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Historic drivers of onshore wind power and inevitable future trade-offs

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Abstract

The required acceleration of onshore wind deployment requires the consideration of both economic and social criteria. With a spatially explicit analysis of the validated European turbine stock, we show that historical siting focused on cost-effectiveness of turbines and minimization of local disamenities, resulting in substantial regional inequalities. A multi-criteria turbine allocation approach demonstrates in 180 different scenarios that strong trade-offs have to be made in the future expansion by 2050. The sites of additional onshore wind turbines can be associated with up to 43% lower costs on average, up to 42% higher regional equality, or up to 93% less affected population than at existing turbine locations. Depending on the capacity generation target, repowering decisions and spatial scale for siting, the mean costs increase by at least 18% if the affected population is minimized – even more so if regional equality is maximized. Meaningful regulations that compensate the affected regions for neglecting one of the criteria are urgently needed.

The deployment of low-carbon technologies is a key measure to tackle climate change. As the global energy system transformation progresses, low-cost wind energy has become a mainstream electricity source[1] with further cost reductions expected until 2050[2–4]. According to the European Commission's own 2050 scenarios, onshore wind is expected to remain the leading renewable energy source in Europe in terms of installed capacity and should grow from about 200 GW today to 750 GW (about 1,900 TWh)[5,6]. This means accelerating the onshore wind expansion in Europe significantly, despite it having recently stalled in many European countries such as Germany[6] in contrast to global trends[7].

Due to growing social disputes around onshore wind expansion[8–10], increasing and allocating the deployment of onshore wind requires stakeholders to also address criteria beyond the usually-emphasized cost-effectiveness[11,12]. Firstly, energy system optimization rooted solely in economic relationships is largely disconnected from the advancement of human well-being[13]. Wind turbines often produce **disamenities** for residents living nearby, e.g., due to noise emissions, shadowing, or changes in landscape aesthetics. The relevance of a disamenity typically depends on the distance to and the amount of affected population[14–16], so they may vary substantially across existing and potential sites of wind turbines. To increase well-being, these disamenities need to be considered when determining a socially acceptable spatial allocation of wind power deployment.

Secondly, a cost-effective approach leads to wind power expansion being distributed unequally across regions, as wind farms are concentrated in a few locations with good wind conditions[12,17]. In contrast, an approach that considers **regional equality** may account for opportunities for local communities, such as job creation or economic benefits through ownership or compensation schemes[11,18–20] and could thus enhance the acceptance and expansion of onshore wind. In some countries, a more even distribution of turbines may also result in less need for transmission grid expansion. In Germany, for this reason, a southern quota has already been mandated in the tendering process for new wind farms to prevent further predominant turbine concentration in the north of the country[17]. Besides these positive influences of onshore wind, however, the above-mentioned disamenities also necessitate a fair and even distribution of turbines to address local citizens' perceptions of distributing benefits and burdens of wind energy projects[20]. Only a few studies investigated the trade-offs between regional equality and cost-effectiveness in the expansion of the wind power fleet in Germany[17,19] or in holistic energy system analyses of Switzerland[21], Central Europe[22], or whole Europe[23,24]. With equality measurements at the municipal[17,21], county (NUTS-3)[22], federal state[19] or national (NUTS-0)[23] level, these articles show that higher regional equality in renewable capacity is possible with an increase in energy system costs.

Whilst **cost-effectiveness** has certainly been a priority, the extent to which social criteria like disamenities and regional equality have been considered in the historical onshore wind expansion cannot be clearly stated and requires investigation. In literature, the existing European onshore wind fleet has so far only been investigated with regard to technical criteria such as current and future capacity factors, which are the main descriptors for the cost-effectiveness of the locations, whereby planned or approved wind farms were assumed as future locations[25].

Motivated by the necessary acceleration of onshore wind energy expansion in Europe, we first analyse the cost-effectiveness, disamenity and regional equality of the historical onshore wind development. Using spatially explicit turbine locations, we examine which target criteria have historically been of major importance in individual European countries and assess the countries' performances in the selection of favourable turbine sites. The findings serve as a benchmark for evaluating the future expansion: based on the existing turbines, we then analyse the untapped potential in each country and optimize the spatially explicit onshore wind expansion in Europe by 2050 in a total of 180 scenarios. We measure

- the optimum achievable cost-effectiveness on the basis of the turbine levelized cost of electricity (LCOE, *Low LCOE* scenarios),
- the lowest achievable disamenities for the local population caused by the turbines (*Low disamanities*),
- the maximal achievable regional equality of all NUTS-3 regions measuered by the Gini index (*High equality*),

as well as the trade-offs between these criteria. Disamenities are minimized in scenarios with as few affected inhabitants as possible within a radius of up to 1 km, 2 km, 3 km or 4 km from the turbines (*Low disamenities* scenarios). We also analyse the opposite scenario with as many affected inhabitants as possible, to maximize the regional equality (*High equality* scenarios). The equality is measured at the NUTS-3 level using the Gini index, though not based on income as in its original form, but instead based on the total electricity generation by the turbines in relation to the total electricity demand in all sectors by 2050. The target criteria and trade-offs between them are examined at the European, national (NUTS-0) and county (NUTS-3) level with a low (500 GW), medium (750 GW) or ambitious (1000 GW) expansion target and starting from a repowered or non-repowered turbine stock. Repowering the existing turbine fleet requires fewer additional turbines in order to achieve the capacity targets. Since assumptions regarding turbine technology are highly significant for the potential estimate[26], we use turbine potentials for 2050[27,28] with larger rotors and therefore decreasing spacing as well as increasing total turbine investments. The historically selected onshore wind sites are assigned LCOEs for 2050 for better comparability with the expansion scenarios.

Strong allocation disparities among European countries

The locations of existing turbines in Europe with a capacity of about 200 GW exhibit mean LCOEs of 5.0 €-cent$_{2050}$/kWh and affect about 4,015 inhabitants per turbine within a 4 km radius on average (see Figure 1). For smaller radii, this latter value decreases to 2,134 (3 km), 872 (2 km) and 203 (1 km) inhabitants, respectively. In terms of regional equality, turbines are spread very unevenly across Europe, with a Gini index of about 0.82.

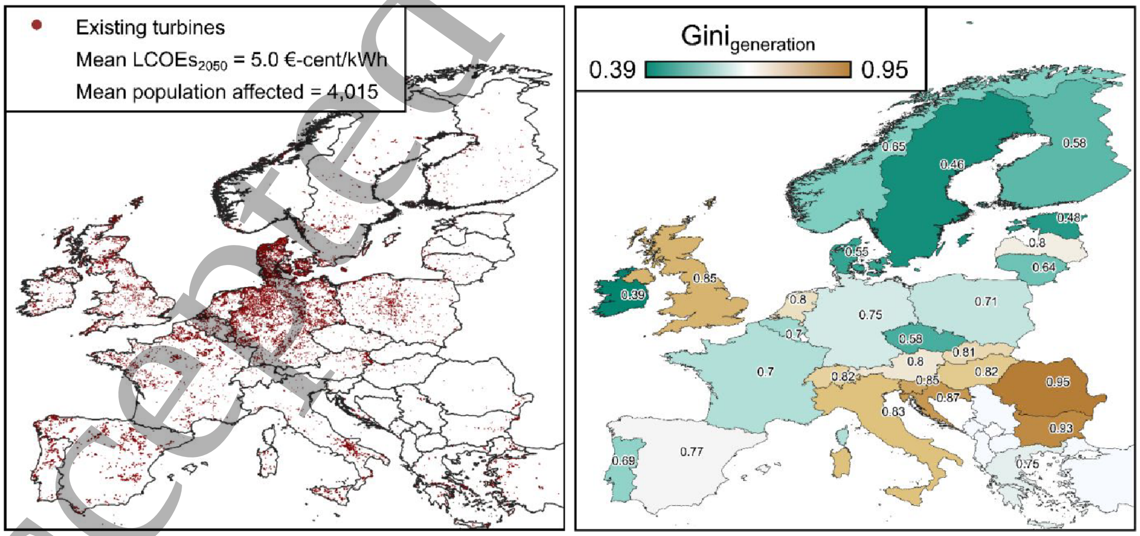

Figure 1: Existing wind turbines in countries of the EU-28, European Free Trade Association (EFTA) as well as EU Candidate Countries (CC-5). The left panel shows the onshore wind turbines retrieved from the Overpass API (red dots). The right panel shows the Gini coefficients for all countries. These were calculated based on the distribution of turbine generation per electricity demand of NUTS-3 regions (see method section).

Although only about 2% of the European onshore wind potential (13 TW)[27] has been exploited so far, some countries show significantly higher exploitation shares (Figure 2). Especially in Germany (DE) and Denmark (DK), comparatively large shares of the potential sites are already exploited. On the other hand, some countries have a very low onshore wind development relative to their very high cost-efficient potential, such as Finland (FI), Ireland (IE), Norway (NO) or Sweden (SE). However, compared to the mean Gini index in Europe of 0.82, some of these latter countries show high regional equality with Gini indexes of 0.39 (IE), 0.45 (SE) and 0.58 (FI).

The LCOEs of the turbines most likely played a major role in the spatial allocation of historical onshore wind power expansion (Figure 2 and Figure 3). In general, the European countries show lower shares of already exploited sites with higher LCOEs (see Figure 2). Some countries such as Belgium (BE), Netherlands (NL) or Poland (PL) have already exploited more than 50% of their most cost-effective sites (≤ 3 €-cent$_{2050}$/kWh), but these sites are usually rather rare. In Germany (DE), which has a relatively low potential in terms of land area or population, even up to LCOE classes of 12 €-cent$_{2050}$/kWh, more than 5% of the sites have already been occupied with onshore wind turbines. In Denmark (DK), the potential has even been exploited to at least 7% for each LCOE range.

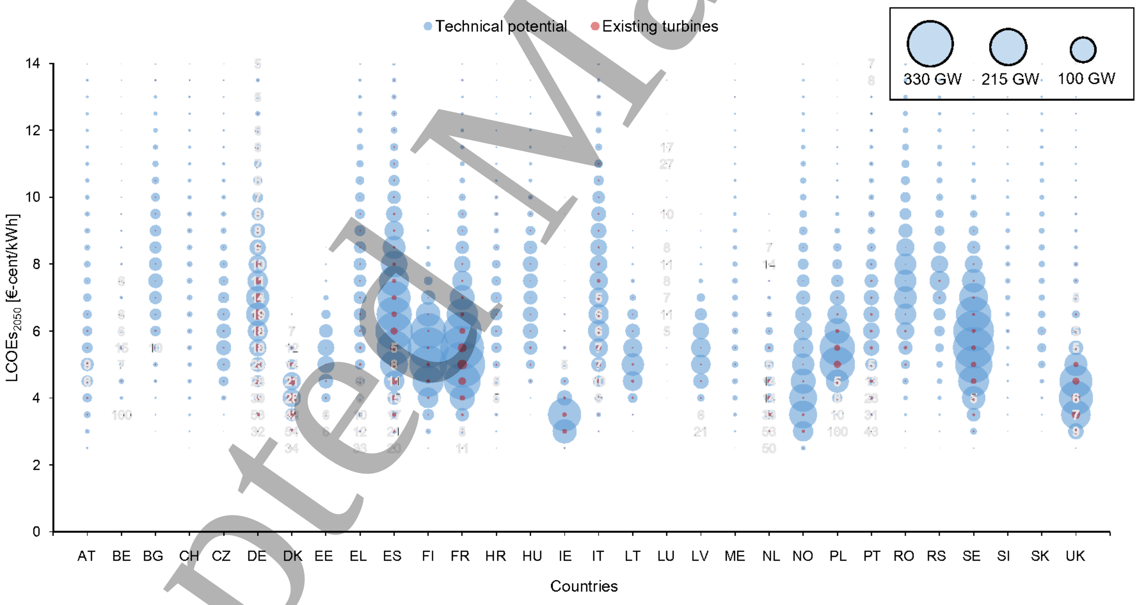

Figure 2: European technical onshore wind potential for 2050 (blue bubbles) and the potential equivalent of already occupied sites by existing turbines (red bubbles). The potential is classified in LCOE steps of 0.5 €-cent/kWh and the bubble size indicates the capacity in GW. The share of the utilised potential is indicated as a bubble label for values from 5% upwards. The country codes are assigned according to Table S1 in the Supplementary material.

Overall, there are strong allocation disparities among European countries. For example, while onshore wind turbines were distributed most equally in Ireland (IE) (Gini index of 0.39, Figure 1), the LCOEs of the turbines did not seem to play a predominant role (Ratio of mean LCOEs of existing and potential turbines of about 1.0, Figure 3). Therefore, this development in Ireland could represent a kind of misgovernment (second quadrant in Figure 3), as decisions were made based on the affected population as well as equality and somewhat neglect costs. However, as mentioned, Ireland also has exceedingly high cost-effective wind potential compared to most other countries, which could potentially reduce the prominence of LCOE in historical planning. On the other hand, Sweden (SE) has identified relatively cost-efficient locations (LCOE ratio of 0.85, Figure 3) while achieving relatively high regional equality (Gini index of 0.45, Figure 1), but with a very large fraction of the population affected (population ratio of 2.5, Figure 3). This planning policy could possibly lead to increased public opposition towards onshore wind in the future (fourth quadrant in Figure 3). However, more and more wind farms are also planned in the remote and sparsely populated north of Sweden, such as the Önusberget wind farm, which will be the largest single onshore wind farm in Europe with 753 MW when completed[29]. The wind turbines of the Önusberget wind farm would affect on average only 3 people in 4 km distance and the sites have low LCOEs of about 6 €-cent$_{2050}$/kWh. This trend could thus significantly reduce the affected population ratio in Sweden in the future. Greece (EL) shows the best combination of low LCOEs and low affected population (ratios of 0.72 and 0.38), but the regional equality value is quite low (Gini index of 0.75). Regarding the former two criteria, the historical onshore wind development in Greece thus indicates good practice (first quadrant in Figure 3). None of the European countries is located in the third quadrant in Figure 3, which would probably lead (or already has led) to a rejection of the planned wind turbines due to neglect of the costs as well as disamenities.

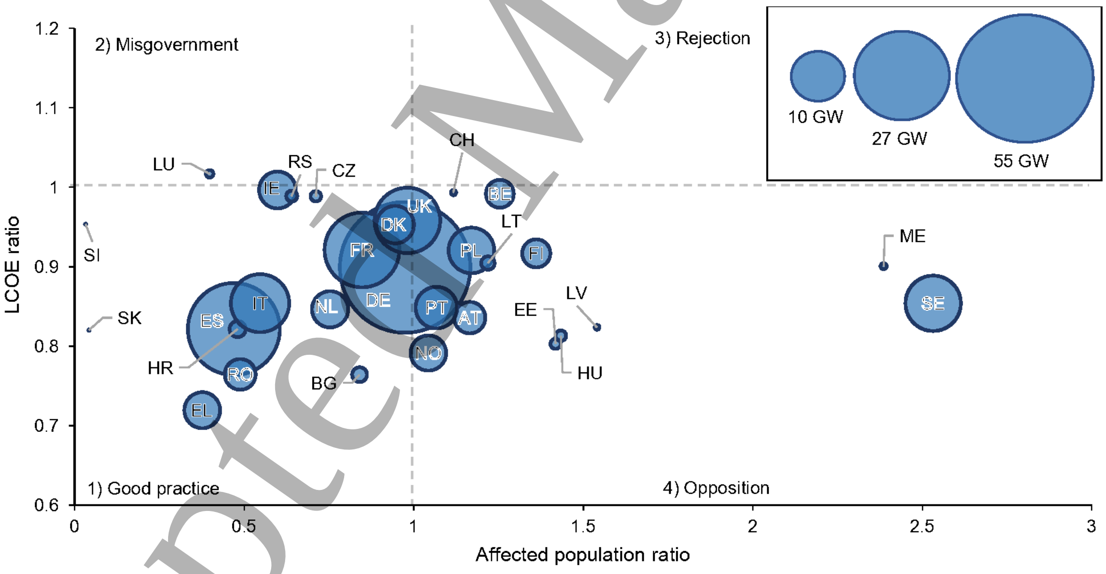

Figure 3: Ratios between mean LCOEs or mean affected population in 4 km radius of the existing onshore wind turbine fleet and the means of the total onshore wind potential of the respective country. A value below one therefore suggests that more consideration was given to the corresponding criterion (LCOEs or affected population) when allocating the turbine locations. A value above one suggests that little consideration was given to a criterion. The bubble sizes indicate the capacities of the onshore wind fleets in 2020[6]. The country codes are assigned according to Table 1 in the Supplementary material. The first quadrant shows ***good practice****, as in these countries the most cost-effective locations for the turbines were chosen, as well as at locations far away from the population. The second quadrant would represent a kind of* ***misgovernment****, as decisions were made based on the affected population and largely neglect costs. Turbines that have both high LCOE and affect many inhabitants would probably be mostly* ***rejected*** *- hence there are no bubbles in quadrant 3. The fourth quadrant shows the countries that attach great importance to low-cost locations but neglect the impact on the population. This could lead to increased public* ***opposition*** *towards onshore wind in the future. The relative differences in the affected population ratio between the individual countries are still evident at disamenity distances below 4 km between turbines and the population (see Figure S1 in the supplementary material).*

In general, the affected population ratio for Europe increases degressively with distance (Figure 4), which illustrates that greater weight has been placed on affecting as few inhabitants as possible at lower distances between turbines and population. This suggests that disamenities had an impact on turbine location choice, but this impact decreases with distance from the turbine. This analysis of the historical deployment thus already shows that the onshore wind expansion is probably not possible without trade-offs. The following analysis of the allocation of future expansion further elucidates this.

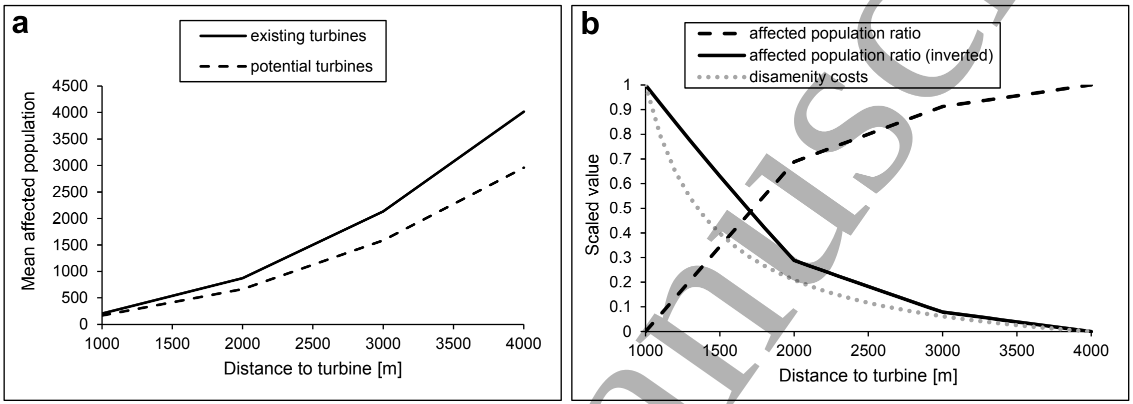

Figure 4: The mean affected population and disamenity costs as a function of distance. Panel (a) shows the mean affected population for the existing and the potential turbines in Europe. Panel (b) illustrates the population affected by existing turbines in Europe relative to the affected population at potential turbine sites compared to an empirically derived[30] curve for disamenity costs for the affected population caused by wind turbines. For better comparability, the curves in panel (b) are scaled to values between 0 and 1. In addition, the affected population ratio curve has been inverted for better comparability. A low value of this curve means that the affected population ratio is high, which in turn means that in comparison to the potentially placeable turbines, less importance was attributed to the impact on the population by turbines at a corresponding distance. The fact that the value is 1 at a distance of 1 km and then regresses to 0 means the following: at a distance of 1 km, strong attention is paid to selecting turbine locations that affect as few people as possible. At 4 km, significantly less importance is attached to the number of people affected by the turbines at that distance. The curves for "affected population ratio (inverted" and "disamenity costs" in panel (b) are comparable in their course. Thus, the real allocation follows the empirically derived external costs caused by the proximity to the wind turbines. Interpolation points for the affected population ratio are values at 1 km, 2 km, 3 km, and 4 km.

Widely differing locations for turbine expansion

If the future onshore wind expansion is optimized at the European level, significant differences in turbine locations are observed, depending on the scenario (Figure 5). The expansion is limited to a few countries when LCOEs or affected populations are minimized, respectively. In the former case, when a large generation capacity is added, the low-cost potentials in Ireland, Norway, and the United Kingdom are mainly exploited (42%, 27%, and 18% of all added turbines, respectively, in Figure 5a and Figure 5b). The results in the *Low LCOE* scenarios are logically not affected by a different distance for measuring the affected population.

If the affected population is minimized (*Low disamenities* scenarios), Nordic countries all take a prominent role, as does Spain, which is sparsely populated in many regions. In the scenario with the largest onshore wind expansion, i.e. with an expansion target of 1000 GW and no repowering of existing plants, and a 2 km disamenity distance, most generation capacity is added in Spain and Finland (51% and 23%, respectively, in the scenario in Figure 5c). When measuring the disamenity distance in a 4 km radius, the share of the two countries decreases and Norway and Sweden take over the major roles in the expansion (Figure 5d). These Nordic countries stop contributing if only a very small amount of capacity is expanded (scenarios with 500 GW expansion target and repowering of existing plants in Figure 5e und Figure 5f). The first, smaller capacity extensions seem to be predominantly installed in Spain, which accounts for as much as 97% of the installed generation capacity in the scenario shown in Figure 4f.

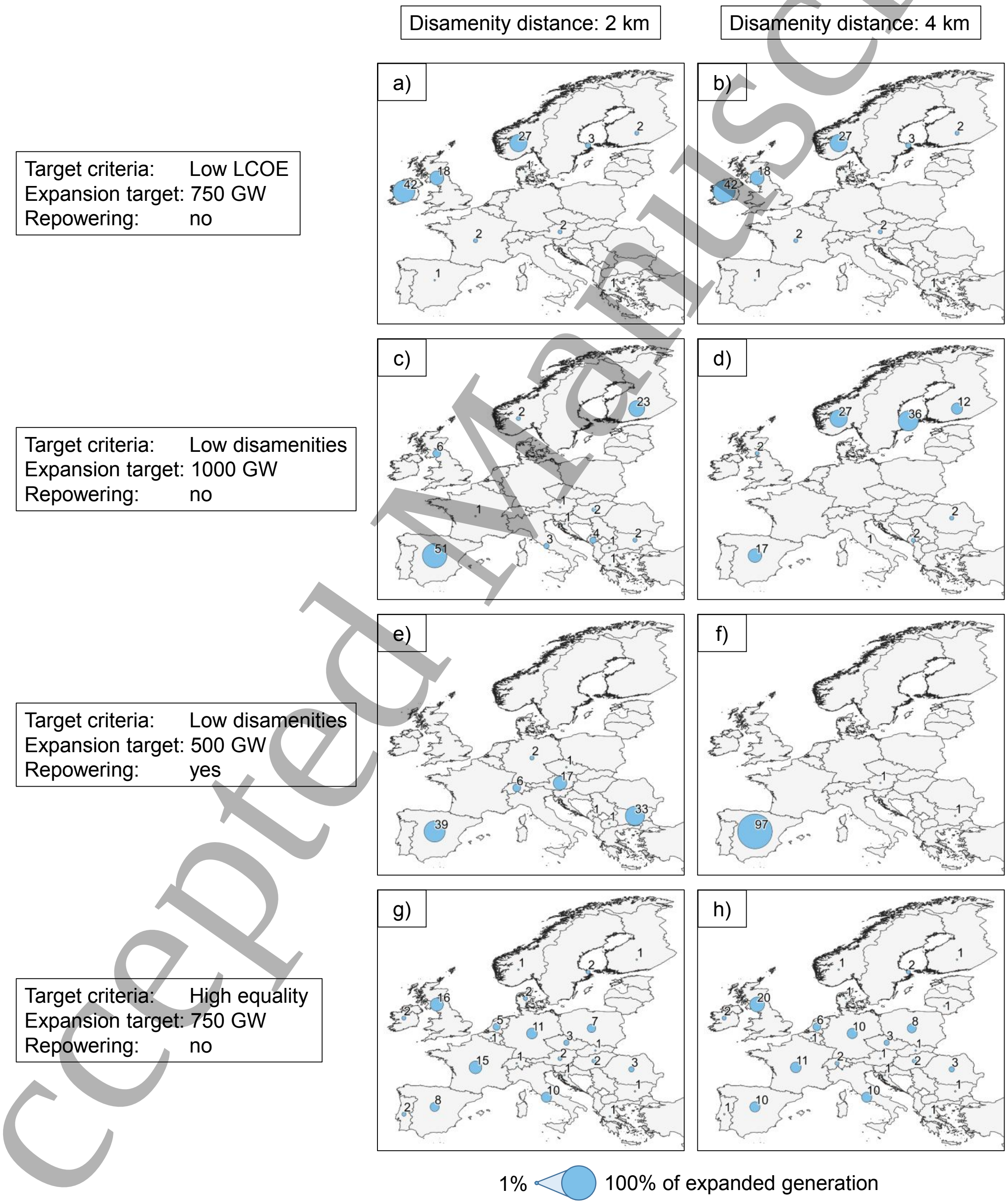

Figure 5: Eight exemplary onshore wind expansion scenarios from the set of 180 scenarios, from the perspective of a central planner at the European level. A distinction is made between the target criterion, the expansion target, whether the existing

turbines are repowered and up to which distance the affected population is measured (disamenity distance). The blue bubbles show the countries' share of the total added onshore wind generation capacity in the respective scenarios. The results of the "Low disamenities" scenario are shown for an expansion target of 1000 GW without repowering of the existing turbines and for 500 GW with repowering, in order to show the difference for a maximum deviation of the capacity to be expanded. For comparability with the other scenarios with 750 GW expansion target, we note that the percentage distribution in scenarios c-d for 750 GW is very similar to the one with 1000 GW.

In the *High equality* scenarios, the additional turbines are distributed much more evenly among the individual countries (Figure 5g-h) than in the previously discussed scenarios. This can be attributed to the fact that onshore wind turbines are located in more densely populated regions in almost all countries now, especially in the United Kingdom, which shows the largest increase in generation capacity. This more even distribution is associated with higher regional equality, as will be discussed in more detail below.

Significant differences also emerge in expansion allocation at the country level (e.g. in Germany, Figure S6). However, we only address the locations in the case of European-wide optimization here, as addressing the differentiation for individual countries or NUTS-3 regions would require excessive low-level detail. When optimized at the country level, the locations in Germany in the scenarios with minimization of LCOEs and minimization of affected population (largely) correspond to those from previous studies on German onshore wind expansion[17,30,31]. In the following, the analysis deals with all 180 scenarios, i.e. also for individual countries or NUTS-3 regions.

Reducing disamenity drives up costs and inequality

Choosing a spatial allocation of wind turbines that affect fewer people nearby would be associated with a high trade-off in terms of LCOEs. Depending on the scenario, a reduction of disamenities (*Low disamenities*) would increase LCOEs (*Low LCOE*) by 18% to 105% on average (Figure 6). The mean LCOEs of the expanded turbines in the *Low LCOE* scenarios are consistently below the mean LCOEs of the existing turbine sites of 5€-cent$_{2050}$/kWh (between 0.5% and 43% lower), while they are above this level in the other scenarios with very few exceptions. Lower values than those realized with the existing turbines are also achievable for the other two target criteria, which again illustrates that historical siting decisions seem to have involved trade-offs between the target criteria. Placing turbines as close as possible to the population (*High equality*) increases the average LCOEs even more, between 129% and 218%. This suggests that the wind conditions near settlements are worse than in rural areas – which has also been suggested in studies on the relation between landscape scenicness and wind potentials[9,30,31].

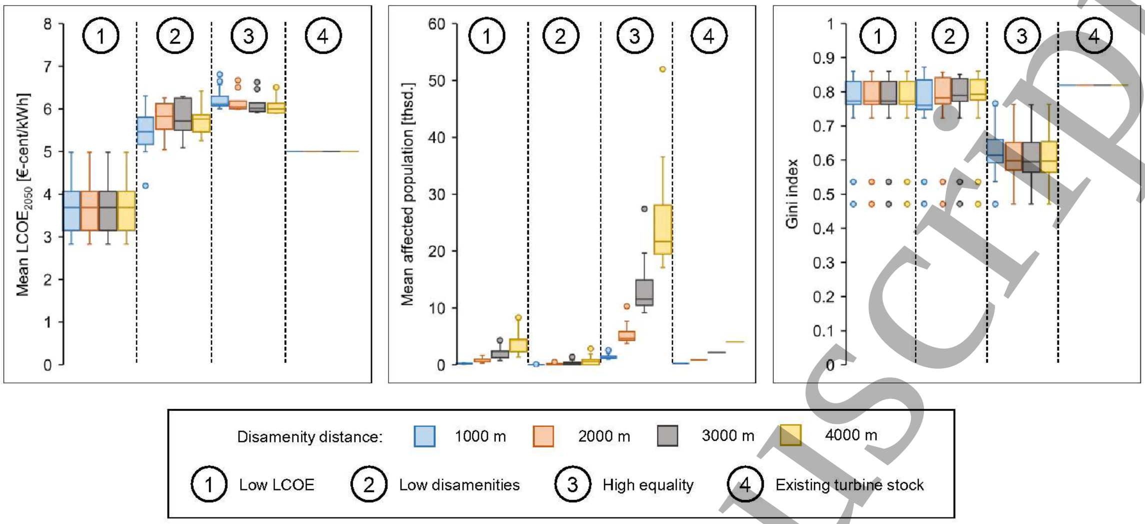

Figure 6: Boxplots of LCOEs, affected population and Gini index of 180 different expansion scenarios. The boxplots are differentiated according to the target criterion and by the distance to turbines up to which the affected population is considered. The median is represented by the horizontal line, and outliers by dots.

Relative to the existing turbines, the expanded turbines in the *Low disamenities* scenarios affect between 80% and 93% fewer people on average at a distance of 1 km to 4 km (Figure 6). In the *Low LCOE* scenarios, the affected population varies between -6% and +6% compared to the existing turbines. Thus, the historical allocation is more aligned with minimizing LCOEs than minimizing disamenities. However, the fact that the latter also mattered for siting wind turbines is further shown by the significantly higher possible affected population values in the *High equality* scenarios, which are between 155% and 602% higher than for the existing installations. Nevertheless, the proximity of the turbines to the population significantly increases regional equality by 25% (expressed by a change in the Gini index value) on average by 2050 in the *High equality* scenarios. Even in the majority of *Low LCOE* and *Low disamenities* scenarios, the additional turbines increase the equality (+8% and +6% on average, respectively). This implies that the expanded turbines have to be distributed across new regions, as the regions of the previously utilised, favourable locations lack additional potential sites.

No optimal spatial planning scale

An optimal spatial scale for locating onshore wind turbines does not exist. As shown, the larger the spatial scale, the more flexibility is given for the allocation. Hence, allocating at the European level allows the selection of sites with minimum LCOEs and minimum affected population (Figure 7). When optimizing at this level, it is even possible to select only turbine locations that do not affect any population. Compared to optimizing at the European level, LCOEs and affected population increase by 0.74 €-cent$_{2050}$/kWh and 294 persons or by 0.98 €-cent$_{2050}$/kWh and 804 persons on average if expansion is optimized at the NUTS-0 and NUTS-3 levels respectively (in scenarios *Low LCOE* and *Low disamenities*). However, the optimization at European level also (still) leads to the selection of only the few most suitable sites, which in turn reduces the regional equality. This equality becomes higher at smaller spatial scales. In the *Low LCOE* and *Low disamenities* scenarios, optimization at the European level would even reduce regional equality (Gini index of up to 0.86, Figure 7) compared to existing plants (Gini index of 0.82). When optimizing at the NUTS-3 level, the Gini index reaches its minimum value of 0.47, which corresponds to a reduction of 58% compared to the status quo. Most no-regret sites, i.e. sites chosen under any scenario[32], exist between scenarios at NUTS-3 and NUTS-0 (35%) scale, followed by Europe and NUTS-0 (32%) and Europe and NUTS-3 (22%).

Regarding the further scenario specifications, the following can be learned from Figure 7, Figure S5 and Figure S6: the more turbine sites are added, the worse the mean values of the target criteria LCOEs and affected population become and the better the regional equality may be achieved. In other words, in addition to the decentralization of the optimization level (as shown above), a higher capacity target and the decision against repowering existing turbines lead to worse values for LCOEs and affected population of the added turbines, but improved Gini indices. This illustrates that while there is great untapped onshore wind potential in Europe, the best sites are not inexhaustible. In general, these effects are similar for all distances used to measure disamenities (compare Figure 7 with Figure S2, Figure S3 and Figure S4).

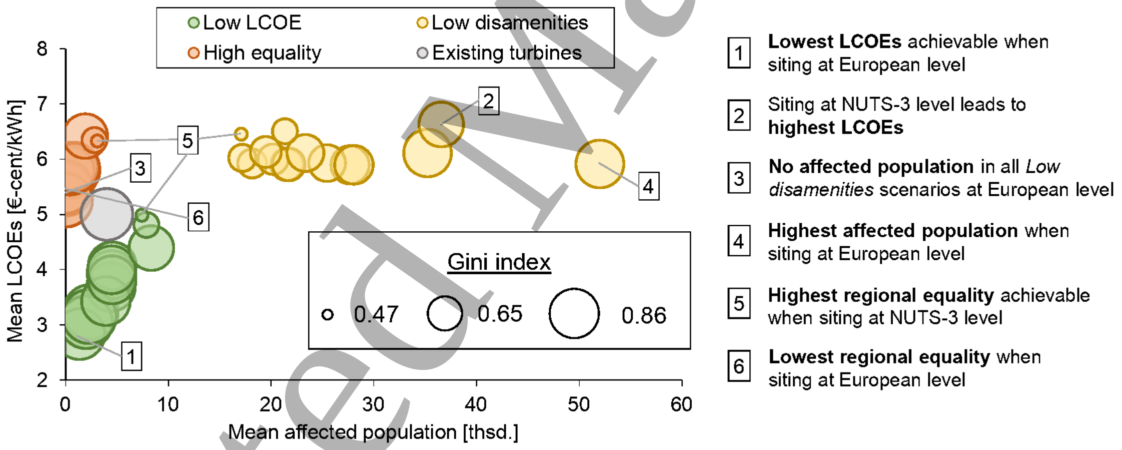

Figure 7: Mean LCOEs, mean affected population and Gini index for 45 different expansion scenarios with the different target criteria "Low LCOE", "Low disamenities" and "High equality" as well as existing wind turbines. Figure S5 shows these scenarios further differentiated by the spatial scale (Europe, NUTS-0, NUTS-3), the expansion target (500 GW, 750 GW, 1000 GW) as well as by the repowering decision. Affected population is measured up to a distance of 4 km (see Figure S2 for the scenarios with 1 km, Figure S3 for 2 km and Figure S4 for 3 km). Figure S6 shows the exact turbine locations for some of the scenarios.

Discussion

In 2016, a group comprising social scientists, a community representative and a wind industry advocate suggested four key factors for onshore wind deployment: socially mediated health concerns, the distribution of financial benefits, meaningful engagement and serious treatment of landscape concerns[8]. While our analysis shows for the first time a spatially explicit European turbine expansion, taking into account some of the most relevant factors, namely cost-effectiveness, disamenity and regional equality, not all of the key issues can be considered. Whereas "socially mediated health concerns" are included through the disamenity analysis and "distribution of financial benefits" at least partially through the consideration of cost-effectiveness as well as regional equality, "meaningful engagement" and "landscape concerns" are neglected. The examination or even quantification of meaningful engagement across the broad scope of our analyses is practically impossible. The landscape impact of onshore wind, on the other hand, has already been quantified in previous studies for individual countries such as Germany[10,17,30,31] and Great Britain[9,33]. The integration of this dimension fails on the European level due to the unavailability of data on the beauty or quality of landscapes.

Our analysis **first** demonstrates strong disparities among European countries in historical onshore wind deployment. The low expansion level in relation to potential in Ireland, Sweden, Norway and Finland could be related to policy-effects or the low population densities and thus lower energy demands in these countries. In contrast, Germany and Denmark, two countries with higher population densities, already have relatively high shares of exploited potential. Since it will probably become increasingly difficult to find suitable locations for wind turbines in the latter countries in the future, it may be beneficial to optimize the expansion on a European level and exploit the large and cost-effective potentials in the former countries.

Whilst LCOEs and disamenities explain the spatial allocation of existing wind turbines in general, some countries show different results. In Sweden, for example, there seems to have been very little emphasis on minimizing the number of people affected by wind turbines. This apparently cannot be explained by politically driven lower minimum distance rules to settlements or infrastructure, which have been similar to those in other countries[34]. However, the population serves as a direct sink for generation, which may have been of relevance in this case.

Second, while a focus on cost-effectiveness was evident, we also show that disamenities have historically been a key driver of onshore wind development. The affected population ratio in Europe as a function of distance to the existing turbines compared with an empirically-derived[30] curve for disamenity costs for the affected population, show similar courses (Figure 4). In other words, the closer the turbine, the more emphasis was placed in historical siting decisions on affecting as few people as possible. Thus, our findings support the trend of empirically-derived external costs caused by the proximity to the wind turbines. Due to focusing on a few particularly suitable regions regarding LCOEs and disamenities, regional equality has been largely neglected in the past. Previous quantitative studies of renewable expansion in Germany[17,19], Switzerland[21] and Europe[22,24] have shown that an increase in regional equality is associated with a significant increase in energy system costs compared to cost-optimized systems. Especially countries with comparatively low utilization of onshore wind potential, such as Ireland and Sweden, show the highest values for regional equality. This could indicate that an increased expansion requires strong compromises in this criterion in many countries. We also need to clarify that our approach for regional equality of wind turbines does not translate into an equitable energy transition. While some regions might benefit from an equal distribution of turbines, this could on the other hand further disadvantage already marginalized populations. For example, if higher LCOEs result in higher retail electricity prices, this will impose a relatively larger burden on low-income households. The supplementary material provides a detailed discussion of our approach for equality measurement.

Third, our expansion scenarios show that with respect to the three objectives of high LCOE, high regional equality and low affected population, the future allocation of wind turbines can be significantly improved compared to the historical situation. Onshore wind turbine expansion can, on average, result in up to 43% lower LCOEs, up to 42% higher regional equality, or up to 93% less affected population than is the case with existing turbines. However, in only 10% of the expansion scenarios (18 out of 180) are the values of all target criteria superior to those of the historical allocation. This again suggests that unavoidable trade-offs have been made in the past, which will also occur in the future: for example, mean LCOEs increase between 18% and 105%, when local disamenities are minimized, or between 129% and 218%, when local disamenities and thus regional equality are maximized. These outcomes are in line with previous studies on onshore wind expansion or holistic energy system analyses which also found substantial trade-offs between minimizing LCOEs on the one hand and minimizing disamenities[30,31,35,36] or maximizing regional equality[17,19,21,22,24] on the other.

Since low LCOEs are linked to good wind resources and thus to higher annual electricity generation, the minimization of LCOEs at the European level reduces the number of added turbines by about half compared to scenarios with other target criteria. Repowering of the existing turbine fleet has a similar, albeit less pronounced, impact. Both might be decisive for the optimal allocation of future expansion due to increasing land-use constraints and opposition towards onshore wind[37].

By focusing on onshore wind, we have neglected opportunity costs of the required land, e.g. due to other renewable technologies such as photovoltaics. Solar energy expansion could also be associated with lower disamenities, however, recent studies show that solar farms result in externalities of a similar magnitude as onshore wind[38]. Furthermore, our expansion optimization is static, and the actual deployment process is neglected. While we have opted for single-objective optimizations due to the high number of scenarios, a multi-objective optimization of onshore turbine locations in holistic and sophisticated energy system models would provide further useful insights[39,40]. For example, binary decisions could be made for repowering individual existing plants and pareto fronts could provide further insights on the trade-offs between the target criteria. An approach that weights different criteria and optimizes the expansion on this basis could be appropriate. However, a recent article shows the difficulties of reaching an agreement among experts regarding the weighting of criteria for onshore wind allocation[32]. In addition, implementing a siting approach that accounts for disamenities does not necessarily lead to greater acceptance of wind turbines. Previous research emphasizes that acceptance is a multifaceted function of wind turbine exposure, personal attitudes, social norms, and procedural and financial involvement in wind turbine siting decisions[41–44]. Also, among the people who reject wind turbines, mostly "vocal minorities" actively express their resistance, which emphasizes the need for identifying the general standpoints by enquiring[45,46]. On the other hand, the majority may accept wind turbine siting decisions but not publicly support wind turbines - while a small minority is willing to engage and oppose wind turbines[47–49].

Fourth, the greatest degree of allocation flexibility is naturally available at the European level and decreases towards the NUTS-3 level. If the LCOEs or the affected population are minimized at the European level, the added turbines will be concentrated in a few countries, mainly in the north of Europe (Ireland, United Kingdom, Norway, Sweden, Finland), which have very good and large untapped wind potentials. This can partly be explained in that we only considered turbine LCOEs and the typically higher system LCOEs[50] due to power grid integration[51,52], balancing and profiling requirements are neglected. The concentration of large capacities in the north of Europe with long distances to other consumers are likely to be challenging to integrate into the European energy system and could lead to strong curtailments. Although economic curtailment could be system serving by ensuring grid reliability, excessive curtailments can affect the financial viability of renewable energy projects[53], which has been experienced in the past in European[54] and Chinese[55,56] regions. Since grid integration costs can roughly double the cost of wind farms depending on the distance to transformers and consumers[9], this criterion should be considered in future studies for both historical analysis and future expansion of onshore wind. Nevertheless, wind projects such as the Önusberget wind farm mentioned above, show that large wind farms are increasingly planned in the remote and sparsely populated north of Europe. Promising options to reduce or prevent (further) renewable energy curtailment include energy storage technologies and hydrogen generation, which have strong synergies with onshore wind system integration[57,58]. Although our results provide important insights into the trade-offs in Europe's onshore wind expansion, consideration of the system LCOEs including grid integration could lead to further important findings in future studies. Recent energy system analyses for Europe show that continent-wide renewable energy allocation is the cheapest, but requires large grid extensions. In contrast, small-scale planning (NUTS-3 regions in our analysis) is more cost-intensive and requires more generation infrastructure[59].

Fifth, the study shows that no optimal spatial scale exists for optimizing the expansion. While optimizing at the European level offers the greatest flexibility and thus the best achievable values for LCOEs and affected population, the NUTS-3 level should be chosen as the spatial allocation scale if the focus is on increasing regional equality. In theory, a non-linear (see Equation 3 in Methods) optimization of regional equality could also be performed at the European level and the results would be similar to those of our analyses at the NUTS-3 level. While in reality energy systems are mostly planned at the national level and lower (NUTS-3 or municipalities), it is questionable whether coordinated onshore wind planning at the European level will take place in the future, or is even realistic. Furthermore, it is questionable whether all countries would participate proportionally in the future expansion as assumed here. The analysis of the existing turbine stock has shown that so far in some countries (e.g. Switzerland, Czech Republic, Hungary or Slovakia) there is almost no utilization of the existing potential. Empirical studies show that under-utilization may be due to various drivers including the ambition and design of national support policies as well as economic drivers (e.g., electricity prices, cost of capital, GDP)[60,61]. Whilst it is doubtful whether this policy will change in the future, however, the growth rate of onshore wind, which has never exceeded 1% in Europe, must be accelerated significantly to meet 1.5°C-compatible scenarios[62] and take advantage of the cost benefits of early decarbonisation[63].

Conclusion

Onshore wind expansion has historically focused on cost-effectiveness while disamenities were given subordinate consideration and regional equality was largely neglected. In light of increasing local opposition to new wind turbines, consideration of disamenities and regional equality is expected to become more important in future turbine allocations. However, our study confirms that such a shift in priorities may involve strong trade-offs in cost-effectiveness. Consequently, disamenities and regional equality cannot be addressed by siting decisions alone. Financial and procedural participation may help reducing perceived disamenities at the local scale and improve regional equality in the distribution of benefits and costs of wind power deployment. In addition, repowering of existing turbines at good sites could help to avoid many less favorable sites in the future.

Methods

In this Method section, we explain the GIS analyses and the developed MATLAB simulation model for analyzing the current European onshore wind fleet as well as the spatial allocation for expanding this fleet until 2050. Please refer to the Supplementary material for the identification and validation of existing and potential turbine locations.

Measurement of disamenity

In addition to the positive externalities in terms of emission mitigation, wind power also entails negative externalities, such as a lower quality of life due to noise and visual impacts, as well as threats to wildlife[64]. These disamenities play a key role in the political debate and must be considered in the placement of turbines. The findings of a life-satisfaction study in Germany suggest that negative externalities of onshore wind turbines on residential well-being seem spatially restricted to about 4 km around households[16]. A further study in England and Wales focussing on visual environmental impacts of wind turbines, shows that wind farm visibility reduces local house prices, which implies substantial visual environmental costs[65]. This price reduction falls to under 2% for distances between 2 and 4 km. Another article finds that onshore turbines in Denmark impact residential property prices in a 3 km radius[66]. Furthermore, wind farm infrasound and low-frequency noise exceeds the audibility threshold only at distances up to 4 km from the wind farm[67]. Therefore, as in other studies[30], we assume that local disamenities caused by wind turbines diminish at a distance of 4 km. This distance could increase in the future, however empirical studies do not yet show a clear trend on how future turbine designs with larger, but also fewer and more widely spaced turbines will affect disamenity distances[38].

We determine the number of residents affected by an existing or potential wind turbine in a GIS analysis as follows: first, geodesic buffers with radii of 1 km, 2 km, 3 km or 4 km are created around the respective turbines to account for different levels of disamenity. Second, European population data[68] on a 1 km² grid level are intersected with these buffers. For each grid cell intersected by the buffer, the affected population number is assigned to the corresponding turbine. In the process, some inhabitants could be counted multiple times due to many proximate turbines.

Measurement of historical turbine allocation targets

The OpenStreetMap[69] data on existing turbines can only be used for the locations, as information on capacity etc. is incomplete or hardly available. Therefore, we intersect the existing turbine sites with the potential sites for 2050 using buffers of 1,088 m (geodesic)[27]. Thus, LCOEs for 2050 can be assigned to the turbine sites by using the values of the intersected potential sites (see Figure 1 and Figure 2). Thereby, we assume that in 2050 the same sites will be used with repowered turbines, resulting in fewer turbines at these sites due to the higher minimum distances between the larger turbines. This approach enables an economic comparability of the sites.

The mean LCOEs or disamenity of existing turbines alone would not compare well between countries. Higher mean LCOEs in a country could simply reflect the poorer economic onshore wind potential of that country and not necessarily be related to inefficient allocation. Similarly, a higher value for the mean affected population could be due to a higher population density in a country. To ensure comparability of the historical turbine allocations between countries, we therefore normalise the mean values of LCOEs ($\overline{LCOE_{ex,c}}$) and disamenity of the existing turbines (*ex*) of a country (*c*) by dividing them by the mean LCOEs ($\overline{LCOE_{pot,c}}$) or disamenity of the total turbine potential (*pot*), here for example for the LCOEs:

$$r_{LCOE,c} = \frac{\overline{LCOE_{ex,c}}}{\overline{LCOE_{pot,c}}} = \frac{\frac{\sum_{i=1}^{ex} LCOE_i \cdot E_i}{\sum_{i=1}^{ex} E_i}}{\frac{\sum_{i=1}^{pot} LCOE_i \cdot E_i}{\sum_{i=1}^{pot} E_i}} \#2$$

The ratio depends on the LCOEs and the electricity generation (*E*) of turbine *i*. The resulting ratios are shown in Figure 3.

Measurement of regional equality

In this study, we measure regional equality from a county level (NUTS-3[70]) perspective, similar to other energy economics studies[22]. Through GIS intersection analyses, we assign existing and potential turbines to the NUTS-3 regions. In addition, we use publicly available data for annual electricity demands in 2050 for all NUTS-3 regions from the eXtremOS project[71]. These future electricity demands are available for industrial, residential, tertiary and transport sectors[71] (see individual descriptions for the detailed models of every sector[72]). As in other studies[19,22,23], we measure regional equality using the Gini index, where x is the annual generation of wind turbines per annual electricity demand in NUTS-3 region j or k, and n represents the total number of regions:

$$Gini\ index = \frac{\sum_{j=1}^{n}\sum_{k=1}^{n}|x_j - x_k|}{2 \cdot n^2 \cdot \bar{x}} \#3$$

A Gini index of 0 means the highest and of 1 the lowest regional equality score. If a percentage change in regional equality is mentioned in the main text, this means a percentage change in the Gini index.

Expansion methodology and scenarios

On the basis of a newly developed heuristic, the existing and potential turbine locations and various scenario criteria (highlighted in **bold** hereafter), the European wind turbine fleet is expanded. The distribution of the turbines is performed from a macroeconomic perspective, i.e. increasing local support, e.g. through community energy[73], has not been considered. The scenarios studied are designed to assess the trade-offs between cost-effectiveness, local amenities and regional equality for different capacity targets, repowering decisions and spatial allocation scales (Figure 8). Firstly, different expansion targets are examined in terms of the targeted capacity, namely **500 GW**, **750 GW** and **1,000 GW**. On the one hand, this allows us to analyse the impacts of less ambitious as well as more ambitious capacity targets. On the other hand, we also consider Norway, the United Kingdom and Switzerland, countries that do not (or no longer) belong to the European Union and thus may not participate in meeting the 750 GW target. Furthermore, since the capacity targets formulated by policymakers may result in significantly different electricity generation volumes for turbines with the same capacity due to site-dependent wind conditions[17], we multiply these capacities by the mean annual full load hours (approx. 2500 h) of all potential turbines in Europe in 2050 (i.e. converted to approx. **1,250 TWh**, **1,900 TWh** and **2,500 TWh**). This ensures the same amount of electricity generation in all scenarios.

Secondly, a distinction is made between **repowering** and **not repowering** the existing turbines by 2050. In the case of repowering, the current capacity increases from about 200 GW (about 500 TWh) to about 400 GW (about 1,100 TWh). As described above, buffers are created around the existing turbines and the capacities of the intersected potential turbines by 2050 at the locations of the existing turbines are used. In the case of non-repowering, the potential turbines located in the buffers of the existing turbines are excluded as options for expansion.

Thirdly, a distinction is made between different spatial allocation scales, namely central turbine allocation at the **European**, **national** (NUTS-0) and **county level** (NUTS-3). At the European level, the previously described data are sufficient for the turbine expansion. In the case of the NUTS-0 or NUTS-3 level, the European capacity targets are allocated to the individual countries or counties on the basis of the shares of electricity demand[71]. This involves subtracting the generation capacity of the existing turbines in the respective regions from the target values. At the NUTS-0 level, turbine capacities are known, but this is not the case for the NUTS-3 level. Hence, in the latter case, only the scenarios with repowering of the existing plants are considered, instead of incorporating uncertainties with the assumption of current capacities. Turbine allocation at the European level represents the optimal case here, allocation at the NUTS-0 or NUTS-3 level the more realistic ones. The scenarios at NUTS-3 level are also used to examine the impacts of higher regional equality.

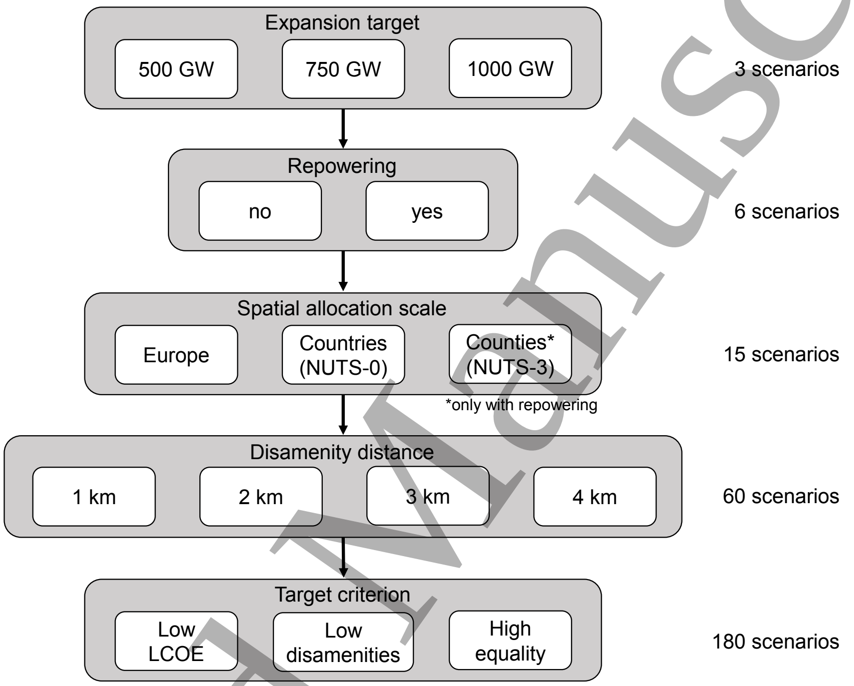

Figure 8: Compilation of all criteria considered in this study to define the onshore wind power expansion scenarios. Since the optimizations at NUTS-3 level are only possible with repowered turbines at the locations of currently existing turbines, the combination of all criteria results in a total of 180 different scenarios.

Fourthly, the affected population is measured for scenarios with distances from the turbine of up to **1 km**, **2 km**, **3 km** and **4 km**. This allows the influence of various degrees of disamenities to be evaluated, which, as described above, decrease with distance.

Lastly, all these criteria are investigated in scenarios with different target criteria. Firstly, in a turbine expansion where turbine LCOEs are minimized to maximize the cost-effectiveness of the turbine stock (**Low LCOE**). Secondly, for an expansion that minimizes the affected population, i.e. to minimize local disamenities (**Low disamenities**). And thirdly, by maximizing the affected population, on the one hand to maximize regional opportunities such as economic benefits or job creation, but also to show the impact on LCOEs and regional equality when disamenities are neglected (**High equality**). A total of 180 scenarios result from the combination of the different criteria. In the heuristic, the potential turbines are sorted and selected on the basis of the target criteria at European, NUTS-0 or NUTS-3 level. Since the approach is not multi-objective, but instead considers only one target criterion per scenario, global optima result in the heuristic. This MATLAB algorithm runs until the generation target is met and takes about three hours for all scenarios.

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