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How much wind power potential does europe have? Examining european wind power potential with an enhanced socio-technical atlas

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ABSTRACT

The continuous development of onshore wind farms is an important feature of the European transition towards an energy system powered by distributed renewables and low-carbon resources. This study assesses and simulates potential for future onshore wind turbine installations throughout Europe. The study depicts, via maps, all the national and regional socio-technical restrictions and regulations for wind project development using spatial analysis conducted through GIS. The inputs for the analyses were based on an original dataset compiled from satellites and public databases relating to electricity, planning, and other dimensions. Taking into consideration socio-technical constraints, which restricts 54% of the combined land area in Europe, the study reveals a nameplate capacity of 52.5 TW of untapped onshore wind power potential in Europe - equivalent to 1 MW per 16 European citizens – a supply that would be sufficient to cover the global all-sector energy demand from now through to 2050. The study offers a more rigorous, multi-dimensional, and granular atlas of onshore wind energy development that can assist with future energy policy, research, and planning.

1. Introduction

The European Commission's energy strategy for 2050 explicitly calls for a substantive increase in installed renewable energy capacity and a concomitant reduction of emission of greenhouse gasses (Carvalho, 2012), with wind energy being recognized in various studies to be a critical enabler for achieving 100% national renewable energy penetration (Marvel et al., 2013; Arnqvist, 2015; Windeurope, 2018). Such conclusions are often supported on the grounds that wind energy has immense technical potential to deliver useful electricity and energy services. As Archer and Jacobson (2005) projected, capturing 20% of global technical potential of wind power would satisfy the entire world's need for energy, and using more advanced wind turbine technologies in the pipeline would (Marvel et al., 2013) yield a potential global nameplate capacity of 400,000 GW (Arnqvist, 2015).

In Europe, a total of 169 GW of wind power nameplate capacity (31.3% of the world's total capacity) was installed at the end of 2017 (Windeurope, 2018), with the majority of the nameplate capacity located onshore in Western European countries. This represents nearly one-third of global wind power generation nameplate capacity. Fig. 1 illustrates that despite all of the promise of offshore wind, onshore wind power installations still dominate the market, and continue to grow in significant numbers annually in Europe.

Despite progressive growth, the ambitious goals from the European Energy Commission can only be reached by installing more wind power nameplate capacity (both onshore and offshore) and improving the efficacy of existing wind power systems. The European Commission projects that new installations and upgrades will total at least 100,000

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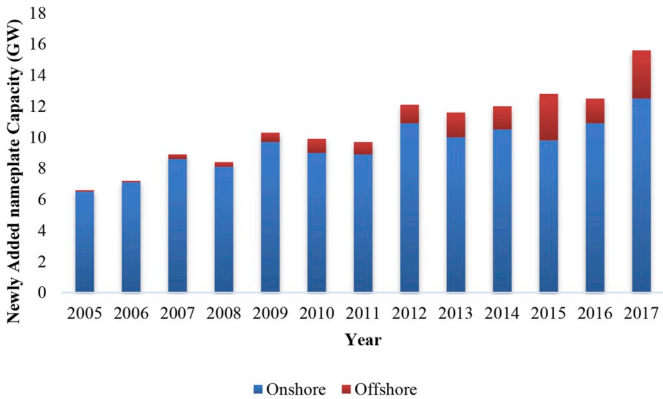

Fig. 1. The annual wind power development in europe.

wind turbines before 2050 (European Commission, 2010).

However, the European Commission has also recognized that growing public opposition could make it difficult to reach this ambitious target (European Commission, 2010). Public opposition is complex, and it often stems from visual (aesthetic), environmental, and socioeconomic concerns, especially in regard to onshore wind projects (Enevoldsen and Sovacool, 2016). Concern is exacerbated when local policies fail to provide clear guidelines for wind project development (Enevoldsen and Sovacool, 2016). In sum, the erosion of public support and siting increasing costs coupled with the emergence of promising innovations in offshore foundations (Sovacool and Enevoldsen, 2015) and the allure of more reliable offshore wind conditions have tempered onshore wind growth projections and positioned offshore wind installations as the systems with greatest growth potential in Europe in the coming years (IRENA, 2018).

Yet, the sheer magnitude of the required build out of renewable energy compels national planners to explore all siting options, including the prospects of exploiting untapped onshore wind power potential. Onshore wind energy deployment continues to be supported by various national policies (Valentine, 2014a), with policy focusing on minimizing public opposition and reducing the cost of developing onshore projects (Enevoldsen and Valentine, 2016). Onshore projects continue to play an important role in national and regional energy strategies. Indeed, Jacobson and colleagues (Jacobson et al., 2017) contend that onshore wind power will continue to be a dominant energy resource in Europe with a projected installation of up to 10,288 GW in onshore wind power nameplate capacity by 2050.[1] Even in locations such as the Nordic region, already known for aggressive wind deployment in countries such as Denmark, wind energy production is expected to grow fivefold from 7% of regional electricity supply to 30% by 2050, with two thirds of this additional generation capacity expected from onshore installations (Sovacool, 2017). Based on the above, it is clear that effective siting strategies for facilitating onshore wind project development are needed to bolster the transition towards a European continent powered by 100% renewables.

A first step in developing a wind power development strategy for Europe is to quantify wind power potential at a scale that exhibits sufficient detail to guide site selection in a comprehensive enough manner to highlight threats to site development so that siting and stakeholder engagement strategies can be developed. Technologically, wind energy potential has already been calculated through an ever expanding body of physical science work. For example, in 2009, the European Environment Agency (EEA) published a report on the wind energy potential in Europe (European Environment Agency, 2009). Onshore technical potential was estimated to be 45,000 TWh/yr by 2030. One other noteworthy aspect of the European Energy Commission study was a forecast of where electricity from wind systems will be least expensive within the EU (European Environment Agency, 2009). The study concluded that preferred sites are located mainly in Western Europe due to the favorable wind speeds and flat areas. Switzerland, Austria, Norway, Northern Spain and the southern and southeastern parts of France, which all benefit from higher elevations, were the only exceptions. Other studies echoed the assessment that Western European countries were the most promising targets for wind power (Archer and Jacobson, 2005) (The Global Wind Atlas, 2017). The European Energy Agency report partially explained the bias toward wind power development in Western Europe by noting that wind power developments in Eastern European countries may not be cost-competitive until 2030 (European Environment Agency, 2009).

Unfortunately, these analyses of wind power potential share numerous shortcomings that prevent strategic planning. One study found that when environmentally protected zones and other areas of ecological sensitivity were factored into the equation, realizable technical potential drops nearly 13% to 39,000 TWh/yr (European Commision, 2018). In addition, the 2009 wind map produced in the EEA report is now outdated because technical nameplate capacity estimates were based on the deployment of turbine technology that is now more than a decade old. Furthermore, assessment tools have become more sophisticated over the past decade and yield far better resolution for planners. Increasingly, Geographical Information System (GIS)-based wind atlases are being developed which include more parameters than previous atlases that were limited to potential site identification through only the exclusion of national parks and nature preserves. New atlases have been developed using advanced GIS data at both the national and sub-national levels and provide far more detailed insight into prospective wind energy sites. They employ resolution that focuses attention on houses, roads, and protected areas. They also are able to identify far more exclusionary factors including national restrictions due to military interests, politically restrictive areas, and terrains not suitable for wind power generation (Sliz-Szkliniarz and Vogt, 2011) (Noorollahi et al., 2016).

Nevertheless, such studies have never been aggregated on a continental scale. Thus, the dual aim of this study is to both update wind power potential estimates for Europe while also introducing a more qualitative, refined socio-technical dimension to the analysis in order to help policymakers and wind developers prioritize realizable potential. The study therefore presents a socio-technical wind atlas for all European countries – it intend aims to answer the critical question: How much wind power potential does Europe have after infrastructure, built-up areas, and protected areas are factored in?

2. Research methods

In our nation by nation analysis, the foundation of our methodology is predicated on high spatial resolution of the wind data. The process began with a high-resolution mesoscale wind data set. For this model, a set of restrictions to wind power planning based on limitations posed by infrastructure, built-up areas and protected areas were identified and layered onto the map. This map can therefore be considered to be a socio-technical wind atlas, where the socio-technical analysis is predicated on an interdisciplinary analysis combining 1) common wind atlas construct 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. Our analysis reflects a more detailed analysis of realizable technical potential by incorporating restrictions into the analysis. This approach was inspired by the work of Sovacool (2014) who suggested that energy engineering must become more interdisciplinary by taking into account social science and social challenges if it is to yield useful insights for policymaking and planning.

[1] Jacobson et al. (2017) included all of Russia, which is why that number has been multiplied by 0.25 in order to define the European potential of the country.

Although there are precedents of wind atlases that integrate restrictions into technical wind power potential analysis using GIS-based software, Enevoldsen and Permien (2018) note that the majority of these studies were carried out only for single countries or based on low-resolution datasets. None exhibit the level of aggregation that our model represents. It merits noting that previously proven methods were used to guide our methodological choices, such as Noorollahi and colleagues work (Noorollahi et al., 2016), which applied restrictions to wind condition analysis in order to define the level of suitability for new wind projects.

We decided to make use of open data for our analysis for transparency purposes following Enevoldsen and Permien (2018) who employed a similar approach of defining constraints for wind power development based on open data. However, because the spatial coverage of this study is greater, an adaptation of the approach (Enevoldsen and Permien, 2018) was made and global rather than regional or national sources were accessed when possible.

From a tool perspective, QGIS (QGIS, 2018), an open source GIS, was used in this study to access, process and analyze siting restrictions and lay these “no go” zones over the wind potential maps, however, other GIS programs could replace QGIS (Enevoldsen and Permien, 2018). The reason for selecting QGIS is that it is the most used open source GIS program and complements the open data applied in this study. This will enhance replicability and future updates to the analysis.

To ensure consistency in the data processing and information layering, a sequential process was undertaken which gradually layered each category of data using QGIS. To guide this process, the functions expressed in Table 1 were used:

Table 1
The functions carried out in QGIS.

Function	Short Description
< Add Field >	Attaching a new attribute field to the selected layer
< Buffer >	Creating a polygonal zone around the features in the selected layers with a specified distance
< Fill by Expression >	Using a query to copy values into an attribute field
< Merge >	Adding layers together including all features and attributes
< Re-project Layer >	Using a coordinate transformation to convert the selected layer into another Coordinate Reference Systems (CRS)
< Export Features >	Saving all or only selected geometries and attributes of a layer to a new layer
< Select by Expression >	Using a query to single out features from a layer
< Simplify Geometries >	Reducing the number of points defining a polygon or line feature to reduce the size but at the cost of detail

Although while mapping natural protected areas, various buildings and infrastructure would follow the process described in Table 1 and Fig. 2, a more nuanced approach was needed to process the waterways and rivers. These water bodies are defined as a line feature in the data, while the riverbanks and lakes are defined through polygon constructs. The waterways and rivers are delineated on one layer whilst the riverbanks and lakes are delineated in a different layer. The aim of this procedure is to create one layer showing all areas containing water. Furthermore, in order to depict the actual width of the waterways and rivers, the OSM data attribute “width” was used. Since the buffer method is using a value to create a spatial polygon on each side of the line feature, half of the “width” was used to create polygons representing the actual size of the waterway and rivers. In order to avert zero values in the expression, which would result in errors, a case-expression was defined. Once processed, the resulting layer was merged with the layer including riverbanks and lakes to create a water layer.

2.1. *Constructing the socio-technical wind atlas*

The overall basis of our approach is predicated on guidance from Voivontas (1998) who suggested that the estimation of a region's maximum wind energy output must include constraints which exclude sites where wind power potential is not realizable due to social constraints. A schema of the process leading to the socio-technical wind atlas is illustrated in Fig. 2.

Restrictions were categorized into three main groups: infrastructure, buildings, and protected areas. They are described further in Table 2. The restricted areas and associated shapefile layers were processed using QGIS. The geoprocessing algorithms *Select*, *Simplify*, and *Re-Project* were run to process these layers. As an additional next step, the layers were buffered with country specific distance regulations.

There were some critical assumptions made in the process of overlaying restrictions onto the wind maps. Some countries do not have comprehensive regulations covering all infrastructure, buildings, and protected areas, and therefore proxies of 200 m (infrastructure) and 1000 m (buildings) were applied in order to adhere to modern wind turbine general safety measures. For existing wind turbines, a buffer proxy of 700 m was applied to minimize potential wake effects (Hou et al., 2015). The next step was to combine the restrictions in each country into a unified layer structure covering Europe. Several restrictions overlap with each other; consequently, a three-step procedure suggested by Enevoldsen and Permien (2018) was used to compute the available potential. In the process, a rasterizing algorithm was used to convert the complex vector layers into a 10×10 m grid containing country boundaries and restrictions. The resulting grids in GEOtiff format were then withdrawn, resulting in a unified layer showing the potential area available for onshore wind power in Europe after all restrictions have been included.

3. Evaluation of the wind atlas

This section presents key elements of the wind atlas and discusses implications that arise from the data.

3.1. *Estimating wind resources*

Fig. 3 illustrates how diverse Europe's wind resources are. The map in Fig. 3 presents the annual mean wind speeds 100 m above ground level, and covers all of the European countries targeted in this research.

By examining Fig. 3, it is apparent that higher wind speeds are observed along the Atlantic Ocean, North Sea and Baltic Sea coasts as well as throughout the UK, Iceland, Ireland, and Denmark. There are also strong wind speeds along the southern coast of France and along the coastlines of the Aegean Sea. Wind speeds are significantly lower in the southern part of Germany, the central, southern, and eastern sections of Spain, the eastern region of France, the central regions of Italy, the Balkans, the central part of Eastern Europe, the south-eastern part of Norway, and the Northern part of Sweden.

Clearly this suggests that a one-size-fits-all wind power development policy will not suit Europe. For nations with coastlines that border the Atlantic or even for other coastal zones such as along the Aegean and Mediterranean seas, a focus on coastal development policy is likely to optimize economic performance. However, as we are seeing in Germany and Denmark, over-development in any one area runs the risk of engendering public opposition. Meanwhile, the inland regions in many of the nations with ample coastal wind power potential will likely need government support in order to attract wind power developers to

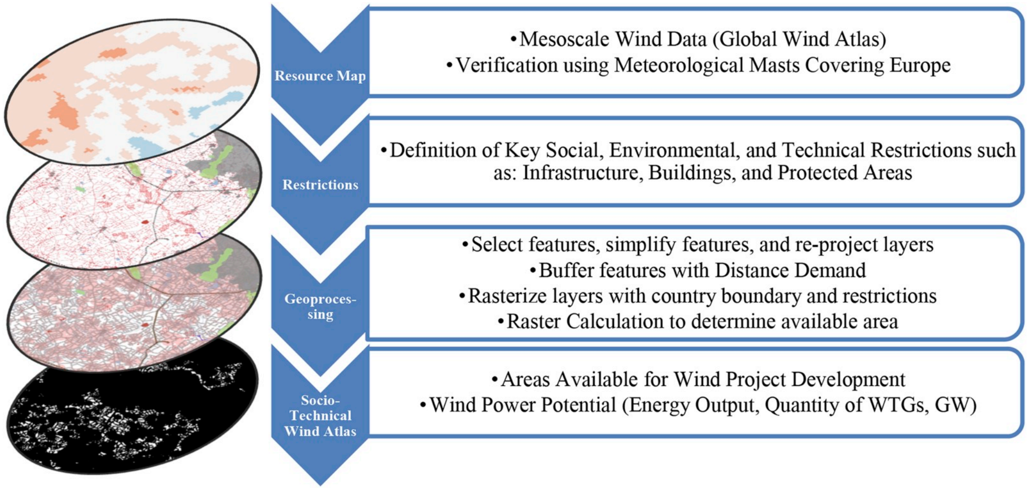

Fig. 2. The process of constructing a socio-technical wind atlas for western europe.

Table 2
Restrictions and Sources for the socio-technical wind atlas for Europe.

Restriction	Content	Description	Source
Infrastructure	Roads, waterways, airports, and railways	Distances need to be kept from roads and railways, mainly due to safety issues.	OpenStreetMap (geofabrik.de)
Buildings	Residential, industrial, military, public, and existing wind turbines	Distances to buildings are considered one of the most important restrictions, especially as the distance, or lack thereof, to residential buildings has caused numerous complaints and eventually stopped the development of wind projects (Enevoldsen and Sovacool, 2016).	OpenStreetMap (geofabrik.de)
Protected Areas	Castles, monuments, areas protected by Natura2000, Special Protection Area, Flora Fauna Habitat, etc.	Different regulations exist in each of the targeted countries; yet, for all the countries, a longer distance from historical landmarks is mandated. Similarly, wind turbines cannot be deployed in areas protected by the Natura 2000 regulations.	Natura2000 (Copernicus/European Environmental Agency)

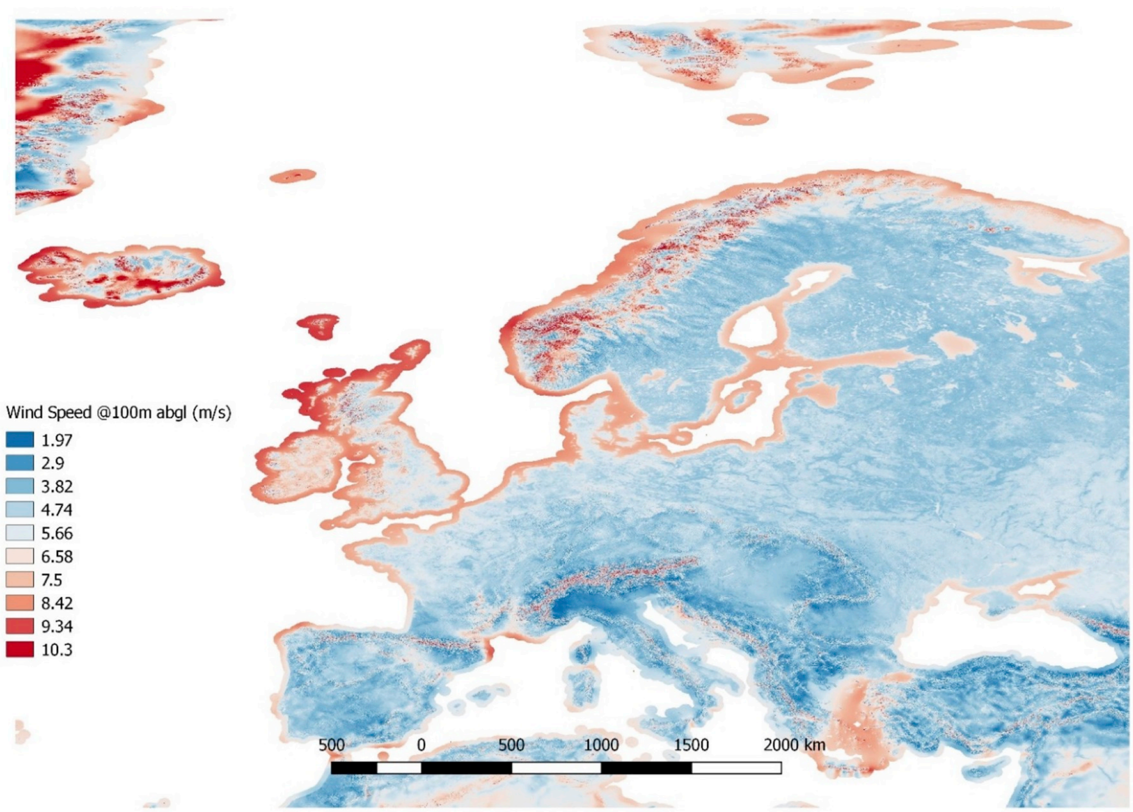

Fig. 3. Annual mean wind speeds at 100 m above ground level in Europe (Wind data from (The Global Wind Atlas, 2017)).

sites with lower wind potential.

For other nations, such as Spain, Italy and the central part of Eastern Europe, robust policies will be needed to even attract developers' attention. The revenues from producing wind energy in these nations are going to be lower than in nations such as Denmark and Germany, due to inferior wind potential. This places governments in these regions at a disadvantage when it comes to meeting European renewable energy targets through wind system installations.

3.2. Compiling wind data and power curves

The extensive dataset from Noorollahi and colleagues (Noorollahi et al., 2016) created by the World Bank and the Technical University of Denmark was used as our foundational wind resource map. The data is based on a mesoscale model with a spatial resolution of 0.01° × 0.01°, approximately 1 × 1 km, and an hourly temporal resolution. The benefit of using this specific dataset stems from the height availabilities, as it records wind conditions at 100 m. This height correlates best with the average hub heights of turbines found in Europe, which range from 80 to 125 m onshore. The dataset was validated by testing it against 27 meteorological masts located across Europe, with the recognition that the topography and surface obstacles can widely differ, from the flat agriculture areas in the Netherlands and the large British forests, to the complex regions in Sweden, and that global data sets might miss such nuances. The exact locations of the meteorological masts have been anonymized due to a confidentiality agreement with the data provider.

The majority of the measurements at the meteorological masts were at 100 m, comparable with data from the mesoscale model. However, when data was not available at 100 m, measurements were extrapolated from 5 to 10 m above the ground to 100 m using the wind profile law presented in (1).

$$V = V_{ref} * \frac{\ln \frac{z}{z_0}}{\ln \frac{z_{ref}}{z_0}} \tag{1}$$

where V is the wind speed at height z above ground level, V_{ref} is the known wind speed at height z_{ref} above ground level, and z_0 is the roughness length for momentum. The data are presented in the graphs in Figs. 5, 6 and 7 in the supplemental information. Key differences for wind speed and dominating wind directions for the three most prominent geographic configurations (forest, flat and complex) are illustrated in Table 3.

The data presented in Table 3 confirm previous studies that have examined the disparities of wind conditions in wind sites surrounded by forests, and/or complex terrain (Arnqvist, 2015) (Enevoldsen, 2016). Despite the expected challenges of irregular wind flows, the median wind speed difference varies between 0.43 m/s in flat terrain to 0.57 m/s in complex terrain and one sector (30°) for the wind direction. The wind data were often divided into 12 sectors, meaning that the even 5 degrees of difference would have been translated into one sector or 30°. For the purpose of constructing our wind atlas, this variance is not considered to be significant.

Table 3
Difference between the mesoscale dataset and the physical measurements.

Configuration	Measure	Wind Speed Difference (m/s)	Dominating Wind Direction (°)
Forest	Mean	0.53	33
	Median	0.45	30
	Max	1.40	90
	Min	0.07	0
Flat	Mean	0.49	17
	Median	0.43	30
	Max	1.20	30
	Min	0.03	0
Complex	Mean	0.62	67
	Median	0.57	30
	Max	1.45	150
	Min	0.05	0

It merits noting that in order to create a wind atlas that is useful to policymakers and developers, the energy potential and restrictions were calculated for the different countries using the power curve and specifications from a multi-megawatt wind turbine, the Envision 4.5–148 wind turbine. A 4.5MW wind turbine was chosen to serve as a proxy for an optimal turbine size for the present time. This wind turbine type suits most onshore sites due to its large generator, variability to accommodate changing wind speeds, and its large rotor diameter, which can capture the energy of low wind speed sites and maximize the energy output from high wind speed sites.

3.3. Accounting for restrictions and limitations

Once restrictions were introduced to the technical wind power potential map, the resulting country map (in SI Section 6) reveals that infrastructure and buildings are the two major obstacle groups impeding wind project development. It merits noting that the barriers posed by these restrictions are not uniform in every nation. The population density in European nations varies greatly from 13 people/km^2 in Norway to 409 people/km^2 in the Netherlands. Therefore, the built-up environment does not pose nearly the restrictions in Norway as it does in the Netherlands. Protected areas also vary substantially between European countries. It merits further note that road and railway networks, as well as waterways, are relatively homogenously distributed throughout Europe.

In addition, since wind turbines should not be deployed on mountains due to the installation cost and potential breakdown risk, the following areas were considered non-applicable for wind project development: The French Alps (14,792 km^2), the Pyreness (13,215 km^2), the mountains of southern Spain (14,793 km^2), the Norwegian and Swedish mountains (71,564 km^2), the German mountains in Tyrol (1730 km^2), and the mountains of great Britain (4233 km^2).

4. Results: a socio-technical analysis of european onshore wind energy

The number of potential realizable wind turbine installations were based on the following calculation for the area required per wind turbine generator (WTG):

$$Potential\ WTGs = \frac{Available\ Area\,(m^2)}{(4.375 \times 148m) \times (4.375 \times 148m)} \tag{2}$$

This number has then been divided with the nameplate capacity per turbine (4.5MW) in order to estimate the potential installed nameplate wind capacity (See Table 4).

Our socio-technical analysis reveals at least two significant findings.

4.1. Onshore wind energy potential in europe exceeds total global energy demand forecasts for 2050

Our findings suggest that Europe has far greater potential for onshore wind energy than previously suggested. The combined area of the European countries targeted in this research is approx. 1,0737,064 km^2, where the European part of Russia (3,960,000 km^2) is the largest landmass and Malta (316 km^2) the smallest. Within the European landmass 5,841,503 km^2 constitutes restricted area, meaning that the remaining 4,895,560 km^2 can be used for wind project development. If this were fully realized it would equate to a shift in turbine density in Europe increasing from 1 MW per 4564 inhabitants to 1 MW per 15 inhabitants (approximately). See Fig. 8 S.5 for the current potential power density in Europe. Fig. 4 below highlights the power density potential in Europe.

Table 4
Summarizing the output of the socio-technical wind atlas estimations for Europe.

Parameter	Finding	Comments
Area (km^2)	10,737,064	54% of the European land is restricted for onshore wind project development.
Restricted Area (km^2)	5,841,503	Restrictions are however expected to increase as the population increases
Area for wind project development (km^2)	4,895,560	
Potential number of wind turbines	11,676,773 wind turbines equal to 52,545,479 MW installed	Based on previous studies, the cost for installing this amount of onshore wind turbines would be in the range of 1.20–1.65 \$/W (Lazard, 2017), without considering economies of scale
Potential power output	138,090 TWh or 497 EJ (EJ) when assuming a capacity factor of 30%	The expected energy demand in the World in 2050 is 430 EJ (DNVGL, 2017).

This estimate of realizable potential should not be misconstrued as being the same as viable realizable potential. Non-restricted land might not be available for wind project development due to other land use conflicts, private ownership, and social opposition (Enevoldsen and Sovacool, 2016). However, viability in this sense is more about planning strategy. For example, as argued by Hou and colleagues (Hou et al., 2015) wind turbines can, and have, often been deployed in agricultural areas, side-stepping land use conflicts.

The data and maps for each country are listed in the supplemental information section 6. Furthermore, given the variance in area of each European country, an analysis has been carried out to examine the potential MW/km^2 for each of the countries in Fig. 5. The combined potential is 4.893 MW/km^2 which is a staggering number compared to the current 0.017 MW/km^2. Interestingly, large non-EU countries such as Turkey, Russia, and Norway have the greatest potential for future wind power density.

Europe has sufficient wind energy resources in onshore locales alone to meet and significantly exceed existing targets. The findings in the socio-technical wind atlas can be compared to previous studies (Jacobson et al., 2017) (Windeurope, 2018) and official national targets for the European countries' wind nameplate capacity. Such comparative analysis has been carried out and is presented in Fig. 6.

The current nameplate capacity and the 2020 targets are based upon on– and offshore wind power, which further indicates that some countries need to develop offshore wind farms in order to reach the targets, such as the Netherlands (7.296 GW for 2030), Belgium (1.681 GW for 2030), and Malta (0.048 GW for 2030). The comparisons to the 2020 and 2030 targets are listed in the SI Section 6.1. In addition, according to Fig. 5,Luxembourg (0.48 GW for the onshore 2050 target) and Malta (00.098 GW for the onshore 2050 target) would not be capable of reaching the onshore 2050 targets unless they implement new policies for land use restrictions.

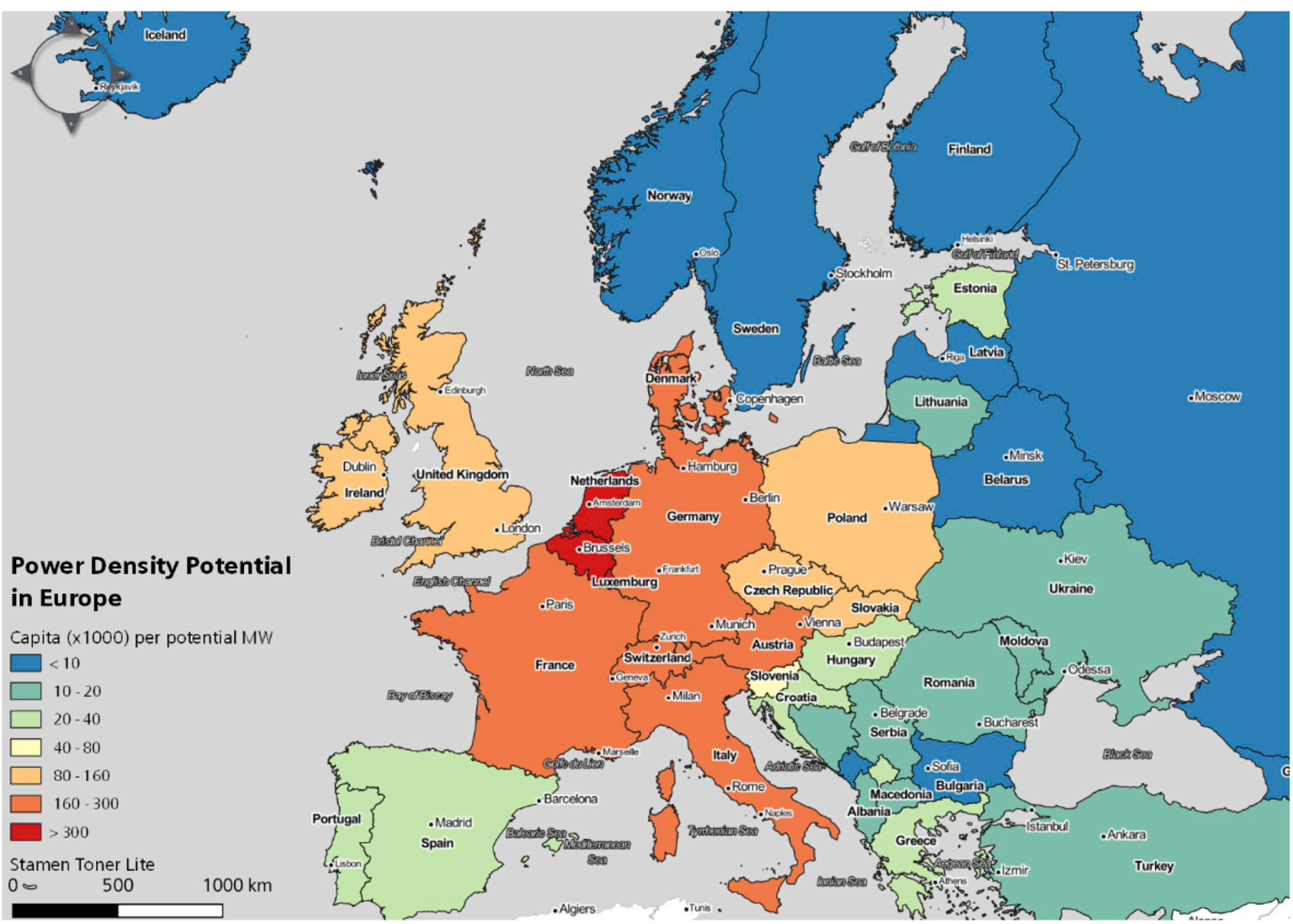

Fig. 4. Potential power installation (MW) per capita in Europe.

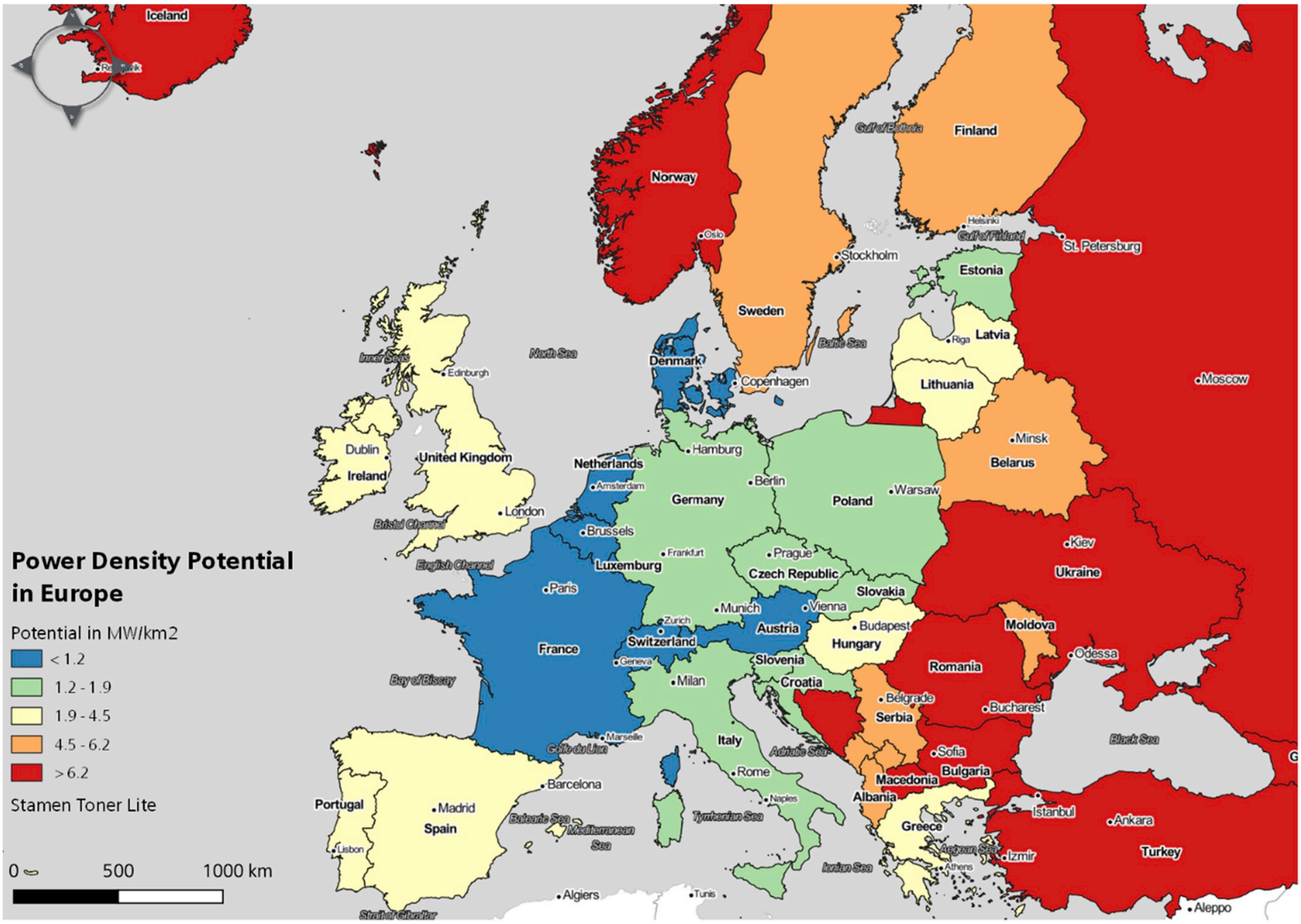

Fig. 5. The onshore potential for wind energy in Europe (MW/km^2).

4.2. Wind has a much smaller environmental footprint than previously envisioned

Our study challenges some of the conventional views about land use and the footprint of wind turbines. The spacing density of multi-megawatt wind turbines was examined by Enevoldsen and Valentine (2016) for global onshore wind turbines with a mean European spacing density of 4.375D X 4.375D (Median minimum of 3.45 times the rotor diameter and median maximum of 5.3 times the rotor diameter).

5. Conclusion and further research

The policy impetus in the EU has been to exploit offshore wind potential (Enevoldsen and Valentine, 2016) for various reasons including: i) offshore wind resources are stronger, ii) more predictable, iii) less turbulent at sea, iv) with fewer obstacles or changes in land topography to alter or slow wind speeds (Enevoldsen et al., 2018), v) more limited concerns about potential negative externalities such as visual impact, noise, and social opposition when done over the horizon and, vi) have lower wind-shear and fewer physical restrictions (such as passage under bridges) impeding transport and construction from harbor to site. Therefore, it is understandable that offshore wind power development will continue to be central to the EU's low-carbon transition.

However, as energy planners have learned in the past, relying on one technology or one development strategy engenders unnecessary risks that are abated through diversification strategies (Sovacool et al., 2016). When it comes to wind power development, an upsurge in opposition to coastal developments could expose nations that invest only in offshore wind farms to NIMBY risk. Moreover, as climate change progresses, intensification of coastal storm activity places any system that relies largely on offshore wind power at risk of system-failure. Moreover, despite technological advances, onshore wind power is still a cheaper source of wind power generation. Offshore wind power comes with a levelized cost of electricity (LCOE) of 0.14 $/KWh, yet, with a recent all-time low LCOE of 0.056 $/KWh (Energyworld.Com, 2019). TheLCOE of onshore wind power is 0.06 $/KWh (IRENA, 2018). For all of these reasons, further onshore wind power development should not be dismissed.

Our study suggests that realizable onshore wind power potential using existing technology in Europe alone is sufficient to generate enough power to satisfy total energy demand between now and 2050. Overall, our study concludes that realizable onshore wind power potential throughout Europe is much larger (A generation of 138,090 TWh/yr) than previous studies (39,000 TWh/yr (European Commision, 2018)). Our estimate is more than three times the potential revealed by the European Environment Agency in 2009 (Enevoldsen and Valentine, 2016). This finding questions the academic and industrial concern of land use being a major constraint for renewable energy development. Future modeling exercises, technological pathways, and national scenarios ought to be recalibrated appropriately.

The discrepancy in findings is partly because our model integrated the role of current technology that has advanced considerably since the 2009 study was conducted. However, the discrepancy also highlights the statistical deviations that exist when conducting such studies. In our study, we have been very liberal in our identification of exploitable

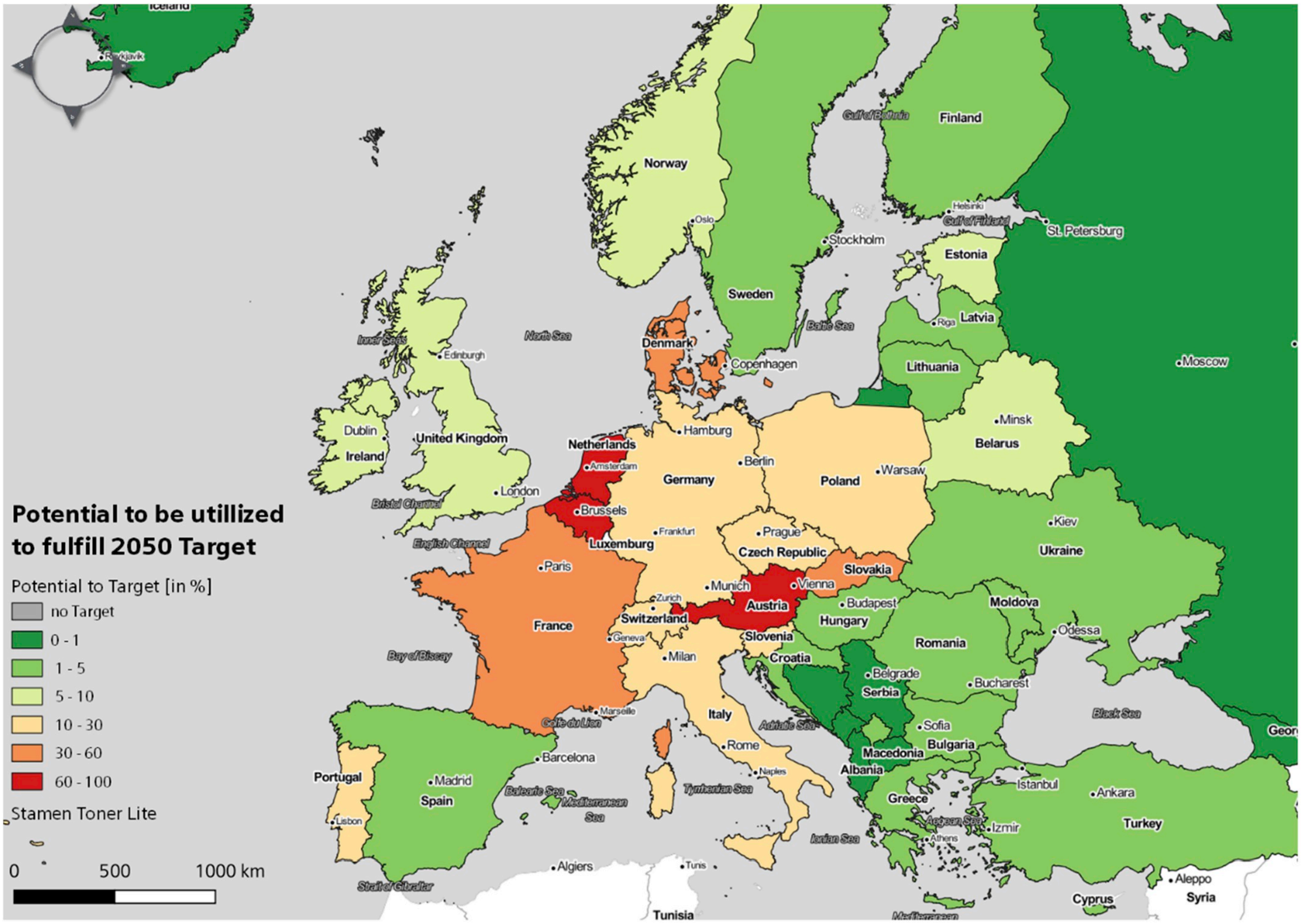

Fig. 6. The Difference between the potential nameplate capacity and the 2050 (Onshore) targets.

land. We have assumed that all of the land that we identified as being "non-restricted" can be developed. As we acknowledged earlier, much of this land will be under private ownership and subject to the aspirations of the land owners. Our estimate is "realizable" only in the context of be capable of development and unfettered by physical restrictions. Our estimate does not take into consideration social willingness to accept wide scale development and does not delve deeply enough to highlight site specific factors that might prohibit development (e.g. competing land uses that are more economically attractive, physical attributes such as marshy soils that might complicate project development).

Notwithstanding these reservations, the results of this analysis reveal considerable onshore wind power potential exists at levels than far surpass previous estimates. In combination with offshore wind power potential and solar PV potential in areas where restrictions prohibit wind farms, it is clear that there is more than enough clean energy potential to meet Europe's aspiration to move to 100% renewable energy generation, even when electric vehicle transport power needs are factored in.

The results of this study also highlight one other important insight in regard to these types of energy potential assessments: the assessment will change drastically if technology advances. This suggests that our finding that onshore wind power alone, if fully exploited, could satisfy global power needs represents a conservative estimate for future energy requirements given that wind power technology is still advancing.

In terms of future research directions, the methodological approach and application of open source data allows this study to be replicated for any continent, suggesting that this study can serve as a global planning tool for assessing global wind power potential and assisting in national and international wind project planning. Future studies can also employ this methodological approach as a foundation for more detailed studies, e.g. micro-siting of power output potentials, optimization of European wind power expansion, etc. To do so would mean additional layers of analysis simply need to be incorporated into the model.

At the planning level, the socio-technical wind atlas can provide guidance to European policymakers on where their wind power resources lay, which communities would be impacted, and how extensive the wind power potential is. The individual high-resolution country maps will furthermore assist the planning of future renewable energy systems, as countries and regions will understand how much power can be generated through onshore wind resources, and therefore, highlight any supply gaps that might exist, which would require investment in alternative energy resources.

In extension of this work for Europe, future studies might be able to determine where a unified European wind power program should deploy wind farms in order to utilize the wind resources across the continent. Examining the wind atlas, it also becomes clear that wind turbine manufacturers will be forced to innovate on solutions for areas with wind speeds below 6 m/s because much of Europe is characterized by wind speeds that are between 3-6 m/s.

Critics will be tempted to point out that the stochastic nature of wind power – sometimes wind blows, sometimes it does not – suggests that, in the absence of adequate storage, concluding that onshore wind power potential in Europe is sufficient to cover global demand is disingenuous. Others might be tempted to question the practicality and viability of establishing wind turbines at the level of density used in the model. After all, even at 40% levels, onshore wind power has been challenged by NIMBY opposition in Europe (Valentine, 2014b). To both critics the response is the same. Realizable wind power potential studies are not to be treated as blueprints for development. Such studies help policymakers understand what is possible as a ceiling, help planners target areas of particular attraction, and help us understand where we are in terms of state of play concerning a given technology and its potential. For onshore wind power potential, our study suggests that still the horizon is bright for this particular application in the wind energy sector and that European aspirations for a 100% renewable energy grid are within our collective grasp technologically.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enpol.2019.06.064.

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