On the socio-technical potential for onshore wind in Europe: a response to Enevoldsen et al. (2019), Energy Policy, 132, 1092-1100

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Abstract

A recent article in this journal claimed to assess the socio-technical potential for onshore wind energy in Europe. We find the article to be severely flawed and raise concerns in five general areas. Firstly, the term socio-technical is not precisely defined, and is used by the authors to refer to a potential that others term as merely technical. Secondly, the study fails to account for over a decade of research in wind energy resource assessments. Thirdly, there are multiple issues with the use of input data and, because the study is opaque about many details, the effect of these errors cannot be reproduced. Fourthly, the method assumes a very high wind turbine capacity density of 10.73 MW/km^2 across 40% of the land area in Europe with a generic 30% capacity factor. Fifthly, the authors find an implausibly high onshore wind potential, with 120% more capacity and 70% more generation than the highest results given elsewhere in the literature. Overall, we conclude that new research at higher spatial resolutions can make a valuable contribution to wind resource potential assessments. However, due to the missing literature review, the lack of transparency and the overly simplistic methodology, Enevoldsen et al. (2019) potentially mislead fellow scientists, policy makers and the general public.

Keywords

Onshore wind; resource assessment; public acceptance; barriers; feasibility

1 Introduction

Resource assessments for renewable energy is an active field of research driven by the worldwide push towards more sustainable energy systems. Significant attention has been devoted to this area in research and literature over the past decades, leading to substantial methodological improvements and more reliable resource estimates. One area which has seen particular methodological focus is improving the ways in which such studies account for non-technical (e.g. social) constraints for renewable resources like onshore wind (e.g. Jäger et al. 2016, Höltinger et al. 2016, Harper et al. 2019, Eichhorn et al. 2019).

Against this background, a recent paper in this journal seemed upon first impression to be a welcome contribution. It presents a resource assessment for onshore wind in Europe, purporting to evaluate the *socio-technical* potential for this technology (Enevoldsen et al. 2019). Indeed, the article received intensive media attention upon its publication in July 2019, partly due to the enormous European onshore wind potential implied[1].

A closer reading of the article, however, reveals five severe shortcomings, which we address in the following section:

1. **Potential definitions:** the paper employs the term *socio-technical* without clearly defining or differentiating it from related terms (section 2.1).
2. **Lack of a literature review of the state of the art:** the paper fails to account for substantial progress in this area and ignores the body of recent literature (section 2.2).
3. **Opaque and incorrect use of input data:** the contribution lacks transparency in its application of existing datasets and in some cases is demonstrably incorrect[2].

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[1] For example a search on 26.11.19 for “wind potential Europe” revealed the following online articles amongst the top fifteen results on Google: Wind it up: Europe has the untapped onshore capacity to meet global energy demand (https://www.sussex.ac.uk/news/media-centre/press-releases/id/49312); Study shows huge potential of Europe’s onshore wind (https://www.theengineer.co.uk/onshore-wind-untapped-europe/); Europe's 52.5TW onshore wind potential revealed (https://renews.biz/54837/europes-525tw-onshore-wind-potential-revealed/); Europe could power the world with onshore wind (https://www.anthropocenemagazine.org/2019/08/europe-could-power-the-world-with-onshore-wind/); Europe Could Power The Entire World With Onshore Wind Farms Alone (https://www.sciencealert.com/europe-could-power-the-entire-world-with-enough-onshore-wind-farms); Turning Europe into a giant wind farm could power the entire world (https://www.weforum.org/agenda/2019/08/europe-giant-wind-farm-could-power-entire-world/).

[2] A recent corrigendum (Enevoldsen et al. 2020) corrects the citation and description of the data, but not its application as outlined in section 2.3.2.

Given the incomplete description of how data were used, the full extent of the error introduced by incorrect data usage is difficult to estimate (section 2.3).

4. **Oversimplified methods without validation:** the paper employs overly simplistic methods which are substantially behind the state of the art, are not validated and, in most areas, impose considerable bias on the results (section 2.4).
5. **No consideration of other recent results:** the controversial results are only compared with a single outdated study, and not put into the context of the larger body of recent work on wind resource assessments (section 2.5).

The remainder of this response addresses these five points in turn before closing with an overall conclusion.

2 The five weak points of Enevoldsen et al.

2.1 Potential definitions

In the field of resource assessments for renewable energies, it is common to distinguish between different kinds of potential. For example, five different potential categories can be defined as shown in Table 1 (Hoogwijk et al. 2004, Jäger et al. 2016). The table shows these potential terms alongside possible definitions and examples of energy policy relevance.

Table 1: Overview of different potential definitions and examples of their policy relevance

Potential term	Defined as…	Policy relevance, e.g.
Theoretical potential	…the total energy content of wind globally.	Generally irrelevant
Geographical potential	…(the amount of wind energy across) the total area available for wind turbines	Generally irrelevant
Technical potential	…the electricity that can be generated from wind turbines within the geographical potential with a given turbine technology (e.g. current, future).	Wind industry R&D, innovation and market dynamics
Economic potential	…a subset of the technical potential that can be realized economically.	Energy-political frameworks
Feasible potential	…reflecting non-technical constraints.	Public acceptance, market barriers, inertia

Within this context, it is difficult to situate Enevoldsen et al.'s (2019) approach combining a "1) common wind atlas methodology centering on information about wind resources, with 2) high resolution exclusion of areas where wind project development is hampered by socially centered constraints to siting". A problem with this second claim is that it blurs technical constraints (e.g. exclusion criteria for infrastructure, as in the geographical potential definition in Table 1) with some constraints relating to social acceptance (more details in section 2.3). Enevoldsen et al. claim that "the erosion of public support and siting increasing costs [sic] coupled with the emergence of promising innovations in offshore foundations […] have tempered onshore wind growth projections" and call for a "more qualitative, refined socio-technical dimension" in the assessment of wind power potentials, which should consider that "public opposition is complex, and it often stems from visual (aesthetic), environmental, and socioeconomic concerns, especially in regard to onshore wind projects.” However, they fail to define exactly what their socio-technical potential is and, based on the presented information, we must conclude that they do not (attempt to) consider any of these complex social constraints in their approach; thus their potential should be considered a technical one, despite the title of the paper.

2.2 Literature review and state of the art

Enevoldsen et al. (2019) contains 13 self-citations from a total of 29 references (i.e. 45%), which is extremely high for a peer-reviewed original research article (van Noorden & Chawla 2019). The authors overlook more than a decade of research in resource assessments for onshore wind. Instead they repeatedly stress the novelty of their study, especially regarding its continental application and supposed use of high-resolution data. The authors directly claim that “none [of the preceding literature] exhibit the level of aggregation that [their] model represents.” Whilst Enevoldsen et al. (2019) is indeed one of the first studies to employ the high-resolution Global Wind Atlas V2 (cf. section 2.3), it is by no means the first to provide results at their level of aggregation for the whole of Europe (cf. e.g. Ryberg et al. 2019a, Bosch et al. 2017, McKenna et al. 2015). Figure 1 gives an overview of the main results from other exemplary literature with a similar spatial scope (large-scale international studies in a European context).

Selected studies have also recently attempted to frame social acceptance issues in the context of wind power potential studies, which Enevoldsen et al. (2019) do not. For example, Höltinger et al. (2016) present a participatory approach with key stakeholders to consider the effect of socio-political and market acceptance on techno-economic potentials for wind in Austria. In a study of the *feasible* wind energy potential for the

Baden-Württemberg region of Germany, Jäger et al. (2016) analysed the public's views with respect to their aesthetic appreciation of the landscape. Considering rules of local planning and the level of social acceptance of wind in specific landscapes resulted in a feasible potential at around 50% of the previously-determined technical potential and a substantial shift in the location of this potential due to different wind park spacing and size assumptions. Also, Harper et al. (2019) present a Multi-Criteria Decision Analysis (MCDA) approach that considers technological, legislative and social constraints in a British context. Finally, Eichhorn et al. (2019) developed a sustainability assessment framework for possible wind sites, including environmental, social, technical and economic asepects, and applied it to Germany.

Missing this literature means that Enevoldsen et al. (2019) fail to embed both their methodology (section 2.4) and results (section 2.5) into the broader scientific discourse. Especially during the last half decade, a thread of research has emerged that focuses on developing and applying methods to assess the impact of social constraints on wind resource assessments. For a contribution aiming to assess the socio-technical constraints for onshore wind energy in Europe, these (or similar) studies are a necessary point of reference.

2.3 Data

2.3.1 Geospatial data and land-use constraints

Enevoldsen et al.'s (2019) stated aim was to determine "how much wind power potential [Europe has] after infrastructure, built-up areas, and protected areas are factored in". This implies that at least these three considerations (infrastructure, built-up areas, and protected areas) must be addressed in detail for all of the countries included in their analysis. However, such a detailed analysis is not possible without further geospatial data sources not mentioned in the paper.

The first geospatial dataset of importance is OpenStreetMap (OSM), which the authors have used to represent all infrastructure (including roads, waterways, airports, and railways) as well as all buildings (including residential, industrial, military, public, and existing wind turbines). The OSM database is constructed by means of user-volunteered input, which naturally calls into question its completeness. Validation of OSM data shows that, while the completeness of street data is high (>95%) for most Western European countries, for other European countries such as Turkey (79%), Albania (75%), and, most notably, Russia (47%) it is significantly lower (Barrington-Leigh et al. 2017). In comparison, the completeness of buildings in OSM is often found to be much less; example estimates include 23% for Saxony, Germany in 2013 (Hecht et al. 2013) and 57% for Lombardy, Italy (Broveli & Zamboni 2018). In addition to missing a large portion of real buildings, another issue with Enevoldsen et al.'s use of OSM for building data is that of filtering. When using the same OSM extract source as Enevoldsen et al. (geofabrik 2019), it becomes clear that 33% of buildings in Germany, as an example, are unlabeled; meaning that without the use of additional data sources it is impossible to distinguish buildings in the manner implied by the authors. Ultimately, when evaluating geospatial exclusions from infrastructure and buildings across Europe, Enevoldsen et al. (2019)'s reliance on OSM alone is not sufficient for a detailed wind energy potential estimate.

The second geospatial data source employed by Enevoldsen et al. (2019) is the Natura2000 dataset (EEA 2016), which the authors claim to have used to determine the geospatial positioning of "castles, monuments, areas protected by Natura2000, Special Protection Area, Flora Fauna Habitat, etc". However, the Natura2000 (EEA 2016) dataset describes itself as "a network of core breeding and resting sites for rare and threatened species, and some rare natural habitat types … across all 28 EU countries". This raises two issues: firstly, the Natura2000 database only contains data for protected areas relating to birds and endangered species, and thus is not suitable for locating castles and monuments (EEA 2016); and secondly it only covers the EU28, and thus has no representation in many of the countries that Enevoldsen et al. (2019) claim to have evaluated, including Norway, Iceland, Switzerland, Ukraine, Belarus, Moldova, Serbia, Albania, Montenegro, Turkey, Georgia, and Russia. In total, these missing countries make up 59% of the area the authors evaluated. Once again, when evaluating geospatial exclusions from protected areas and historical sites across the whole of Europe, Enevoldsen et al. (2019)'s sole reliance on the Natura2000 dataset is far from sufficient.

Furthermore, Enevoldsen et al. (2019) claim to exclude areas for wind turbine siting with the vague concept of "socially centered constraints". Yet the subsequently applied constraints include a mixture of around 16 constraints (located using OSM and Natura2000), which are largely of a technical or legal nature. Notably, they have not included those factors contributing to social acceptance identified in their own previous publication (Enevoldsen & Sovacool 2016, Tables 2 and 3). Additionally, missing or contradictory descriptions of the buffer distances applied to the set of employed constraints hinder understanding and reproducibility of the study. Enevoldsen et al. (2019) write that “proxies of 200 m (infrastructure) and 1000 m (buildings)” are used, while in the Supplementary Material (Figure 3) half of the width of waterways, rivers, riverbanks and lakes is defined as the buffer distance. It remains unclear which buffer was applied to castles and monuments, which belong to the restriction type “Protected Areas” and for which only “longer distances from historical landmarks” is stated. Overall, no explanation or comparison to literature is given for the chosen constraints or buffer distances.

2.3.2 Wind data

As presented in Figure 1, many studies have analyzed the resource potential for onshore wind in Europe and its sub-regions. All these analyses rely on high quality meteorological datasets relating to both long- and short-term wind resource availabilities. Common methodologies involve estimating wind turbine performance from static wind-resource maps (e.g. NEWA Consortium 2019, DTU 2019) and from climate model reanalysis products (Olauson 2018, Hersbach et al. 2019, Nuño et al. 2018). Well-known advantages and challenges are associated with either approach (Ramon et al. 2019, Sanz Rodrigo et al. 2016, Staffell & Pfenninger 2016), resulting in a recent trend towards combining aspects of both for energy system modelling (Ruiz et al. 2019; Bosch et al. 2018; Gruber et al. 2019, Ryberg et al. 2019b).

In comparison, the description of wind data sources in Enevoldsen et al. (2019) is highly opaque and does not make any reference to these trends in the wind energy literature[2]. The source they reference when describing their input data analyzes wind energy resources in western Iran (Noorollahi et al. 2016), with no apparent use of the

Global Wind Atlas that Enevoldsen et al (2019) seem to refer to when stating that their dataset was created by the World Bank and the Technical University of Denmark. This is surprising, as Enevoldsen and colleagues claim to have used a dataset with (a) spatial resolution of approximately 1 x 1 km and (b) hourly temporal resolution. In contrast, the GWA (GWA V2.1 at the time of the publication of the manuscript, since updated to GWA V3: DTU 2019) had (a) a horizontal resolution of 9 km x 9 km, while the microscale downscaling of the GWA2 was available at a spatial grid spacing of 250 m x 250 m. Moreover, the GWA is (b) not available in hourly resolution but represents the wind climatology of the past decade reporting a 10-year means of hourly wind speeds. This is also relevant in the context of the validation results reported in Table 3 of Enevoldsen et al. (2019). As information on the validation sample is largely missing, validation might be compromised due to different underlying time periods. Finally, their use of the dataset to estimate the energy outputs (by combining the power curve with the site-specific wind speed distribution) is not described – instead a constant capacity factor seems to have been employed as discussed in the following section.

In summary, the utilized datasets and/or their description are inadequate or incorrect in parts. The completeness of the OSM database and the content of the Natura2000 dataset make them inappropriate to be employed for wind resource assessments over the spatial domain investigated by Enevoldsen et al. (2019) without further analysis or validation, and the application exclusion zones and buffers on these datasets are not well justified or described. Finally, the employed GWA2 wind data provides high-resolution annual average wind speeds, but not hourly time series data as stated in the paper. Without further assumptions, it is therefore not possible to estimate energy yields from onshore wind turbines across this domain. In total, these points have the following consequences: (a) resource potentials are estimated at too high levels because availability of land-area is overestimated, as the incomplete coverage and detail within the data sources will arbitrarily increase land availability, (b) due to partly incomplete definitions of exclusion zones and buffers, it is hard to compare results to other, similar studies, and (c) the confusion on the data sources used for estimating wind power output makes validation through comparison with the results of others impossible without further information.

2.4 Methodology

To determine the capacity potential, Enevoldsen et al. (2019) assume a single capacity density value (in MW/km^2) which is multiplied by the total available land of each country. This is far simpler than the methods used elsewhere and demonstrably leads to errors due to overlooking important techno-economic characteristics of turbines, especially the dimensions, the power curve and the costs (McKenna et al. 2014).

The employed capacity density value is not stated in Enevoldsen et al. (2019), but can be back-calculated from the Supplementary Material as 10.73 MW/km^2. While the implied capacity density is high, it is technically possible and similar capacity densities have been used in other studies (e.g. Ryberg et al. 2019b, McKenna et al. 2015).

More problematic is the application by Enevoldsen et al. of one capacity factor of 30% for all of Europe. Global average capacity factors for onshore wind have indeed increased from 27% in 2010 to 34% in 2018 (IRENA 2019), and will most likely continue to do so. But these vary strongly by location: for example, in 2018 the 5-year running mean capacity factor in Germany was 19% (Fraunhofer IEE 2018) compared to 25% in the UK (BEIS 2018). Employing a single capacity would also seem to defeat the object of using high spatial resolution wind speed data, as outlined in the preceding section.

The assumed capacity factor also stems from the specific power (ratio of generator capacity to rotor swept area) of the chosen turbine, the Chinese Envision 4.5-148, at 262 W/m^2. There is a weak downward trend in the mean specific power of European onshore turbines, from 300 W/m^2 in 2014 to 280 W/m^2 in 2018 (WindEurope 2018). So the selected turbine's specific power is well below average for the European stock.

For comparison, the 160 turbine power curves available in the Renewables.ninja software (Pfenninger & Staffell 2016) have an average specific power of 380±88 W/m^2. A simulation using the WTPC model (Saint-Drenan et al. 2019) shows that the Envision 4.5-148 would yield a capacity factor of 26.1% for a location in central Germany, compared to 17.5% for a more average turbine with 380 W/m^2 specific power. Scaling this result to the whole of Europe would imply an energy potential one-third lower than given by Enevoldsen et al. (2019).

The dense packing of wind turbines implied by the assumptions of Enevoldsen et al. overlooks the negative relation between capacity density and capacity factor, as the capacity factor depends on rotor size relative to nameplate capacity. Rotor size, in turn, affects the distances at which turbines can be installed without causing array losses due to wake effects. Using the proposed configuration (turbines in a large array spaced at

4.375D X 4.375D) would incur massive array losses (Volker et al. 2017), possibly even up to around 90% (Gustavson 1979).

In addition, previous work has shown the importance of validating simulated outputs against measured wind power production (the energy domain) rather than wind speeds (the meteorological domain) (Staffell & Pfenninger 2016). It is laudable that the authors validated their input wind data (the Global Wind Atlas) against meteorological observations from wind masts *(main manuscript, Section 3 and Supplementary Material)*. However, it is unclear how this builds upon the validation already performed by the creators of the atlas (DTU Wind 2019). It is also unclear how this validation is relevant to the study, as it appears as though the Global Wind Atlas is not used to derive any of the final results. As noted above, the authors simply assume 30% capacity factor across the entire continent of Europe when calculating the energy production potential *(main manuscript, Table 4)*.

While there is potential for improving capacity factors, much of this is based on moving to taller turbines and lower power densities, some technical improvements moving turbine efficiency closer to the Betz' limit and better locations offshore (Caglayan et al. 2019, Staffell & Pfenninger 2016). There is a more limited potential for improving onshore capacity factors as a result of restrictions on turbine height (due to social constraints such as visual impact) and lower wind resource availability. The combination of high turbine density and capacities with low specific power, without accounting for the associated array losses, mean that Eneveldsen et al.'s (2019) method greatly overestimates the generation potential.

2.5 Results

For the reasons outlined above, Enevoldsen et al. (2019) determine a very high potential for onshore wind in Europe: a total area of almost 4.8 million km^2 (2.8 million km^2 excluding Russia), an installed capacity of 53 TW (29 TW) and an annual generation of 138 PWh (77 PWh). The Supplementary Material from Enevoldsen et al. (2019) includes results at the country level, which can be employed for comparison. Figure 1 illustrates some of these results in comparison with 13 other studies, for the whole of Europe excluding Russia.

Overall, Enevoldsen et al. (2019) derive a potential for Europe that is at least 120% higher in terms of installed capacity and 70% higher in terms of generation, than all previous results in this area (Figure 1). In their own discussion of the results, the authors limit their comparison to those of the EEA (2009) study, which has a much higher area (5.4 million km^2) and the highest installed capacity across Europe (13 TW) of all studies reviewed here. We note that in section 5 of the manuscript, the authors also refer to the Natura2000 database as *European Commission 2018* for a value of 39 PWh, but this reference must be incorrect (the cited database relates to protected areas, cf. section 2.3.1 in this response) and also contains a dead link.

When compared to the mean of all 13 studies, the results from Enevoldsen et al. (2019) suggest 35% more area, 150% more installed capacity, 266% more generation and 17% higher full load hours. Their upper ceiling for wind power generation assumes that wind turbines would cover 40% of Europe’s land area, which is surprising given that this potential is supposed to reflect a socio-technically feasible one. More concerning is the lack of contextualisation and critical discussion of these results, especially as research in recent years (e.g. Jäger et al., 2016; Scherhaufer et al. 2018; Harper et al. 2019) has made progress in deriving more meaningful, feasible potentials for renewable energies through integrated assessments that include some market, organizational and social barriers. Instead the authors restrict their commentary on these findings to questioning “the academic and industrial concern of land use being a major constraint for renewable energy” and suggesting that “national scenarios ought to be recalibrated appropriately”.

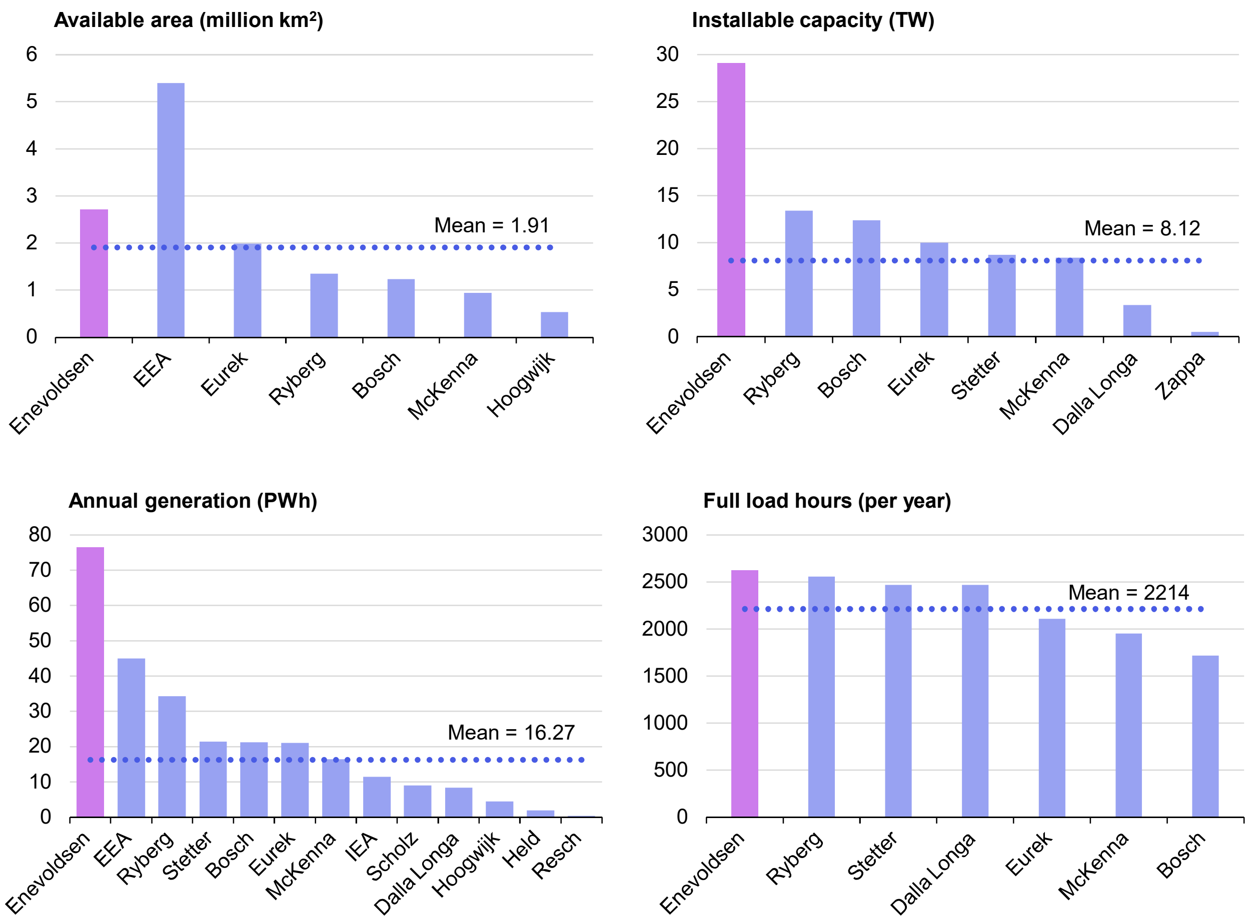

Figure 1: Comparison of results from Enevoldsen et al. (2019) with 13 other studies for the European continent excluding Russia. Dotted lines give the mean of the other 13

studies. Not all 13 studies report all results, which accounts for the different samples in the four panels. For sources see text and references.

3 Conclusions and policy implications

In the sense that it is one of the first studies to employ the latest Global Wind Atlas to assess European onshore wind potentials, Enevoldsen et al. (2019) is a valuable contribution. However, as outlined in the preceding section, the paper suffers from fundamental flaws. While we agree that a novel, social dimension needs to be included in the assessment of wind power potentials, we fail to see how the chosen methodological approach stands up to such demands. Even if it could, it remains unclear whether a specific offset distance is effective in reducing social conflicts towards the expansion of wind energy. Visibility is only partly related to distance; other environmental or socio-economic concerns towards wind energy are much more complex.

In terms of the employed data, the author's claims to have evaluated the onshore wind land eligibility of Europe with "a more qualitative [and] refined socio-technical dimension" do not appear to be well-founded. The two datasets used to represent socio-technical points of interest are not nearly complete enough to achieve the paper's stated objective across the whole regional scope. Moreover, the authors do not discuss the suitability of the chosen datasets for use in their analysis and therefore seem unaware of their limitations. The authors also employ the Global Wind Atlas as the main source for their annual average wind speeds, but both refer to this dataset incorrectly[2] and make a very simplified turbine capacity factor assumption of 30%, which demonstrates a fundamental misunderstanding of onshore wind resources.

The paper overlooks more than ten years of research in this field and therefore employs a methodology that is outdated, inaccurate, and in some cases simply incorrect. The land use constraints are incomplete and rely on partly unreliable input data. The one selected turbine is not representative of the European stock and the assumed 30% capacity factor is unrealistic, both of which bias the results in a particular direction. Finally, the employed method is neither validated nor accompanied by a sensitivity analysis, both standard practice for a modelling exercise such as this one.

Due to the inferior method employed, the results are impractical. The authors reach very large potentials for onshore wind energy in Europe, which require covering around 40% of the continent's area in wind parks with a very high capacity density. These results are not only much higher than most other previous studies, they cannot credibly be interpreted as "socio-technical", even in the broadest sense.

In the context of energy transitions, wind potential assessments provide indispensable inputs to energy modelling and energy policy development, and can potentially contribute to a cost-efficient realization of climate and energy targets. Research in this field that breaks new ground by improving methodologies, considering additional aspects (e.g. public acceptance) and/or exploiting new datasets stands to contribute to this ongoing scientific and energy-political discussion. As for any scientific research, transparency, reproducibility and openness should be embraced as cornerstones (Allison et al. 2016, Nosek et al. 2015), especially as energy modelling is noted for lagging behind other disciplines (Pfenninger et al. 2017). Overall, then, we conclude that new research at higher spatial resolutions can make a valuable contribution to this field, but due to the missing literature review, the lack of transparency and the inferior methodology, Enevoldsen et al. (2019) instead potentially misleads fellow scientists, the general public and policy makers.

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