An Innovative Method to Evaluate the Real Performance of Wind Turbines: Case Study from Mauritania

Original
An Innovative Method to Evaluate the Real Performance of Wind Turbines: Case Study from Mauritania / Amato, Angela; Spertino, Filippo; Malgaroli, Gabriele; Ciocia, Alessandro; Heiba, Bamba; Yahya, Ahmed Med; Mahmoud, Abdel Kader. - ELETTRONICO. - (2021). ((Intervento presentato al convegno 2021 IEEE International Conference on Environment and Electrical Engineering and 2021 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe) tenutosi a Bari, Italy nel 7-10 Sept. 2021 [10.1109/EEEIC/ICPSEurope51590.2021.9584790].

Publisher:
IEEE

Published
DOI:10.1109/EEEIC/ICPSEurope51590.2021.9584790

An Innovative Method to Evaluate the Real Performance of Wind Turbines: Case Study from Mauritania

line 1: 1st Given Name Surname
line 2: *dept. name of organization (of Affiliation)*
line 3: *name of organization (of Affiliation)*
line 4: City, Country
line 5: email address or ORCID

line 1: 2nd Given Name Surname
line 2: *dept. name of organization (of Affiliation)*
line 3: *name of organization (of Affiliation)*
line 4: City, Country
line 5: email address or ORCID

line 1: 3rd Given Name Surname
line 2: *dept. name of organization (of Affiliation)*
line 3: *name of organization (of Affiliation)*
line 4: City, Country
line 5: email address or ORCID

line 1: 4th Given Name Surname
line 2: *dept. name of organization (of Affiliation)*
line 3: *name of organization (of Affiliation)*
line 4: City, Country
line 5: email address or ORCID

line 1: 5th Given Name Surname
line 2: *dept. name of organization (of Affiliation)*
line 3: *name of organization (of Affiliation)*
line 4: City, Country
line 5: email address or ORCID

line 1: 6th Given Name Surname
line 2: *dept. name of organization (of Affiliation)*
line 3: *name of organization (of Affiliation)*
line 4: City, Country
line 5: email address or ORCID

***Abstract*— The power-wind speed curve of a Wind Turbine (WT) is measured by the manufacturer in ideal conditions, and the wind speed is detected at the entrance of the WT rotor. However, in wind power plants, this quantity is rarely available because, generally, the wind speed is measured by an anemometer behind the WT. In this case, this value is lower than the wind speed at the entrance of the WT rotor. As a result, the WT performance, evaluated using these wind speed data, may be unrealistic. Thus, their correction is needed to be compared with manufacturer declaration. In this context, the present work proposes an innovative method to correctly assess the performance of WTs. In particular, it is based on the manufacturer curve, correcting the wind speeds measured behind the WTs rotor. The correction is applied to one WT (rated power = 2 MW) of a wind farm in Mauritania.**

Keywords—Wind Turbines, wind speed correction, WT efficiency evaluation, manufacturer power curve.

I. INTRODUCTION

In the last decades, the spread of the Renewable Energy Sources (RES) is rapidly increasing due to the growing energy consumptions and the need for meeting the requirements of minimum environmental impact [1]. In this context, Wind Turbines (WTs) represent an effective solution to generate electricity, being reliable, environmentally friendly, and with low marginal costs [2]. However, WTs are intermittent, as well as other RES. The installation of a storage may mitigate this drawback, increasing their availability [3]. During 2020, new European wind installations were about 15 GW, reaching a total capacity of 215 GW at the end of 2020 [4]. Wind turbines can be fixed or variable speed. The main difference between these two typologies consists of the adjustment of the rotor speed. Indeed, variable speed WTs can adapt their rotor speed to maximize the conversion of the aerodynamic wind power in electricity [5]. Nevertheless, variable speed WTs require the measurement of the wind speed. This task is performed by an anemometer, which increases the cost and the size of the system. This device is, generally, positioned behind the WT rotor. In such condition, the stream tube expands before and after the three-bladed rotor. Thus, its cross section increases, while its kinetic energy (and its speed) decreases with respect to the unperturbed wind flow [6]. However, the power curve provided by the manufacturer for each turbine is traced considering the speed of the wind flow at the entrance of the WT rotor. Therefore, the measured wind speed cannot be used to compare the WT performance with the manufacturer data. Indeed, according to this speed value, the turbine may outperform the manufacturer declaration. Hence, a correction of the experimental wind speed is required. Moreover, the power curve by the manufacturer is provided (according to the International Standards in IEC 61400-12-1 [7]) in ideal conditions of minimum turbulence, flat terrain and absence of wakes due to obstacles. In literature the most common techniques to correct the wind speed by the WT anemometer are two [7, 8]. However, these methods require additional measurements by a meteorology mast in the neighbourhood of the turbines. Generally, this information is missing in wind power plants, and these corrections cannot be applied.

In the present work, an alternative method is proposed to correct the performance of wind turbines. This methodology is based on the manufacturer power curve, and it overcomes the issues of the most common techniques in literature. Indeed, this method requires the measurement by the WT anemometer only, and it is applied to a case study in Mauritania.

This paper is organized as follows: section II describes the steps of the proposed method. Section III defines the main quantities evaluated in the work. In section IV, the case study is presented, and section V reports the results of the correction. Finally, section VI contains the conclusions.

II. DESCRIPTION OF THE METHOD

The proposed method aims to correctly assess the efficiency of WTs starting from the knowledge of the manufacturer power curve and the wind speed detected by the WT anemometer v_{raw}. This methodology assumes that the manufacturer power curve describes the best performance of the turbine: thus, for a specific wind speed, the maximum achievable power is the value stated by this curve. As a result of this method, for each output power P_{k} from the manufacturer curve, an analytical equation is obtained between each manufacturer wind speed v_{k}, and a specific experimental wind speed.

In particular, the methodology consists of the following steps:

- Step A: Normalization of experimental data to condition of reference air density. The manufacturer power curve describes the performance of WTs in conditions of reference air density (at 0 m above sea level and 15 °C, $\rho_{\mathrm{ref}} = 1.225$ kg/m^3). However, the experimental data are not measured in this condition, and they need to be normalized in order to perform a comparison with the manufacturer curve. According to [7], the experimental data for WTs with active power control can be corrected using the following equation:

$$v_{\mathrm{WT}} = v_{\mathrm{raw}} \cdot (\rho_{\mathrm{air}}/\rho_{\mathrm{ref}})^{1/3} \qquad (1)$$

  where v_{WT} is the wind speed corrected to the reference air density condition, and ρ_{air} is the air density during the experimental acquisition.

- Step B: Removal of experimental data with turbulence larger than 10% [9]. Experimental data are measured with a fixed time interval (10 min is a common time step of averaging the sampled points). For each measured wind speed, the turbulence is the ratio between the standard deviation of the wind speed and its average value in the time interval [10].

- Step C: Selection of the experimental set S_{k}. Considering the manufacturer power curve, a working point k, corresponding to power P_{k} and wind speed v_{k}, is selected. Then, a dataset containing the experimental data in the neighbourhood of P_{k} is identified. In particular, the experimental wind speeds v_{WT} with power between $P_{\mathrm{k}} \cdot (1 - \varepsilon)$ and $P_{\mathrm{k}} \cdot (1 + \varepsilon)$ are identified. In the present work, ε is = 0.01. S_{k} is mathematically described as follows:

$$S_{\mathrm{k}} = \left\{\left\{v_{\mathrm{WT,i}}, P\left(v_{\mathrm{WT,i}}\right)\right\}: P\left(v_{\mathrm{WT,i}}\right) \in \quad [P_{\mathrm{k}} \cdot (1-\varepsilon), P_{\mathrm{k}} \cdot (1+\varepsilon)]\right\} \qquad (2)$$

- Step D: Evaluation of the Empiric Cumulative Distribution Function (ECDF) for a specific wind speed. For each value of v_{k} (in Fig. 1, $v_{\mathrm{k}} = 8$ m/s), the corresponding ECDF can be approximated by a proper Probability Density Function (PDF) $f(v)$. In this case, the ECDF is approximated by the PDF of the factorial function Γ:

$$f(v) = \frac{{v_{\mathrm{k}}}^{a-1}}{b^{a} \cdot \Gamma(a)} \cdot e^{-\frac{v}{b}} \quad (v_{\mathrm{k}} \geq 0) \qquad (3)$$

  where $\Gamma(x)$ is the gamma function [11]; a is the ratio between the square of the mean value of S_{k} and the square of the standard deviation of S_{k}. The quantity b is the ratio between the mean value of S_{k} and a.

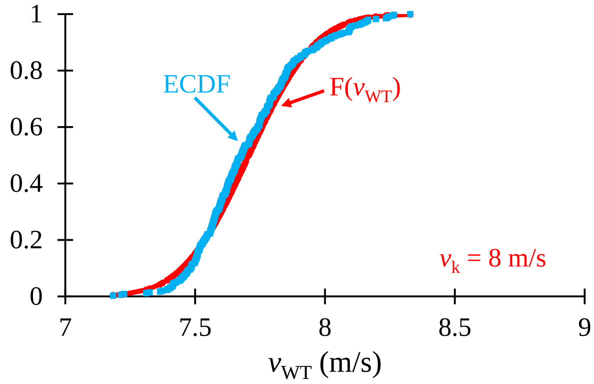

Fig. 1. Evaluation of ECDF and PDF for $v_{\mathrm{k}} = 8$ m/s.

- Step E: Selection of $v_{\mathrm{k}}^{5\%}$. Starting from the PDF $f(v)$, the wind speed with the 5% of probability to not be exceeded in S_{k} ($v_{\mathrm{k}}^{5\%}$) is identified. The quantity $v_{\mathrm{k}}^{5\%}$ is lower than 95% of the wind speeds in S_{k}. The value 5% is selected according to the uncertainty of the WT measurement system. Steps C-E are repeated for each working point of the manufacturer power curve (thus, for each $P_{\mathrm{k}}(v_{\mathrm{k}})$).

- Step F: Linear regression of experimental wind speeds. A linear equation that describes v_{k} as a function of the corresponding $v_{\mathrm{k}}^{5\%}$ is identified. The fit of the linear regression to the experimental data is evaluated through the parameter R^2, which ranges from 0 (non-suitable models) to 1 (best model).

The proposed method is only applicable for wind speeds corresponding to a WT output power lower than the nominal one. For higher values, the correspondence between the wind speed and the output power is not unique, as the rated power can be obtained for several wind speeds.

III. ESTIMATION OF WT EFFICIENCY

The ratio between the electric power output by a WT and the aerodynamic wind power entering its rotor is the average WT efficiency η, considering both powers as average values within 10 min or other average intervals.

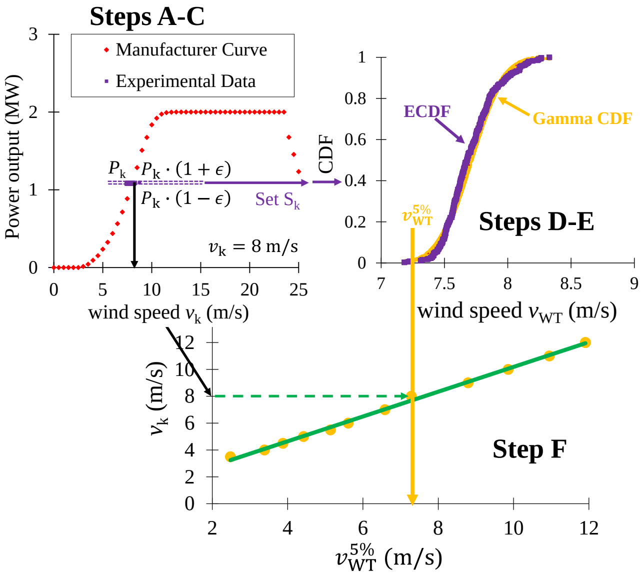

Fig. 2. Scheme of the proposed methodology.

In particular, the aerodynamic wind power P_{aer} is defined in the following way [12]:

$$P_{\text{aer}} = \frac{1}{2}\rho_{\text{air}}\frac{\pi}{4}D^2 v_{\text{entr}}^3 \tag{4}$$

where D is the WT diameter and v_{entr} is the wind speed at the entrance of the WT rotor. The efficiency can be calculated with a different equation. Indeed, it is also, for a specific time interval Δt, the ratio between the electrical and the aerodynamic energies (E_{el} and E_{aer}, respectively) [13]. Assuming the power quantities to be average values within Δt, the efficiency η is the ratio between the electrical and the aerodynamic powers (P_{el} and P_{aer}, respectively) [14]:

$$\eta = \frac{P_{\text{el}}}{P_{\text{aer}}} = \frac{P_{\text{el}} \cdot \Delta t}{P_{\text{aer}} \cdot \Delta t} = \frac{E_{\text{el}}}{E_{\text{aer}}} \tag{5}$$

In this work, a weighted yearly efficiency η^* is also evaluated [15]. This quantity is defined on a yearly basis in the following way:

$$\eta^* = \frac{\sum_{\text{year}}(\eta_k \cdot E_k)}{\sum_{\text{year}}(E_k)} = \frac{\sum_{\text{year}}(\eta_k \cdot E_k)}{E_{\text{y,exp}}} \tag{6}$$

where η_k is the efficiency of the turbine, E_k is the generated energy in the k$^{\text{th}}$ time interval (Δt = 10 min) and $E_{\text{y,exp}}$ is the generated WT energy during one year. In this work, the efficiencies η and η^* are estimated, in conditions of reference air density with equation (1), for raw and corrected wind speeds. The capacity factor of a WT is, for a specific time interval, the ratio between two quantities. The numerator is the generated electric energy by the WT, while the denominator is the energy that the WT may generate in the same time interval, working at its rated power [16]. Similarly, the number of equivalent hours h_{eq} provides the number of hours (equivalent from the energy viewpoint) for which the WT is operational at its nominal power for one year. In fact, this quantity is the ratio between the yearly generated energy and the WT rated power [17]. The availability factor is the percentage of operation time during which the WT is expected to operate. In particular, it is the ratio between the WT uptime and its global operation time, including downtimes due to failures or maintenance operations [18, 19].

IV. CASE STUDY

The above-described method is applied to one WT of a wind farm (rated power = 30 MW) in Nouakchott (Mauritania, Africa), using data from a measurement campaign in 2017.

Fig. 3. Wind power plant in a flat terrain.

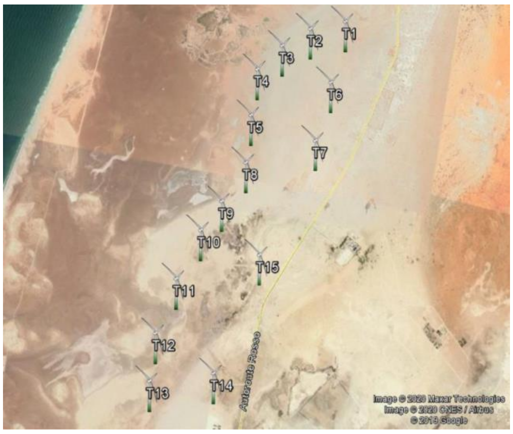

Fig. 4. Location of the wind power plant (satellite view).

Each WT has a nominal power of 2 MW, hub height = 90 m and a three-bladed rotor. Its cut-in speed $v_{\text{c-in}}$ is equal to 3 m/s, while the cut-out speed $v_{\text{c-out}}$ is 25 m/s, and the rated wind speed is 14 m/s. A cup anemometer acquires the direction of the wind speed and its absolute value, providing an uncertainty between 0.17 m/s and 0.5 m/s [20].

V. RESULTS

The electric power measured by WT sensors (blue dots) and the manufacturer curve (red line) are presented in Fig. 5. In this case, the experimental data are not corrected: indeed, many points are to the left of the manufacturer curve. This behaviour is not realistic because WTs cannot outperform the manufacturer's statement, and this is due to a wrong measurement of the wind speed. This quantity is measured by the WT anemometer (hence, behind the rotor). On the contrary, the manufacturer power curve (red line) is provided considering the wind speed detected at the entrance of the rotor (thus, it refers to the unperturbed wind flow in front of the WT).

Applying the method proposed in this work on the measured wind speeds, the linear regression presented in Fig. 6 is obtained ($R^2 = 0.974$). The performance of the WT is limited to a constant power after its rated wind speed. For this reason, this method cannot be applied for values close to and above the rated wind speed. In this work, the correction is performed in the range 4 m/s - 11 m/s. Moreover, according to the cumulative function of the wind speed distribution for this site (Fig. 7, blue line), about 90% of detected wind speeds (green arrow) are in this range.

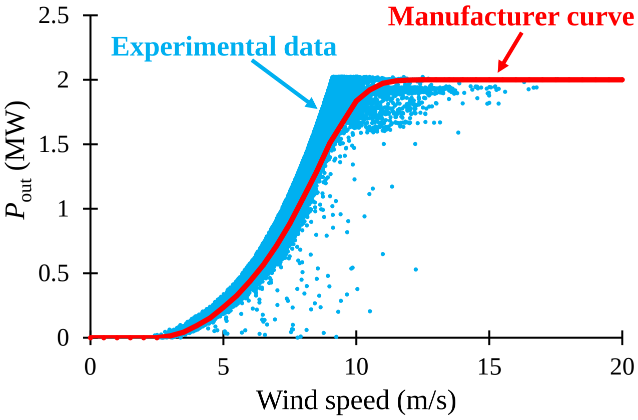

Fig. 5. Uncorrected data vs. Manufacturer power curve.

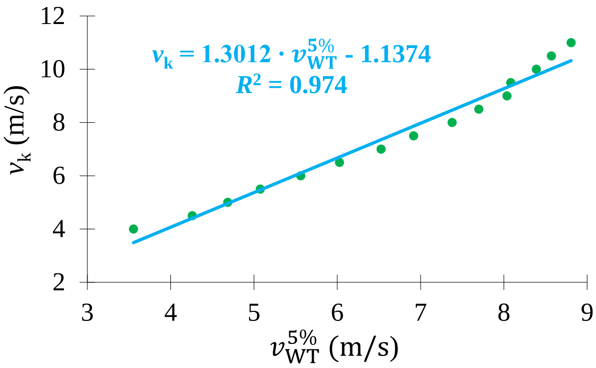

Fig. 6. Regression results of the three methods.

Although this methodology can be applied to a limited range of wind speeds, it does not require any information beyond the measurements by the WT anemometer. Therefore, this correction is of interest for the wind farms without experimental data by a meteorological station nearby the turbines. Fig. 8 shows the measured electric power (blue dots) as a function of the wind speed corrected using the equation in Fig. 6. With respect to Fig. 5, experimental data after correction are to the right of the manufacturer power curve (red line). Thus, corrected data obviously confirm that the WT does not outperform the manufacturer data for the majority of points. Moreover, Fig. 8 indicates that the correction is less effective at low wind speeds (< 6 m/s) because of the lack of experimental data in that region (more than 90% of the corrected wind speeds are > 6 m/s). However, the energy generation at low wind speeds is significantly lower than at the medium wind speeds, which are the most frequent for this site, according to the PDF in Fig. 7.

The average yearly efficiency $\bar{\eta}$ is the mean value of the efficiencies η evaluated in each 10-min time interval. In the wind speed range 4 m/s - 11 m/s, $\bar{\eta}$ for raw data is equal to 49.4%. This value is unrealistic as it results higher than the maximum efficiency stated by the manufacturer (46.8%). On the contrary, after the correction, the average yearly efficiency assumes a realistic value, decreasing to 34.7%. As a result, $\bar{\eta}$ for corrected data is ≈30% lower than the raw data. Similarly, the weighted yearly efficiency η^* after the correction is ≈30% lower than the uncorrected value. Indeed, η^* before and after the method is 50.0% and 34.9%, respectively. The efficiencies $\bar{\eta}$ and $\eta^*$are also evaluated over narrower wind speed ranges. For wind speeds between 4 m/s and 6 m/s, $\bar{\eta}$ is 44.6% for raw data and decreases to 35.7% (≈-20%) after the correction.

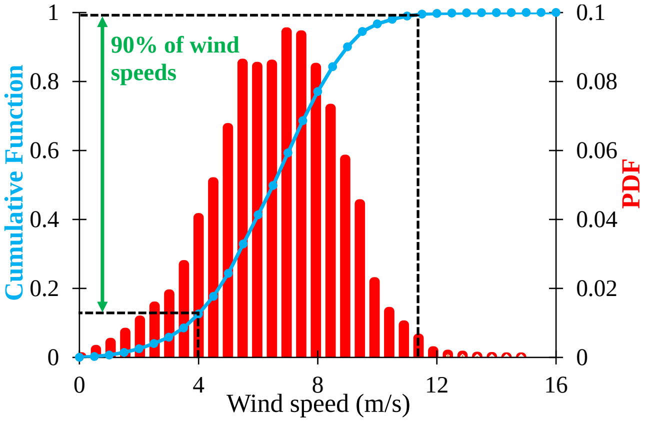

Fig. 7. Cumulative function and PDF of wind speed distribution.

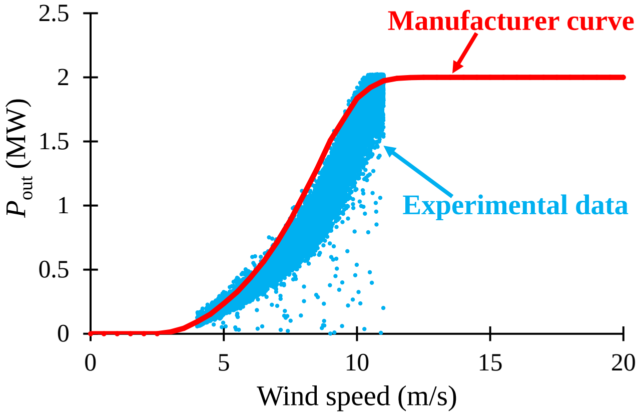

Fig. 8. Corrected data vs. Manufacturer power curve.

The weighted yearly efficiency after the method also decreases by ≈20%, from 46.0% to 36.6%. For wind speeds in the range 6 m/s - 11 m/s, the difference between the efficiency results with raw and corrected data is greater. Indeed, $\bar{\eta}$ is 50.1% for raw data and 34.6% after the correction (≈-31%), and η^* decreases by ≈30%, from 50.1% to 34.8%.

In addition, the monthly capacity factor of the WT under study is evaluated for 2017. This quantity ranges from 27.7% in September to 69.6% in February, as shown in Fig. 9. The yearly capacity factor is 49%. Regarding the number of equivalent hours, the WT operates at its rated power for 4284 h. Finally, the availability factor is 84.5% for 2017.

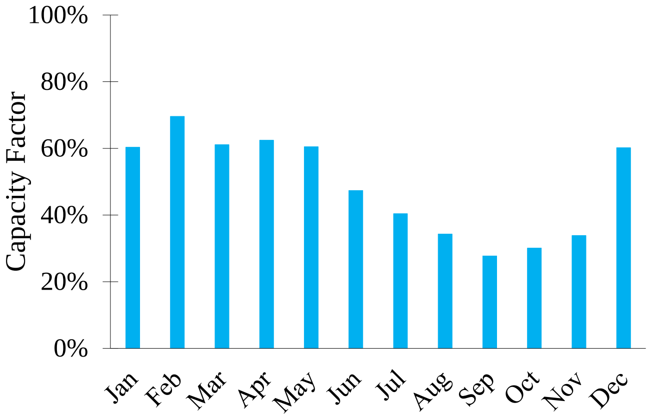

Fig. 9. Average monthly capacity factors.

VI. Conclusions

The power-wind speed curve of a Wind Turbine (WT) is measured by the manufacturer considering the wind speed detected at the entrance of the WT rotor. However, in wind power plants, this quantity is rarely available because, generally, the wind speed is measured by an anemometer behind the WT. This quantity is lower than the value at the entrance of the WT rotor, and the WT performance evaluated using this wind speed may be unrealistic. This work proposes an innovative method to correctly assess the performance of WTs. In particular, the correction evaluates the wind speed at the entrance of the WT rotor using the measurements by the turbine anemometer and the manufacturer power curve. The presented methodology is applied to one 2 MW wind turbine of a wind farm in Mauritania. The results show that, in the range 4 m/s - 11 m/s, the average and weighted yearly efficiencies using uncorrected data (49.4% and 50.0%, respectively) exceed the performance declared by the manufacturer. After the correction, these quantities decrease by ≈30%, reaching realistic values of 34.7% and 34.9%, respectively. The evaluation of the efficiencies over narrower wind speed ranges demonstrates that the correction is more effective in the range 6 m/s - 11 m/s, which contains the most frequent wind speeds. The capacity factor is higher in winter and spring months, reaching the maximum value in February (≈70%). The yearly capacity factor is 49%. Finally, the availability factor of the WT under study is 84.5% for 2017.

References

[1] International Energy Agency (IEA), “Global Energy Review 2021”, available at https://www.iea.org/reports/global-energy-review-2021

[2] International Renewable Energy Agency (IRENA), “Future of wind: Deployment, investment, technology, grid integration and socio-economic aspects”, available at https://www.irena.org/publications/2019/Oct/Future-of-wind

[3] A. Ciocia, A. Amato, P. Di Leo, S. Fichera, G. Malgaroli, F. Spertino, S. Tzanova, ”Self-Consumption and Self-Sufficiency in Photovoltaic Systems: Effect of Grid Limitation and Storage Installation,” Energies 2021, 14, 1591.

[4] Global Wind Energy Council (GWEC), “Global Wind Report 2021”, available at https://gwec.net/global-wind-report-2021/

[5] S. M. Islam, C. V. Nayar, A. Abu-Siada, and M. M. Hasan, “25 - Power Electronics for Renewable Energy Sources” in Power Electronics Handbook, 4th ed., Elsevier: 2018, pp.783-827.

[6] J. D. Sørensen, and J. N. Sørensen, “6 - Aerodynamic design of wind turbine rotors” in Wind Energy Systems - Optimising Design and Construction for Safe and Reliable Operation, vol. 10, Woodhead Publishing: 2011, pp.160-207.

[7] IEC 61400-12-1:2017 - Power performance measurement of electricity producing wind turbines.

[8] A. Carullo, A. Ciocia, P. Di Leo, F. Giordano, G. Malgaroli, L. Peraga, F. Spertino, and A. Vallan, “Comparison of correction methods of wind speed for performance evaluation of wind turbines”, Proc. of 24th IMEKO-TC4 International Symposium, 2020 September 14-16, pp. 291-296.

[9] V. Cocina, P. Di Leo, M. Pastorelli, and F. Spertino, “Choice of the most suitable wind turbine in the installation site: A case study," 2015 International Conference on Renewable Energy Research and Applications (ICRERA), Palermo, 2015, pp. 1631-1634.

[10] C. MacEachern and İ. Yıldız, “1.16 Wind Energy,” Comprehensive Energy Systems, 2018, pp. 665-701.

[11] P. J. Davis, “Leonhard Euler's Integral: A Historical Profile of the Gamma Function”, American Mathematical Monthly, vol. 66, Issue 10, 1959, pp. 849-869.

[12] M. Kesraoui, S. A. Lagraf, and A. Chaib, “Aerodynamic power control of wind turbine using fuzzy logic,” 2015 3rd International Renewable and Sustainable Energy Conference (IRSEC), 2015, pp. 1-6, doi: 10.1109/IRSEC.2015.7455110.

[13] A. Sedaghat, A. Mostafaeipour, M. Rezaei, M. Jahangiri, and A. Mehrabi, “A new semi-empirical wind turbine capacity factor for maximizing annual electricity and hydrogen production,” International Journal of Hydrogen Energy, vol. 45, Issue 32, 2020, pp. 15888-15903.

[14] F. Spertino, A. Ciocia, P. Di Leo, G. Iuso, G. Malgaroli, and L. Roberto, “Experimental testing of a horizontal-axis wind turbine to assess its performance,” 22nd IMEKO TC4 International Symposium and 20th International Workshop on ADC Modelling and Testing 2017: Supporting World Development Through Electrical and Electronic Measurements, 2017-September, pp. 411-414.

[15] A. Carullo, A. Ciocia, G. Malgaroli, and F. Spertino, “An Innovative Correction Method of Wind Speed for Efficiency Evaluation of Wind Turbines”, ACTA IMEKO 2021, Under review.

[16] R. Ghajar, R. Chedid, and M. Badawieh, “Wind turbine optimal site matching based on capacity and availability factors,” 2015 International Conference on Clean Electrical Power (ICCEP), 2015, pp. 253-257, doi: 10.1109/ICCEP.2015.7177632.

[17] R. Laleman, L. Balduccio, and J. Albrecht, “The Role of Biomass in the Renewable Energy System,” 25th International Conference on Efficiency, Cost, Optimization and Simulation of Energy Conversion Systems and Processes, Proceedings, 2012, vol. 5, pp. 381-408.

[18] F. Spertino, E. Chiodo, A. Ciocia, G. Malgaroli, and A. Ratclif, “Maintenance Activity, Reliability Analysis and Related Energy Losses in Five Operating Photovoltaic Plants,” 2019 IEEE International Conference on Environment and Electrical Engineering and 2019 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe), Genova, Italy, 2019, pp. 1-6, doi: 10.1109/EEEIC.2019.8783240.

[19] F. Spertino, E. Chiodo, A. Ciocia, G. Malgaroli, and A. Ratclif, “Maintenance Activity, Reliability, Availability, and Related Energy Losses in Ten Operating Photovoltaic Systems up to 1.8 MW”, (2021) IEEE Transactions on Industry Applications, 57 (1), pp. 83-93, doi 10.1109/TIA.2020.3031547.

[20] B. Heiba, A. Yahya, M. Taha, N. Khezami, and A. Mahmoud,. “Performance analysis of 30 MW wind power plant in an operation mode in Nouakchott, Mauritania,” 2021, vol. 12, pp. 532-541.