Evaluation of ERA-Interim and NCEP-CFSR Reanalysis Datasets against in-situ Measured Wind Speed Data for Keti Bandar Port, Pakistan

Zia ul Rehman Tahir*, Muhammad Salman Sarfraz*, Muhammad Asim*, Muhammad Sajid Kamran*, Shahid Imran*, Nasir Hayat*

*Department of Mechanical Engineering, University of Engineering and Technology Lahore, Pakistan

ziartahir@uet.edu.pk

Abstract. The evaluation and comparison of reanalysis datasets (NCEP-CFSR and ERA-Interim) against mast measured wind data for Keti-bander port of Pakistan have been performed. In the last decade, wind farms have been developed on the land, but there is still need for the development of offshore wind farms on the 1100 km coast of Pakistan. The wind data measured at the Keti Bandar Port of Pakistan at different heights for the duration of 20 months has been used in this study. The evaluations of satellite datasets against measured data were done based on statistical analysis, monthly mean time series and Weibull probability distribution function. The wind data at 30 m, 60 m and 85 m was extrapolated using the Logarithmic law from 10 m height. At 30 m height both satellite datasets show very good agreement with measured data, the predictions of CFSR data are much better than ERA-Interim. The percentage difference for mean wind speed, wind power density and Weibull parameters at 30 m are less than 5%. Overall NCEP-CFSR gave better results compared to ERA-Interim. These results may be used for the offshore wind resource assessment for Pakistan due to unavailability of offshore wind speed data.

1. Introduction
Pakistan has been facing a shortage in the supply and demand of electricity over the past decade, so looking for alternative resources of energy like the wind is a good sustainable option. Due to the skewness of energy production systems towards fossil fuels, the economy of the country is badly affected because of high prices of fossil fuels and high dependence on oil price changes, leading to cost vulnerability [1-3]. The solution to reducing the dependency on fossil fuel i.e. residual furnace oil, diesel oil, etc. is to invest in renewable energy technologies. A share of 1.48% of the total energy supply is being produced from renewable energy sources in Pakistan[4]. Several countries are successfully dealing with growing energy demand by installing Renewable based energy resources[5, 6]. Fortunately, Pakistan is blessed with the plentiful potential of renewable energy sources. Pakistan’s possibilities of using renewable energy resources that include Solar, Wind, Hydel and Biomass Energy, etc. [2, 7-12].

Pakistan Meteorological Department (PMD) has assessed the coastline of Pakistan during 2002, and it shows wind energy potential along the coastline of Sindh and Balochistan [13]. Pakistan has a total potential of wind energy about 346GW, out of which 120GW is feasible [14]. Pakistan has a total installed capacity of 789 MW out of which 199MW was added in 2017 [4]. Country’s wind energy has
a share of 1.48% to total energy generation till 2017. Based on available grid infrastructure in the country, the government has set a target for adding additional 1,200 MW of wind power by 2020, out of which 400MW will be added in 2018.[4]. There was not a single grid-connected wind farm exists in Pakistan until 2009, three grid-connected wind farms with total capacity of 150 MW had been added and 2.6 GW wind form will be added by 2030 [15]. The exponential increase in renewable energy projects especially wind projects is attracting attention day by day and for installation of such projects. An accurate wind potential estimate is of key importance. The installation of a wind mast to measure surface data is a costly process, satellite datasets can be used as an alternative to surface measured data.

Satellite reanalysis datasets are evaluated on the basis of the comparison performed with surface measured data. This method is most commonly used in recent studies for the different location [16-19]. The measured and satellite data was compared in three ways; using correlation by finding different statistical parameters, by monthly time series [19-22] and Weibull probability distribution function[23-25]. The statistical tools used in this analysis are; mean bias error (MBE), mean absolute error (MAE), root mean square error (RMSE) and correlation coefficient (R). For European region, Carvalho et al. [16, 25, 26] evaluated a number of satellite simulated datasets with surface measured datasets, for Iberian Peninsula analysis for offshore wind satellite data using ERA-Interim and NCEP-CFSR was reported. The evaluation of wind satellite data including ERA-Interim and NCEP CFSR for Portugal region was reported in Ref [26]. Staffell et al. [27] discussed the simulation of present and future wind speed for 23 European countries including ERA-Interim and NCEP- CFSR. Based on all these comparative and evaluative studies, this paper discussed the results and found quite reasonable comparisons.

Pakistan has a coastal line of around 1100 km, but neither an offshore wind farm developed nor offshore wind resource assessment was performed for Pakistan. The wind speed measured data port of Keti Bandar is compared with reanalysis datasets which could be used for the offshore wind resource assessment of Pakistan. The reanalysis datasets of ERA-Interim and CFSR is evaluated for the coastal line of Pakistan, to determine which one of these satellite datasets shows better results with measured wind data and the results presented here can be of great value for the offshore wind resource assessment for Pakistan due to insufficient or unavailability of offshore wind speed data. The evaluation of NCEP CFSR and ERA-Interim datasets has been performed using statistical parameters: MAE, MBE, STDE, RMSE and R. The comparison of these results with previously published results have been performed thus validating results and identifying satellite estimates variations for the South Asian region. This study is an initiative towards wind resource assessment for potential sites in Pakistan.

2. Wind Data
Alternative Energy Development Board of Pakistan (AEDB) along with United Nations Development Programme (UNDP) under the Global Environmental Facility (GEF) Wind Energy Program had installed three wind masts in the Gharo-Keti Bandar Wind Corridor [28], in order to facilitate the growth of wind energy. The AEDB-UNBDP Keti Bandar mast was installed in Keti Bandar town in the south-east of Karachi [28] at the start of 2009, the geographical location of the site is 24° 11’ 49.18” N and 67° 37’ 38.67” E. The location of the mast is about 30 km away from the shore. The mast consists of five anemometers at measurement levels of 85 m (two anemometers), 60 m, 30m, and 10m to measure wind speed and two wind vanes at 83.5 m and 28.5 m to measured wind direction. The data for 20 months duration from 1st March 2009 to 31st October 2010 was used to evaluate satellite reanalysis data for this study.

The monthly mean wind speed of the measured data is presented in Figure 1. There are two anemometers at 85 m height so the average wind speed from two anemometers is calculated. The mean wind speed at 85 m, 60 m, 30 m and 10 m are 6.93 m/s, 6.53 m/s, 5.55 m/s and 4.31 m/s respectively. The monthly mean wind speed at 85 m ranges from 5.49 m/s to 8.57 m/s, the maximum is in May and minimum in October. There is a general trend of increase in wind speed from January to May, then decrease from May to October, then a slight increase from October to December and finally decrease from December to January.
To extrapolate wind speed different methods have been developed over time, assuming wind shear profile follows either a logarithmic-linear law, a logarithmic law or a power law [29]. The vertical wind shear profile using simple mean wind speed is shown in Figure 2. The measured data is used to get the best fit for Power law [30] and Logarithmic law [31, 32] of vertical interpolation of wind speed. The power law exponent (alpha) used in Power law was calculated as 0.209 and surface roughness used in logarithmic law was calculated as 0.228 m. The logarithmic law has been commonly used in various recent studies for the validation of reanalysis data with surface measured data [33-38], as it provides the interpolation or extrapolation of wind speeds over a range of wind speeds, locations and altitudes [29, 39].

The ERA-Interim reanalysis [40] is the third generation reanalysis developed by the European Centre for Medium-Range Weather Forecasts (ECMWF) released in 2006 is based on the calculations using an integrated forecast system model. It is a global reanalysis dataset having a spatial resolution of 0.75°×0.75° (~80 km) and a temporal resolution of six hours, the wind data is available from 1979 to onwards at 10m to 270 m height above ground. The ERA-Interim wind data was downloaded with a spatial resolution of 0.125°×0.125° (~13 km) at 10 m height above ground.

The Climate Forecast System Reanalysis (CFSR) [41] is the third generation reanalysis product developed by the National Centers for Environmental Prediction (NCEP) released in 2010. This is a global reanalysis dataset having a spatial resolution of 0.5°×0.5° (~55 km) and a temporal resolution of six hours. The wind data is available from 1979 to onwards at 10 m and 22 m height above ground.
3. Methodology
The measured data and reanalysis data (termed as satellite data now) was compared in three common ways; statistical analysis using correlation and finding different statistical parameters, monthly time series and Weibull probability distribution function. The reanalysis data sets of NCEP-CFSR and ERA-Interim are compared with measured data of wind speed at different heights. The reanalysis datasets were available at six hours durations so measured data was calculated for six hours duration from 10 minutes duration. The reanalysis wind speed data at the mast location was calculated from the four nearby grid locations using bilinear interpolation.

The Logarithmic law will be used in this study for interpolation or extrapolation of wind speed because it has been commonly used in previous studies [33-38] to extrapolate wind speed by satellite datasets. The ERA-Interim data is available at the vertical height of 10 m, wind speed data was vertically extrapolated using the Logarithmic law at 30m, 60 m and 85m height. The surface roughness used in Logarithmic law was downloaded for temporal resolution of six hours from the ECMWF website. The NCEP-CFSR data is available at the vertical height of 10 m and 22 m so satellite data was extrapolated using Logarithmic law from these two heights at 30 m, 60 m and 85 m. The measured data at 22 m height was interpolated using the logarithmic law, using surface roughness length for each time step.

4. Results
The evaluation of satellite wind speed was performed in three ways; monthly mean time series, statistical analysis and Weibull probability distribution function. This section presents the results obtained from three methods of comparison.

4.1. Time Series
The monthly mean wind speed at 10 m, 30 m, 60 m and 85 m from measured and ERA-Interim data is presented in Figure 3. There is a consistent overestimation of satellite wind speed at 10 m. At 30 m height, there is an overestimation of wind speed except for winter of 2009-10 so the over MBE is low. At 60 m and 80 m height, the trend is quite similar, but the satellite wind speeds are underestimated.

![Figure 3. Monthly mean wind speed from measured and ERA-Interim data](image-url)

The monthly mean wind speed at 10 m, 30 m, 60 m and 85 m from measured and NCEP-CFSR data is presented in Figure 4. There is a constant bias for 10 m height, satellite wind speed was overestimated. At 30 m, trends are closely related with minimum bias. At 60 m and 80 m the trend is of CFSR wind speed is like ERA-Interim. Both satellite data underestimate wind speed in winter, low wind speed in June 2009 was estimated well by CFSR, whereas not be ERA-Interim. For this location and duration discussed CFSR data gave a better estimation of wind speed compared to ERA-Interim.
4.2. Statistical Analysis

The statistical parameters to compare the satellite data with measured data are; mean bias (MBE), mean absolute error (MAE), the root mean square error (RMSE), and correlation coefficient (R). A positive bias means that the satellite data is overestimated and vice versa. Bias, MAE, RMSE and R of both satellite datasets for six hours and 24 hours duration is presented in Table 1. The best results, characterised by higher values of correlation coefficient and lower values of errors, are highlighted in bold. The daily data for ERA-Interim shows better comparison compared to six hourly data whereas the best results are at 30 m height. Similarly, the daily data for NCEP-CFSR shows better comparison compared to six hourly data whereas the best results are at 30 m height. The NCEP-CFSR data shows better agreement with measured data in terms of errors compared to ERA-Interim but NCEP-CFSR has a lower value of R compared to ERA-Interim.

Table 1. Statistical analysis of the comparison between measured and satellite mean wind speed data

| Satellite Data | Height (m) | 6 Hourly | Daily | 6 Hourly | Daily |
|---------------|------------|----------|-------|----------|-------|
|               |            | MBE      | MAE   | RMSE     | STDE  | R     | MBE  | MAE  | RMSE | STDE  | R     |
| ERA-Interim   | 10 m       | 0.897    | 1.295 | 1.600    | 1.057 | 1.637 | 0.761 | 0.897 | 1.057 | 1.237 | 0.852 |
|               | 30 m       | 0.192    | 1.157 | 1.506    | 0.740 | 0.811 | 0.192 | 0.811 | 1.050 | 1.032 | 0.835 |
|               | 60 m       | -0.341   | 1.246 | 1.678    | 0.720 | -0.341| 0.899 | 1.275 | 1.229 | 0.805 |        |
|               | 85 m       | -0.513   | 1.340 | 1.846    | 0.700 | -0.513| 0.982 | 1.425 | 1.329 | 0.788 |        |
| NCEP-CFSR     | 10 m       | 0.508    | 1.107 | 1.425    | 0.739 | 0.794 | 0.508 | 0.794 | 0.981 | 0.839 | 0.835 |
|               | 22 m       | 0.017    | 1.086 | 1.418    | 0.719 | 0.731 | 0.017 | 0.731 | 0.941 | 0.941 | 0.812 |
|               | 30 m       | -0.075   | 1.151 | 1.516    | 0.699 | 0.751 | -0.075| 0.751 | 0.970 | 0.967 | 0.811 |
|               | 60 m       | -0.639   | 1.409 | 1.799    | 0.655 | -0.639| 1.001 | 1.313 | 1.147 | 0.764 |        |
|               | 85 m       | -0.842   | 1.580 | 2.032    | 0.612 | -0.842| 1.143 | 1.512 | 1.256 | 0.741 |        |

The scatter plots of measured wind speed and satellite estimates of wind speed for four heights (10 m, 30 m, 60 m and 85 m) are presented in Figure 5. At 10 m height, a best-fit line of ERA is parallel to the 1-1 line with an offset which shows a constant overestimation whereas CFSR line is intersecting 1-1 line which shows that lower winds are overestimated, and higher winds are underestimated. At 30 m height best-fit line form ERA is parallel and very close to 1-1 line whereas the behaviour of the CFSR line is like 10 m height. At 60 m height ERA line is parallel to 1:1 but higher winds are slightly underestimated, the trend is like ERA line at 85 m. The CFSR data is underestimating high wind speeds and overestimating lower wind speeds at all heights, although wind speed dispersion is not consistent...
over the 1-1 line for all heights. The values of correlation coefficient tend to decrease with an increase in height for both satellite datasets. Correlation values of Era-Interim are better than CFSR for all 10, 30, 60 and 85m heights. Also, the performance of Era-Interim is better than CFSR datasets based on gradient values.

![Figure 5](image.png)

**Figure 5.** Correlation between surface measured and satellite wind speed

4.3. **Weibull Probability Density Function**

The Weibull probability density function is widely used to represents wind speed distribution due to its flexibility and simplicity. The scale factor $A$ is related to mean wind speed while shape factor $k$ is equivalent to the standard deviation [42]. The value of $A$ and $k$ for both measured and satellite data for six hours duration is given in Table 2, for satellite data percentage error is presented in parentheses next to the value. The measured mean wind speed at different heights and standard deviation in parenthesis are presented in Table 2. The mean wind speed for the complete duration from satellite data show good agreement with measured data at higher heights within 5% error, the same agreement is for Weibull factors $A$ and $k$. 
Figure 6. Weibull PDF between surface measured and satellite wind speed

Table 2. Statistics of the comparison between measured and satellite six-hourly mean wind data

| Wind Data | Height (m) | Mean wind speed (m/s) | Wind power density (W/m²) | Weibull scale factor $A$ (m/s) | Weibull shape factor $k$ |
|-----------|------------|-----------------------|---------------------------|--------------------------------|------------------------|
| Measured  | 10 m       | 4.524 (1.850)         | 88                        | 5.106                          | 2.595                  |
|           | 22 m       | 5.444 (1.858)         | 136                       | 6.089                          | 3.071                  |
|           | 30 m       | 5.549 (1.960)         | 157                       | 6.382                          | 3.067                  |
|           | 60 m       | 6.529 (2.023)         | 232                       | 7.384                          | 3.502                  |
|           | 85 m       | 7.043 (2.133)         | 274                       | 7.813                          | 3.560                  |
| ERA-Interim| 10 m      | 5.423 (19.87%)        | 127 (54.55%)              | 6.071 (18.90%)                 | 3.032 (16.84%)         |
|           | 30 m       | 5.901 (6.34%)         | 164 (12.10%)              | 6.606 (3.51%)                  | 3.008 (-1.92%)         |
|           | 60 m       | 6.313 (-3.31%)        | 202 (-6.90%)              | 7.068 (-4.28%)                 | 2.993 (-14.53%)        |
|           | 85 m       | 6.533 (-7.24%)        | 224 (-12.41%)             | 7.315 (-6.37%)                 | 2.980 (-16.29%)        |
| NCEP-CFSR | 10 m       | 5.031 (11.21%)        | 108 (22.73%)              | 5.628 (10.22%)                 | 3.039 (17.11%)         |
|           | 22 m       | 5.460 (0.29%)         | 136 (0.00%)               | 6.101 (0.20%)                  | 3.158 (2.83%)          |
|           | 30 m       | 5.631 (1.48%)         | 148 (-5.73%)              | 6.287 (-1.49%)                 | 3.191 (4.04%)          |
|           | 60 m       | 6.012 (-7.92%)        | 178 (-23.28%)             | 6.704 (-9.21%)                 | 3.264 (-6.80%)         |
|           | 85 m       | 6.201 (-11.96%)       | 195 (-28.83%)             | 6.912 (-11.53%)                | 3.291 (-7.56%)         |
The Weibull probability distribution function curve of four heights are presented in Figure 6. PDFs of satellite datasets have similar trend for a specific height and it varies for different heights. Figure 5(a) reveals that PDFs of both satellite datasets are shifted towards the right which lower wind are overestimated and higher winds are underestimated which shows overall underestimations. PDF of CFSR is closer to measured data compared to ERA so again at 10 m height wind speed estimates of CFSR are better than ERA. The spread of the CFSR wind data is lesser than Era-Interim for 10 m, while it has the percentage error of 10.22% in the Weibull scale factor which is responsible for positive skewness in the Era-Interim wind data which can be seen in Fig 5 (a). The PDFs of satellite data at 30 m height are close to measured data PDF, the shapes of all PDFs are similar, the satellite PDFs have lower values of percentage errors of shape factor. The scale factor for the ERA is higher than CFSR.

The lower winds in Era-Interim are underestimating the measured wind data while higher winds are overestimating the surfaced measured data with an overall overestimation for 10 and 30m and vice versa for 60 and 85m height. Although CFSR dataset is underestimating lower wind speed and overestimating higher wind speeds for 10m only and vice versa for the rest of heights. Both the datasets show approximate the same results for 30m height with Weibull shape factor error of -1.92% for Era-Interim and 4.04% for CFSR, which are the lowest among all the heights being compared.

5. Discussion
The mean wind speed for the whole duration is presented in Table 2, for both satellite the percentage error is positive at 10 m which decrease with height and changes to negative, the minimum percentage error is at 30 m height. The wind power density for satellite and measured data is presented in Table 2, the percentage error for wind power density is minimum at 60 m which are around 5%. The results of the present study were compared with the results of the previous studies reported for the European and Antarctic region by other researches to see the reliability of reanalysis datasets for Pakistan.

For six hourly data of ERA-Interim, the lowest values of MBE, MAE and RMSE are for 30m, and lowest values of STDE and correlation coefficient are for 10m. The best values of MBE, MAE, RMSE, STDE and correlation coefficient are 0.192 m/s, 1.157 m/s, 1.506 m/s, 1.325 m/s and 0.761 respectively. The values of MBE decrease up to 30m height with an overestimation of wind dataset and then decrease negatively for higher heights with an underestimation of the dataset. Garmashov et al. [17] compared Era-Interim over Black Sea speed at 10 m height MBE, RMSE and R values are 0.35 m/s, 1.90 m/s and 0.75. Carvalho et al. [26] compared Era-Interim for Portugal at 10m height, the values of statistical parameters MBA, RMSE, STDE and R were 0.34 m/s, 2.10 m/s, 2.02 m/s and 0.79 respectively. A comparison of the present analysis and previous analysis of wind speed reveals that Era-Interim data has better R values in Europe compared to Pakistan [16, 25] [17].

For six hourly data of NCEP-CFSR, the lowest values of MBE, MAE and RMSE are for 22m, and lowest values of STDE and correlation coefficient are for 10m. The best values of MBE, MAE, RMSE, STDE and correlation coefficient are 0.017 m/s, 1.086 m/s, 1.418 m/s, 1.331 m/s and 0.739 respectively. Carvalho et al. [43] evaluated satellite datasets (NCEP NCAR, ERA-interim and CFSR) for Iberian Peninsula and came at the conclusion that the results of CFSR are better than those shown by NCEP NCAR but worse than ERA-interim where the comparison has been performed for 5 potential sites and the values of MBE, RMSE and R for CFSR data range from 0.38 m/s to 0.82 m/s, 1.77 m/s to 2.33m/s and from 0.83 to 0.90 respectively for wind speed. Overall at 30m both CFSR and Era-Interim show very good results in term of statistical analysis, probability distribution function and time series comparison.

6. Conclusions
The evaluation of the NCEP-CFSR and ERA-Interim against the measured wind speed data has been presented for the first time for the coastline of Pakistan. The wind industry in Pakistan is under development stages with the possible potential of the offshore wind farm, this study will be an initiative toward the development of the offshore wind farms in Pakistan. The results presented here can be of
excellent value for the offshore wind resource assessment for Pakistan due to insufficient or unavailability of offshore wind speed data.

The evaluation of satellite wind speed data against measured data was done based on monthly mean time series, statistical analysis, regression plots and probability distribution function. The monthly mean time series comparison reveals that CFSR data gave a better estimation of wind speed compared to ERA-Interim. The NCEP-CSFR data shows better agreement with measured data in terms of errors compared to ERA-Interim but NCEP-CFSR has a lower value of R compared to ERA-Interim. The performance of Era-Interim is better than CFSR datasets based on regression plots and a best-fit line. The comparison of PDFs of both satellites shows the similar trend at a different height. Overall NCEP-CFSR gave better results compared to ERA-Interim.

7. References

[1] Mahmood A, Javaid N, Zafar A, Ali Riaz R, Ahmed S and Razzaq S 2014 Pakistan's overall energy potential assessment, comparison of LNG, TAPI and IPI gas projects Renewable and Sustainable Energy Reviews 31 182-93

[2] Hong S-Y and Pan H-L 1996 Nonlocal Boundary Layer Vertical Diffusion in a Medium-Range Forecast Model Monthly Weather Review 124 2322-39

[3] Sher H A, Murtaza A F, Addoweesh K E and Chiaberge M 2015 Pakistan’s progress in solar PV based energy generation Renewable and Sustainable Energy Reviews 47 213-7

[4] Rehman S, Halawani T and Husain T 1994 Weibull parameters for wind speed distribution in Saudi Arabia Solar Energy 53 473-9

[5] Chou M-D and Lee K-T 1996 Parameterizations for the absorption of solar radiation by water vapor and ozone Journal of the atmospheric sciences 53 1203-8

[6] Parrish D F and Derber J C 1992 The National Meteorological Center's Spectral Statistical-Interpolation Analysis System Monthly Weather Review 120 1747-63

[7] Mirza I A, Khalil M S, Amer M and Daim T U 2015 Policies and Programs for Sustainable Energy Innovations: Renewable Energy and Energy Efficiency, ed T U Daim, et al. (Cham: Springer International Publishing) pp 55-81

[8] Mirza U K, Ahmad N, Harijan K and Majeed T 2009 Identifying and addressing barriers to renewable energy development in Pakistan Renewable and Sustainable Energy Reviews 13 927-31

[9] Tahir Z R and Asim M 2018 Surface measured solar radiation data and solar energy resource assessment of Pakistan: A review Renewable and Sustainable Energy Reviews 81 2839-61

[10] Zameer H and Wang Y 2018 Energy production system optimization: Evidence from Pakistan Renewable and Sustainable Energy Reviews 82 886-93

[11] Amjad M, Zafar Q, Khan F and Sheikh M M 2015 Evaluation of weather research and forecasting model for the assessment of wind resource over Gharo, Pakistan International Journal of Climatology 35 1821-32

[12] Mabel M C and Fernandez E 2008 Analysis of wind power generation and prediction using ANN: A case study Renewable energy 33 986-92

[13] Lun I Y and Lam J C 2000 A study of Weibull parameters using long-term wind observations Renewable energy 20 145-53
[14] Bagiorgas H S, Mihalakakou G, Rehman S and Al-Hadhrami L M 2012 Wind power potential assessment for seven buoys data collection stations in Aegean Sea using Weibull distribution function Journal of Renewable and Sustainable Energy 4 013119

[15] Siddique S and Wazir R 2016 A review of the wind power developments in Pakistan Renewable and Sustainable Energy Reviews 57 351-61

[16] Carvalho D, Rocha A, Gómez-Gesteira M and Santos C S 2014 Comparison of reanalyzed, analyzed, satellite-retrieved and NWP modelled winds with buoy data along the Iberian Peninsula coast Remote sensing of environment 152 480-92

[17] Garmashov A V, Kubryakov A A, Shokurov M V, Stanichny S V, Toloknov Y N and Korovushkin A I 2016 Comparing satellite and meteorological data on wind velocity over the Black Sea Izvestiya, Atmospheric and Oceanic Physics 52 309-16

[18] Winterfeldt J 2008 Comparison of measured and simulated wind speed data in the North Atlantic. Universität Hamburg Hamburg)

[19] Song L, Liu Z and Wang F 2015 Comparison of wind data from ERA-Interim and buoys in the Yellow and East China Seas Chinese journal of oceanology and limnology 33 282-8

[20] Rashmi R, Polnikov V, Pogarskii F, Gomorev I, Samiksha V and Vethamony P 2016 Long-Term Variability of the Wind Field over the Indian Ocean Based on ERA-Interim Reanalysis Atmosphere-Ocean 54 505-18

[21] Kiss P, Varga L and Jánosi I M 2009 Comparison of wind power estimates from the ECMWF reanalyses with direct turbine measurements Journal of Renewable and Sustainable Energy 1 033105

[22] Luo Y, Wang D, Gamage T P, Zhou F, Widaneage C M and Liu T 2018 Wind and wave dataset for Matara, Sri Lanka Earth System Science Data 10 131

[23] Chang T P 2011 Performance comparison of six numerical methods in estimating Weibull parameters for wind energy application Applied Energy 88 272-82

[24] Werapun W, Tirawanichakul Y and Waewsak J 2015 Comparative study of five methods to estimate Weibull parameters for wind speed on Phangan Island, Thailand Energy Procedia 79 976-81

[25] Carvalho D, Rocha A, Gómez-Gesteira M and Santos C S 2014 Offshore wind energy resource simulation forced by different reanalyses: comparison with observed data in the Iberian Peninsula Applied Energy 134 57-64

[26] Carvalho D, Rocha A, Gómez-Gesteira M and Santos C S 2014 WRF wind simulation and wind energy production estimates forced by different reanalyses: comparison with observed data for Portugal Applied Energy 117 116-26

[27] Staffell I and Pfenninger S 2016 Using bias-corrected reanalysis to simulate current and future wind power output Energy 114 1224-39

[28] Memon N, Jafari A H, Yousuf I and Khan S A 2010 Analysis of data of AEDB-UNDP (WEP) wind masts installed in Gharo-Keti Bandar wind corridor. AEDB, Islamabad, Pakistan)

[29] Schallenberg-Rodriguez J 2013 A methodological review to estimate techno-economical wind energy production Renewable and Sustainable Energy Reviews 21 272-87

[30] Hellmann G 1914 Über die Bewegung der Luft in den untersten Schichten der Atmosphäre: Königlich Preussischen Akademie der Wissenschaften)
[31] Manwell J F, McGowan J G and Rogers A L 2009 Wind Energy Explained: Theory, Design and Application: Wiley

[32] Gualtieri G and Secci S 2011 Comparing methods to calculate atmospheric stability-dependent wind speed profiles: A case study on coastal location Renewable Energy 36 2189-204

[33] Staffell I and Green R 2014 How does wind farm performance decline with age? Renewable Energy 66 775-86

[34] Carvalho D, Rocha A, Gómez-Gesteira M and Silva Santos C 2014 Comparison of reanalyzed, analyzed, satellite-retrieved and NWP modelled winds with buoy data along the Iberian Peninsula coast Remote Sensing of Environment 152 480-92

[35] Hawkins S, Eager D and Harrison G P 2011 Characterising the reliability of production from future British offshore wind fleets. In: IET Conference on Renewable Power Generation (RPG 2011), pp 1-6

[36] Ruti P M, Marullo S, D’Ortenzio F and Tremant M 2008 Comparison of analyzed and measured wind speeds in the perspective of oceanic simulations over the Mediterranean basin: Analyses, QuikSCAT and buoy data Journal of Marine Systems 70 33-48

[37] Dhanju A, Whitaker P and Kempton W 2008 Assessing offshore wind resources: An accessible methodology Renewable Energy 33 55-64

[38] Petersen E L, Mortensen N G, Landberg L, Højstrup J and Frank H P 1998 Wind power meteorology. Part I: climate and turbulence Wind Energy 1 2-22

[39] Fox N I 2011 A tall tower study of Missouri winds Renewable Energy 36 330-7

[40] Dee D P, Uppala S M, Simmons A J, Berrisford P, Poli P, Kobayashi S, Andrae U, Balsamo M A, Balsamo G, Bauer P, Bechtold P, Beljaars A C M, van de Berg L, Bidlot J, Bormann N, Delsol C, Dragani R, Fuentes M, Geer A J, Haimberger L, Healy S B, Hersbach H, Holm E V, Isaksen L, Källberg P, Köhler M, Matricardi M, McNally A P, Monge-Sanz B M, Morcrette J J, Park B K, Peubey C, de Rosnay P, Tavolato C, Thépaut J N and Vitart F 2011 The ERA-Interim reanalysis: configuration and performance of the data assimilation system Quarterly Journal of the Royal Meteorological Society 137 553-97

[41] Saha S, Moorthi S, Pan H-L, Wu X, Wang J, Nadiga S, Tripp P, Kistler R, Woollen J, Behringer D, Liu H, Stokes D, Grumbine R, Gayno G, Wang J, Hou Y-T, Chuang H-y, Juang H-M H, Sela J, Iredell M, Treadon R, Kleist D, Delis P V, Keyser D, Derber J, Ek M, Meng J, Wei H, Yang R, Lord S, Dool H v d, Kumar A, Wang W, Long C, Chelliah M, Xue Y, Huang B, Schemm J-K, Ebisuzaki W, Lin R, Xie P, Chen M, Zhou S, Higgins W, Zou C-Z, Liu Q, Chen Y, Han Y, Cucurull L, Reynolds R W, Rutledge G and Goldberg M 2010 The NCEP Climate Forecast System Reanalysis Bulletin of the American Meteorological Society 91 1015-58

[42] Carvalho D, Rocha A, Gómez-Gesteira M and Silva Santos C 2014 WRF wind simulation and wind energy production estimates forced by different reanalyses: Comparison with observed data for Portugal Applied Energy 117 116-26

[43] Carvalho D, Rocha A and Gómez-Gesteira M 2012 Ocean surface wind simulation forced by different reanalyses: Comparison with observed data along the Iberian Peninsula coast vol 56