Energy Policy 91 (2016) 75–86

Contents lists available at ScienceDirect

Energy Policy

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

Global assessment of onshore wind power resources considering the distance to urban areas ☆

Diego Silva Herran [a,b,*], Hancheng Dai [b], Shinichiro Fujimori [b], Toshihiko Masui [b]

[a] Project Team for Risk Information on Climate Change, Japan Agency for Marine-Earth Science and Technology, 3173-25 Showa-machi, Kanazawa-ku, Yokohama 236-0001, Japan
[b] Center for Social & Environmental Systems Research, National Institute for Environmental Studies, 16-2 Onogawa, Tsukuba-City, Ibaraki 305-8506, Japan

HIGHLIGHTS

- Global onshore wind resources were assessed including the distance to urban areas.
- We evaluate the impact of transmission losses and cost, and visibility restrictions.
- The distance to urban areas' impact was considerable, depending on the supply cost.
- This factor's importance was secondary to economic, land use, and technical factors.
- Neglecting this factor resulted in an overestimation of global wind resources.

ARTICLE INFO

Article history:
Received 23 July 2015
Received in revised form
3 December 2015
Accepted 21 December 2015
Available online 11 January 2016

Keywords:
Onshore wind power
Global resource assessment
Distance to urban areas

ABSTRACT

This study assessed global onshore wind power resources considering the distance to urban areas in terms of transmission losses and costs, and visibility (landscape impact) restrictions. Including this factor decreased the economic potential considerably depending on the level of supply cost considered (at least 37% and 16% for an economic potential below 10 and 14 US cents/kWh, respectively). Its importance compared to other factors was secondary below 15 US cents/kWh. At higher costs it was secondary only to land use, and was more important than economic and technical factors. The impact of this factor was mixed across all regions of the world, given the heterogeneity of wind resources in remote and proximal areas. Regions where available resources decreased the most included the European Union, Japan, Southeast Asia, the Middle East, and Africa. The supply cost chosen to evaluate the economic potential and uncertainties influencing the estimation of distance to the closest urban area are critical for the assessment. Neglecting the restrictions associated with integration into energy systems and social acceptability resulted in an overestimation of global onshore wind resources. These outcomes are fundamental for global climate policies because they help to clarify the limits of wind energy resource availability.

1. Introduction

Wind energy is considered a major alternative energy supply among the renewable energy technologies, and its use will avoid greenhouse gas (GHG) emissions, diversify energy sources, and reduce the dependence on foreign energy supplies. Wind power generation has experienced considerable growth in recent decades compared to other renewable energy technologies. The global wind power supply increased from 4 to over 400 TWh/yr between 1990 and 2011, with an average growth in annual capacity of around 25%. The outlook for wind power penetration suggests that its share of the total global power supply will increase from 2% to 6–13% (International Energy Agency, 2013c). With this rapid expansion, some issues constraining the practical utilization of wind resources that were absent or not apparent in the past are attracting the attention of policymakers and research communities (EWEA, 2009; GEA, 2012; International Energy Agency, 2013a; Wiser et al., 2011). Examples of such restrictions include the

☆ The English in this document has been checked by at least two professional editors, both native speakers of English. For a certificate, please see: ⟨http://www.textcheck.com/certificate/mCQyBx⟩.

* Corresponding author at: Project Team for Risk Information on Climate Change, Japan Agency for Marine-Earth Science and Technology, 3173-25 Showa-machi, Kanazawa-ku, Yokohama 236-0001, Japan.
E-mail addresses: silva.diego@jamstec.go.jp (D. Silva Herran), dai.hancheng@nies.go.jp (H. Dai), fujimori.shinichiro@nies.go.jp (S. Fujimori), masui@nies.go.jp (T. Masui).

http://dx.doi.org/10.1016/j.enpol.2015.12.024
0301-4215/

capability of power systems to integrate large amounts of electricity that are geographically dispersed and variable within short time frames, acceptability by local communities, the impact on natural environments, and the impact on birds and bats.

Some of these issues are linked to the distance of the wind power supply to urban areas. On the one hand, wind resources far from the main demand centers prevent their integration into existing power systems,[1] in particular, due to the added cost of extending transmission lines (Hoppock and Patiño-Echeverri, 2010). On the other hand, the proximity to populated areas impacts the health of local residents (due to noise and visual annoyance) and landscape values, resulting in opposition to (or low acceptability of) the construction of wind farms (Cohen et al., 2014). These issues may hamper the actual potential for wind power penetration in the future. The implications of the location of wind energy resources with respect to population have been overlooked in global assessments. Although the remoteness of high-quality wind resources and the proximity of wind turbines to populated areas are broadly acknowledged (EWEA, 2009; GEA, 2012; International Energy Agency, 2008; Wiser et al., 2011), their impact on wind resource availability is largely absent from global assessments.[2] Past assessments have focused on physical, geographical, and technical restrictions in the harnessing of wind power (Archer and Jacobson, 2005; de Vries et al., 2007; Grubb and Meyer, 1993; Hoogwijk et al., 2004; Lu et al., 2009; Sorensen and Meibom, 2000; Zhou et al., 2012). In general, they suggest that available wind resources considerably exceed current and future energy consumption, with a wide range of estimates depending on the assumptions made regarding the techno-economic performance of wind farms and land use restrictions, notwithstanding the low spatial resolution of wind speed datasets available at the global scale. Early studies by Grubb and Meyer (1993) and Sorensen and Meibom (2000) used gridded data under a geographic information system (GIS) approach to assess the availability of global resources. Hoogwijk et al. (2004) used a similar approach to evaluate the sensitivity of global energy potential to several parameters related to land use suitability, capacity density and efficiency of wind farms, and cost factors. An extension of this assessment considered several scenarios for the competition of land among wind, solar, and biomass energy supply (de Vries et al., 2007). Using a similar approach, Zhou et al. (2012) provided an updated estimation using more recent wind speed data, introducing transmission costs, and evaluating the variability of the economic potential for three cases. Some studies have focused on accurate estimations of wind speed and power output from wind turbines, and have summarized the availability of wind resources only in terms of technical energy potential, without indicating any economic valuation (Archer and Jacobson, 2005; Lu et al., 2009).

We introduced the distance to urban areas as a new factor in the estimation of the global energy potential of onshore wind energy, and evaluated its importance compared to the other factors in the assessment. A model based on gridded data was used to estimate the global energy potential of onshore wind. The distance to urban areas was used to explicitly introduce power losses and the additional investment costs from electricity transmission, and visibility restrictions in the proximity of urban areas, which represented concerns with respect to negative impacts on the landscape. The impact of including (or neglecting) this factor in the assessment of energy potential was evaluated. A sensitivity analysis was conducted to evaluate the importance of parameters related to the distance to urban areas, with respect to other parameters used in the assessment related to land use, technical, and economic factors. This study extends the scope of previous global wind resource assessments to factors related to the integration of wind power into energy systems, and its social acceptability.

We considered how decision makers and technological developments affect the range of available wind energy resources. More specifically, we assessed these issues with regard to the spatial distribution of wind resources in relation to urban areas. Given that cities are assumed to be the main centers of energy demand and supply of technology, the distance between cities and wind resources can be used to assess how distance and location affects the feasibility of wind power. The distance between potential wind farm sites and urban areas is a matter of concern in studies at the local, regional, and national scale (i.e., a site-specific issue). We highlighted the need for approaching spatial aspects in global studies, at least in an approximate way, when considering a more comprehensive assessment of global wind resources. The remainder of this paper is organized as follows. Section 2 describes the model used for estimating the global energy potential of onshore wind, the main assumptions, and the analytical procedure. Section 3 presents the outcomes from the model with respect to parameters related to the distance to urban areas, and the outcomes of the sensitivity analysis. Section 4 discusses the implications of the study, the uncertainties in the assessment with respect to the quantification of the distance to urban areas and other factors in the assessment. The final section presents the conclusions of the study.

2. Methods

2.1. Outline of the methodology

We assessed global onshore wind resources using a model that estimates the global technical and economic potential of onshore wind energy from large-scale turbines. The distance to urban areas was incorporated into the assessment the power losses and investment costs from electricity transmission, as was the constraint of the visibility of large-scale wind power plants from urban areas. In addition, a sensitivity analysis was conducted by considering low, medium, and high values of several parameters regarding land use and technical and economic factors of the assessment (see Fig. 1).

2.2. Wind resource model

The Renewable Energy Potential Model (REPM) was used to estimate the technical energy potential, the economic energy potential, and the corresponding cost-supply curves of onshore wind using large-scale turbines. The model combines several gridded data and parameters under a geographic information system (GIS) framework (Ikegami, 2009; Silva, 2012). Outputs for energy potential, capacity, total supply cost, and unit supply cost were calculated for grid cells of 0.5 arc-min, and aggregated into 17 world regions. The main inputs to the model include monthly averages of wind speed (Surface meteorology and Solar Energy (SSE), 2005), elevation (Hastings and Dunbar, 1999), slope (Ikegami, 2009), land cover (U.S. Geological Survey (USGS), 2005), protected areas (IUCN and UNEP, 2010), and parameters related to wind turbine

[1] These issues refer mainly to the difficulty for existing electricity supply systems to incorporate large amounts of wind power due to geographic dispersion, and the hourly and daily variability of power output (which results in an unpredictable supply). Technical constraints and costs related to the provision of a variable energy supply depend on the characteristics of the power supply system (availability of a flexible power supply, load duration curves, etc.), and not only on the characteristics of the resource. Therefore, this aspect of wind power integration (providing a variable energy supply) is excluded from this study.

[2] Zhou et al. considered transmission costs in a global assessment of onshore wind resource but did not provide an explicit analysis of the implications of introducing this factor into the estimation.

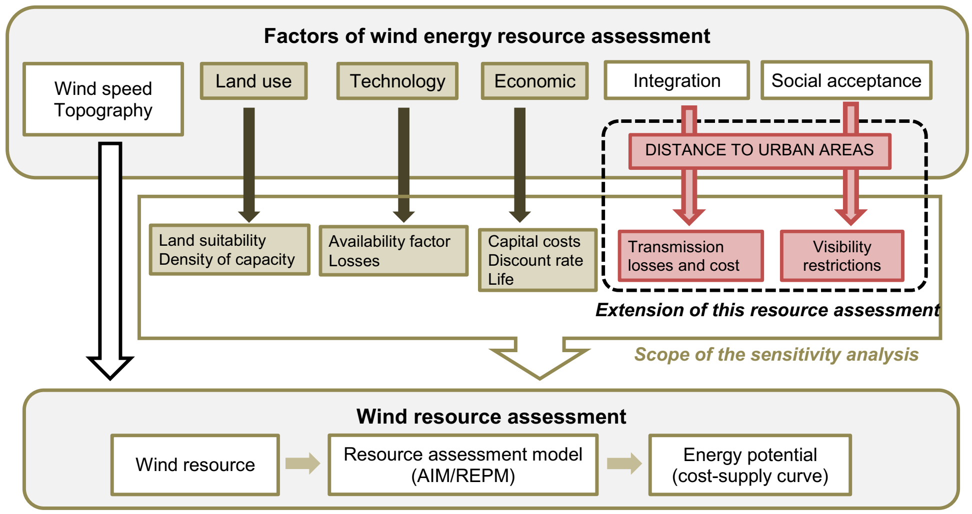

Fig. 1. Scope of the wind resource assessment. Shaded boxes indicate the factors and related parameters included in the scope of the sensitivity analysis. Red boxes indicate new factors included in the assessment. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

technology performance and cost.

The technical energy potential is defined as the amount of electricity that can be potentially generated from wind turbines (grouped in wind farms) after accounting for restrictions and losses in power output due to geographic and technological factors. Geographic restrictions include a maximum elevation (2000 m) and slope of terrain (20%) above which installing turbines is not technically feasible, and areas that are excluded from the development of wind power due to the land cover type (land covered permanently by water or ice, urban land) or the designation of protected area status. The technical energy potential for each grid cell was calculated using the following equation:

$$Q_{Tech} = A_G\,{}^{*}r_{LC}\,{}^{*}\rho_{Capac}\,{}^{*}T_{FullLoad}\,{}^{*}f\,{}^{*}\eta\,{}^{*}\alpha_{Correct}\,{}^{*}(1{-}L_{Tr}/100)\,{}^{*}D_{Urb}$$

where Q_{Tech}=Technical energy potential (MWh/yr); A_G=Grid cell area (m^2); r_{LC}=Land suitability factor for a given land cover type (–); ρ_{Capac}=Density of wind turbine capacity (MW/m^2); $T_{FullLoad}$=Equivalent operating hours of wind turbine at full load capacity (h/yr); f=Availability factor of wind turbine (–); η=Efficiency of wind turbine array (wind farm) (–); $\alpha_{Correct}$=Power correction factor (–); L_{Tr}=Losses due transmission (%/km); D_{Urb}=Distance to closest urban area (km).

The economic potential is defined as the technical potential after considering the economic performance of wind power (i.e., turbine, operating, and other costs), and is usually expressed as the amount of energy output available at a cost per power output (referred to as unit supply cost) lower than a given threshold value. Average electricity prices are commonly used as the reference threshold value. In this study, the global economic potential corresponds to the sum of the technical potential of grid cells with unit supply costs below a given cost threshold. The unit supply costs for each grid cell were calculated as follows:

$$Uc = [(C_{Turb} + C_{OM})\,{}^{*}CRF_{Turb} + (C_{Tr}\,{}^{*}CRF_{Tr}\,{}^{*}D_{Urb})]\,{}^{*}P/Q_{Tech}$$

where Uc=Unit supply cost at grid cell (USD/MWh); C_{Turb}=Investment cost of wind turbine (USD/MW); C_{OM}=Operation and maintenance cost (USD/MW); CRF_{Turb}=Capital recovery factor for annualizing the investment cost of a wind turbine (yr^{-1}); P=Capacity (MW); C_{Tr}=Investment cost of transmission lines (USD/MW/km); CRF_{Tr}=Capital recovery factor for annualizing the investment cost of transmission lines (yr^{-1}).

The model assumes that electricity is generated with large-scale wind turbines that were evenly distributed within grid cells. These turbines correspond to a rated capacity of 2 MW, operating at wind speeds between 3 and 25 m/s, and with maximum power output at 12 m/s wind speed (Vestas, 2013). Full load hours are the hours within a year that the turbine operates at full (i.e., rated) capacity. This parameter is calculated based on the frequency of wind speeds and their corresponding power output. The wind speeds used correspond to monthly averages at 50 m from ground (Atmospheric Science Data Center, 2005), and are corrected to hub height (80 m) with a shear exponential formula. This wind speed is used to evaluate the frequency of wind speed from a Rayleigh distribution function for intervals of 1 m/s within the range of turbine operation (3–25 m/s). The power output for each wind speed evaluated was obtained from the power curve defined for the turbine (Vestas, 2013). The values of the main parameters used in the assessment are listed in Table 1.

The land suitability factor is the fraction of the total area available that is suitable for installing wind turbines for a given type of land cover (Table 2). It represents restrictions due to competition with other land uses, technical constraints, environmental regulations, and the degree of acceptability by local residents and decision makers. Given that this factor is highly dependent on local conditions and subjective values toward wind power developments, its definition in global studies is rather arbitrary. Therefore, values were set to maintain consistency with those used in previous global assessments. This parameter is considered highly uncertain, and has a large impact on the estimated wind energy potential (Hoogwijk et al., 2004; Zhou et al., 2012).

2.3. Distance to urban areas

The sensitivity of the global wind energy resource potential with respect to the distance to urban areas was evaluated with respect to transmission losses, transmission investment costs, and visibility constraints. The distance to urban areas was used as a proxy to estimate the distance required to install additional transmission capacity, and the threshold distance from residential areas to account for the restricted installation of wind farms due to landscape impact concerns. The distance to urban areas represents the shortest path to the closest urban area based on gridded "cost-distance." The shortest path assumes movement between the center points of cells across a gridded surface accounting for obstacles appearing along the direction of movement (Silva et al., Forthcoming).

Table 1
Values assumed for the sensitivity parameters.

Factor	Parameter	Units	Value			Remarks
			High[a]	Med	Low[b]	
Land use	Land suitability factor	[%]	10–70	50–60	10–30	See Table 2
	Density of capacity	[MW/km^2]	9	5	2	(Zhou et al., 2012)
Technical	Array efficiency	[%]	90	80	70	High value same to Zhou et al. (2012)
	Availability factor	[%]	97	90	80	High value same to Zhou et al. (2012)
Economic	Capital cost	[USD/kW]	1200	1800	2400	(International Energy Agency, 2012a), low and high values from Zhou et al. (2012)
	Discount rate	[%]	5	10	12.5	Low and mid values from range assumed in Bruckner et al. (2011), high value from International Energy Agency (2012a)
	Life	[yr]	30	25	20	Low value from Bruckner et al. (2011), high value from Zhou et al. (2012)

[a] Values in “High level” represent optimistic assumptions on the resulting wind energy potential (i.e. a parameter set to High-level value assumption results in higher energy potential compared to the Medium level).
[b] Values in “Low level” represent pessimistic assumptions on the resulting wind energy potential (i.e. a parameter set to Low-level value assumption results in lower energy potential compared to the Medium level).

Table 2
Values assumed for land suitability factors.

Land cover type[a]	Land suitability factor [%]		
	High[b]	Med[c]	Low[c]
All forests, closed shrublands, woody savannas	10	0	0
Open shrublands, savannas, grasslands	70	50	20
Croplands, cropland/natural vegetation mosaic	70	60	30
Barren or sparsely vegetated	70	50	10
Permanent wetlands, urban and built-up, snow and ice, water bodies	0	0	0

[a] Land cover categories and definitions from IGBP land cover dataset (U.S. Geological Survey (USGS), 2005).
[b] Defined taking as guideline the range of intermediate and extreme values in other studies.
[c] Based on the low value in de Vries et al. (2007).

2.3.1. Transmission losses and costs

Transmission losses indicate the loss in electricity output along transmission infrastructure (lines and substations) between a wind power plant and the closest urban area. Values were expressed as an average per length and the capacity of the transmission line, which corresponded to the range reported in the literature for high-voltage alternate current (HVAC) and high-voltage direct current (HVDC) power transmission. HVAC is the conventional option for power transmission, while HVDC is a more recent technology that is gaining importance due to its higher technical performance in long-distance projects, despite comparatively higher costs (Delucchi and Jacobson, 2011). Transmission costs indicate the investment cost per length and capacity of the transmission infrastructure, and were adopted from a previous study that evaluated this factor when considering the global potential of wind energy (Zhou et al., 2012). These values represent the construction and connection costs of transmission lines, towers, and substations reported for wind farm projects.

2.3.2. Visibility restrictions

Wind power installations may not be feasible in locations where the turbines are clearly visible from nearby households, because they generate a considerable impact on the landscape that is unacceptable for local residents. This restriction has often been reported as an obstacle for the development of wind farms and some countries have defined guidelines for wind power projects taking into account landscape impacts (Wiser et al., 2011). To consider this restriction in the assessment, areas deemed suitable for installing wind turbines were restricted to locations within a threshold distance from the closest urban area. For locations within/beyond these distances a total rejection/acceptance of wind farms was assumed. We adopted a rather moderate stance to set these threshold distances (10, 20, and 30 km) based on recommendations made in a report surveying the visibility of wind farms in a state in the USA (Sullivan et al., 2012). Although this report clearly states that their findings were far from being a final guideline for visibility impact assessments, the survey is comprehensive enough to provide ranges of visibility distances based on observations of multiple wind farm sites under a variety of weather conditions, times of the day, and seasons. Thus, we adopted distance thresholds that were shorter than those suggested by the report to conduct visibility impact assessments (16–48 km).

2.4. Procedure of the assessment

Three levels were considered for assessing onshore wind resources: parameters included in the estimation, the assumed value of each parameter (i.e., leading to high, medium, or low values of the economic potential), and the unit supply cost used to evaluate the economic potential. A summary of the cases analyzed is presented in Table 4. The parameters corresponding to each aspect and their values are listed in Tables 1 and 3.

First, the effect of including (or neglecting) parameters related to the distance to urban areas (transmission losses and costs, and visibility restriction) on the economic potential of onshore wind was assessed. Three cases were considered by assuming values that resulted in low, medium, and high levels of the economic potential. For example, high values of the efficiency parameters led to a “high” economic potential, while high values assumed for the cost parameters resulted in a “low” economic potential. The estimated potential was compared to the case neglecting these factors. Values corresponding to a medium level were assumed for all other parameters.

In the second stage of the assessment, the importance of the distance to urban areas was evaluated by a sensitivity analysis of several factors used in the global assessment of wind resources. Three factors were compared: land use, technical, and economic factors. Each of these described the uncertainty in the wind energy potential from contrasting points of view. Other aspects, such as uncertainty in wind speeds, topographic conditions, wind turbine height, balancing of the variable power supply from wind farms, and environmental impacts were excluded from the analysis. The factors included in this study were selected so that they could be directly linked to decision makers and wind energy policies. In addition, the method allowed for a straightforward evaluation of these factors.

The analysis focused on the economic potential below 10 and 14 US cents/kWh. These threshold values were chosen to reflect

Table 3
Values assumed for parameters related to the distance to urban areas.

Parameter	Units	Value			Remarks
		High[a]	Med	Low[b]	
Transmission investment cost	[USD/kW/km]	0.373	0.745	1.491	(Zhou et al., 2012)
Transmission losses	[%/km]	0.005	0.010	0.015	Low based on WinDS model assumption (NREL/US Department of Energy, 2008); high based on a range of values suggested by Delucchi and Jacobson (2011); medium represents losses in present networks (mainly HVAC transmission line).
Visibility	[km]	10	20	30	Distance from the closest urban area; values based on Sullivan et al. (2012).

[a] Values in "High level" represent optimistic assumptions on the resulting wind energy potential (i.e. a parameter set to High-level value assumption results in higher energy potential compared to the Medium level).
[b] Values in "Low level" represent pessimistic assumptions on the resulting wind energy potential (i.e. a parameter set to Low-level value assumption results in lower energy potential compared to the Medium level).

those used in the literature to identify the economic potential of wind power resources, and to consider differences among regions as well as possible changes in future electricity prices. For example, wholesale electricity prices (those paid to electricity generators) are expected to rise by 15% on average by the year 2030 according to the International Energy Agency World Energy Outlook (IEA WEO), due to higher fuel and material costs, as well as the implementation of carbon taxes and renewable energy subsidies (International Energy Agency, 2012b). In particular, carbon taxes may increase average electricity prices in the long term under stringent climate targets (Clarke et al., 2014).

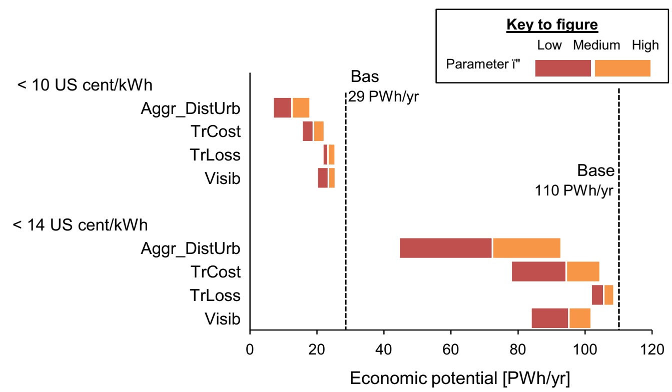

Fig. 2. Global onshore wind economic potential below 10 US cents/kWh (upper panel) and below 14 US cents/kWh (lower panel) for the reference case (dotted lines) and cases considering the distance to urban areas. Orange and red bars indicate the outcomes for assumptions corresponding to high and low values of each parameter, respectively. The white line between the bars indicates the outcomes for medium values. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3. Results

3.1. *Impact of the distance to urban areas on global wind resources*

3.1.1. *Global outcomes*

Onshore wind resources evaluated at supply costs below 10 and 14 US cents/kWh are presented in Fig. 2. The outcomes for the reference case (Base) are indicated by dotted lines, and the ranges of results introducing parameters related to the distance to urban areas are indicated by colored bars. In the reference case, which neglects whether resources are far from or close to urban areas, the total wind resources were 29 and 110 PWh/yr for unit costs below 10 and 14 US cents/kWh, respectively. Introducing the distance to urban areas reduced the economic potential by an amount ranging from small to considerable. This impact was larger at lower unit supply costs. The separate parameters related to the distance to urban areas reduced the economic potential by up to 45% and 29% for each cost threshold, respectively. Transmission investment costs had the strongest impact, followed by visibility constraints. Including all of the factors reduced the economic potential below 10 US cents/kWh by at least 37% and below 14 US cents/kWh by 16%.

The economic potential in a wider range of unit supply costs is presented in Fig. 3. The impact of the distance to urban areas was largest at around 10 US cents/kWh. At higher supply costs, the impact gradually diminished. Unlike the other parameters, the highest impact due to visibility restrictions was observed at around 7 US cents/kWh. The impact of transmission investment costs was most relevant between 8 and 15 US cents/kWh, while visibility was the most relevant parameter outside this cost range. Thus, for this cost range only, the remoteness of wind power sites (i.e., transmission investment costs) was more relevant than proximity to urban areas. The share of transmission costs among the total costs, shown in Fig. 4, ranged from 4% to 7% (equivalent to 0.1–1.2 US cents/kWh) using medium values for the parameters related to distance to urban areas, while it reached 14% when using low values. Transmission losses and cost affected the profitability of global wind resources in a nonlinear fashion. This is a result of the spatial distribution of wind resources with respect to urban areas. As reported by Silva et al. (Forthcoming), the

Table 4
Cases considered in the assessment of global onshore wind resources.

Case name	Explanation
Base	Reference case neglecting the distance to urban areas (i.e. neglecting transmission investment cost and losses, visibility restriction); all parameters set to medium (M) values (see Table 1).
Aggr_DistUrb (H/M/L)	Base case including high (H)/medium (M)/low (L) values for parameters related to the distance to urban areas (transmission investment cost, transmission losses, visibility restriction).
TrCost (H/M/L)	Base case including high (H)/medium (M)/low (L) values for transmission investment cost.
TrLoss (H/M/L)	Base case including high (H)/medium (M)/low (L) values for transmission losses.
Visib (H/M/L)	Base case including high (H)/medium (M)/low (L) values for visibility restrictions.
Parameter (H/L)	Base case using high (H)/low (L) values of the target parameter (e.g. land suitability factor, availability factor, capital cost, etc.).

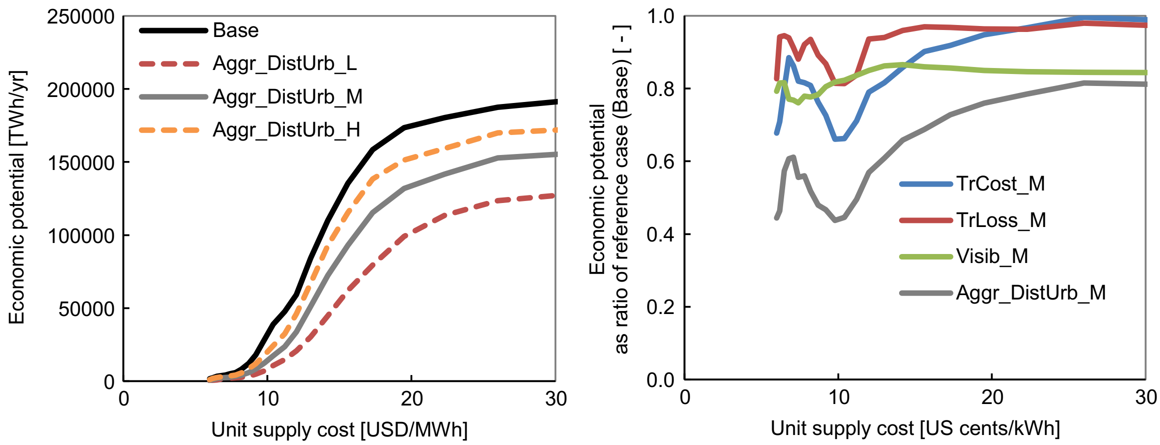

Fig. 3. Cost-supply curve of the global wind economic potential with and without considering the distance to urban areas. Absolute values (left panel) and the proportion of the reference potential (Base) (right panel).

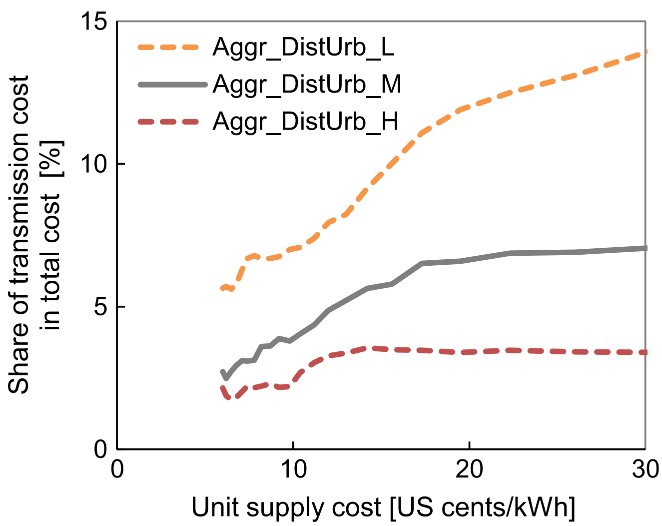

Fig. 4. Share of transmission costs in the total supply cost of global onshore wind resources for three levels of assumptions in parameters related to the distance to urban areas.

proximity of wind resources to urban areas follows a distribution that is skewed toward short distances.

3.1.2. Regional outcomes

Introducing distance to urban areas had a mixed impact across all regions of the world (see Table A1 in the appendix for the definition of regions). As indicated in Fig. 5, relative to the reference case (Base) the economic potential below 10 US cents/kWh was lowest in the EU (23% for medium values), Japan (5%), Southeast Asia (5%), Middle East (29%), North Africa (3%), and the rest of Africa (23%). In absolute terms (see Table A2 in the appendix), half of the global reduction was concentrated in Africa (24% of the total global reduction), former Soviet Union (14%), and EU (14%). Large reductions were also observed in North America (7%), Middle East (7%), and China (7%). Comparing the impact among distance-related parameters revealed the imbalance between wind resources located remote from and in proximity to urban areas in each region. For wind resources below 10 US cents/kWh, regions where resources decreased mainly due to transmission losses and costs, such as Oceania, Africa, and Canada, had a relatively high share of their wind resources far from urban areas. In contrast, regions where the impact of visibility was larger, such as India, Europe, Japan, and Southeast Asia, had most of their wind resources located close to urban areas. Thus, this distribution of impacts was related to population density. The results showed that Turkey lacks suitable onshore wind resources for this cost supply level (10 US cents/kWh). However, wind power generation in Turkey in 2012 was more than 5 TWh/yr (International Energy Agency, 2013b). This value is smaller than the economic potential estimated below 14 US cents/kWh, and indicates that using a threshold value as low as 10 US cents/kWh to evaluate the economic potential is not appropriate for this region. Actual electricity prices in Turkey were 14–19 US cents/kWh in 2013 (International Energy Agency, 2014).

The impact of the distance to urban areas across world regions for an energy potential below 14 US cents/kWh (shown in Fig. 6) was smaller than for an economic potential below 10 US cents/kWh, but had a similar regional distribution. Remarkable changes were observed only in Oceania, India, and China. In Oceania, the decrease in resource availability increased to become a considerable fraction of the global total reduction (from 5% to 11% of the global reduction). In India, the aggregated impacts of distance to urban areas reduced the economic potential from 51% to 22% relative to the reference case for medium values of the parameters. In China, remote resources lost their importance relative to proximal resources given the large decrease in resource availability due to visibility restrictions.

Compared to the current electricity demand (see Table A2 in the Appendix), the reduction in economic potential below 10 US cents/kWh was substantial (i.e., the resulting resource available after introducing the distance to urban areas decreased and was similar to the electricity demand) in most regions, with the exception of Oceania, South Asia, Canada, Latin America, and North Africa. While the scale of resource loss due to the distance to urban areas was small in regions such as Japan (76 TWh/yr), the resulting amount of resource would not enable its share of the total power supply to be higher than 10%. On the other hand, in regions where the loss was large compared to electricity consumption, such as the USA (1178 TWh/yr), the resulting wind resources could potentially have a larger share of the power supply (close to 60%).

3.2. The importance of distance to urban areas compared to other factors of the assessment

After introducing distance to urban areas using the middle values of each factor, the resulting global potential was 13 and 72 PWh/yr for supply costs below 10 and 14 US cents/kWh, respectively. These values, which were equivalent to 44% and 66% of those in the case without including the distance to urban areas (Base), were used as a reference to conduct a sensitivity analysis of

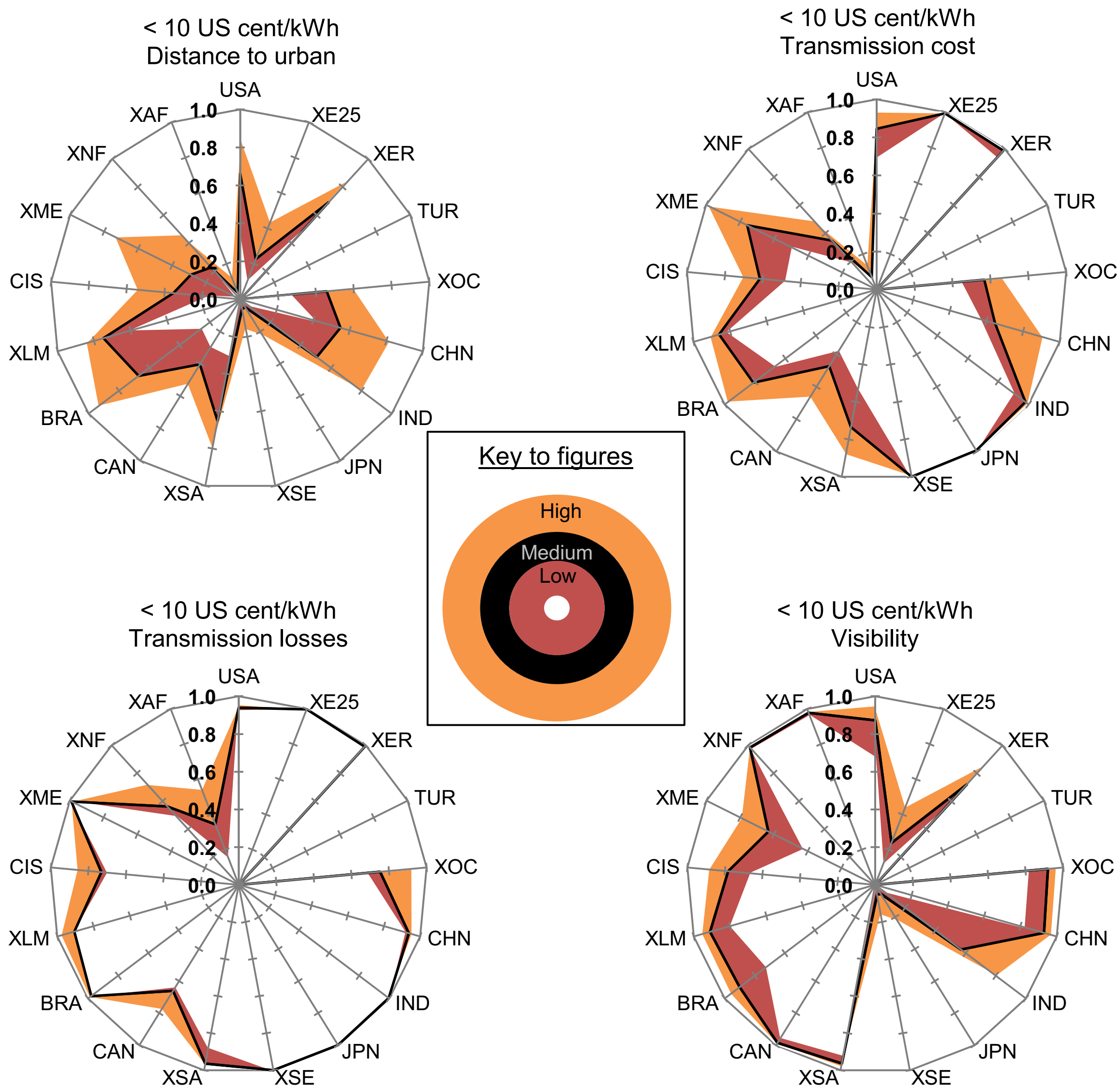

Fig. 5. The onshore wind resource below 10 US cents/kWh for regions of the world after considering the distance to urban areas as a proportion of the reference case (base) (see Table A1 for the definition of regions). The orange and red areas indicate the outcomes for assumptions corresponding to high and low values of the parameters, respectively. The black line in-between indicates outcomes for medium values. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

several factors of the estimation. The results, shown in Fig. 7, indicate that in a comparison of three different factors, the distance to urban areas had a secondary influence on the global potential of onshore wind. A combination of the assumptions made with high and low values of the parameters changed the reference economic potential below 10 US cents/kWh by around 37–75%. In contrast, parameters related to economic factors, in particular the discount rate and capital cost, altered the base potential by close to 400% when using high values and by more than 60% when using low values. Technical and land use factors changed the base potential by 39–80% for high values and by 60–64% for low values. At supply costs below 14 US cents/kWh, the order of importance of the four parameters considered remained more or less unchanged, although there were relatively smaller changes compared to the reference energy potential. In particular, the impact of economic parameters decreased, changing the level of economic potential by around 60% for high values and 37–61% for low values. Land use factors had almost the same level of importance as economic factors. At cost levels higher than 15 US cents/kWh, the distance to urban areas was secondary only to land use, and more important than economic and technical factors (see supplementary information for details).

The outcomes of the sensitivity analysis suggest that the distance to urban areas is a minor factor in the global availability of onshore wind resources. However, it should be noted that neglecting this factor resulted in considerable overestimates, and that its relevance depended on the level of supply cost chosen to evaluate wind resources.

4. Discussion

4.1. Implications of the study

Introducing the distance to urban areas made possible the explicit assessment of some factors related to the integration and social acceptability of onshore wind power in terms of transmission losses and cost, and visibility impacts. The effects of these factors on the global availability of onshore wind resources, and their importance compared to other aspects of the assessment,

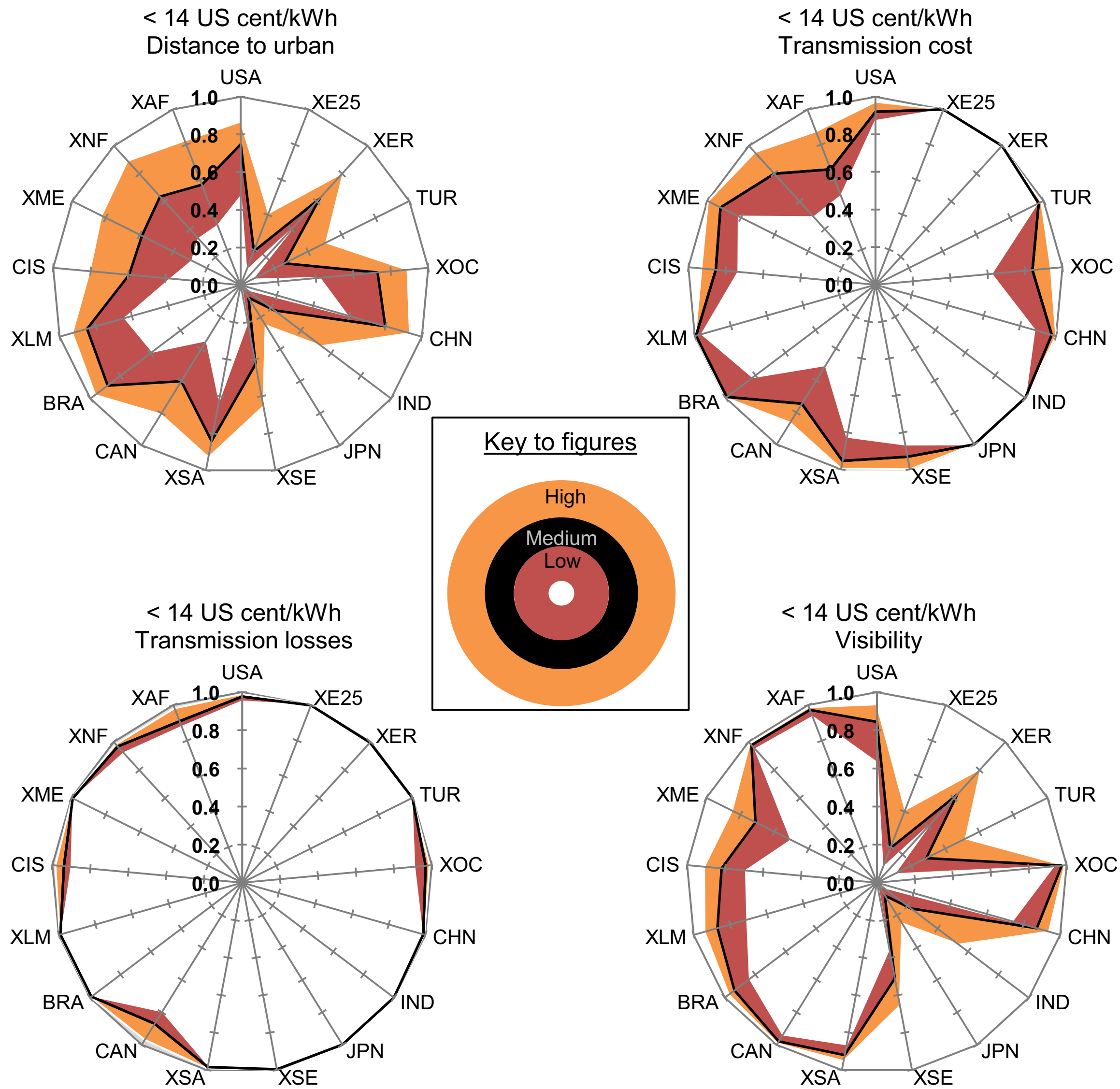

Fig. 6. Onshore wind resource below 14 US cents/kWh for regions of the world after considering the distance to urban areas as a proportion of the reference case (base) (see Table A1 for the definition of regions). The orange and red areas indicate the outcomes for assumptions corresponding to high and low values of the parameters, respectively. The black line in between indicates outcomes for medium values. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

were considerable depending on the level of supply cost considered.

Choosing a meaningful value of supply cost to evaluate the availability of wind resources is difficult. Average electricity prices are a common reference used to evaluate the annual average economic potential of wind power supply; however, they vary among regions and over time depending on several factors. The actual penetration of an alternative energy supply is strongly influenced by the balance between electricity prices and supply costs. A comprehensive characterization of the economic potential should account for short-term fluctuations in electricity prices and cost ranges that are acceptable for wind power generation across different countries. Current retail prices range between 7 and 40 US cents/kWh, depending on the region and sector, with an average value of 13.5 for industrial comsumption and 22 cents/kWh for households (International Energy Agency, 2014). Moreover, wind power and other alternative energy sources are becoming feasible in regions where low electricity prices and more dynamic power markets exist. In the long-term, carbon taxes are expected to change the balance of price and supply costs in favor of low carbon energy technologies, such as wind power. In addition, changes in the share of technologies and the demand for electricity, as well as subsidies and regulations affect the average electricity price. For example, in a study of mitigation scenarios based on integrated assessment modeling (IAM), Dai et al. (2016) showed that under a climate mitigation target of 450 ppm atmospheric CO_2, the average power price would be over 20 US cents/kWh in 2050. With this in mind, in our study, we used 10 and 14 US cents/kWh to reflect a range of possible prices.

The global economic potential of onshore wind in this study was in the low range of the estimates reported in recent literature (see Table 5). Other studies have made relatively optimistic assumptions, in particular for land use and the economic valuation of wind power supply. In particular, land suitability factors vary widely across studies. Values for barren and desert areas are mixed (from less than 10–90%), while land cover categories such as forests had large values (> 30%) in at least one study. The total wind power resource considering the cost threshold in the pessimistic case of Zhou et al. (2012) was similar to that of the case using medium values of parameters in this study. In contrast, Hoogwijk

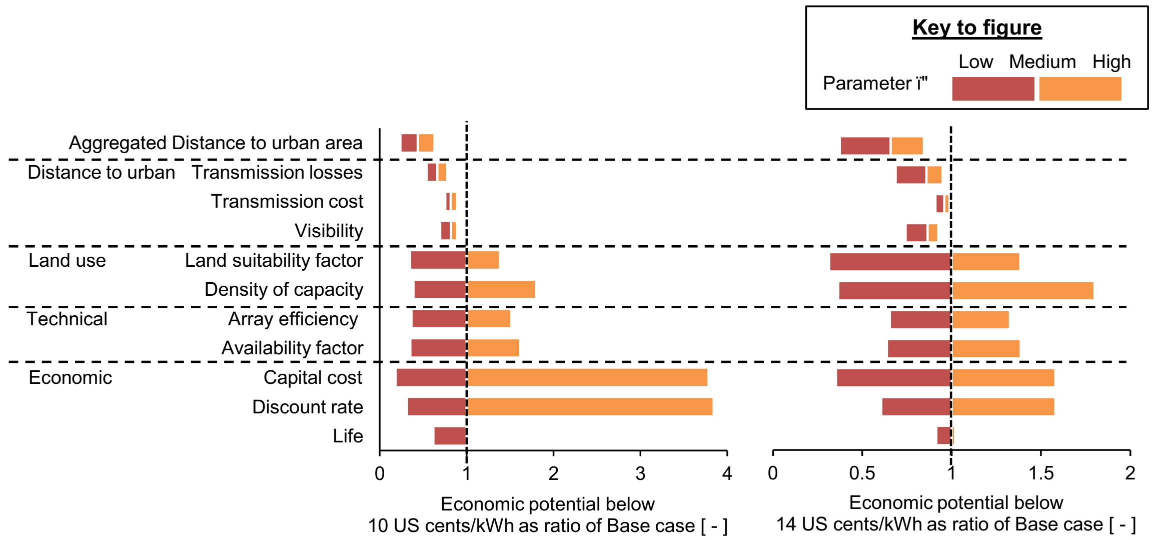

Fig. 7. Sensitivity of the global wind energy resource below 10 US cents/kWh (left panel) and 14 US cents/kWh (right panel) with respect to the distance to urban areas and other factors. Reference case (dotted line) corresponds to the case neglecting the distance to urban areas and with all parameters set to medium values. The orange and red bars indicate outcomes for assumptions corresponding to high and low values of parameters, respectively. The white line between bars indicates outcomes for medium values. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 5
Comparison of our results with global assessments of onshore wind energy resources reported in the literature.

Study	Case	Energy potential [PWh/yr]				
		Unit supply cost [US cent/kWh]				Total
		7	9	10	12	
Base	L[a]	0	0	0	0	24
	M	4	18	29	59	213
	H[b]	461	549	551	556	634
Aggr_DistUrb	L[a]	0	0	0	0	15
	M	3	8	13	34	172
	H	393	478	497	510	578
Zhou et al. (2012)	L		50			224
	M		119			644
	H		150			813
De Vries et al. (2007)	L			23		62
	H			39		80
Hoogwijk et al. (2004)	L					19
	M	21		53		96
	H					210
Lu et al. (2009)	M				690	1100

[a] All parameters set to low (L) values. The economic potential in this case is observed only at unit supply costs above 12 US cent/kWh.
[b] All parameters set to high (H) level.

et al. (2004) and de Vries et al. (2007) reported values for the total availability of wind resources that were relatively smaller, while the total resource under economic limitations was similar to that of the case with medium values of parameters in this study. The differences in the total availability of wind resources are a consequence of contrasting assumptions related to land use and technical aspects, as well as differences in wind speed data. Focusing on the land use and technical aspects, both Hoogwijk et al. (2004) and Zhou et al. (2012) refer to the same land suitability factors and very similar values for density and capacity, and technical factors. The results reported by Lu et al. (2009) are the highest of all studies and are comparable to the case in this study when assuming high values for all parameters. Those authors also used global GIS data to estimate the technical energy potential of wind resources with capacity factors above 20% (equivalent to a supply cost threshold of 12 US cents/kWh based on assumptions with medium values of parameters as used in this study) but neglected land suitability factors and the costs of technology.

Compared to the actual average capacity factor of installed onshore wind energy generation for selected global regions (see Table A3 in the appendix), we found that the majority of these values (ranging between 13% and 30%) fell within a range corresponding to the economic potential of between 10 and 20 US cents/kWh estimated in this study. The current capacity factor in Turkey is considerably larger than the highest value indicated by the model. This may be due to the existence of sites with high-quality wind resources that were not captured by the coarse resolution of the wind speed dataset. Values for China, the EU (25 countries), and Japan fell outside the 20 US cents/kWh threshold, suggesting either that the model overestimated the actual quality of wind resources in these regions or that the actual capacity did not include all of the optimal wind resources available.

In addition to onshore wind supply, offshore locations also offer a large source of wind resources. Electricity output from offshore wind turbines is larger, given that wind speeds over the ocean are subject to less friction than over the land. Moreover, larger turbine blades can be deployed because transporting and installing large parts by ship can avoid the physical restrictions experienced with onshore installations (Wiser et al., 2011). Transmission investment costs, as well as operation and maintenance costs, are larger and more difficult to install than their onshore counterparts. In contrast, land use permits and topographic obstacles are less cumbersome issues. Offshore installations may have more acceptability as they are physically separated from human settlements, although attitudes towards offshore landscapes are uncertain.

Although the assumption of parameters was not harmonized with other studies, it can be assumed that introducing the distance to urban areas to them would have a similar magnitude of effect as in this study. The outcomes provided by this study should not be considered a best estimate among wind resource assessments but rather as quantitative proof of the scale of the effect of including/neglecting the distance to urban areas in the assessment, and as an advance towards a more comprehensive assessment. Several uncertainties and differences in parameter assumptions, methodological approaches, and data sources (in particular wind speeds) prevent us from claiming that this study is more suitable than others. Accounting for the distance to urban areas actually introduces more uncertainties to the assessment. In the following subsections these uncertainties are discussed in detail. Uncertainties related to other factors are discussed in the supplementary information.

4.2. Uncertainties regarding the distance to urban areas

The characterization of transmission losses and costs is affected by the actual length of the transmission line. Assuming that urban areas are the endpoint of transmission lines is subject to error because the actual connection point is likely to be an existing transmission line or substation. On the other hand, urban areas are a suitable proxy when considering two factors. First, the future expansion of transmission networks in regions with large shares of the population currently without access to electricity is likely to occur from or close to urban areas, which are the main sources of electricity demand. Second, expected future growth in electricity demand will require upgrading the capacity of existing transmission lines. Moreover, the aging of current transmission lines will involve adding new transmission capacity, although such capacity cannot be directly associated with the potential supply from onshore wind. Although we neglected the future growth in urban areas, it can be anticipated that the effects of larger urban areas will be small at the global scale, as it will be on the scale of a few kilometers. Nevertheless, the increased number of settlements with populations and areas large enough to be considered urban areas in global land cover datasets may affect the estimation of the distance to the closest urban area.

With regard to transmission costs, the values reported in the literature correspond to a wide range of values. In this study, the three assumed values (50% deviation from the medium value) adequately captured this variability. The level of costs depended on project-specific conditions that involved not only technical and logistic (distance) factors but also regulatory factors affecting the viability of projects, which was dependent on local regulations (Mills et al., 2009).

Social acceptance of wind power is acknowledged in global resource assessments but is not explicitly quantified. It has been indirectly accounted for in previous studies by means of land suitability factors, which represent the fraction of land in a given location suitable for installing wind turbines. By introducing restrictions in terms of the visibility of wind farms, this study provided a “first glance” of the effects of this issue on the availability of wind resources. Nevertheless, we recognized several limitations in the assessment of visibility restrictions.

The distance to the closest urban area is not the most suitable indicator for assessing the impact of the visibility of wind farms. Instead, viewsheds can indicate areas from which a given location is visible, accounting for slope and terrain features. Settlements may also refer to rural populations in addition to urban centers. Capturing these two features will require considerable computing power, and will be easier for local or regional studies. The definition of threshold distances to indicate the level of acceptability due to visibility concerns is contentious. The literature does not explicitly mention such values. Furthermore, we assumed locations within/beyond these distances indicated a total rejection/acceptance of wind farms. There is a lack of consistent evidence to indicate a direct correlation between proximity to urban areas and the opposition of urban residents to wind farm development (Swofford and Slattery, 2010). Moreover, the applicability of the same threshold distances across different regions is questionable, as opinions toward the impact of wind farms on landscapes is likely to differ.

It may be more suitable to adopt a “rate of acceptance” representing the likelihood of a wind farm to be accepted by a neighboring population, for example through an associated willingness to pay, as has been considered in some studies (Ladenburg and Dubgaard, 2007). Moreover, proximity alone cannot explain the acceptability of wind farms in terms of visibility concerns. Other factors determining the rate of acceptance of wind farms will likely involve density, setting (urban or rural), the level of awareness and education of nearby populations, wind farm traits (density of capacity, number of turbines and their extension, hub height, operation settings), and the exposure of the population to existing wind farms. Some of these factors are identified in the literature regarding best practices and social acceptance of wind power projects. In addition, there are several countermeasures to minimize the impact of the visual intrusion on landscapes, such as the application of coatings to blades that decrease the reflectance of light, and guidelines for number and size of turbines in a wind farm (European Commission, 2011; Huber and Horbaty, 2010; Wiser et al., 2011). Overall, a review of quantitative studies of the relationship between the acceptance and visibility of wind power is necessary.

Visibility is just one of the many factors driving social acceptability. Other factors include impacts on the population living near to wind farms due to noise from turbines, and moving shadows (flickering) produced by rotating blades. These impacts can be mitigated by setting a distance buffer from human settlements. Impacts on birds and bats are also a matter of concern. The assessment of migration routes and proximity to zones of wildlife conservation is a well-established practice when locating wind farms (International Energy Agency, 2008, 2013a; Wiser et al., 2011). Another factor to consider is the impact on landscapes of natural, historical, or recreational value. These impacts are difficult to assess because they depend on subjective judgments and personal values toward landscapes and the environment.

In addition to transmission and visibility issues, the distance to urban areas may also be applied for a preliminary assessment of the effect of logistic costs. These costs refer mainly to the construction of roads necessary to access the wind farm' site, the additional costs of the transport of wind turbines and other components, as well the increased operation and maintenance costs due to the longer distance from urban areas. Some sources indicate that logistic costs correspond to around 10% of the capital cost of wind farms (Blanco, 2009).

5. Conclusions and policy implications

We conducted a global assessment of onshore wind resources, incorporating the distance to urban areas as a novel aspect. The effect of introducing this factor was evaluated in terms of power losses and costs from additional electricity transmission infrastructure, and visibility restrictions due to concerns of landscape impacts near urban populations. It was found that the effect of these factors on the global availability of onshore wind resources is considerable, depending on the level of supply cost considered. For example, at supply costs close to current average electricity prices (10 US cents/kWh) wind resources decreased at least by 37% compared to a reference case that neglected the distance to urban areas. At higher supply costs (14 US cents/kWh) the decrease was 16%. Overall, global wind resources were mostly affected by transmission costs in the low range of unit costs, while visibility issues became more important as more expensive wind resources were deployed. The impact of the distance to urban areas was heterogeneous across all regions of the world, with a considerable loss in economic potential in the EU, Japan, Southeast Asia, the Middle East, and Africa. In regions with extensive unpopulated areas, transmission losses and costs were the most relevant factors related to the distance to urban areas, while in densely populated regions visibility was the major factor.

Table A1
Key to world regions considered in the assessment.

Region code	Region name	Region code	Region name
USA	United States of America	XSA	South Asia
XE25	EU (25 countries)	CAN	Canada
XER	Rest of Europe	BRA	Brazil
TUR	Turkey	XLM	Rest of Latin America
XOC	Oceania	CIS	Former Soviet Union
CHN	China	XME	Middle East
IND	India	XNF	North Africa
JPN	Japan	XAF	Rest of Africa
XSE	Southeast Asia		

Compared to other aspects of the assessment, changes in the parameters related to the distance to urban areas had a relatively small impact on the global availability of wind resources. Again, the level of supply costs defined to evaluate the availability of resources changed the relative importance of the distance to urban areas. At low supply costs (around 10 US cents/kWh), the distance to urban areas had a relatively minor impact, and was similar in importance to land suitability factors and the lifetime of turbines. In contrast, at high supply costs (around 15 US cents/kWh and above), the distance to urban areas had a similar level of importance as the technical and economic aspects of wind power, and was secondary only to the land use aspect. The value of the unit supply cost chosen to evaluate the economic potential, and the uncertainties influencing the estimation of the distance to the closest urban area in the short and long terms, are critical for determining the importance of the distance to urban areas in the assessment of global onshore wind resources.

This study explicitly quantified (although in a partial manner) the scale of restrictions associated with the integration of wind power into energy systems, and the social acceptability of large scale wind power plants. Thus, it broadens the scope of previous global wind resource assessments. This information is of fundamental importance for researchers and policy makers interested in climate change mitigation policies, to clarify the limits of wind energy resources that can actually be supplied at the global scale.

Table A3
Average capacity factor for selected world regions from this study's estimates and statistics (see Table A1 for definition of regions).

	Average capacity factor from estimated economic potential			Average capacity factor in year 2011 (International Energy Agency, 2013b)
	Unit supply cost [US cent/kWh]			
	10	14	19.5	
USA	30	24	20	29
EU25	34	30	26	22
Turkey	0	20	16	30
China	31	25	22	13
India	29	22	17	17
Japan	29	25	25	22
Brazil	29	22	17	22
Middle East	28	23	19	27
Africa	29	23	20	28

The estimation contained major uncertainties regarding the use of the distance to urban areas as a proxy to determine the length of transmission infrastructure and visibility restrictions. A comprehensive review of the drivers of social acceptance and its relationship with proximity to population is needed before the rate of acceptance due to visibility impacts can be introduced into future assessments. Future changes in electricity prices, wind power costs, and the urban population are also important uncertainties.

Acknowledgments

This study was supported by the Environment Research and Technology Fund (2-1402) of the Ministry of the Environment of Japan.

Appendix A

see Appendix Table A1–A3

Table A2
Onshore wind energy potential for 17 regions for two levels of economic potential for the Base case and the case considering the distance to urban areas (AggrDistUrb).

	Electricity consump.	Energy potential < 10 US cent/kWh [TWh/yr]				Energy potential < 14 US cent/kWh [TWh/yr]			
	2012[a]			Distance to urban areas				Distance to urban areas	
	[TWh]	Base	Aggr_DistUrb[b]	Max[c]	Min[d]	Base	Aggr_DistUrb	Max[c]	Min[d]
USA	4069	3478	2300	2613	1613	10,149	7595	8527	5434
XE25	2818	2975	675	1295	293	4386	847	1797	358
XER	546	938	649	763	461	1358	845	1097	537
TUR	207	0	0	0	0	47	12	23	3
XOC	278	1523	697	769	535	15,112	11,026	12,480	7670
CHN	4694	2687	1475	1915	1212	7926	6324	6851	5257
IND	940	10	5	7	0	161	36	87	6
JPN	989	80	4	18	0	233	18	58	1
XSE	1486	42	2	7	0	221	95	127	59
XSA	142	2525	1645	1810	1057	6665	5614	5829	4660
CAN	543	2135	860	967	712	5035	3022	3498	1992
BRA	498	56	38	44	28	867	767	803	623
XLM	757	2665	1996	2124	1690	6189	5251	5686	4248
CIS	1357	3466	1224	1591	802	17,534	10,438	12,051	8193
XME	847	1627	472	830	138	6786	3979	4912	2557
XNF	266	1667	379	629	246	13,651	8685	10,633	5142
XAF	358	2716	95	320	57	13,647	7802	9044	5505
World	20,915	28,594	12,518	14,821	9538	109,972	72,358	80,194	57,769

[a] Data from IEA (International Energy Agency, 2014).
[b] The AggrDistUrb case uses same assumptions to Base case including parameters related to distance to urban areas.
[c] Largest value among cases TrLoss, TrCost and Visib corresponding to the high level.
[d] Smallest value among cases TrLoss, TrCost and Visib corresponding to the low level.

Appendix B. Supplementary material

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.enpol.2015.12.024.

References

Archer, C.L., Jacobson, M.Z., 2005. Evaluation of global wind power. J. Geophys. Res.: Atmos. 110, D12110.

Atmospheric Science Data Center, 2005. Wind speed at 50 m above the surface of the Earth (10-year monthly & annual average for July 1983–June 1993), Surface meteorology and Solar Energy (SSE) Release 5 Data Set, NASA Langley Research Center (LaRC).

Blanco, M.I., 2009. The economics of wind energy. Renew. Sustain. Energy Rev. 13, 1372–1382.

Bruckner, T., Chum, H., Jäger-Waldau, A., Killingtveit, Å., Gutiérrez-Negrín, L., Nyboer, J., Musial, W., Verbruggen, A., Wiser, R., 2011. Annex III: cost table. In: Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Seyboth, K., Matschoss, P., Kadner, S., Zwickel, T., Eickemeier, P., Hansen, G., Schlömer, S., von Stechow, C. (Eds.), IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Clarke, L., K.J., Akimoto, K., Babiker, M., Blanford, G., Fisher-Vanden, K., Hourcade, J.-C., Krey, V., Kriegler, E., Löschel, A., McCollum, D., Paltsev, S., Rose, S., Shukla, P. R., Tavoni, M., van der Zwaan, B.C.C., van Vuuren, D.P., 2014. Assessing transformation pathways. In: Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., Kriemann, B., Savolainen, J., Schlömer, S., von Stechow, C., Zwickel, T., Minx, J.C. (Eds.), Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Cohen, J.J., Reichl, J., Schmidthaler, M., 2014. Re-focussing research efforts on the public acceptance of energy infrastructure: a critical review. Energy 76, 4–9.

Dai, H., Silva Herran, D., Fujimori, S., Masui, T., 2016. Key factors affecting long-term penetration of global onshore wind energy integrating top–down and bottom–up approaches. Renew. Energy 85, 19–30.

de Vries, B.J.M., van Vuuren, D.P., Hoogwijk, M.M., 2007. Renewable energy sources: their global potential for the first-half of the 21st century at a global level: an integrated approach. Energy Policy 35, 2590–2610.

Delucchi, M.A., Jacobson, M.Z., 2011. Providing all global energy with wind, water, and solar power, part II: reliability, system and transmission costs, and policies. Energy Policy 39, 1170–1190.

European Commission, 2011. Guidance document. Wind energy developments and Natura 2000. European Union; Publications Office of the European Union, Luxembourg.

EWEA, 2009. Wind Energy: The facts. European Wind Energy Association.

GEA, 2012. Global Energy Assessment – Toward a Sustainable Future, Cambridge University Press Cambridge, UK and New York, NY, USA, The International Institute for Applied Systems Analysis, Laxenburg, Austria.

Grubb, M.J., Meyer, N.I., 1993. Wind energy: resources, systems and regional strategies. In: Johansson, T.B., Kelly, H., Reddy, A.K., Williams, R.H. (Eds.), Renewable Energy: Sources for Fuels and Electricity. Island Press, Washington, DC, USA, pp. 157–212.

Hastings, D.A., Dunbar, P.K., 1999. Global Land One-km Base Elevation (GLOBE) Digital Elevation Model Documentation. NOAA National Geophysical Data Center, Boulder, Colorado.

Hoogwijk, M., de Vries, B., Turkenburg, W., 2004. Assessment of the global and regional geographical, technical and economic potential of onshore wind energy. Energy Econ. 26, 889–919.

Hoppock, D.C., Patiño-Echeverri, D., 2010. Cost of wind energy: comparing distant wind resources to local resources in the Midwestern United States. Environ. Sci. Technol. 44, 8758–8765.

Huber, S., Horbaty, R., 2010. IEA Wind Task 28. Social acceptance of wind energy, State-of-the-Art Report. International Energy Agency.

Ikegami, T., 2009. Methodology for Estimation of the Renewable Energy Potential (in Japanese), National Institute for Environmental Studies (NIES).

International Energy Agency, 2008. Renewable Energy Essentials. Wind OECD/IEA, Paris.

International Energy Agency, 2012a. Energy Technology Perspectives 2012: Pathways to a Clean Energy System. OECD/IEA, Paris.

International Energy Agency, 2012b. World Energy Outlook 2012. OECD/IEA, Paris, France.

International Energy Agency, 2013a. IEA Technology Roadmap: Wind Energy. OECD/IEA, Paris.

International Energy Agency, 2013b. IEA World Energy Balances, pp. 1960–2012.

International Energy Agency, 2013c. World Energy Outlook 2013. OECD/IEA, Paris.

International Energy Agency, 2014. Key World Energy Statistics. OECD/IEA, Paris.

IUCN, UNEP, 2010. The World Database on Protected Areas (WDPA). UNEP-WCMC, Cambridge, UK.

Ladenburg, J., Dubgaard, A., 2007. Willingness to pay for reduced visual disamenities from offshore wind farms in Denmark. Energy Policy 35, 4059–4071.

Lu, X., McElroy, M.B., Kiviluoma, J., 2009. Global potential for wind-generated electricity. Proc. Natl. Acad. Sci. USA 106, 10933–10938.

Mills, A., Wiser, R., Porter, K., 2009. The Cost of Transmission for Wind Energy: A Review of Transmission Planning Studies. Lawrence Berkeley National Laboratory, USA.

NREL/US Department of Energy, 2008. 20% Wind energy by 2030. Increasing Wind Energy's Contribution to US Electricity Supply. US Department of Energy, USA.

Silva, D., 2012. AIM-Renewable Energy Potential Model Manual. NIES, Japan.

Silva, D., Ashina, S., Fujino, J., Forthcoming. Evaluating the impact of distance to energy demand on the global energy potential of solar and wind.

Sorensen, B., Meibom, P., 2000. A global renewable energy scenario. Int. J. Glob. Energy Issues 13, 96–276.

Sullivan, R.G., Kirchler, L.B., Lahti, T., Roche, S., Beckman, K., Cantwell, B., Richmond, P., 2012. Wind Turbine Visibility and Visual Impact Threshold Distances in Western Landscapes. Argonne National Laboratory, UChicago Argonne, LCC, Argonne, IL, USA.

Surface Meteorology and Solar Energy (SSE), 2005. Wind Speed At 50 m Above The Surface Of The Earth (10-year Monthly & Annual Average for July 1983–June 1993), Release 5 Data Set ed, Atmospheric Science Data Center, NASA Langley Research Center (LaRC).

Swofford, J., Slattery, M., 2010. Public attitudes of wind energy in Texas: local communities in close proximity to wind farms and their effect on decision-making. Energy Policy 38, 2508–2519.

U.S. Geological Survey (USGS), 2005. MODIS/Terra Land Cover Type Yearly L3 Global 1 km SIN Grid, Land Processes Distributed Active Archive Center (LPDAAC).

Vestas, 2013. 2 MW Platform (catalog). Vestas Wind Systems, Denmark.

Wiser, R., Yang, Z., Hand, M., Hohmeyer, O., Infield, D., Jensen, P.H., Nikolaev, V., O'Malley, M., Sinden, G., Zervos, A., 2011. Wind energy. In: Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Seyboth, K., Matschoss, P., Kadner, S., Zwickel, T., Eickemeier, P., Hansen, G., Schlömer, S., von Stechow, C. (Eds.), IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Zhou, Y., Luckow, P., Smith, S.J., Clarke, L., 2012. Evaluation of global onshore wind energy potential and generation costs. Environ. Sci. Technol. 46, 7857–7864.