



COB-2021-0622

ANALYSIS OF WAKE EFFECT ON THE ANNUAL ENERGY PRODUCTION OF WIND FARMS

Matheus de Oliveira Camelo
Gabriel Ivan Medina Tapia

Universidade Federal do Rio Grande do Norte, Departamento de Engenharia Mecânica, Laboratório de Sistemas Térmicos e Energias Alternativas (LSTEA). Campus Universitário Lagoa Nova, CEP 59078-970, Natal, RN, Brasil.

matheusocamelo@gmail.com

gabriel.medina@ufrn.br

Abstract. *This paper analyzes the impact of aerodynamic wake phenomenon caused by wind turbines on the power generation of other turbines inside the same wind farm, which can significantly affect the energy production of the farm. The relevance of the work is associated with the great expansion of the wind power industry which has been experienced in the last years around the world and particularly in Brazil. Therefore, the objective of this work is to evaluate the Annual Energy Production (AEP) of different wind farm layouts affected by wake effect. In addition, the variation in wind speed in a given location throughout the year should also be considered by using an annual series of wind speed data. With this purpose, the adopted methodology is a mathematical modeling by Jensen multiple wake model with adaptation of a MATLAB computational algorithm to calculate the Annual Energy Production and the layout efficiency of wind farms with unidirectional wind. The results obtained by the algorithm were consistent with values reported in literature for unidirectional wind and multidirectional wind with constant wind speed, thus validating the values calculated by the algorithm. In the case of multidirectional wind with variable wind speed, the difference between the results was significant, thus proving how important is the use of the proper wind speed data. Furthermore, it was verified that more efficient wind farm layouts can have an AEP similar to that from less efficient layouts with fewer installed turbines, thus reducing the required investment.*

Keywords: *wake effect, Jensen model, wind power, wind farm*

1. INTRODUCTION

In recent years, the world has experienced a significant growth of the renewable energy industry. This growth may be attributed both to the growing concern about the environmental impact caused by the use of fossil fuels and to technological development and the extensive scientific work produced. Wind power is one of the main energy sources nowadays, since wind farms do not emit carbon dioxide in the atmosphere, and the growth of this industry has created many jobs (ABEEólica, 2021).

From 2011 to 2020, Brazil's wind power industry received US\$ 35.8 billion in investments, thus leading to a growth in installed capacity from 1.5 GW in 2011 to 17.7 GW in 2020. In consequence, wind energy is currently ranked second in Brazilian electricity matrix, with 10.8% of the total installed capacity of power generation, and Brazil, which was ranked 15th in the world ranking of wind energy installed capacity in 2012, is now ranked 7th. The Northeast region of the country concentrates 80% of Brazilian wind farms, since it has one of the most favorable winds for power generation in the world. The state of Rio Grande do Norte, specifically, is the largest wind energy producer in the country, with more than 190 wind parks and an installed capacity of 5.57 GW, about 30% of the national amount (ABEEólica, 2021).

The presented context shows the importance that the development of studies and research in the field of wind energy has, particularly, in regions where wind farms have been installed frequently, like the state of Rio Grande do Norte. However, before building a wind park and even acquiring wind turbines for the execution of a wind power project, local geography must be studied carefully, especially the wind regime and the terrain characteristics. The placement of wind turbines on the terrain must be done in order to minimize the consequences of wake effect, which can impact significantly the productivity of the wind farm.

The wake effect of a wind turbine is an aerodynamic phenomenon that occurs when the wind flows through the blades of the turbine. The wake is the space behind the turbine rotor where the flow turbulence is increased and the average wind speed is reduced in relation to the atmospheric free wind speed, due to the kinetic energy extracted by the rotor and converted into rotation mechanical energy. Consequently, if there are turbines downstream other turbines, they receive wind with reduced speed, thus causing a decrease in their energy production (Hau, 2013). The solution for this problem is to define the placement of the turbines so that the distances between them are increased and the consequences of wake effect are minimized. In other words, the layout of the wind farm must be optimized in order to obtain the maximum possible productivity.

A common practice to evaluate the performance of a wind farm is to calculate the Annual Energy Production (AEP), which is the total amount of energy generated by the park for one year (Hau, 2013). A way to measure the impact of wake effect on a wind farm's productivity is to calculate the layout efficiency or wake coefficient (González-Longatt *et al.*, 2012). Furthermore, in preliminary studies before the park's installation, the use of an annual series of wind speed data measured in the location is important for the analysis to be more realistic.

The study of the impact of wake effect on the energy production of a wind farm requires the implementation of a physical-mathematical modeling able to describe the phenomenon. Therefore, the purpose of this work is to evaluate the Annual Energy Production of several wind farm layouts affected by wake effect, by selecting and studying a mathematical model of wake and using an annual series of wind speed data. For this, a computational algorithm must be implemented and used with the layouts to be analyzed, as it was already done by Camelo and Medina (2020).

2. LITERATURE REVIEW

2.1 Power curve of a wind turbine

The relation between the incoming wind speed of a wind turbine and the mechanical power that it converts is given by Eq. (1), where P is the converted mechanical power, V_0 is the incoming wind speed, ρ is the air density, A_0 is the area of the turbine rotor and c_p is the power coefficient (Hau, 2013).

$$P = \frac{1}{2} c_p \rho A_0 V_0^3 \quad (1)$$

The power coefficient of a wind turbine is defined as the ratio of the mechanical power converted by the rotor (P) to the total power available in the undisturbed wind (P_0). This coefficient is related to the ratio of the wind speeds before to after the plane of the turbine rotor. Since the air speed after the turbine cannot be zero, it is not possible to convert the full power available in the wind into mechanical power, which would be $c_p = 1$. Instead of this, it can be demonstrated that the theoretical maximum power coefficient of any wind generator, called the Betz limit, is $c_p = \frac{16}{27} \approx 0.593$ (Hau, 2013). In practice, wind turbines reach power coefficients about 0.45 (Amarante *et al.*, 2003) or 0.5 in the case of modern and optimized turbines, according to Hansen (2015). The thrust coefficient (c_T), in its turn, is associated with the thrust force exerted by the wind on the turbine rotor. Its value, at the Betz limit, is $c_T = \frac{8}{9} \approx 0.889$ (Hansen, 2015).

As it can be observed in Eq. (1), the power converted by a wind turbine increases with the cube of the wind speed (Hau, 2013; Hansen, 2015). Therefore, it is possible to generate the power curve of the turbine, which relates the incoming wind speed on the rotor blades to the converted mechanical power. Figure 1 presents a power curve provided by Mosetti *et al.* (1994) that was used in the analyses of this work. However, it can be noted that the converted power does not infinitely obey the cubic function, but it reaches a constant maximum level known as the rated power. Moreover, it can also be noted that the wind with very low speeds has no potential for power generation, whereas the wind with very high speeds causes the turbine to be turned off in order to avoid structural damage.

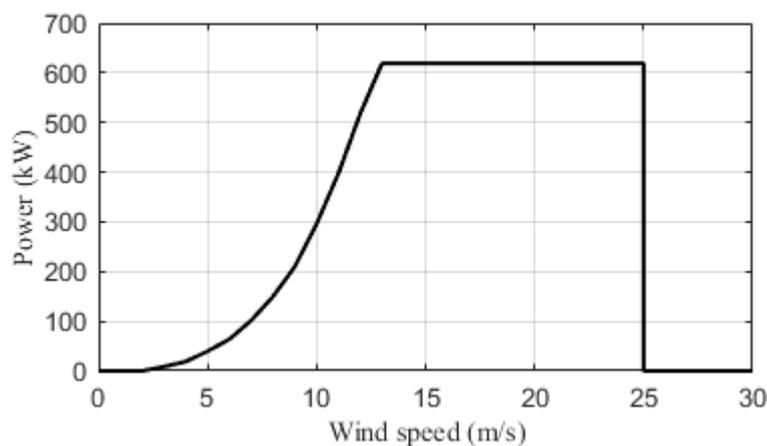


Figure 1. Power curve of a wind turbine with a rated power of 620 kW (own work based on Mosetti *et al.*, 1994).

2.2 Jensen model for wake effect

The physical-mathematical modeling selected for implementation on this work was the one by Jensen (1983), who considered that the diameter of the wake behind a wind turbine increases linearly from the plane of the rotor. Therefore, the radius of the wake of a turbine (r) is given by a linear function of the distance downstream the turbine (x) as it is presented in Eq. (2). In Eq. (2), r_0 is the radius of the turbine rotor and α is the entrainment constant, which is the slope of the line (Jensen, 1983). As it can be seen in Eq. (3), this constant is a function of the turbine hub height (h) and of the terrain surface roughness (z_0), the value of which depends on the local terrain characteristics (González-Longatt *et al.*, 2012). Figure 2 shows the linear expansion of the wake of a wind turbine as modeled by Jensen.

$$r = r_0 + \alpha x \quad (2)$$

$$\alpha = \frac{1}{2 \ln\left(\frac{h}{z_0}\right)} \quad (3)$$

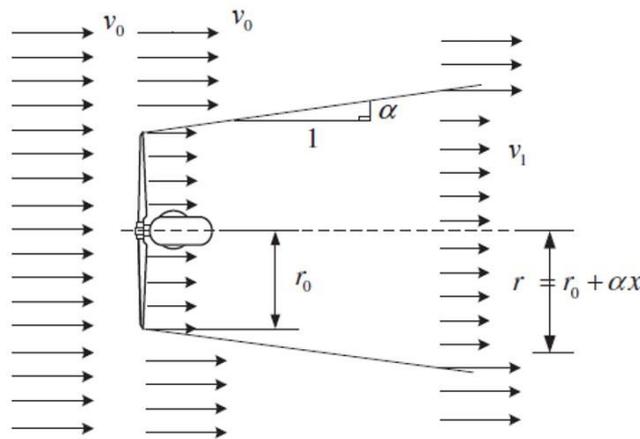


Figure 2. Linear expansion of the wake of a wind turbine according to Jensen (adapted from González-Longatt *et al.*, 2012 by Camelo and Medina, 2020).

The behavior of the wind speed in the wake of a turbine can be described by a balance of air momentum between the plane of the rotor and a plane located at a distance x downstream the turbine. This balance was developed by Jensen (1983) and reviewed by González-Longatt *et al.* (2012), thus resulting in Eq. (4), which provides the wind speed at a distance x from the turbine (v_1). In Eq. (4), v_0 is the free wind speed, r_0 is the radius of the turbine rotor, r is the radius of the wake at that location (given by Eq. (2)) and c_T is the thrust coefficient of the selected wind turbine model.

$$v_1 = v_0 + v_0(\sqrt{1 - c_T} - 1) \left(\frac{r_0}{r}\right)^2 \quad (4)$$

2.3 Jensen model for multiple wakes

Jensen wake model can be used to evaluate the incoming wind speed of a wind turbine that is affected by the wake of another turbine, as given by Eq. (4), but it is not enough for a complete analysis of a wind farm where there are many turbines, and consequently, there are many wakes that can overlap; in this case, a downstream turbine can be shadowed by the wakes of more than one upstream turbine. Furthermore, a downstream turbine can be only partially shadowed by one or more upstream turbines, as it can be seen in Figure 3 (González-Longatt *et al.*, 2012).

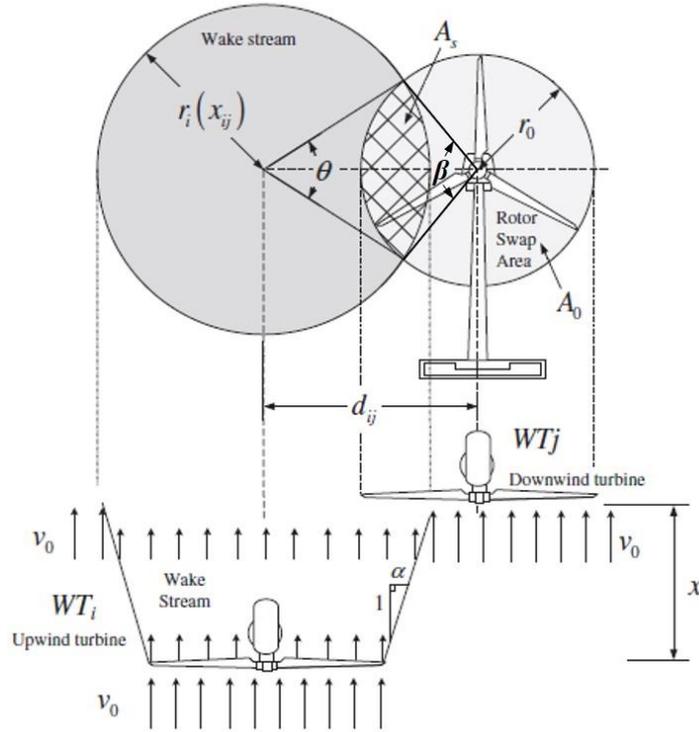


Figure 3. Partial shadowing of the wake of an upstream turbine on the rotor of a downstream turbine (adapted from González-Longatt *et al.*, 2012 by Camelo and Medina, 2020).

Based on Figure 3, where the considered wind turbines have the same rotor diameter, Farias and Couto (2013) derived equations to calculate the shadowed area indicated in the figure (A_s) by using the indicated angles (β and θ). Therefore, the area shadowed by the wake of an upstream turbine i on a downstream turbine j is given by Eq. (5), where r_0 is the radius of the turbine rotor, R_{ij} is the radius of the wake and the angles β and θ are given, respectively, by Eq. (6) and Eq. (7). The term d_{ij} , which appears in Eq. (6) and Eq. (7), is the lateral distance between the turbines, which can also be seen in Figure 3.

$$A_s = r_0^2(\theta - \sin \theta \cos \theta) + R_{ij}^2(\beta - \sin \beta \cos \beta) \quad (5)$$

$$\beta = \cos^{-1} \left(\frac{R_{ij}^2 + d_{ij}^2 - r_0^2}{2d_{ij}R_{ij}} \right) \quad (6)$$

$$\theta = \cos^{-1} \left(\frac{r_0^2 + d_{ij}^2 - R_{ij}^2}{2d_{ij}r_0} \right) \quad (7)$$

Modeling multiple combined wakes in a wind farm requires the determination of a resultant incoming wind speed for every turbine in the farm. This resultant speed combines the effect of all the wakes affecting each of the turbines and its calculation is necessary so that the power converted by the turbine affected by wake effect can be evaluated by using the power curve of the wind generator. Therefore, González-Longatt *et al.* (2012) presented Eq. (8), which provides the resultant incoming wind speed for every downstream turbine j (v_j). In Eq. (8), v_0 is the free wind speed, v_{ij} is the wind speed on turbine j affected by the wake of every upstream turbine i and x_{ij} is a shadowing factor defined as the ratio of the shadowed area of the upstream turbine i on the downstream turbine j (A_s , given by Eq. (5)) to the area of the turbine rotor (A_0). Equation (8) must be used for all the n turbines existing in the wind farm.

$$v_j = v_0 - \sqrt{\sum_{i=1}^n x_{ij}(v_{ij} - v_0)^2} \quad (8)$$

3. METHODOLOGY

3.1 Annual series of wind speed data

The calculation of the Annual Energy Production of a wind farm, as intended by this work, requires not only the value of the average wind speed in the location where the farm would be installed, but also the behavior of the wind speed throughout the year. A common way to obtain the frequency distribution of the wind speed over a year is using the Weibull distribution, a probability density function which provides a good approximation for normal wind regimes. The Weibull function gives the frequency of occurrence of a given wind speed all over the year and depends on a scale parameter (C) and a shape parameter (k) the calculation of which needs measurements performed over several years (Hau, 2013).

Another way to calculate the Annual Energy Production of a wind farm in a given location is the direct use of an annual series of wind speed data measured in that location at intervals of 10 minutes or 1 hour. The state of Rio Grande do Norte is the region chosen for the selection of wind speed data, given the significance that this state has in the Brazilian wind power industry (ABEEólica, 2021). An appropriate elevation to obtain wind speed data for power generation purposes is 50 m. However, due to unavailability of detailed wind speed data at that elevation for the chosen region, the database provided by the National Institute of Meteorology (INMET, 2020), which has wind speed data measured at a 10 m height in several locations in Rio Grande do Norte, was used. Since this height is not the most appropriate for large-scale power generation, the data measured at 10 m were extrapolated to 50 m by the logarithmic wind profile formula.

The logarithmic wind profile formula is based on the approximation of the velocity profile in the atmospheric boundary layer as a logarithmic profile. This approach is valid in the layer closest to the ground (less than 100 m height) and takes into consideration the local surface roughness of the terrain (z_0) (Hau, 2013). The logarithmic formula is presented in Eq. (9). Given a reference elevation h_1 where the wind speed v_1 is known, the speed v_2 at a selected elevation h_2 can be calculated. This method was implemented by Neiva *et al.* (2017) in the production of the new Brazilian Wind Energy Potential Atlas with data measured in 2013.

$$v_2 = v_1 \frac{\ln\left(\frac{h_2}{z_0}\right)}{\ln\left(\frac{h_1}{z_0}\right)} \quad (9)$$

The data series provided by INMET for some locations in Rio Grande do Norte were analyzed and one of those locations was selected. At first, the cities of Touros, Macau and Mossoró were the best options because they are located next to the biggest wind farm clusters in the state. However, it was verified that the data series measured in those cities either were incomplete or contained errors, therefore, the city of Natal was chosen. The annual series of wind speed data used in this work, obtained from the INMET portal, is the result of measurements performed from 1 January 2019 to 31 December 2019 at a 10 m height by a measurement tower located at the Central Campus of the Federal University of Rio Grande do Norte in Natal. The time interval between two consecutive measures is 1 hour.

The wind speed data were extrapolated from a 10 m elevation to a 50 m elevation by using Eq. (9). For this, a terrain surface roughness value (z_0) was selected for the city of Natal. By observing the roughness map from the Atlas of Wind Energy Potential of Rio Grande do Norte (Amarante *et al.*, 2003), the terrain surface roughness in Natal is between 2.0 m and 3.0 m. However, according to Hau (2013), the terrain roughness is about 1.0 m in cities. Farias and Couto (2013) reported the intermediary value $z_0 = 1.6$ m in big cities and this value was the chosen one. This terrain surface roughness value was used to extrapolate the wind speeds measured at a 10 m height to a 50 m height, but it is not necessarily the same roughness value used in the analyses of wake effect in wind farms.

3.2 Algorithm for calculating Annual Energy Production

The analysis of the consequences of wake effect on the Annual Energy Production of wind farms was implemented as a MATLAB computational algorithm. Part of this algorithm is essentially the same one developed by Camelo and Medina (2020) based on the work by Farias and Couto (2013). However, the algorithm was modified to receive annual series of wind speed data and to calculate the Annual Energy Production of wind farms, instead of calculating only the instantaneous power.

The algorithm receives, as input data, a binary matrix of positions which represents the turbines layout in the wind farm. Therefore, the analyzed layouts must always represent rectangular lands where the turbines are positioned. The dimensions of the rectangular land are also inputted into the algorithm, as well as the terrain surface roughness. The dimensions of the matrix of positions could be variable, but this work considered only 10×10 matrices. Thus, there are 100 cells where wind turbines can be located. Another input data of the algorithm is the annual series of wind speed data, but it receives only the magnitude of the velocity and not its direction, thus being limited to unidirectional wind analyses. The algorithm also receives the power curve of the selected wind generator, the turbine hub height, the rotor diameter and the thrust coefficient.

After receiving input data, the algorithm uses equations (Eq. (2) to Eq. (8)) to calculate the resultant incoming wind speed on each of the turbines in the wind farm every hour in the year. With the power curve, the power converted by each turbine every hour in the year, in kW, is calculated. The sum of all these powers gives the Annual Energy Production, in kWh, of each turbine and also of the entire wind park. The ratio of the AEP of the wind farm to the number of hours per year is the average power of the farm, while the ratio of the AEP considering wake effect to the AEP neglecting wake effect is the layout efficiency or wake coefficient (González-Longatt *et al.*, 2012). The algorithm procedure is summarized by the flowchart in Figure 4.

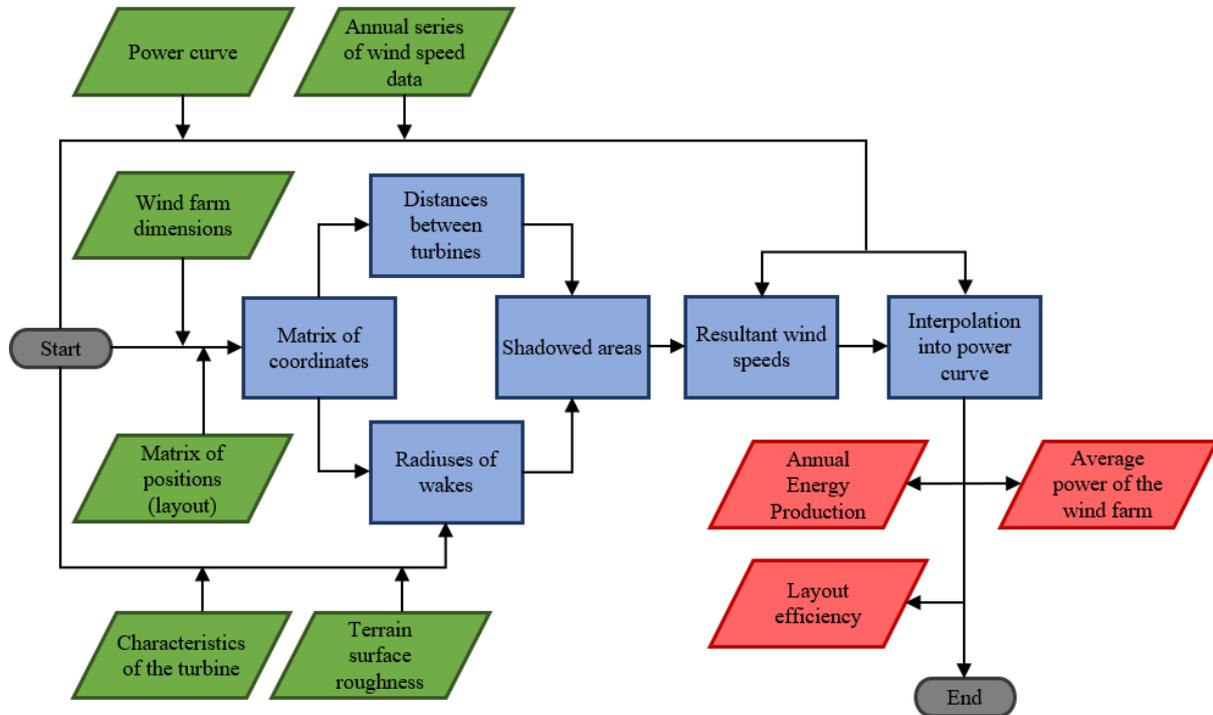


Figure 4. Flowchart of the algorithm.

4. RESULTS AND DISCUSSION

The wind farm layouts analyzed by the algorithm of this work were obtained from Grady *et al.* (2005) and González *et al.* (2010). Both works developed optimization algorithms for wind farms. The work by Grady *et al.* (2005) reviewed the results from Mosetti *et al.* (1994), while González *et al.* (2010) analyzed some of the layouts from Grady *et al.* (2005) and performed some own analyses.

The first wind farm layout analyzed by the algorithm of this work is a very simple case obtained by González *et al.* (2010) by using optimization. This layout is really very simple and has only 6 turbines positioned on a square land with dimensions 4,000 m by 4,000 m, as it can be seen in Figure 5. It was selected only to verify that the developed algorithm is effective and provides good results since it is a simple case in which the wind was considered as unidirectional, as well as the algorithm of this work does, and the Annual Energy Production was explicitly reported, unlike other layouts for which only the average power was reported.

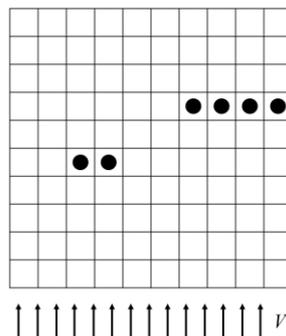


Figure 5. Layout with unidirectional wind optimized by González *et al.* (2010) (own work based on that reference).

Other characteristics that make the layout in Figure 5 the most appropriate for comparison are: the adopted wind regime, which was a Weibull distribution with a scale parameter $C = 8.5$ m/s and a shape parameter $k = 2$, while the series of wind speed data measured in Natal has an average speed of 7.2 m/s at a 50 m elevation; and the reported reference elevation, which is also 50 m. The rated power of the wind turbines used by González *et al.* (2010) in this layout varies between 1.67 MW and 2.00 MW, thus the wind turbine used in the analysis of this work is Vestas V90 – 2.0 MW, which has a diameter of 90 m and the power curve presented in Figure 6. The terrain surface roughness is 0.055 m. The thrust coefficient is considered as 0.88, which approximates the ideal power coefficient of 0.593. The results for this layout are presented in Table 1.

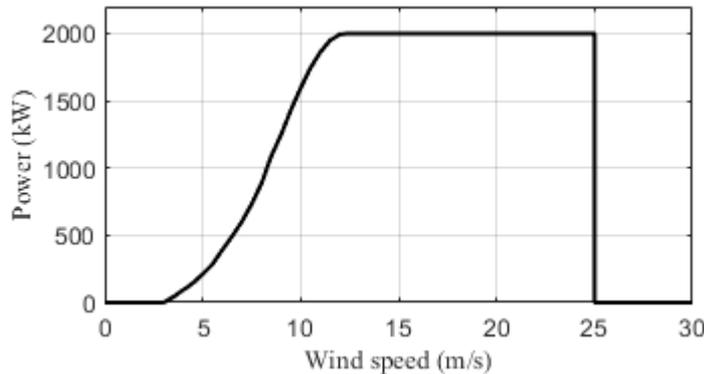


Figure 6. Power curve of the wind turbine Vestas V90 – 2.0 MW (own work based on Bauer and Matysik, 2017).

Table 1. Results of AEP and average power for the layout in Figure 5.

Algorithm	AEP, GWh	Average power, kW
González <i>et al.</i> (2010)	41.72	4,763
This work	42.56	4,858

As it can be noted in Table 1, the results obtained by the algorithm are compatible with the results reported in literature, thus proving the effectiveness of the algorithm. However, this is the ideal case for comparisons using the algorithm because it considers unidirectional wind, as well as the modeling adopted in this work.

Since the wind farm layout presented in Figure 5 is the ideal situation for comparisons with the algorithm, other layouts from Grady *et al.* (2005) and González *et al.* (2010) were put for analysis. This second analysis was performed with the layout in Figure 7a, from Grady *et al.* (2005), and the layout in Figure 7b, from González *et al.* (2010), which were analyzed by González *et al.* (2010) considering multidirectional wind with a constant speed of 12 m/s. Therefore, in this case, the series of wind speed data measured in Natal was replaced by the hypothesis of constant wind speed throughout the year. The dimensions of the wind farm are 2,000 m by 2,000 m, the terrain roughness is 0.3 m and each of the layouts has 39 turbines. The wind turbine model is the same used by González *et al.* (2010) and its power curve, provided by Mosetti *et al.* (1994), was presented in Figure 1. The turbine has a hub height of 60 m, a rotor diameter of 40 m and a thrust coefficient of 0.88. The results were reported in Table 2.

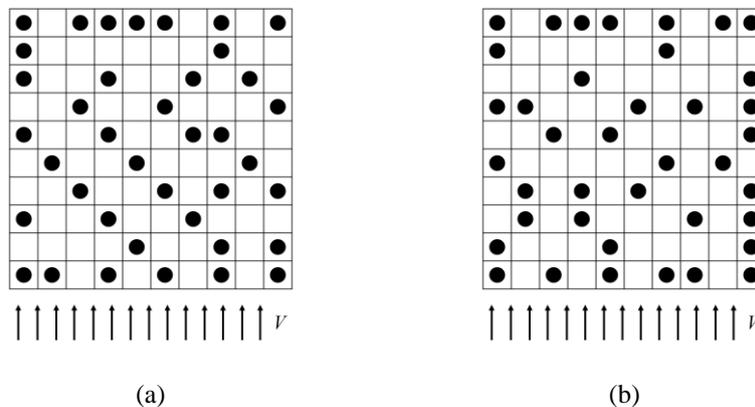


Figure 7. Layouts with multidirectional wind and constant wind speed optimized by González *et al.* (2010): (a) layout from Grady *et al.* (2005); (b) layout from González *et al.* (2010) (own work based on the indicated references).

Table 2. Results of AEP, average power and layout efficiency for the layouts in Figure 7.

Layout	González <i>et al.</i> (2010)	This work		
	Average power, kW	AEP, GWh	Average power, kW	Layout efficiency, %
Grady <i>et al.</i> (2005)	17,363	148.66	16,971	84.1
González <i>et al.</i> (2010)	18,065	142.35	16,250	80.5

The comparison between the average power reported in literature for both layouts and the average power calculated by the algorithm indicates that the results are similar. Although there is a difference of about 10% in the worst case, even greater differences would be expected because the algorithm of this work analyzes only unidirectional wind, whereas the results calculated by González *et al.* (2010) take into consideration the variable wind direction. The results presented in Table 2 suggest that, at least in the analyzed layouts, the variation in wind direction was not a determining factor for the calculation of the power generation of a wind farm. Layout efficiency was also included among the results in order to show that, in the case of previously computationally optimized layouts, the layout efficiency can reach values as high as 80% or 90%. The values in Table 2 were calculated by the algorithm of this work with unidirectional wind, which means that the actual layout efficiencies are even higher.

The third analysis was performed with the layout in Figure 8a, from Grady *et al.* (2005), and the layout in Figure 8b, from González *et al.* (2010), which were analyzed by González *et al.* (2010) considering multidirectional wind again, but this time the wind speed is also variable. They considered three possible wind speeds: 8 m/s, 12 m/s and 17 m/s. Each speed level has a frequency of occurrence that is reported in the work by Grady *et al.* (2005), thus simulating a real wind speed distribution. Therefore, in this case, the series of wind speed data measured in Natal was considered. The dimensions of the wind farm, the terrain roughness and the wind generator model are the same as in the previous analysis and each of the wind farms has 39 turbines. The results were reported in Table 3.

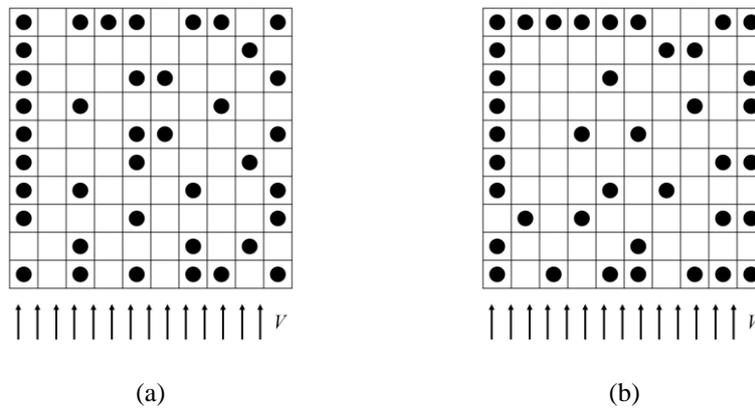


Figure 8. Layouts with multidirectional wind and variable wind speed optimized by González *et al.* (2010): (a) layout from Grady *et al.* (2005); (b) layout from González *et al.* (2010) (own work based on the indicated references).

Table 3. Results of AEP, average power and layout efficiency for the layouts in Figure 8.

Layout	González <i>et al.</i> (2010)	This work		
	Average power, kW	AEP, GWh	Average power, kW	Layout efficiency, %
Grady <i>et al.</i> (2005)	32,228	43.53	4,969	78.6
González <i>et al.</i> (2010)	32,739	45.66	5,213	82.5

It can be noted, by observing Table 3, that the results obtained by the algorithm for the average power of the layouts in Figure 8 are very different from the values reported by González *et al.* (2010) in their paper. Unlike the previous analysis, in which the values were similar even with different wind direction approaches, the errors in the current analysis reach about 85%. This result could be explained both by the multidirectional wind considered by González *et al.* (2010) and neglected by the algorithm of this work as well as by different ways to vary the wind speed. However, the previous analysis indicated a small influence of the variation in wind direction on the obtained results.

The variable speed, in its turn, may be the determining factor for the detected differences. In the previous analysis, the wind speed was considered as constant and equal to 12 m/s by González *et al.* (2010) and also by the algorithm of this work. In this new analysis, the series of wind speed data measured in Natal was considered, while González *et al.* (2010) used a frequency distribution with three speed levels: 8 m/s, 12 m/s and 17 m/s. The average wind speed calculated with the data from Natal is 7.2 m/s, whereas the average speed of the frequency distribution used by González *et al.* (2010) is 14.9 m/s. According to the power curve of the wind turbine (Figure 1), for 7.2 m/s, the extracted power is 113 kW, but for 14.9 m/s, the extracted power is the rated power, 620 kW. This is the most likely reason for the differences obtained between the results reported in Table 3.

The impact of wake effect on the Annual Energy Production of wind farms and how important is considering it in the project of a layout of turbines can be better verified by analyzing a layout with a larger number of turbines that has a similar energy output. Taking the results of the third analysis (Table 3) as an example, a less efficient layout can be designed to generate a similar amount of energy at the cost of a larger number of turbines in the wind farm. An example is presented in Figure 9. In Table 4, the results of the previous analysis (layouts in Figure 8) were reported together with the results for the layout in Figure 9.

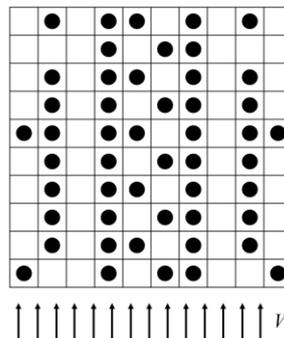


Figure 9. Wind farm layout with 50 turbines.

Table 4. Results of AEP, average power and layout efficiency for the layouts in Figure 8 and in Figure 9.

Layout	Number of turbines	Results of the algorithm		
		AEP, GWh	Average power, kW	Layout efficiency, %
Figure 8a (Grady <i>et al.</i> , 2005)	39	43.53	4,969	78.6
Figure 8b (González <i>et al.</i> , 2010)	39	45.66	5,213	82.5
Figure 9 (own work)	50	47.88	5,466	67.4

Table 4 shows that the Annual Energy Production and the average power of all three wind farm layouts are similar. Nevertheless, the layout in Figure 9 has 50 turbines, while the layouts in Figure 8 have 39 turbines. It is indeed natural that a wind farm with more turbines has a higher AEP; however, its layout efficiency is much lower, thus indicating that fewer turbines could be used to generate a similar amount of energy. Whereas the number of turbines of the layout in Figure 9 is 28% greater than the number of turbines of the layouts in Figure 8, its AEP is only about 10% higher than the AEP of the layout by Grady *et al.* (2005) and only about 5% higher than the AEP of the layout by González *et al.* (2010). Therefore, analyzing the efficiency of a wind farm layout before building the farm can save money and make the investment more sustainable.

5. CONCLUSIONS

The objective of this work was performing analyses of the impact of wake effect on the productivity of a wind farm. The power generation of a wind park can be measured by the Annual Energy Production and the losses due to wake effect can be measured by the layout efficiency. A MATLAB computational algorithm was adapted to receive an annual series of wind speed data and to calculate the Annual Energy Production of wind farms with different layouts. The effect of multiple wakes on wind farm layouts was described by Jensen wake model. The wind speed data were measured by a meteorological tower in Natal, Rio Grande do Norte, at a 10 m height and the values were extrapolated to a 50 m height.

The first obtained results suggested a good compatibility between the values calculated by the algorithm and the values reported in literature. Therefore, the adopted wake effect model and the algorithm are able to obtain valid results. More detailed results indicate that considering the wind as unidirectional or multidirectional is an important decision, which can substantially change the calculated values. However, the most significant modification was the variation in wind speed. It was verified that the use of a series of wind speed data measured in a real location and the use of a frequency

distribution of wind speed resulted in very different values for the Annual Energy Production of the same layout of turbines. This is easily explained by the fact that the two data sets do not represent the same wind regime, which evidences the need of considering the proper wind speeds in the preliminary design of a wind farm. An additional study proved that the analysis of the layout efficiency of wind parks can reduce the number of turbines needed to generate a similar amount of energy, and consequently, can reduce the required investment.

Although good results were obtained, some limitations of this research can be mentioned. The algorithm was prepared to operate with an annual series of wind speed data extracted from historical data, which means that a wind farm layout designed by following this methodology would have an optimal placement of wind turbines based on those data measured in the past. However, possible future changes in the wind regime, mainly due to climate change, could cause this optimal placement to become out of date, thus decreasing the layout efficiency of the wind farm already in operation. An alternative to using an annual series of wind speed data would be the use of frequency distributions of hourly wind speeds, which was not considered in this work, but could change the calculated results.

Future improvements in this developed work could include a multidirectional modeling of the wind, since the unidirectional modeling seems too simplified, and also the use of wind speed data measured at the height where the turbine hub will be installed, instead of using data measured at lower elevations and extrapolating them by the logarithmic wind profile formula; this extrapolation can add error to the study. These improvements could be the object of research for future works to be developed.

6. ACKNOWLEDGEMENTS

This research was developed at the Laboratory of Thermal Systems and Alternative Energy of Federal University of Rio Grande do Norte (LSTEA/UFRN) supported by the National Council for Scientific and Technological Development (CNPq).

7. REFERENCES

- ABEEólica, 2021. *InfoWind 21*. Associação Brasileira de Energia Eólica (ABEEólica), São Paulo, http://abeeolica.org.br/wp-content/uploads/2021/06/2021_06_Infowind21.pdf. Accessed 16 June 2021.
- Amarante, O.A.C., Silva, F.J.L., Rios Filho, L.G., and Vidal, M.J.B., 2003. *Wind Energy Potential of the State of Rio Grande do Norte* (in Portuguese). Companhia Energética do Rio Grande do Norte (COSERN), http://www.cresesb.cepel.br/publicacoes/download/atlas_eolico/atlas_eolico_RN.pdf. Accessed 14 June 2021.
- Bauer, L. and Matysik, S., 2017. *Vestas V90 - 2,00 MW - Wind turbine*. Wind Turbine Models, <https://en.wind-turbine-models.com/turbines/16-vestas-v90>. Accessed 11 June 2021.
- Camelo, M.O., and Medina T., G.I., 2020. "Study of Wake Effect in Wind Farms Applied to the State of Rio Grande do Norte". In *Proceedings of the 18th Brazilian Congress of Thermal Sciences and Engineering – ENCIT 2020*. Online Conference, Brazil.
- Farias, B., and Couto, T.G., 2013. *Positioning wind turbines in a wind farm using Genetic Algorithm* (in Portuguese). Undergraduate Final Project, Bachelor of Mechanical Engineering, University of Brasília, Brasília, Brazil.
- González, J.S., Rodriguez, A.G.G., Mora, J.C., Santos, J.R., and Payan, M.B., 2010. "Optimization of wind farm turbines layout using an evolutive algorithm". *Renewable Energy*, Vol. 35(8), pp. 1671–1681.
- González-Longatt, F., Wall, P., and Terzija, V., 2012. "Wake effect in wind farm performance: Steady-state and dynamic behavior". *Renewable Energy*, Vol. 39(1), pp. 329–338.
- Grady, S.A., Hussaini, M.Y., and Abdullah, M.M., 2005. "Placement of wind turbines using genetic algorithms". *Renewable Energy*, Vol. 30(2), pp. 259–270.
- Hansen, M.O.L., 2015. *Aerodynamics of Wind Turbines*. Routledge, London, 3rd edition.
- Hau, E., 2013. *Wind turbines: Fundamentals, Technologies, Application, Economics*. Springer, Berlin, 3rd edition.
- INMET, 2020. *Annual Historical Data* (in Portuguese). Instituto Nacional de Meteorologia (INMET), Brasília, <https://portal.inmet.gov.br/dadoshistoricos>. Accessed 31 May 2021.
- Jensen, N.O., 1983. *A note on wind generator interaction*. Risø National Laboratory. Risø-M, No. 2411. Roskilde, Denmark.
- Mosetti, G., Poloni, C., and Diviacco, B., 1994. "Optimization of wind turbine positioning in large windfarms by means of a genetic algorithm". *Journal of Wind Engineering and Industrial Aerodynamics*, Vol. 51(1), pp. 105–116.
- Neiva, A.C.B., Dutra, R.M., Melo, S.R.F.C., Guedes, V.G., Cabrera, A.A.M., Almeida, W.G., and Braz, R.O., 2017. *Brazilian Wind Energy Potential Atlas: Simulations 2013* (in Portuguese). Centro de Pesquisas de Energia Elétrica (CEPEL), Rio de Janeiro, http://novoatlas.cepel.br/wp-content/uploads/2017/03/NovoAtlasdoPotencialEolico_BrasileiroSIM_2013.pdf. Accessed 18 May 2021.

8. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.