# Evaluation of Global Onshore Wind Energy Potential and Generation Costs

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S *Supporting Information*

ABSTRACT: In this study, we develop an updated global estimate of onshore wind energy potential using reanalysis wind speed data, along with updated wind turbine technology performance, land suitability factors, cost assumptions, and explicit consideration of transmission distance in the calculation of transmission costs. We find that wind has the potential to supply a significant portion of the world energy needs, although this potential varies substantially by region and with assumptions such as on what types of land can be used to site wind farms. Total global economic wind potential under central assumptions, that is, intermediate between optimistic and pessimistic, is estimated to be approximately 119.5 petawatt hours per year (13.6 TW) at less than 9 cents/kWh. A sensitivity analysis of eight key parameters is presented. Wind potential is sensitive to a number of input parameters, particularly wind speed (varying by −70% to +450% at less than 9 cents/kWh), land suitability (by −55% to +25%), turbine density (by −60% to +80%), and cost and financing options (by −20% to +200%), many of which have important policy implications. As a result of sensitivities studied here we suggest that further research intended to inform wind supply curve development focus not purely on physical science, such as better resolved wind maps, but also on these less well-defined factors, such as land-suitability, that will also have an impact on the long-term role of wind power.
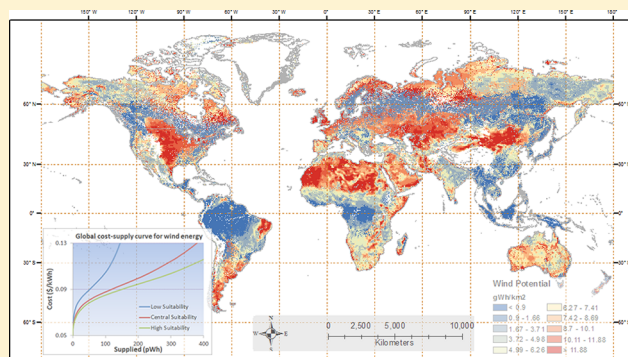
1. INTRODUCTION

Wind power is a renewable energy source with potential to reduce greenhouse gas emissions and local air pollutants associated with the burning of fossil fuels. However, the precise role that wind energy might play, at regional and global levels, remains unclear, for several reasons. One reason is that there are still large uncertainties about the amount of wind that can be effectively incorporated into electricity grids. Another reason is that there are still large uncertainties about the supply and cost of wind energy.

Improved information regarding global wind energy potential can help decision-makers gain insight into the wind resource and its spatial distribution. Another reason to develop supply and cost information and to understand the surrounding uncertainties is that this information is an important input to integrated assessment and energy-economic models. These models are used extensively to explore the nature of climate mitigation over decadal to century scales, and they are important tools to inform national and international dialogues regarding climate policy and transition pathways to a lower-carbon future.[1,2]

There are several previous studies examining global and regional onshore wind supply. Hoogwijk et al.[3] estimated onshore wind energy potential based on annual wind speed data from the Climate Research Unit (CRU). Lu et al.[4] used Goddard Earth Observing System Data Assimilation System data. Archer and Jacobson[5] used wind speed data from a network of sounding stations. The global potential of wind electricity from Hoogwijk et al. is 96 pWh per year (10.96 TW, pWh is converted to TW by dividing by the number of hours in a year) at cutoff costs of about $1/kWh.[3] 690 pWh annual (78.8 TW) onshore wind energy potential with capacity factors >20% is estimated from Lu et al.[4] Global wind power generated at locations with mean annual wind speeds ≥6.9 m/s is 72 TW from Archer and Jacobson.[5] In addition to the evaluation of wind potential from land-surface turbines, Archer and Caldeira estimated the wind power resource at altitudes between 500 and 12 000 m above ground.[6] Among these studies, the work of Hoogwijk et al.[3] was designed to be used in integrated assessment and energy-economic models.

Constructing a consistent estimate of global and regional onshore wind potential is a challenge because global data sets with sufficient resolution to resolve areas of high-speed wind are not publically available. Additional limitations include the use of coarse spatial resolution input data such as land cover,[3,4]

limited or no consideration of economic factors, limited consideration of environmental and geographic constraints, and the need to update wind technology assumptions.

It should be noted that wind energy potential has also been evaluated at the regional scale, often using higher-resolution or more robust wind speed information than at the global level.[4,6−14] Although improved data, spatial resolution and analytic techniques are used in these more detailed assessments, there are still limitations for global analysis because they are neither comprehensive in terms of world regions nor produced from consistent methodologies and assumptions.

This study has two purposes. The first purpose is to produce an updated estimation of global wind potential, with a special focus on making these useful for the energy modeling community. The paper builds on the methodology used in Hoogwijk et al.,[3] expanding on it in several important ways including the incorporation of more comprehensive wind speed data from National Centers for Environmental Modeling (NCEP),[15] the use of hourly wind data, updated technology parameters, and the use of transmission costs.

The second purpose of this study is to improve understanding of the major sources of uncertainty that influence wind energy supply estimates. In addition to well-known uncertainties in the spatial and temporal variations of wind speed, this study aims to also highlight the role of a range of additional assumptions, particularly those surrounding the suitability and intensity by which land can be used for wind power and cost and financing assumptions. Understanding the impact of these parameters will enhance our understanding of wind energy in general, and it will also help to guide future research.

2. MATERIALS AND METHODS

The methodology used in this study to produce wind supply curves can be broken into four steps, largely following the method of Hoogwijk, et al.[3] Wind speed is calculated at the turbine hub height, followed by the determination of the energy extracted by a representative turbine, which is then adjusted based on a set of land and elevation exclusions, and finally used to estimate energy costs. A detailed description is provided in Supporting Information (SI) Text 1.

2.1. Step 1: Wind Speed. Wind speed determines the amount of kinetic energy that can potentially be intercepted by a turbine. There are two elements that must be addressed. The first step is the collection of available wind data, which are generally estimated at heights different from the standard wind turbine hub heights (80−100 m). The second step is the calculation of the speed at a specified hub height based on the wind speed data and surface roughness.

We examined a number of global data sets (SI Text 1), and in this study chose the Climate Forecast System Reanalysis (CFSR) wind speed data from NCEP.[15] This data set is publically available, covers a sufficiently long period of time to provide a reasonable baseline, and is one of the higher resolution reanalysis data sets available. The CFSR data has a spatial resolution of 0.3125 degree lat/lon and provides wind speed from 1980 to 2009.[15]

Wind speed at 10 m height was converted to speed at 80 m using a logarithmic wind speed profile (eq 1), as

$$V = V_{10} \frac{\ln\left(\frac{H}{Z_0}\right)}{\ln\left(\frac{10}{Z_0}\right)} \quad (1)$$

where V is the wind speed at the hub height, V_{10} is the wind speed at height of 10 m, z_0 is the surface roughness length, a data product of NCEP/CFSR data set,[15] and H is the hub height. This methodology can be easily applied to a wide variety of data sets and is commonly used to extrapolate wind speeds. We note that the logarithmic profile represents a thermally stable wind profile,[16] which will not be strictly valid in all situations. Given the substantial uncertainties in current wind data sets, however, a more elaborate estimation procedure was not undertaken for this project (SI Text 1). We used the spatially varying roughness length from the CFSR data set for the extrapolation to be consistent with the CFSR data. In previous studies estimated values of roughness length vary by factors of two or sometimes more,[3,14,17,18] so we use a factor of 2 for our sensitivity tests of this variable. The use of an extrapolation introduces some error into the wind estimation, however, it is not clear if a more complex methodology is warranted given the many issues associated with the available global wind data. The sensitivity range used here is sufficient to cover, for example, the extrapolation errors reported by Giordano[19] (SI Text 1).

2.2. Step 2: Technical Wind Energy Potential. We next estimate the wind energy that could be harnessed by wind turbines without considering economic or siting constraints. We will refer to this as the technical wind energy potential, which was estimated as shown in eq 2.

$$E_t = \sum_{i=1}^{8760} \eta_1 \eta_2 \left(\frac{A\delta}{1.5}\right) p_i \quad (2)$$

Where E_t is the wind technical potential (kWh/year), A is the area of each grid cell (km^2), η_1 is the availability factor, η_2 is the array efficiency, δ is average installed power density (MW km^{-2}), and $((A\delta)/(1.5))$ represents the number of turbines (1.5 MW GE turbine) in a given grid cell. p_i is the hourly wind power output from a representative 2008 1.5 MW GE turbine with an 80 m hub height, based on wind speeds determined in Step 1.[20] The availability factor, η_1, accounts for the reliability of the turbine—the fraction of time that it would be operational, assumed to be 97%, based on the 2008 1.5 MW GE turbine.[20] The array efficiency, η_2, accounts for the energy lost when turbines are placed close together in a wind farm. The array efficiency is assumed to be 90%.[3] i is the hour in each year, and wind energy output is also averaged over a 30 year period.

The average power density represents the total capacity installed within a given area, and depends on turbine capacity and spacing between turbines. While a higher power density can result in higher output per unit of land, power output is limited by interference between turbines, whereby the wake from an up-wind turbine will reduce the power output of down-wind turbines.[21] Turbine spacing is, therefore, generally considered as multiples of blade diameter (D). This study uses a central assumption of 5 MW km^{-2}, which was used by Kline et al.[22] and many other studies. Sensitivity tests on these parameters will be presented in Section 3.2.

2.3. Step 3: Exclusions and Suitability (Practical Potential). Not all areas can realistically be used for wind energy production. Therefore, the practical wind energy potential considers geographical exclusions based on protected areas, altitude, and suitability for wind power more generally as a function of land cover types. These three considerations are discussed in turn below. We first removed 14% of land area from total area in consideration by excluding protected areas

using the World Database of Protected Area[23] (SI Text 1). We also exclude area at high elevations (above 2000 m), which removes an additional 5% of area in consideration.

The final consideration is the compatibility of wind development with other land uses and land characteristics, where safety, aesthetic, and logistical considerations come into play. The availability of a specific land type for wind development was included through use of a suitability factor (eq 3).

$$E_a = fE_t \tag{3}$$

where E_a is the wind practical potential, f is the suitability factor based on land characteristics ($-$), and E_t is the wind technical potential. The suitability factor is defined as the fraction from 0 to 1 of the land that could be used for wind turbine development,[3,24] and is assigned to each grid cell based on a land cover map. A literature review of parameters used in previous studies was conducted. A range of values were selected as sensitivity cases as further detailed in the SI Table 3. Land cover type, which is used to assign land suitability factors, is from the 500 m Moderate Resolution Imaging Spectroradiometer (MODIS) map of global land cover.[25,26]

2.4. Step 4: Cost of Wind Electricity. Ultimately, wind energy must compete on an economic basis with other sources of energy. Therefore, the final step is to estimate the economic potential, and to develop wind supply curves, that indicate the amount of wind that would be available in a country or region at a given price.

The cost to generate wind energy in each grid cell was calculated taking into account both turbine costs, which include both capital and operating costs, and the costs of building transmission to bring the wind to the transmission grid. Taking both of these factors into account, the cost of energy (Coe) is given by

$$\text{Coe} = \frac{\gamma(I + LC_L)\delta A}{E_t} + \varepsilon \tag{4}$$

where I is the project capital cost, γ the fixed charge rate (FCR), ε is the annual operation and maintenance (O&M) costs (assumed to be \$0.01/kWh[27]), and A, δ, and E_t are the previously defined grid cell area, average installed power density, and wind technical potential in each grid. All monetary data are in real 2007 U.S. dollars. For further details see SI Text 1.

The central value for project capital cost, I, is taken to be \$1800/kW, which is the value used in EIA's 2010 Annual Energy Outlook.[28] γ reflects financing costs, which accounts for the time value of money and real-world financing constraints that affect the costs of energy technology development projects. For this study, we have set the central assumption to 0.13, which corresponds to a simple interest rate of 12.5% amortized over 30 years, typical of values used for evaluating other energy technologies.[29,30] As further discussed in SI Text 1, we wish to use financing assumptions that represent the total cost of wind power, accounting for the potential shift of costs from the private to the public sector that results from subsidies.

The term LC_L in eq 4 captures the cost of transmitting dispersed wind generation to the electric grid.[31−33] Note that we have not included any costs associated with expansion or improvement of the transmission system. L is the distance from grid to power transmission line (km); and C_L is the unit transmission cost (\$/kW·km). The central value for the unit

cost of transmission is taken to be \$745/MW·km, as used in the NREL ReEDS model.[33]

The explicit incorporation of transmission distance in the research being reported here represents an extension of the approach used in Hoogwijk et al.[3] Transmission distance was rarely explicitly considered in previous studies, where transmission costs were included as a flat rate or representative value[34,35] or proportional to turbine costs.[3] L in eq 4 is estimated as the straight line distance of each grid cell to the existing power line from a global transmission line data set[36] (SI Figure 4).

3. RESULTS AND DISCUSSION

Constructing a consistent estimate of global and regional onshore wind potential is a challenge because global data sets with sufficient resolution to resolve areas of high-speed wind are not publically available. We have used a moderately high-resolution reanalysis data set to examine global and regional wind potential and to examine sensitivities to key assumptions. While the data used here have limitations, we were able to improve upon previous global estimates and identify a number of areas where further research is needed.

3.1. Central Case Results. Wind potential, in terms of electricity generation, and its costs are shown for the central case in Figure 1. A particular focus of this study is the long-term
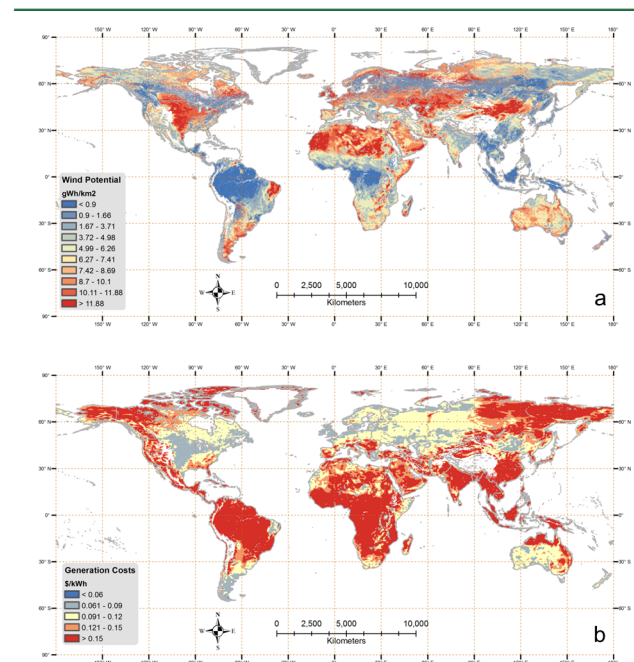

Figure 1. Practical potential per unit area (a) and generation costs (b) of wind electricity in the central scenario. Land areas over 2000 m (no color) were excluded.

potential of wind, and we focus in this discussion on the economic wind potential at costs <9 cents/kWh. While the upper end of this range is relatively expensive at present, lower turbine costs in the future could move much of this potential into a more affordable range.[37] While we use cost as our primary comparison criteria, many studies use capacity factor. For the central parameters used here, a capacity factor of 30% is equal to a generation cost of 11 cents/kWh (for zero transmission distance). Using central parameters, we find a

global onshore economic wind energy potential of 119.5 pWh per year (13.6 TW) at costs below 9 cents/kWh (Figure 2).
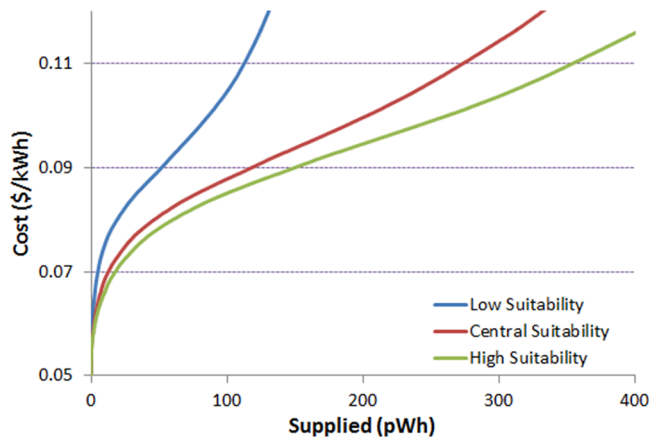

Figure 2. Global cost-supply curve for wind energy using three sets of land suitability factors.

Not surprisingly, the wind energy potential shows large variability across regions (Figure 1 and Figure 3). Different
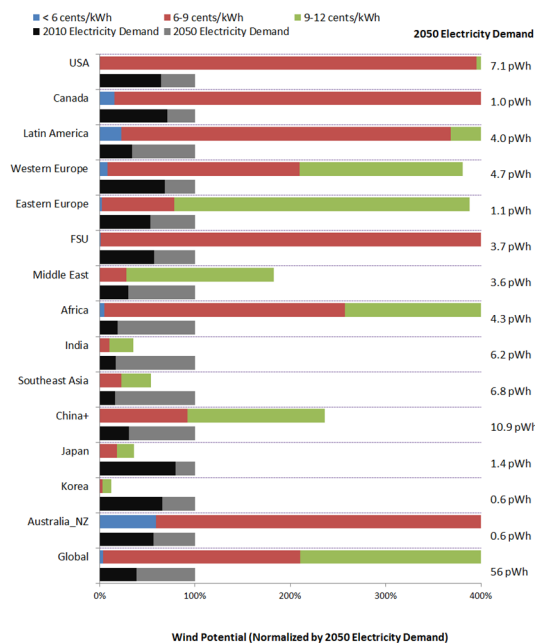

Figure 3. Wind energy potential within cost categories relative to projected 2050 electricity demand at regional level. Values >400% of projected 2050 electricity demand are not shown. The 14 geo-political regions are as defined in the GCAM.

countries are endowed with different wind resources, which may or may not be consistent with the potential needs for power. On one end of the scale, the United States, Canada, Latin America, the Former Soviet Union (FSU), and Australia all have wind resources that, at <9 cents/kWh, are several times projected 2050 electricity demand. The projected electricity demand is from the GCAM integrated assessment model.[38] Wind potential in these countries does not appear to be limited by gross resource supply constraints. On the other end of the scale, Korea, India, and Japan are notable as having relatively small onshore wind resources relative to their projected

demand. In some rapidly growing regions, onshore wind may be able to meet only a limited portion of future demand. While wind potential in South and East Asia (exclusive of China and India) is a substantial portion of current electricity demand, it is a much smaller portion of projected 2050 electricity demand in these regions.

In the central case, the amount of relatively low cost wind (<6 cents/kWh) is small in most regions (except Canada, Latin America, and Australia), generally less than 5% of projected 2050 demand. This is, in large part, due to the bias against high-speed wind areas in the reanalysis data set. In three of the four comparison regions examined (e.g., SI Figure 3), the CFSR data set used here missed 90% of the area with winds power class 5 and above. If even a small portion of the next largest categories consisted, in reality, of areas with higher speed wind, this could provide a significant amount of lower cost wind in many regions.

The importance of this bias depends on the analysis goal. If the goal is to examine the near-term potential for wind resource development, accurate mapping of the highest quality wind regions, for example, class 6 and 7, is critical. For near-term analysis high-resolution regional modeling with its more accurate estimate of higher speed wind areas, is likely necessary.

Even using higher resolution data, however, there is relatively little class 6 and 7 wind, as compared to lower wind speed classes in example regions (SI Figure 3). If wind is to play a large role, lower quality wind resources would need to be used, and a bias against the highest speed winds can be less important. Even for longer-term analysis, however, the global reanalysis data set used here appears to underestimate winds at class 5 and higher. So while the present study can provide an indication of resources in different world regions, further refinement will be necessary. Improved reanalysis data sets that realistically capture winds up to around 8 m/s (the upper limit of class 5 winds) may be sufficient for long-term analysis. Additional details for the estimate of wind resource in each wind class and by country are provided in SI Text 2.

3.2. Sensitivity Analysis. A sensitivity analysis was performed for eight key variables that were determined to have the largest impact on wind potential, as shown in Table 1. A literature review was conducted on each of these parameters in order to select high and low bounds (see SI Text 1 for a full discussion).

Table 1. Variation of the Input Parameters Used in the Sensitivity Analysis

parameter	units	pessimistic	central	optimistic
wind speed	ms⁻¹	0.9 * central case	NCEP/CFSR	1.3 * central case
suitability	/	low in SI Table 3	central in SI Table 3	high in SI Table 3
roughness length	meter	0.5 * central case	NCEP/CFSR	2 * central case
density	MW km⁻²	2	5	9
turbine cost	$/kWh	2400	1800	1200
unit transmission cost	$/ MW·km	1491	745	373
turbine height	meter	60	80	100
fixed charge rate	/	0.156	0.13	0.104

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It is important to note that all of the results in this sensitivity analysis follow directly from the assumed sensitivity ranges. This is particularly important when drawing conclusions about which uncertainties may be more or less important than others. For this study, we have used an implicit approach to include probabilistic information by reviewing the literature to develop estimates of high, central, and low values that were judged by the authors to be roughly consistent in terms of their probability range. These choices are, however, subjective and the results should be interpreted with this mind.

We first examine how changes in parameters impact wind potential, examining the potential below 9 cents/kWh as one measure of potentially usable wind, particularly over a longer-term time horizon. We will also discuss, later in this section, the impact of sensitivity tests on the amount of lower cost wind.

Based on the sensitivity ranges specified in Table 1, wind speed, roughness length, turbine cost, and FCR have the largest impact on wind potential, affecting the available wind energy below 9 cents/kWh by up to 450% (Figure 4). The importance
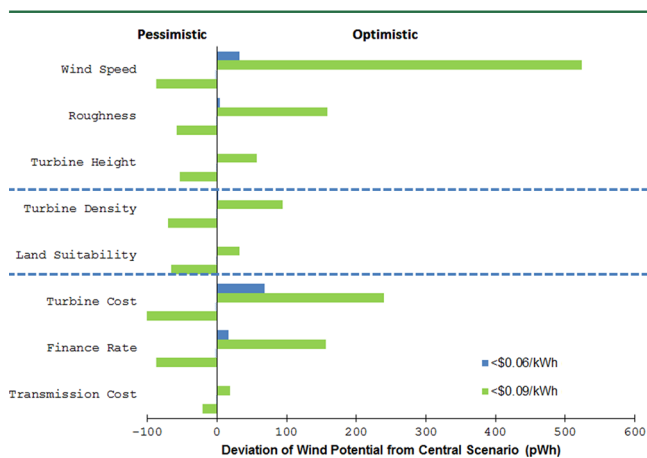

Figure 4. Sensitivity of wind energy potential to eight parameters. Total wind energy potential is 2.1 pWh (0.2 TW) and 117.4 pWh (13.4 TW) below costs of 6 and 9 cents/kWh, respectively in central scenario.

of wind speed is straightforward; if wind speeds are higher, then more wind is available at a given cost point. This speaks to the importance of having a strong understanding of the biases present in existing wind speed data sets. We find, as have previous studies,[4] that the available global wind data are not able to resolve high wind areas, resulting in a likely underestimate, in most regions, of the amount of low-cost wind resources. The amount of this bias appears to differ by region.

The roughness length parameter is, in effect, also an uncertainty in wind speed. As evaluated here, this represents the uncertain extrapolation in the vertical dimension of a presumed known wind speed at a reference height. Wind speed estimation will also depend on the characteristics of nearby terrain, land-surface types, atmospheric stability conditions, wind patterns at higher altitude (e.g., jets) and diurnal differences in wind characteristics. This illustrative sensitivity result indicates the importance of the development of more consistent wind speed estimation methods, preferably providing wind speed over a range of hub heights in order to minimize the need for height extrapolation. This uncertainty is, in large part, due to the complexity of modeling the planetary boundary layer.[39]

The impact of the assumed turbine cost and financing assumptions (e.g., FCR) can be substantial, directly shifting all costs up or down. It is notable that the magnitude of both of these parameters is similar to the impact of wind speed assumptions. This emphasizes that the ultimately realizable wind potential has both economic and physical components.

The next tier of parameters are the assumed land suitability, turbine density, and turbine height, all of which have a smaller impact, but still potentially altering wind potential by up to 50—80%. Increasing turbine height will, in general, increase the wind speed, which increases output and decreases costs. The actual impact of a change in turbine height will depend also on the vertical wind profile, parametrized here as surface roughness, and local wind speed.

The assumptions for land suitability impact wind potential over a large scale. Suitability assumptions alter wind potential globally by about 25% more and 55% less, at 9 cents/kWh, for the optimistic and pessimistic cases (Figure 4). The pessimistic land suitability case has a larger impact on wind potential than the optimistic sensitivity case, particularly at the low cost range (Figure 2). The impact of suitability assumptions varies regionally because of differences in wind potential by land cover classification (SI Table 4, SI Figure 6, SI Figure 7, and SI Text 3). Suitability as a function of land type is certainy an oversimplification. While barren lands, for example, might be suitable in general, barren lands with frequent dust storms might prove to be less than ideal.

Turbine density addresses a similar uncertainty as land suitability: the portion of a given area that can realistically be devoted to wind turbines. We note that the optimistic result for turbine density sensitivity is likely a slight overestimate, since increasing turbine density will result in increased losses due to wind "shading" between turbines and this was not taken into account. The ideal turbine density will depend on detailed topography and logistical issues. In terrain that is not flat, turbines will generally be placed at the higher points, so turbine density will depend on fine-scale topographical features (also referred to as micrositing[39]). In flat terrain, turbines can be spaced more closely, but at a trade-off of slightly higher losses. Logistical issues may also influence turbine spacing: if land is expensive or access road construction difficult, a closer spacing might be advantageous. Given the impact of turbine density assumptions on wind resources further study of the factors that influence turbine density in practice seems warranted.

Transmission cost has a relatively small impact on total wind costs, changing the wind potential at a given cost by about 20%. Amortized over the energy produced over a turbine's lifetime, transmission costs are a relatively small portion of total cost and, therefore, have a relatively small effect. This does not mean, however, that transmission is not an important issue. It may not be possible to site a transmission line through particular areas, in which case either the transmission distance may need to be substantially increased, or certain areas may be effectively inaccessible. When very high transmission costs, for example, 10 times the unit transmission cost used in the central case ($745/MW·km) are considered, the available wind energy potential at reasonable costs (9 cents/kWh) is reduced substantially. In this sensitivity example, wind energy potential is reduced to 80%, 50%, 30% and 30% of the central value for the U.S., Canada, Russia, and China, respectively. This indicates that limits on transmission line construction beyond the explicit costs of infrastructure can have a significant impact on wind resources, particularly in regions such as Canada, Russia, and

China, where much of the wind resource is located far from the current transmission grid.

While the wind potential below 9 cents/kWh is an indicator of the potential long-term role of wind, the amount of lower cost wind is also of importance since low cost wind resources will generally be the first used. Also, if electricity costs do not increase beyond current levels, or new renewable incentives or carbon prices are not put in place, low cost wind resources could be the only resources used. In our central case, there is only a small amount (2.1 pWh) of wind available at less than 6 cents/kWh. A smaller set of variables impact the amount of low cost wind, namely wind speed and turbine cost assumptions, but also, at a lesser level, surface roughness and financing assumptions (FCR). Improved global wind data sets are needed to more accurately quantify the areas of low cost wind. Likewise, a drop in turbine costs[37] at some point in the future would also result in an increase in low cost wind energy.

3.3. Comparison to Other Results. In order to put the results from this work into context, we first, examined the impact of using different wind speed input data sets. We also compare the aggregate results of this study at the global level to other global estimates (SI Text 4).

As implied by the comparison of wind power class among these data sets (SI Figure 8), the CFSR wind speed data generally achieves a more accurate estimate of wind potential than the CRU wind speed data. Comparing results using CFSR data to higher resolution regional wind estimates, we find that wind potential in this study appears to be underestimated in three of the cases where detailed data were available (U.S., China, Pakistan/Afghanistan) and was similar in one additional region (Mongolia). The amount of bias varies across regions and cost levels. We note that the station-based CRU data results in a cost curve for the U.S. that appears to be a significant overestimate, while the wind potential using the CRU data is underestimated in other three subregions (China, Pakistan/Afghanistan, and Mongolia).

We also compared the results of this study to other global wind potential estimates[3,4] (SI Figure 9). The two studies most similar to the present work are Hoogwijk et al.[3] and Lu et al.[4] The values from Hoogwijk et al.[3] are generally lower than those from both the current study and the values from Lu et al.[4] One reason for this is the lower wind speed values for many regions in the CRU data. As noted by Hoogwijk et al.,[3] the CRU wind speed is lower than that from other sources, particularly in regions such as India. The CRU wind speed data was interpolated from station data.[40] The underestimation of wind speed in this data set is likely due to averaging over large areas, which misses high-speed wind especially in areas with limited stations such as India and China. The second reason is that the assumed energy production per turbine is lower in Hoogwijk et al.[3]

Our estimate of wind energy potential is lower overall than that of Lu et al.,[4] who used GEOS assimilation data. A primary reason for this difference is a lower assumed turbine density in the present work. If the Lu et al.[4] estimate is scaled by $5/8$ to account for the different turbine density assumptions, the global technical potential is similar to that from this paper, although some regional differences remain (SI Figure 9).

One factor not considered in the current work is that the large-scale deployment of wind turbines will impact wind fields, reducing the amount of wind energy available elsewhere. Miller et al.[41] estimated that the maximum amount of energy that can be extracted from global land surface wind is 18−68 TW, using

a top-down thermodynamic Earth system perspective. This compares to our central estimate of 13.6 TW at <9 cents/kWh, which indicates that our estimate, at least on the gross level, does not appear to violate fundamental physical limits.

3.4. Discussion. Global onshore wind energy potential at costs below 9 cents/kW is 119.5 pWh per year (13.6 TW) from this study (Figure 2), an amount sufficient to supply a significant portion of world energy needs (Figure 3). At the broadest level, the analysis here finds substantial regional variation in wind potential, and also confirms that a range of assumptions influence the potential supply of wind. Although improved wind speed information will certainly help to refine our understanding of wind supplies and therefore the role of wind in moving to a low-carbon future, a range of other uncertainties are of equal importance.

Because the available global wind data are not able to resolve high wind areas, this results in a likely underestimate, in most regions, of the amount of low-cost wind resources. Higher-resolution regional analysis will be needed to capture high wind areas that are preferred sites in the near-term, although modest improvements in current reanalysis data sets might be sufficient for long-term analysis needs.

The fraction of the landscape that could potentially be used to site wind farms, that is, land suitability assumptions, can also have a large impact on estimated wind potential. A closely related parameter is the assumed turbine density within a wind farm. Further analysis of the underlying characteristics that impact these parameters so that quantitative analysis can move beyond applying values to broad land-classifications would greatly improve wind resource estimates.

While the cost of connecting wind resources to the existing transmission grid does not have a large impact on wind resource estimates, this does not mean that transmission is not a critical element of wind deployment. At higher wind potential, the existing grid may need to be reinforced, which was not considered here. A sensitivity test with very high transmission costs indicates that such limitations can have a substantial impact on wind resources in some regions. As with land suitability, the factors that might or might not limit the transmission expansion needed to use dispersed wind resources, need to be further quantified, and likely cannot be expressed in cost terms alone.

These results also have substantial policy implications because many of the factors that impact the economic potential of wind generation are influenced by policy choices. Policies to lower the cost of renewable generation through changes in financing and accounting rules or feed-in tariffs are well-known. As discussed in SI Text 1, to the extent these are subsidies, then this does not lower the social cost of wind, but shifts the cost from the private to the public sector. Land-use policies, however, will also influence wind potential. Toke et al.,[42] for example, have found that, in addition to financial support, planning systems, the strength of landscape protection organizations, and local ownership patterns also influence wind deployment outcomes.

Only generalized assumptions could be made here for turbine density and land suitability. Given that local institutions appear to be critical to the acceptance, or not, of wind farms,[42,43] more realistic estimates of wind potential will require research that links these local and institutional factors to the physical use of land[44] through to the type of larger-scale metrics used here. Finally, an inability to site transmission lines will have a large impact on wind resources in some regions, and an

improved understanding of the factors that influence transmission siting will also be needed. In closing, we suggest that further research intended to inform wind supply curve development focus not purely on better physical science,[39] such as better resolved wind maps, but also on these less well-defined factors such as land-suitability that will have an impact on the long-term role of wind power.

■ ASSOCIATED CONTENT

ⓢ Supporting Information

Detailed elaboration of the data sets, wind energy potential calculations and sensitivity analysis employed in this study. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

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