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ANALYSIS OF WIND TURBINE PERFORMANCE, OPTIMIZATION, TECHNICAL-ECONOMIC AND ENVIRONMENTAL FEASIBILITY

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Abstract

To make wind energy more usable, a new prototype of high efficiency wind turbine will be developed in this work. For this purpose, a new proprietary mathematical model will be implemented, for the design of wind turbines and new design concepts, in order to maximize the energy capturing capacity of the wind turbine. Currently the numerical simulations for predicting the performance of a wind turbine are carried out with 3D CFD programs (Computational Fluid Dynamic) characterized by high reliability, but which at the same time require significant resources and high calculation times. As an alternative to CFD codes, both the scientific and industrial communities use one-dimensional calculation models. These codes, if properly implemented, can provide sufficiently correct results, but characterized by modest resources and very short calculation times. All this allows to carry out numerous simulations runs in reduced times, reaching the optimal configuration of the turbine in a few minutes. An environmental analysis of the proposed technological innovation, measured making use of the most suitable widespread environmental reporting tools, is then proposed and recommended, through an inventory of the emissions of environmental impacts, according to a Life Cycle Assessment perspective. An evaluation of the competitiveness of the new technology has to be implemented, in comparable contexts, to verify its performance in terms of economic and environmental sustainability. Finally, a cost-benefit verification of the investment and its socio-cultural impact is also necessary, considering the production process of the turbine and its implementation, in view of the decarbonization of the economy too.

Key words: CFD, economic analysis, energy, environmental impacts, wind turbine

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1. Introduction

Nowadays, at both academic and industry level, the most used mathematical model in order to fulfill the fluid dynamic design of wind turbines is the one based on BEM (Blade Element Momentum) Theory (Buhl, 2005; Corten, 2001; Lanzafame and Messina, 2007; Meyer and Kroger, 2001; Moriarty and Hansen, 2005), founded on Glauert theory (Glauert, 1926). Although not offering the accuracy of CFD (Computational Fluid Dynamic) codes, the mathematical model offers several benefits, among which the calculation speed (each numerical simulation is carried out in a few seconds) (Lanzafame and Messina, 2007; Lanzafame and Messina, 2010).

Without going into the details of the mathematical calculation, once the aerodynamic profile to be used in the wind turbines' production has been selected in view of the experimental data regarding lift and drag, the traditional mathematical model determines the wind turbine's twist by imposing an angle of attack along the entire turbine which is equal to the one maximizing the lift and drag ratio. Additionally, during the design phase, a certain

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wind speed is selected, in order to create operating conditions toward power and torque maximization.

The aforesaid process might be implemented when planning a wind turbine able to be employed in several types of installation sites, characterized by different wind speed distributions. Instead, when the goal is the designing of a wind turbine for a specific site, the aforementioned process can not represent the optimal combination of decisions to achieve the maximum level of energy produced in a single year (AEP – Annual Energy Production). Thus, the yet described new designing method becomes essential when a wind turbine must be used with low wind velocity.

In this paper, we will present the methodology that should be adopted in the perspective of AEP maximization in the context of an installation site characterized by limited wind. Moreover, several designing strategies will be employed emphasizing how each one of them increases the AEP in comparison to the energy produced when following the traditional method. We will also introduce the main methodological guidelines concerning the way for taking into consideration the economic and environmental aspects, their impacts and their measurement in the framework of green energy production.

2. Material and methods

The procedure followed for the design of the wind turbine blades object of this work is to:

- establish a design wind speed (called v_0);
- maximize the efficiency for the speed v_0;
- evaluate its performance with variable wind speeds.

As already mentioned, in the literature Gash and Tewele, 2002; Sphera, 2009), there are indicators according to which the design of wind turbine blades must be performed for values of the angle of attack $\alpha=\alpha_{max}$, an angle that maximizes the lift/drag ratio. Following these indicators, the first value of α that was entered as input to the code for the design was precisely α_{max}. In order to find the optimal operating conditions (maximum AEP) a turbine with three blades (N_b), with a tip radius (R_1) equal to 2 m and a hub radius (R_b) of 0.4 m of has been studied. The radial sectors (s) have been set equal to 20 and the wind speed (v_0) equal to 4 m/s, equal to the average speed of the histogram characterizing the installation site shown in Fig. 1. For the wind turbine study, two numerical codes were used (Lanzafame and Messina, 2007), and a value of $\alpha = \alpha_{max}$ (α is the angle of attack, and α_{max} il the angle of attack which maximizes the lift to drag ratio) which for the chosen profile (S809) is equal to 6.16°, has been set. For the determination of the chord, reference was made to the following equation (Eq. 1) based on the still valid theory proposed by Schmitz (1955).

$$c = \frac{1}{N_b} * \frac{16 * \pi * r}{c_L} * \left[sin\left(\frac{\phi}{3}\right)^3 \right] \tag{1}$$

where: Φ is the angle between the air foil chord and the plane of rotation and c_L is the air foil lift coefficient.

Lift and drag experimental coefficient have been taken from scientific literature (Jonkman, 2003) and (Lindeburg, 2003), and have been interpolated as report in Lanzafame and Messina (2007). While the twist value (Θ) was calculated using the following formula (Eq. 2):

$$\vartheta = \phi - \alpha \tag{2}$$

where: α is the angle of attack.

This code outputs the twist values at certain radial position. In order to derive a mathematical function for the twist, a logarithmic polynomial of the fifth order (solid line of Fig. 2) was used to interpolate all the punctual data output from the design code. The logarithmic polynomial has the functional form of:

$$\Theta(r) = a_0 + a_1 lnr + \ldots + a_5[ln(r)]^5,$$

where a_i are constants.

Subsequently, this function was included in the code for the evaluation of performance in off-design conditions. Starting the simulation, the power curve and the power coefficient shown in the graph of Fig. 3 were determined, the graph shows that the c_p is high for values close to the design speed, but decreases rapidly for different values.

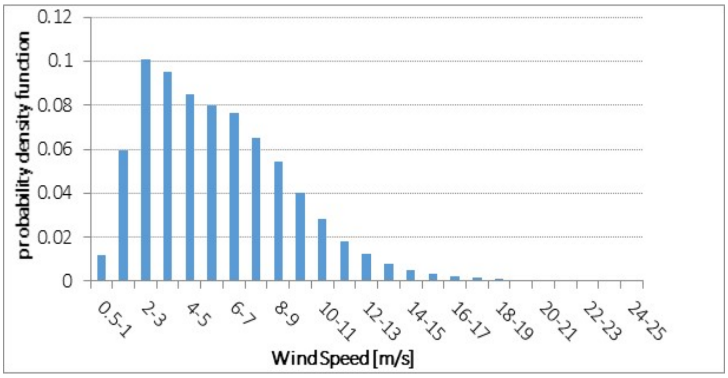

Fig. 1. Wind frequency distribution histogram (Location "Piana di Catania")

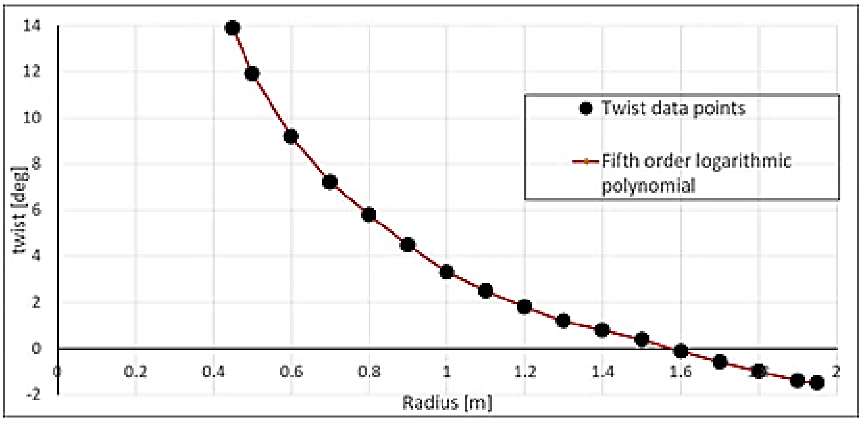

Fig. 2. Blade Twist

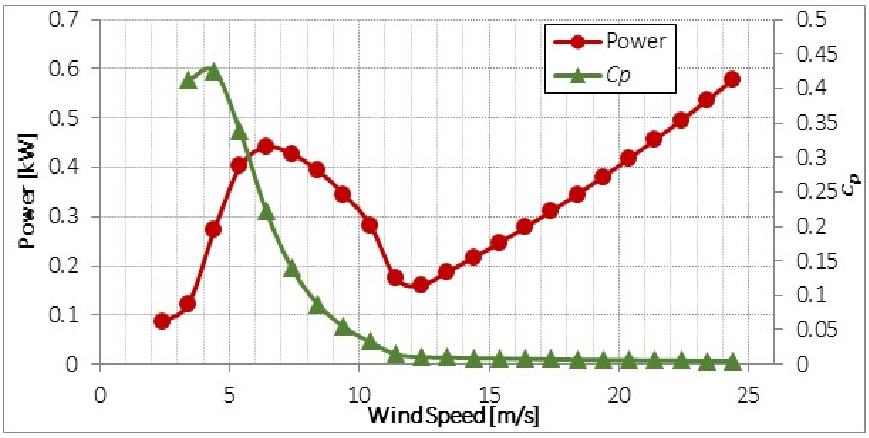

Fig. 3. Wind turbine Performance (P e c_p) designed with $\alpha = \alpha_{max}$ and $v_0 = v_{med}$

Knowing the power curve and comparing it with the wind histogram of the installation site, the AEP was calculated with the following equation (Eq. 3):

$$E_w = \sum_{j=1}^{N'_B} P_w(m_j) f_j \Delta t \tag{3}$$

where: N'_B are the sectors of width w with midpoints m_j, and with frequency f_j.

The graph in Fig. 4 shows the power curve superimposed on the frequency histogram created by collecting wind measurements at the installation site for a year (Δt = 8760 h), with N'_B = 26, w = 1 and m_j = (j-0.5). With these parameters, the estimated AEP was equal to 1674 kWh/y.

Twist correction

From Fig. 2, near the tip, the designed twist has negative value. The torque of the wind turbine depends from a tangential force directed as the rotational velocity. At the radius where the blade twist has negative value, the tangential force can change direction and generate negative torque (only for some sector of the blade). This phenomenon leads to very low c_p values and a decrease in power. Observing Fig. 3, it is possible to notice a strong decrease in power for values between 10 m/s and 15 m/s. To overcome this drawback, the twist of the blade has been modified, and near the tip the twist value has been increased. To obtain a new improved twist, the following correction (Eq. 4) was applied (Lanzafame and Messina, 2010):

$$\vartheta(r) = \sum_{i=0}^{5} a_i \cdot [\ln r]^i + x \cdot r^2 \tag{4}$$

3. Results and discussion

Following the modification reported in Eq. 4, a power curve and a new power coefficient were obtained. Fig. 5 shows that the curves for v <7 m / s remain substantially unchanged with respect to the previous ones, while for v> 7 m / s, a considerable gain is obtained both in terms of power coefficient (c_p) and Power (P).

This is visible in Fig. 5 where the new power and power coefficient curves were compared with the previous ones. Applying Eq. (3), the evaluation of the energy produced annually by the turbine, designed for α=6.16, v_0=4 m/s and with the geometry of the blades characterized by the new twist (x=1.4), an AEP = 2166 kWh/y was obtained.

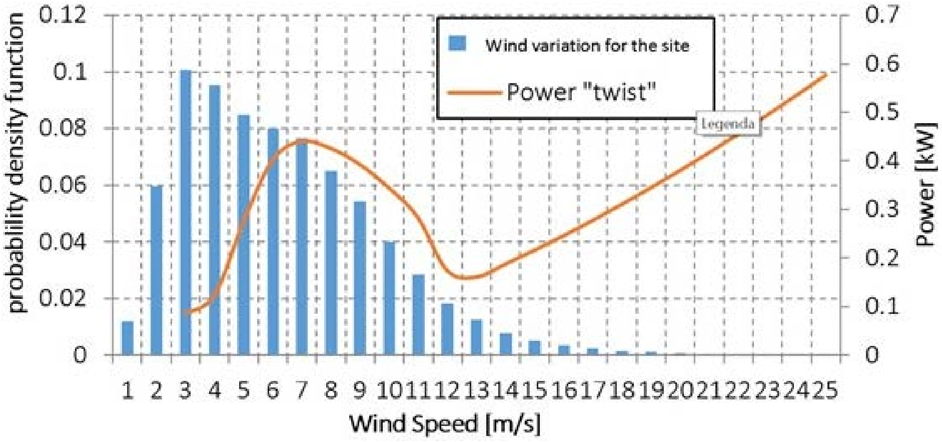

Fig. 2. Wind histogram for site and power curve for WT with $\alpha = \alpha_{max}$ and $v_0 = v_{med}$

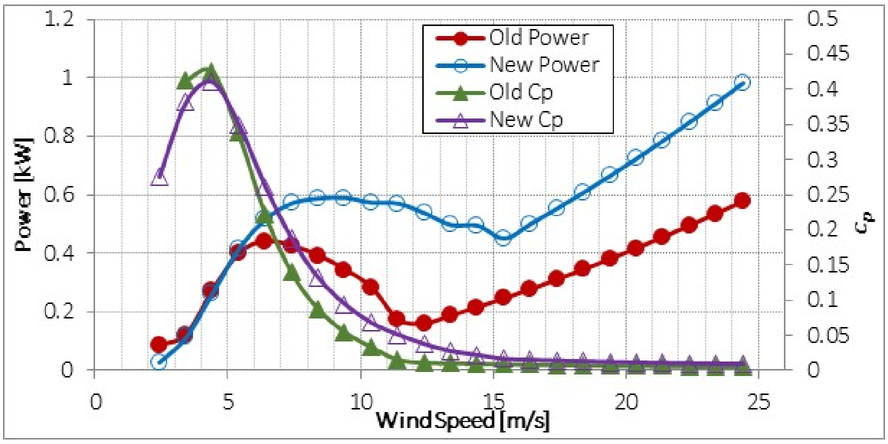

Fig. 5. Comparison between old and new power curves and power coefficient

This means that the twist correction would lead to a higher production of about 492 kWh/y thus obtaining an increase in annual production of just over 30%. To maximize the annual energy production, it is necessary to individuate the optimal values of α, v_0. This may be achieved by employing the calculation procedure previously described to calculate AEP. In a first phase, with the value of $\alpha = \alpha_{max}$ constant, varying the value of v_0 within the interval between 4 and 13 m/s with steps of 1 m/s. After the optimal value for v_0 [$v_{0\ opt(1)}$] was identified – which in this specific case is equal to 10 m/s and for which the AEP has its maximum value – the value of $v_0 = v_{0\ opt(1)}$ has been taken constant and re-runned the simulations allowing the variations of α in the range between 4° and 8°. Also, in such cases the AEP values have been calculated for each value of the angle of attack and without making corrections to the twist.

In conclusion, the point characterized by values of $\alpha = 4°$ and $v_0 = 10$ m/s (twist correction $x = 0.2$) is the optimal point for the planning of a wind turbine that would have an estimated yearly production of 8526 kWh/y. Fig. 6 represents the rotor optimized for the AEP maximization in sites characterized by limited wind. Fig. 7 displays the aerodynamic profile S809 and the twist of the wind turbine rotor. Figs. 8 and 9 display the optimize wind turbine power curve and the optimized wind turbine power coefficient.

Fig. 6. 3D representation of the designed wind turbine rotor

3.1. Economic and environmental aspects

After the assessment of the technical aspect's optimization, it is crucial to examine the economic worth and the environmental impact of the project. At this end, first of all it is necessary to compute the present value of the project cash flows, namely the temporal distribution of its monetary outflows and inflows, and the time horizon of the analysis, that is the economic life of the plant. Actually, we need also to consider several scenarios, by hypothesizing a total private or a partial public funding, through financial subsidies.

The assessment of the outflows seems pretty easy, as we know the costs of all the components of the plant, and the periodical maintenances required. Conversely, more complex is the inflows appraisal, due to the energy price dynamics, the plant obsolescence, the long-lasting economic life of the plant, and so on. In any case, we need to calculate the most important economic and financial indexes (Net Present Value, Internal Rate of Return, Payback Period), suitable to analyse the profitability of the project (Munda and Matarazzo, 2020). This kind of additional analysis is actually very important for the real fulfilment of the plant

Our study becomes even more complex if we aim to analyse the project also from the public decision maker's perspective. Indeed, in such a case, we need to explicitly consider also the economic, social, and environmental effects such as, for instance, employment repercussions, economic multipliers, potential effects on the related industries, economic and environmental sustainability, impact on the landscape. Finally, in order to take into consideration, the time value of the money, we have to adopt as discount rate the marginal production opportunity cost for private entrepreneurs, or the social discount rate for public investments.

3.2. LCC: Life Cycle Costing

LCC is a type of analysis that can be applied in various construction circumstances: for a single complete plant, for a set of components or a single component, to support decision-makers too. This analysis can be used for an existing activity as a method for evaluating future operating budgets, or for evaluating improvement options. The period that used for the analysis should be the entire life cycle of a constructed asset. In order to apply the methodology, the main features of each project should be already well defined. This methodology can improve the transparency of cost composition and decision-making process, supporting in more effective way the achieving the desired objectives.

Thanks to the LCC approach, the overall cost of a project can be determined, including the costs of planning, design, purchase, use, management, maintenance, disposal. Finally, it is used for the financial evaluation of alternative solutions identified in the course of a sustainability analysis (Clasadonte and Matarazzo, 2011).

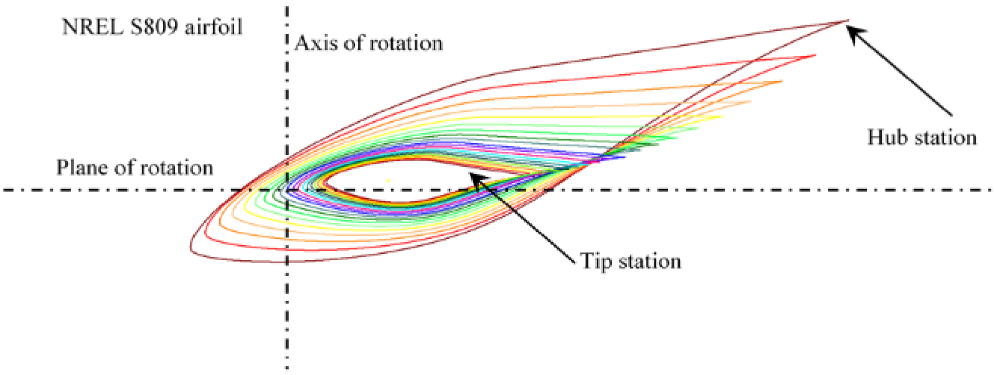

Fig. 7. 2D representation: Taper and twist of the designed wind rotor

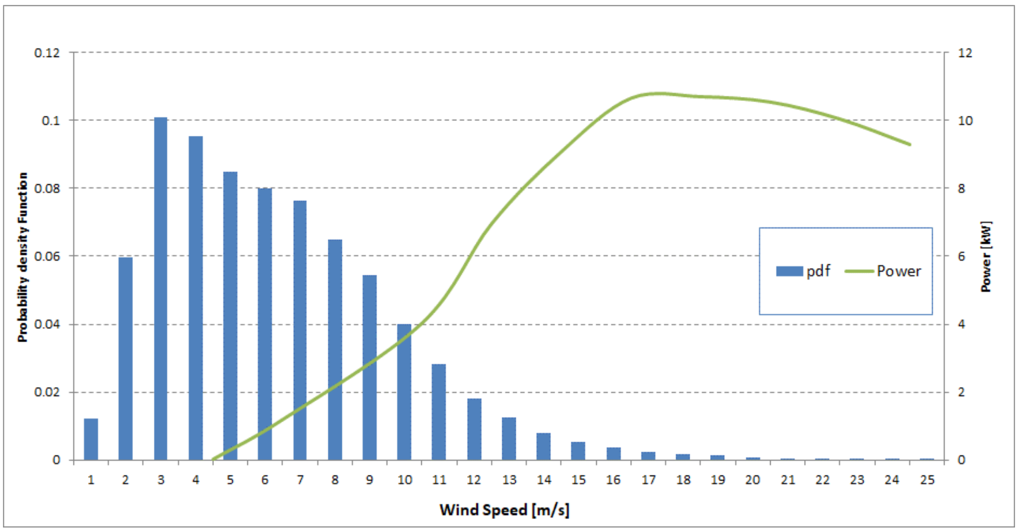

Fig. 8. The final power curves

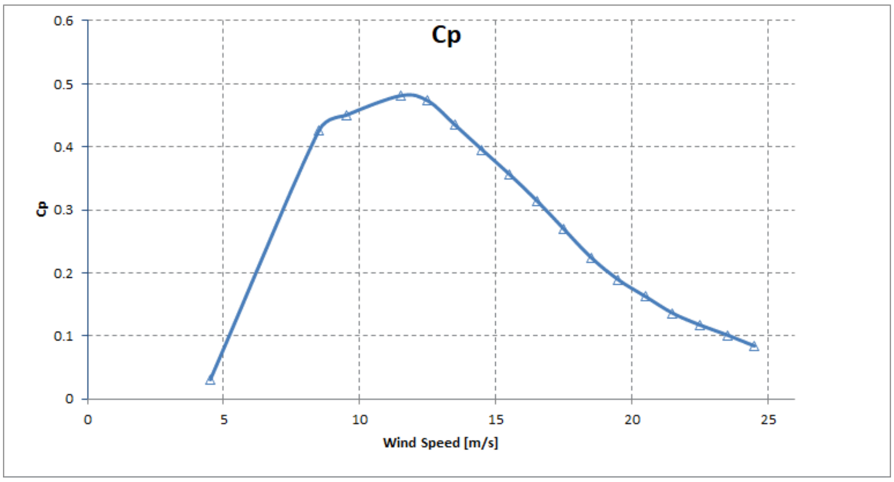

Fig. 9. The final power coefficient curve

LCC is therefore "the tool to support decision-making processes and allocate resources between alternatives of real estate intervention of new construction or renovation", suggesting the most advantageous solution, considering the performance and a time frame equal to the life cycle of the building. The methodology leads to the formulation of more verified solutions related to actual performance, thus arriving at a single indicator, also called "economic efficiency index".

Through this methodology, different projects, materials and technological solutions are evaluated, thus identifying a different relationship between construction cost, maintenance cost, and computing payback period. As a result, it is possible to observe significant differences in current operating costs and maintenance costs, energy consumption and component replacement cycles (UNI EN ISO 14040; UNI EN ISO 14041; UNI EN ISO 14042: UNI EN ISO 14043).

It is important to stress that a "traditional" LCC is not an environmental accounting tool just because it contains life cycle words (Matarazzo et al., 2018) and it is often used in an environmental context. Hence the need to correlate the two different approaches, certainly obtaining an overall vision based on multiple points of views. Analysing LCA and LCC we can see some differences such as: LCC analysis combines all relevant costs for making investment decisions; LCA analysis analytically measures the different possible environmental impacts, based on environmental criteria scores, and the different categories of damage. To date, combining LCA and LCC is a practice that is spreading all over the world as it manages to combine aspects related not only to economic sustainability, but also to environmental sustainability. The application of the joint LCC and LCA provides a solid basis on which to start a rational decision-making process.

4. Conclusions

In this paper a new wind turbine has been proposed for low wind installation site and high-power coefficients.

The optimization of the wind turbine geometry is simple and the methodology is quite original and innovative. It is based on the choice of the design wind speed and the design angle of attack through the use of the Blade Element Momentum Theory.

The final objective is to design a wind turbine able to maximize the Annual Energy Production in low wind installation sites.

In conclusion, it can be said that technical solutions to improve energy efficiency exist, able also to reduce environmental impacts. Moreover, carrying out suitable financial, economic and environmental analyses, keeping up with technology, private companies will be able to implement them. To this end, it is important to make companies increasingly aware of important issues also with regard to their activities and social responsibilities.

In a future paper, we aim to test the wind turbine in conditions of maximum performance. Additionally, once each cost item has been determined, we will apply the LCC analysis through the use of the SIMAPRO software.

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