm layout [100,104–108]. However, these techno-economic approaches usually neglect social aspects or incorrectly blur technical constraints with constraints relating to social acceptance [109]. Whilst social science topics have been gaining more importance in the whole field of energy system analysis [110], however, for some subfields like “equity and distributional effects”, quantitative analyses fail partly because of the high complexity involved [111].

Among the studies considering social aspects in multi-criteria analyses, analytical hierarchy processes together with pairwise comparison methods or fuzzy based decision making procedures both based on expert or stakeholder interviews or surveys are frequently used [30,112–119]. In these studies, the interviews and surveys are used to weight or rank the decision criteria. The number of experts and stakeholders involved most often does not exceed fifteen, which might not suffice to obtain representative results. In addition, the results are limited to the specific regions under observation and the selection of stakeholders is mostly not justified in detail. Another common approach comprises multi-objective optimization [31,33,120–122], which is also applied in the present study.

Some simulations cover more than one country [57], however, most optimizations considering social aspects focus on one country [30,31,33,113,114,120–123] or a region within a country [99,115,116,119,124] with a slight tendency for more recent studies to cover the former. This might be due to improvements in computational capabilities, as multi-criteria assessments are computationally more complex for larger regions or a higher number of criteria.

The criteria stated as social factors in the reviewed studies show a broad variety (see Table A1) and no generally applied definition for social factors can be found. Few if any of these studies adopt an energy democracy perspective lens that emphasizes individual and collective power, democracy and inclusivity as key themes [125]. While some studies model social factors directly, other studies use proxies like distances to settlements. The factors range from impacts on health [116,122–124] across public and political support or success chances [30,113,121] to equitable burden and social chances [33,119,122,123,126]. The most often considered social factor in the identified literature is noise, while equality of burdens or social acceptance are less frequently addressed. Drechsler et al. [33] define the equitable spatial allocation as an even distribution of burdens of renewable energy sources across all people living in the respective area. Burden is defined as the utilized share of the whole wind energy potential in a specific region weighted by the region-specific population. Therefore, people living in areas with a high wind energy potential would have to

Table A1
Social factors or proxies considered in studies on assessing potential onshore wind turbine placements.

Social factors	Reference
strobe effect, sun rays, noise	Kazak et al. [124]
fatality, employment	Laha & Chakraborty [122]
public recognition, government support, distance to city-residential area	Feng [113]
population density, distance from city	Petrov & Wessling [126]
human infrastructure, noise, pollutants, renewable energy sources access rate	Vagiona & Karapanagiotidou [123]
noise by proxy distance to urban areas	Höfer et al. [116]
equitable spatial allocation	Drechsler et al. [33]
landscape impact by proxy distance to urban centers and roads	Weiss et al. [119]
social acceptability	Harper et al. [30]
social opposition indicator	Al Shidhani et al. [121]

face a higher number of wind turbines, which might not be in line with the initial intention of an even distribution of the burdens. The criterion ”social acceptability” is addressed in Harper et al. [30] where it is defined as the chance of getting permission to build the wind turbines derived from previous statistical analysis, while the “social opposition indicator” in Al Shidhani et al. [121] is based on an expert survey exploring the expected social resistance to each considered technology. None of the previous studies have examined the trade-offs between all three criteria cost-efficiency, public acceptance, and equality in onshore wind expansion planning. In addition, another strength of our present analysis is the determination of the optimal turbine locations on national scale in a spatially explicit manner.

OpenStreetMap queries

The existing wind turbines are identified via the Overpass API and the following query:

```
[timeout:900]; area["ISO3166–1″="DE"]->.a;
(node["power"="generator"]["generator:source"="wind"](area.a);way
["power"="generator"]["generator:source"="wind"](area.a);relation
["power"="generator"]["generator:source"="wind"](area.a);
)out qt;>;out qt;
```

The result can then be further processed as a geojson file in a GIS program. The transformers are obtained via the following query, in this example for 110 kV:

```
[timeout:900]; area["ISO3166–1″="DE"]->.a;
(relation["power"="substation"]["voltage"~".*110,000.*"](area.a);way
["power"="substation"]["voltage"~".*110,000.*"](area.a);
relation["power"="sub_station"]["voltage"~".*110,000.*"](area.a);
way["power"="sub_station"]["voltage"~".*110,000.*"](area.a);relation
["power"="station"]["voltage"~".*110,000.*"](area.a);
way["power"="station"]["voltage"~".*110,000.*"](area.a);
); out qt;>;out qt;
```

Correlation coefficients

Table A2

Further information on the scenicness evaluation

The following information is from the German project report by Roth et al. [127]. The survey for evaluating scenicness was conducted using specially-prepared landscape images that are representative of Germany’s range of landscape areas. To ensure this, 30 reference spaces were selected, distributed across the whole of Germany. Each of these spaces covers an area of approximately 130 to 140 km^2. In order to be able to make a representative and at the same time objective selection, on the one hand the large-scale natural units of Germany, defined according to the handbook of the natural division of Germany [128], and on the other hand the main units of the landscape types defined by the Federal Agency for Nature Conservation [129] were used. Attention was paid to an even distribution of the study areas over the whole territory of the country. In the selected study areas, photographs were taken using a Nikon 7200 SLR camera with an AF-S DX Nikkor 18 - 300 mm 1:3.5–65 ED VR lens. Accurate documentation of site coordinates, line of sight, and angle of view of each photo is a prerequisite for the study and was performed using a Solmeta Geotagger Pro2. To ensure the most homogeneous environmental conditions possible when taking the photos, almost all photo sessions were conducted during the months of May through August. From the total selection of photos taken, 25 to 30 photos from each reference space were selected and fed into an online survey. Where they occur, it is noted that forest, water, arable, open land, settlement and infrastructure dominated landscapes are included. Each of the landscape components should occur in various combinations with other landscape components. If possible, a landscape component should also be presented individually to be able to generate data on the influence of only one landscape component unaffected by other landscape components. For this reason, photos of interior views of forests and settlements/towns in the reference areas are also included. Photos with conspicuous individual elements that are not typical of the landscape, e.g. large road signs that attract the viewer’s attention, are not included in the selection if possible.

Participants in the online survey were then first shown 10 landscape photos each, randomly selected from a pool of 822 images. Every respondent had to evaluate these landscape images and could then choose to evaluate up to five additional images. About two-thirds of the respondents chose to evaluate additional images. A one-item-one-screen concept was used, i.e. each screen showed the photo to be evaluated and one question ("How beautiful do you find this landscape?"). The concept was designed to minimize habituation effects among respondents and to be able to investigate sequence effects. A one-week pretest was conducted to ensure that the online questionnaire was technically sound, user-friendly, and that the instructions were clear. 36 participants, composed of respondents from subject-related disciplines as well as laypersons, took part in the pretest. On this basis, the survey could be improved, for example, by providing additional definitions and information before the actual survey. As part of the project, the main part of the respondents was approached using the SoSci Panel (scoscisurvey panel https://www.soscipanel.de/). The SoSci Panel is a project of SoSci Survey and includes over 70,000 primarily German-speaking survey respondents. We collaborated with this socio-demographic panel to actually target a representative sample of the German population. In terms of gender, the sample can be considered representative (see Table A3). However, there is a slight bias toward younger respondents as well as a stronger bias toward above-average school-leaving qualifications and educational attainment among respondents compared with the German

Table A2
Correlation coefficients (CC) for the correlations of various indicators with population size at the municipality level [37,69].

Correlation method	Area [km^2]		Number of unemployed		Number of industrial companies	
	CC	pval	CC	pval	CC	pval
Pearson	0.45	0	0.98	0	0.88	0
Spearman	0.72	0	0.94	0	0.76	0
Kendall	0.53	0	0.80	0	0.59	0

Table A3
Socio-demographic characteristics of the survey sample compared to population statistics. The percentages do not always add up to 100% for the sample since some participants did not indicate an age, school graduation or professional degree.

		Sample	German Population
Gender	Male (%)	46.7	49.3
Age	< 40 years (%)	46.4	42.9
	41–60 years (%)	38.2	28.1
	> 61 years (%)	12.8	29.0
School graduation	“Hauptschule/Realschule” (secondary school)	9.4	52.1
	“Abitur/Fachabitur” (High school)	86.6	33.5
Professional degree	None	7.3	25.2
	“Lehre / Berufsschule” (professional school)	12.3	46.6
	University of Applied Sciences	22.2	9.3
	University	53.2	17.3

population as a whole. In jurisprudence, the "educated, open-minded average observer" is often used in relation to landscape assessment. Based on this basic assumption, the distribution of the survey participants can be considered target-oriented.

The regression equation for scenicness reaches a coefficient of determination (r^2) of 0.639 (Pearson). 17 significant variables (14 that differ across the zone) like water bodies (percentage of view), land use types (percentage of view) or road density (m/km^2) are part of the equation. Beauty is defined primarily by negative influences. Thus, a high beauty score results from the absence of disturbing influences, like traffic infrastructure, arable land as well as industrial/commercial areas, and the presence of positively acting regressors such as forests or water bodies. The density of wind turbines is also included in this calculation. The regression equation is subsequently applied to the entire area of Germany. For more information, please refer to Roth et al. [127].

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