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Mapping of the global wind energy potential using open source GIS data

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ABSTRACT

The request of new energy sources and the need of reduction of CO2 emission in order to mitigate the global warming have driven the deployment of renewable energy sources, among which wind has played in the last ten years the role of major contributor. In this research the global wind energy potential at national scale is assessed using geographic information systems (GIS). The global data of land use, topography and administrative boundaries in GIS format and wind speed measurements of around 12 ’000 worldwide surface stations have been collected. The punctual wind measurements at 10m high of the surface stations have been used to derive a worldwide wind map at 50m, 80m and 130m high using a co-Kriging method. The validation process shows an average value of the uncertainty of 1.1m/s and the spatial distribution of the uncertainties has been mapped. The theoretical, geographical and technical potential of each country have been estimated. The global technical potential at 130m high is around 400 PWh/year considering a power density of 5MW/km^2 which is around 20 times the global electricity consumption of 19.3 PWh in 2011.

INTRODUCTION

At present, a few studies have been carried out in order to assess the global wind energy potential. Early work dates back to nineties (Grubb and Meyer 1993 and Sørensen, 1999) where a first estimate of the energy potential was carried out with coarse global data. In (Hoogwijk, de Vries and Turkenburg 2004) the geographical, technical and economic potential or macro regions using coarse geographical data and different wind databases has been investigated. The world has been discretized in 0.5°x 0.5° cells and the land cover used consisted of 9 classes. The climatic average measured values of 3615 meteo stations spread worldwide have been interpolated without considering the corresponding uncertainties due to the applied model and without carrying out any validation process.
Later work (Archer and Jacobson 2005) aimed at quantifying the world’s wind power potential at 80m high from data measurements at 10m of 7753 surface stations using the data of the National Climatic Data Center and the Forecast Systems Laboratory collected during the period 1998-2002. One tower data of the Kennedy Space Center (Florida) was used to validate the results. The outcome was a general assessment of the global theoretical wind energy potential based on the values of the surface stations but without generating any spatial distribution and considering any constraints. Furthermore the assessment of the potential of each country hasn’t been investigated.
In (Lua, McElroy and Kiviluomac 2009) the global onshore potential has been estimated in 690PWh assuming the limitation of 20% of the suitable land due to constraints such as ice, forests, urban regions etc. but without carrying out any spatial analysis of the suitable land.
More recent work (de Castro et al. 2011) proposed a top-down approach to estimate the global wind energy potential by aknoledging the energy conservation and considering the physical and technological limits. The results show that potential is limited to 1TW due to technological constraints which is much lower than previous estimates. Nevertheless the available land suitable for wind turbines is only assumed to be 20% of the total but not spatially identified.
By using the reanalisys wind speed data combined with the wind turbines performance and the suitability factors of land and cost assumptions, the global onshore wind energy potential has been assessed (Zhou et al. 2012). The methodology applied to supply the wind supply curve is the same applied in the Hoogwijk’s work. The study shows a potential of 119.5 PWh/y (13.6TW installed) at less than 9cents/kWh.
In this research the global wind energy potential at national scale is assessed using geographic information systems (GIS). The global data of land use, topography and administrative boundaries in GIS format and wind speed measurements of around 13’000 worldwide surface stations have been coll ected. A continuos map of the wind speed has been generated and validated using a co-Kriging method with the corresponding Standard Error Map showing the spatial distribution of the uncertainties. The validation of the results enables to quantify the uncertainties when assessing the potential. This aspect plays a fundamenteal role as the wind resource assessment is a critical task when assessing the global potential

DATA AND APPROCH

Dataset used and study area

The open source geodata used used in this study have been collected from different sources and preprocessed before being used as input data.
The Digital Terrain Model (DTM) in raster format with a resolution of 30-arc-seconds has been provided by the United States Geological Service (USGS). The landcover in raster format with a resolution of 300m has been provided by the European Space Agency (ESA); it describes the global landcover divided in 22 classes. The administrative borders of all worldwide countires in shape format has been provided by the Natural Earth Data. The wind speed measurements of meteorological stations used to generate the wind speed map have been provided by the National Oceanic Atmospheric Agency (NOAA). For each country contained in the shapefile, the wind energy estimates have been carried out and then showed in the thematic map.

Approach

In this work three different wind energy potentials have been estimated and compared: theoretical, geographical and technical potential.
The theoretical potential is defined as kinetic energy available per wind mass unit as a function of the wind speed (V), and the air density (ρ) and it is estimated using the following formula:

$$P = 0.5\rho V^3 \qquad (1)$$

Where the air density has been so calculated:

$$\rho = 1.247015e^{-0.000104h} \qquad (2)$$

where h is the elevation of each cell.
The geographical potential is defined as the potential related to the suitable areas for wind energy installation. The regions not suitable for wind energy installations are covered by forests, ice, settlements and higher than a certain altitude. Therefore spatial data such as the land cover and the elevation are used to identify the suitable land and to quantify the geographical potential. The regions whose elevation is higher than 2000m are excluded. The landcover raster divided in 22 classes has been reclassified into a feasibility values comprised between 0 and 1 (Table 1).

Table 1: Landcover classes and suitability factors

Landcover category	Suitability
Post-flooding or irrigated croplands (or aquatic)	0.95
Rainfed croplands	1
Mosaic cropland (50-70%) / vegetation (grassland/shrubland/forest) (20-50%)	0.9
Mosaic vegetation (grassland/shrubland/forest) (50-70%) / cropland (20-50%)	0.7
Closed to open (>15%) broadleaved evergreen or semi-deciduous forest (>5m)	0
Closed (>40%) broadleaved deciduous forest (>5m)	0
Open (15-40%) broadleaved deciduous forest/woodland (>5m)	0.1
Closed (>40%) needleleaved evergreen forest (>5m)	0
Open (15-40%) needleleaved deciduous or evergreen forest (>5m)	0.1
Closed to open (>15%) mixed broadleaved and needleleaved forest (>5m)	0
Mosaic forest or shrubland (50-70%) / grassland (20-50%)	0.5
Mosaic grassland (50-70%) / forest or shrubland (20-50%)	0.7
Closed to open (>15%) (broadleaved or needleleaved, evergreen or deciduous) shrubland (<5m)	0.7
Closed to open (>15%) herbaceous vegetation (grassland, savannas or lichens/mosses)	0.9
Sparse (<15%) vegetation	0.9
Closed to open (>15%) broadleaved forest regularly flooded (semi-permanently or temporarily) - Fresh or brackish water	0
Closed (>40%) broadleaved forest or shrubland permanently flooded - Saline or brackish water	0
Closed to open (>15%) grassland or woody vegetation on regularly flooded or waterlogged soil - Fresh, brackish or saline water	0
Artificial surfaces and associated areas (Urban areas >50%)	0

Bare areas	1
Water bodies	0.8
Permanent snow and ice	0.1
No data (burnt areas, clouds,…)	0

In addition the areas steeper than 20% has been excluded because of technical reasons (transportation, civil works, etc.) unsuitable for wind turbines as used in other studies (Grassi, Chokani and Abhari 2012).
The map of the geographical potential has been created by applying the following relationship proposed by Hoogwijk (Hoogwijk, de Vries and Turkenburg 2004).

$$f_i = (A_i - u_i)/A_i\ a_i\ b_i\ w_i\ r_i \quad (3)$$

Where the f_i is the suitability factor of the cell i, A_i is the raster cell i [km^2], u_i is the urban in cell i [km^2], a_i is the binary weighting factor for bioreserves with $b_i \in (0,1)$, w_i is the suitability factor of the landuse listed in Table 1 and r_i is the suitability factor for wind regime with wind speed less than 4m/s.
By applying the formula 3 a raster map with values comprised between 0 an 1 is obtained.
The technical potential is defined as the feasible potential that can be installed.

$$E_i = fi\ A_i\ \eta_a\ \eta_{ar}\ D\ h_{f,i} \quad (4)$$

Where the E_i is wind energy output of the cell i [MWh/year], f_i is the suitability factor of the cell I (formula 3), A_i is the raster cell i [km^2], η_a is the average wind turbine availability, η_{ar} is the average wind farm array efficiency, D is the power density [MW/km^2] and $h_{f,i}$ full-load hours per year in raster cell i [in hours].
The suitability factor and the full-load hours are strictly correlated to each raster cell. The η_a has been set to 0.95 according to previous work (Grassi, Chokani and Abhari 2012) while the value of array η_{ar} has been set to 90% according to previous studies (Schallenberg-Rodriguez 2013).
The parameter $h_{f,i}$ (full-load hours) has been estimated according to previous study (Abed and El-Mallah 1997) with the following relation:

$$h_{f,i} = 580\ V_{H,i} - 1420 \quad (5)$$

Where $V_{H,i}$ is the average wind speed in raster at the height H measured in m/s. The full-load hours estimated at 130m high has been used in this study according to the commercial wind turbines.
As the wind speed is measured at 10m Above the Ground Level (AGL) while the commercial wind turbines hub height is at 130m high, the wind speed has to be extrapolated with the following relation (Hau 2006):

$$V_H = V_{10}\ \ln(H/z_0)/\ln(10/z_0) \quad (6)$$

Where the V_H is the estimated wind speed at the hub height (i.e. 130m high), V_{10} is the wind speed at the height of 10m above the ground and the z_0 is the value of the aerodynamic roughness. The value of the aerodynamic roughness is derived from the raster of the land cover.
In this work the power density D has been set to a value of 5MW/Km^2 which is lower than the wind power density corresponding to a commercial wind turbine of 7-7.5MW (i.e. ENERCON) which results into 10MW/Km^2 when assuming 1.389WT/Km^2.

Global wind speed map

In order to quantify the global wind energy potential the wind speed map has to be created by interpolating the wind speed measurements of the worldwide irregualarly distributed meteorological stations. The National Oceanic and Atmospheric Administration provides the access to the climate database of more than 13’000 meteo stations (Figure 1) of which the measurements of the last 5 years have been considered.

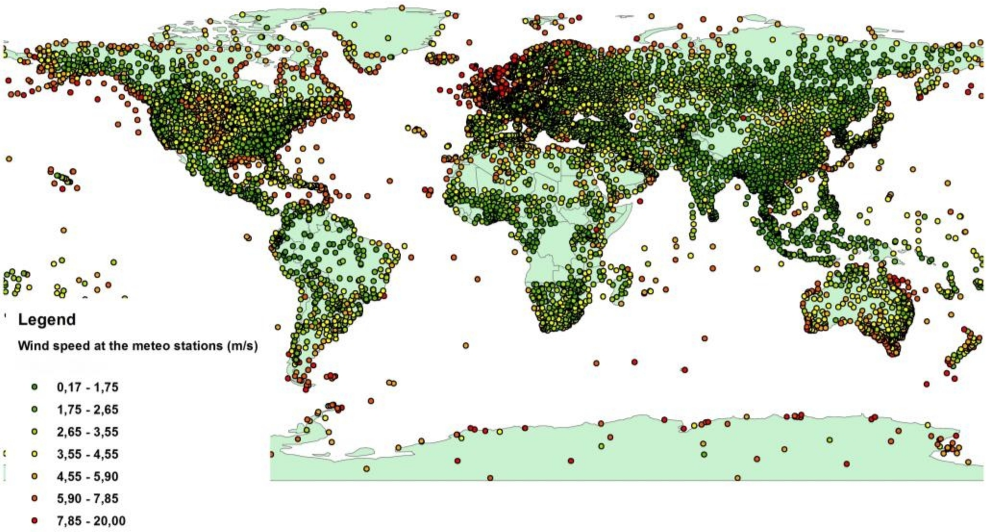

Figure 1: worldwide distribution of the NOAA meteorological stations with the annual mena wind speed (m/s)

Most of the measurements are availbale in Europe, USA and China while in the rest of the wolrd the densitiy of the data measurements is low. This scattered distribution of the stations generates uncertainties when estimating the wind speed in unkown locations faraway from the observations. Previous work demonstrated the efficiency of interpolation methods of climate data by using co-Kriging (Luo, Taylor and Parker 2008), a machine learning technique (F. Veronesi et al. 2015) the spline approach (McVicar et al. 2007) and the internal boundary layer (IBL) method (Verkaik 2001). In this work the Kriging and the co-Kriging approaches have been used and the results compared. In addition the spatial distribution of the uncertainties of the wind speed estimates has been carried out and mapped. Kriging is an interpolation method to estimate respectively predict the variable of interest in unassembled locations from data observed at known locations. Kriging uses variograms to express the spatial variation. It minimizes the error of predicted values which are estimated by spatial distribution of the predicted values. One advantage of Kriging is, that it can use the covariance between two or more variables. In the approach with the Kriging the NOAA observation only have been used while in the co-Kringing approach also the raster data of NASA and the DTM have been used. The validation for the two methods has been compared to identify which one is the most accurate method. The co-Kriging approach performs better than the Kringing and gives a better accuracy when assessing the spatial distribution of the wind speed.
The global RMS of the map created by using Kriging is 1.101m/s while for the same map created with a co-Kriging approach the RMS is 1.124m/s. In previous work (Luo, Taylor and Parker 2008), the RMS of England and Wales obtained using a 5x5km grid resolution was 1.61m/s with an ordinary Kriging. The Figure 2 shows the Standard Error Maps by using the Kriging and the co-Kriging approaches respectively.

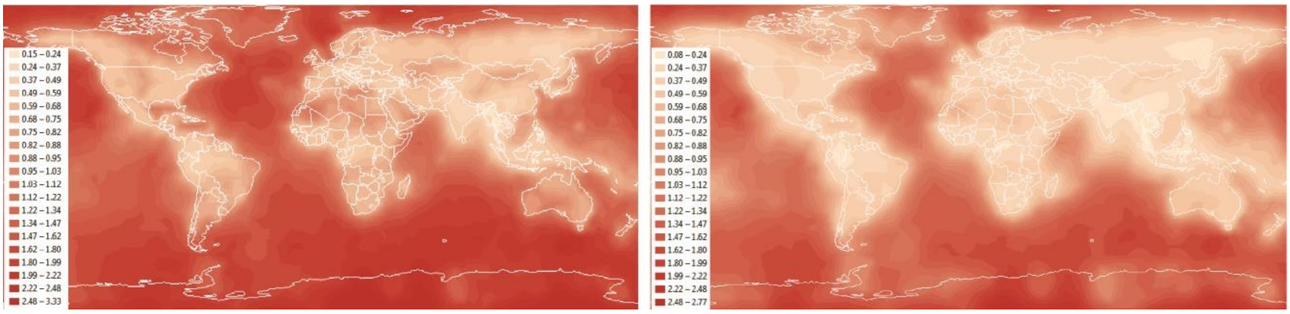

Figure 2: spatial distribtuion of the uncertainties of the wind speed by us by using Kriging (left) and co-Krigining (right)

It can be seen in Figure 2 that the co-Kriging approach allows for a lower variance around the mean value for all predicted points than by using a Kriging method. For this reason the global wind map (Figure 3) at 10km resolution has been created using a co-Kriging method.

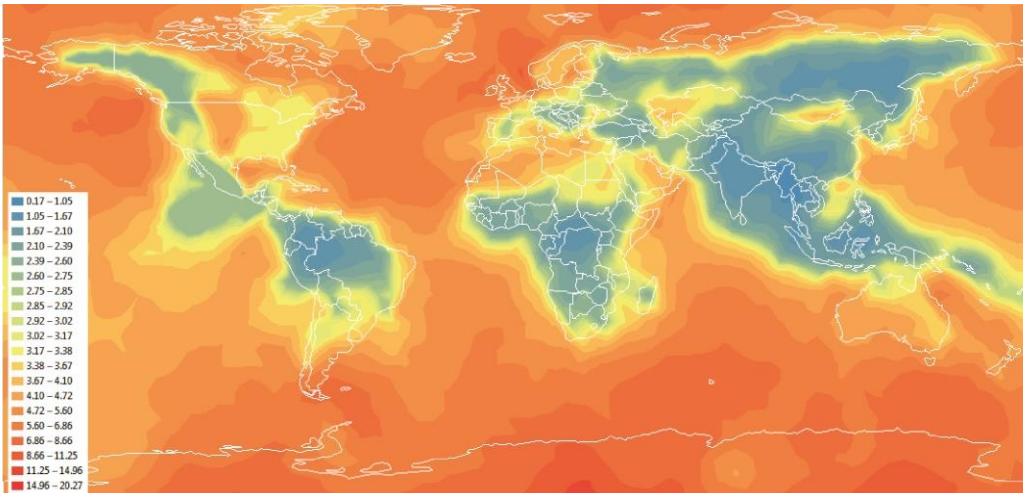

Figure 3: global mean annual wind speed at 10m AGL

RESULTS AND DISCUSSION

The theoretical, geographical and technical potential of the global wind energy potential of each country ahs been quantified. Although the maps show that Antartica and Greenland are included in the estimates, in the final values their contributions has been excluded.

The theoretical potential at 130m AGL has been estimated in 273TW (Terawatt) but it has to be taken into account that the height at which the potential is estimated and the improvement of the technology impact the assessment and make the obtained values not really comparable with previous work when the technology and the wind resource assessment techniques were not as efficient and accurate as nowadays.

The geographical potential map (Figure 4) shows the percentage of suitable land of each country out of the total. The red countries have a low suitable land due to elevation, and vegetation (e.g. tropical forests) or the average wind speed lower than 4m/s at the hub height.

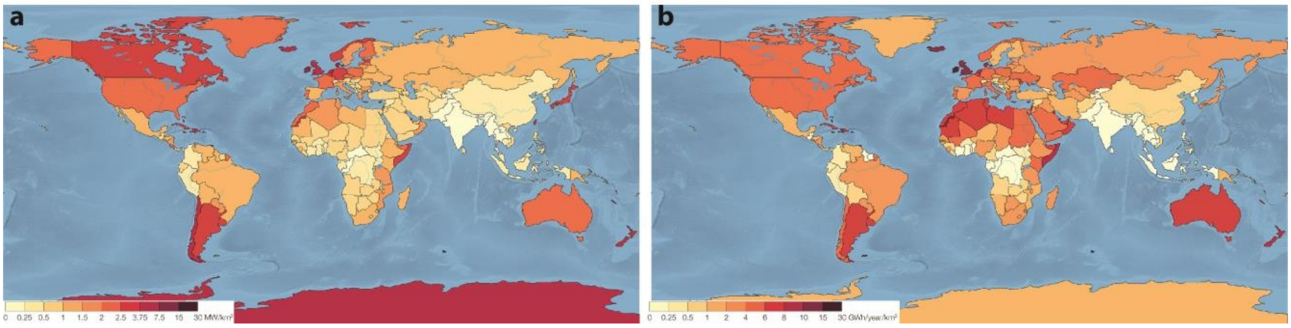

Figure 4: (a) Theoretical potential, (b) technical potential.

This value corresponds to the cut-in whind speed at which the wind turbines start generating electricity. Under these assumptions the geographical potential is quantified into 96TW.

The technical potential at 130m AGL has been estimated in 406PWh/year (Petawatthours per year) considering a power density of 5MW/km ^{2} which is around 20 times higher than the global electricity consumption of 19.3 PWh/year of 2011.

If the power density is in the order of 7.5MW/km ^{2} and 10MW/km ^{2} the estimated electricity potential generation is respectively 609PWh/year and 811 PWh/year.

Countrywise there is a good correlation between the theoretical and the technical potential in the top ten of the countries with the highest potential, in particular due to the high rate of suitable land. Thus country such as Canada, USA, Russia, Australia and Argentina account for around 97.2TW of theoretical potential (out of a global 273TW) and 212.6PWh/year of potential annual electricity generation (out of a global 406PWh/year). When normalizing these values to the available surface in Km ^{2}, Ireland, Danemark and UK are the country that show the highest potential also due to the high wind sped and the relative high rate of suitabile land.

CONCLUSIONS AND FURTHER RESEARCH

In this study the global wind energy potential and electricity generation have been estimated using a GIS tool and open source data. The global continous wind speed maps at 10m, 50m, 80m and 130m AGL have been generated by interpolating the wind speed measurements of around 12’000 worldwide scattered meteorological stations. The co-Kriging approach using the DTM and the landcover has been applied to interpolate observations to produce the 10km resolution map. The co-Kriging approach has been selected in comparison to the Kriging approach because the comparison of the Stanrdad Error Maps shows a better accuracy. The RMS of the two approaches are 1.10m/s and 1.24m/s. The extrapolation of the wind speed at the hub height of 130m AGL has been used to carry out the assessment of global theoretical, geographical and technical potential showing that the largest countries have the absolute highest theoretical and technical potential, while when normalizing these values to surface, Ireland, Danmark and UK show the highest potential. The technical potential is quantified in 406PWh/year which is around 20 times higher than the global annual electricity consumption in 2011.
Despite the resulting wind energy potential, some uncertainties make the assessment overestimated, in particular the lack of the GIS data of infrastructures such as transmission lines and roads and more detailed countrywise GIS data. The availability of transmission lines data enables to exclude those regions that are potentially exploitable but currently far away from interconnection and thus too economically too expansive to be connected to the existing power grid. The availability of countrywise GIS data enables to quantify more in details the suitable lands and thus to refine the estimate of the geographical potential. These are currently the main bottlenecks that can be hardly overcome in particular concerning the transmission line GIS data. The search of countrywise GIS data is more a time consuming task as access to GIS data of some countries is particularly difficult for internal policy (i.e. China).
As future work the grid resolution of 10km should be reduced down to 1-2km in order to better take into account the fragmentation of the landcover and to improve the accuracy of assessment of the suitable land. A sensititvity analysis of the suitability factors would enable to identify those parametrs and landcover classes that affect the geographical potential the most.
The wind speed map and its validation show a relative good accuracy also in comparison with previous studies, nevertheless as future work the grid resolution of 10km should be reduced down to 1-2km in order to investigate its impact on the assessment of the potential.

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