**Wind power integration in ONSSET**

In order to encourage the penetration of wind energy, decision makers must be provided with enough information so that they can support the development of wind energy. Therefore, availability of comprehensive data regarding the spatial distribution of wind energy resources throughout the world is of great importance for its large scale development. The main goal of this study is to visualize the distribution of onshore wind power capacity factor after considering the appropriate wind power technical parameters and land use restrictions. Finally, GIS maps will be prepared to indicate the possible favourable sites having favourable capacity factor throughout the world, which can be used in order to enhance the penetration of wind energy projects in grid and off-grid applications on global scale.

# **Material and methods**

## **Spatial data**

Initially, 20 years raw GIS data of average wind speed at 10m height having spatial resolution of 0.5ox0.5o (approx. 55 km2) available throughout the land area of globe was acquired from National Aeronautics and Space Administration (NASA) for 1995-2014 [29]. NASA provides wind speed in terms of eastward and northward components at 10m height. These two components can be combined together by the Pythagorean Theorem given below to get absolute value of wind speed at 10m height as suggested by [30].

Where, Vh is the absolute wind speed in (m/s), Uh is the eastward wind speed component in (m/s) and Vh is the northward wind speed component in (m/s).

Apart from the global wind speed data layers, in order to prepare the suitability, several spatial data layers were used such as: administrative boundaries of countries, inland water bodies, protected areas, urban areas, digital elevation maps and slope datasets as mentioned in Table 1 here after.

Table 1: List of spatial data layers used in this study

|  |  |  |
| --- | --- | --- |
| Name of spatial data layer | Resolution i.e. size of grid cell | Source |
| Global yearly average wind speed | 0.5o \* 0.5o (approx. 55 km2) | [31] |
| Global elevation map | 0.008 \* 0.008 (approx: 1 km2) | [32] |
| Global slope map | same (derived from elevtion) | [32] |
| Global urban areas | same | [33] |
| Global protected areas | same | [34] |
| Inland water bodies | same | [33] |
| Global country boundaries | NA | [35] |

## **Geographic information system**

The Geographic Information System (GIS) tool can be used for processing the energy resources geographical data. It can capture, store and manipulate the input data to obtain a holistic view of the study. It can be used as a decision support system. It helps in pointing out the potential, which can be used for better transmission and distribution of renewable energy resources in a region. It combines and process large amount of spatial data, which later on becomes more handy and understandable to the decision makers. The application of GIS tool for the assessment of energy resources started in the 1990s and it made a reasonable progress till now. GIS software can be used for the assessment of renewable energy resources just like solar, biomass, wind, and hydro-power etc. on national and global level.

## **Methodology**

In order to estimate the wind energy potential available in each grid cell it is very necessary to obtain the wind speed probability distribution. It provides the repetition frequency of a specific wind speed reading (1 to 25 m/s) at a given site. In this study, due to the availability of yearly average wind speed, the Rayleigh probability distribution was used to estimate the wind speed frequency distribution in each 0.5o\*0.5o (55 km2 approximately) sized grid cell. Later on, for the estimation of the wind power capacity factor, the Rayleigh wind speed probability distribution, the wind turbine power curve, the number of hours in a year, the wind turbine availability factor and other losses were used in order to get the achievable wind power capacity factor in each grid cell. Finally, the spatial distribution of wind power capacity factor was visualized on a GIS map. Additional details on all the methodological steps used in this study are given in the following sections.

### Wind speed extrapolation

The wind speed changes with altitude because of frictional effects at the surface of the earth. Since the wind speed data are given at 10m height [29], a proper extrapolation should be applied in order to obtain wind speed reading at the hub height (55m) of the chosen wind turbine Vestas-44 (V-44) having 600kW rated power. The wind speed extrapolation can be achieved by using the power law equation, which is used by many wind energy researchers in order to extrapolate the reference wind speed to the hub height of wind turbine [30] [36]. It represents a simple model for the vertical wind speed profile and its basic form is:

Where, *U(z)* is the required wind speed in m/s at required height (*z*) in meters, *U(zr)* is the reference wind speed in m/s at reference height (*zr*) in meters, *α* is the dimensionless power law exponent also known as wind shear exponent, one way of handling *α* is from the reference values, which are already known. The following expression form is an empirical method that gives a correlation for the power law exponent as function of velocity and height.

where, *Ur*reference wind speed given in m/s and *Zr* reference height in meters.

### Rayleigh probability distribution

In this study, wind power capacity factor was estimated with the help of Rayleigh probability distribution due to limited availability of long term daily wind speed data. Rayleigh probability distribution is modified form of Weibull probability distribution having assumed value of shape factor k=2. A similar type of study was conducted by the authors of this paper for the African continent [37], where it was concluded that the difference in the energy yield between Rayleigh and Weibull distribution along the whole continent is slightly more than 5%. However the variation at certain sites may be significant and thus the Rayleigh distribution wouldn’t provide accurate estimations when it comes to particular locations. Rayleigh probability distribution of wind speed was estimated by the following equation:

where, *f(U)* is the Rayleigh probability distribution of a wind class, *U* is wind speed reading (1 to 25 m/s) and *Umean* is average wind speed in m/s and k is a unit less shape factor, which is assumed to be equal to 2 for Rayleigh probability distribution.

### Wind power calculation

The power produced by a wind turbine was estimated by combining the Rayleigh wind speed distribution and the manufacturer’s power curve of the selected V-44 wind turbine. The power curve of a wind turbine provides information related to the power output of the wind turbine on the basis of wind speed reading. In Figure 1, the power curve of a V-44 wind turbine is given.

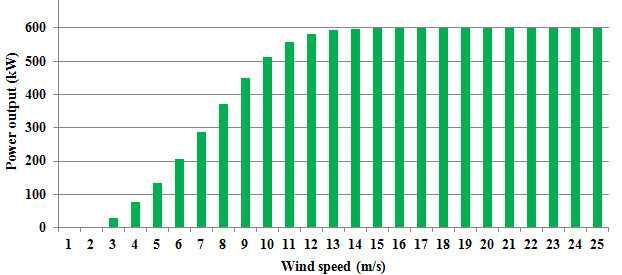


Figure 1: Power curve of V-44 wind turbine

The above power curve together with the wind speed probability distribution was used at each grid cell in order to estimate the wind power production throughout land area. The power production by the wind turbine at a particular point on annual basis is given by the subsequent formula:

where, is the expected wind power, *P(U)* is the power curve of the selected wind turbine, *f(U)* is the Rayleigh probability distribution of a wind class. The wind classes considered for Rayleigh distribution range from 1 to 25 m/s and each class range is 1 m/s.

### Calculation of expected wind energy

The yearly expected wind energy yield of each grid cell was estimated by bringing in the availability factor of a wind turbine and its number of hours in operation during a year. The availability factor of a wind turbine is the percentage of time during which a wind turbine is practically available for electricity production after considering planned outages for scheduled maintenance, inspections and forced outages such as breakdowns, grid outages, and severe weather conditions. Most of the time the availability factor of wind farms typically ranges between 94%–97% while recent data about modern wind farms indicate that the availability factor ranges from 97–99%. For this study, the yearly expected wind energy was calculated by using the following equation.

where, is the yearly expected wind energy, *μ* is the availability factor of the wind farm and *T* is the time in hours of a full year, i.e. 365.25 x 24 hours. It should be mentioned that in this study the used availability factor was equal to 97%.

### Calculation of capacity factor

The capacity factor reflects the potential wind power at a given site and it can be used for comparing different sites before the installation of wind power plants. The capacity factor of a wind turbine is defined as the ratio of the yearly expected wind energy production to the energy production by the same wind turbine at its rated power. The yearly expected wind energy production and the rated power of a single V-44 wind turbine were used to calculate the global wind power capacity factor available in each grid cell. The capacity factor was estimated by the equation below:

where is the rated power of the wind turbine, and *T* is the number of hours in a year.

### Land suitability for wind energy

Wind energy, just like any other energy resource, has some technical, environmental and social requirements. Other practical issues include safety requirements in the form of minimum distance from sites related to infrastructure and ecosystems. Due to these reason, it is necessary to specifically locate the land areas suitable for wind energy installation. In this paper, the suitable land area available for onshore wind energy potential throughout the world was estimated by excluding the inland water bodies, the protected areas, the urban areas, the land areas having slope greater than 18o and the areas with elevation greater than 2000m. Additional details on the restriction data layers are mentioned in Table 1. All the data layers related to land use restriction mentioned in Table 1 were imported into GIS in order to prepare the land suitability map for wind energy on global level.

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