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FORECAST ANALYSIS AND INTEGRATED OPTIMIZATION OF WIND FARM YAW CONTROL USING NUMERICAL SIMULATIONS

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Abstract. *Faced with the considerable increase in the size and number of wind turbine rotors over time due to technological advances aimed at greater efficiency in extracting kinetic energy from the winds and reducing the use of fossil fuels, there is an intrinsic problem of wake effect in wind farms. This effect is intensified by the increase in the area behind the rotors that reduce the wind speed and, consequently, the energy production capacity of turbines that are downstream of others. The integration of the yaw control of the rotors, which in principle follows the wind direction, can also be used to deflect the wake from downstream turbines, as a way of optimizing the wind farm power production. Thus, this work analyses the energy forecasting capacity of wind farms in the software FLORIS and its methodology to optimize the integrated yaw control, assessing its global efficiency of energy production maximization in wind farms where the wake effect is present, analyzing the predicted fluid dynamic behaviour per available wake models, comparing the results with the literature and data from real wind farms. There is a tendency of underestimation of power production in FLORIS in simulations in specific wind conditions in conflict with AEP for a given period, which should be further investigated. In addition, the possibilities of gain in both situations with the integrated optimization of the rotors yaw angle confirm the ability to mitigate the wake effect in the farms.*

Keywords: *wind farms, wake effect, energy forecast, yaw optimization, numerical simulation.*

1. INTRODUCTION

In the midst of the various impacts caused by the emission of greenhouse gases due to the use of fossil fuels, as stated by Tolmasquim (2016), wind energy has become a significant competitor for energy generation. After the rapid expansion of the use of wind energy in the 2000s in European countries and also in the United States, turbine technology has been developing significantly, considerably increasing the number and dimensions of rotors in search of greater efficiency in extracting kinetic energy of the winds, as can be seen in Figure 1.

One of the main problems inherent to the implementation of a wind farm stems from the decrease in speed behind the upstream turbine rotors after the extraction of energy from the wind, also increasing the level of turbulence in the flow and, consequently, the decrease in the power production capacity of the downstream turbines (Shakoor et al., 2016). This phenomenon is known as wake effect and results in a significant decrease in the energy production of the wind farm, thus causing an increase in the cost of energy produced.

These losses can become significant according to the layout of the farm, taking into account the spacing between the turbines, which is generally described by the multiplicity in relation to the diameter of the rotors. Barthelmie et al. (2010) presents the losses in the Middelgrunden, Horns Rey and Lillgrund farms that can reach up to, respectively, 10%, 12.4% and 23%.

Strategies such as yaw misalignment, associated with a control system, make it possible not only to increase the generation of energy produced by the farm, but also to relieve the fluctuating loads produced on the downstream turbines, avoiding continuous stops for maintenance, consequently reducing the cost of producing wind energy (Dijk et al., 2017). In this sense, numerical methods are being explored in wind farm studies to investigate the aerodynamic interaction of turbines. A low-cost open source tool currently available for studying and analyzing wake effects is FLORIS (2020) (FLOw Redirection and Induction in Steady-state) which consists of control and optimization devices that predict the flow field, considering the wakes and energy capture of a wind farm. (Doekemeijer; Van Der Hoek; Van Wingerden,

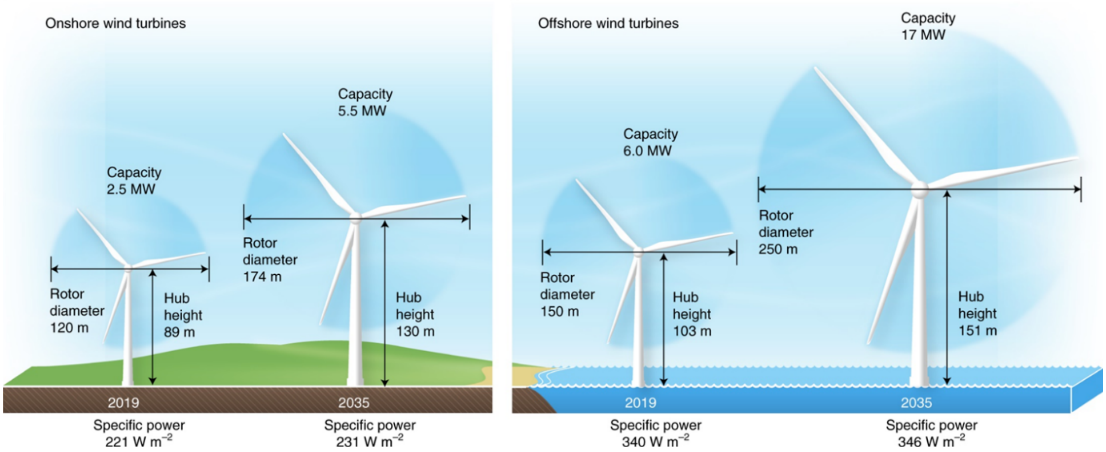

Figure 1. Increase in rotors over the years. Extracted from: Wiser et al. (2021)

2020).

In this work, we employ this tool to model a real wind farm located on a coastal site in the Northeast region of Brazil, and assess its capacity to reproduce the power produced by and wind speed reaching each turbine. We also test the yaw optimization algorithm considering this same farm and environmental conditions, in order to have an idea of the potential gains in annual energy production that could be achieved by collective yaw control.

2. FUNDAMENTALS

2.1 Energy production by a turbine and a wind farm

The production of electrical energy through the use of wind is basically carried out by two processes of energy conversion in the wind turbine. The first concerns the extraction of kinetic energy from the wind through the rotor, transforming it into mechanical energy in the rotating axis and, later, converting the mechanical energy into electrical energy by the generator (Pinto, 2013).

As presented by Bu et al. (2009), the wind energy that can be captured by a turbine taking into account the wind direction in relation to its horizontal axis is expressed by

$$P_t = \frac{1}{2}\rho A V^3 C_p(\lambda, \beta) \cos\theta, \tag{1}$$

where P_t represents the mechanical power output of the wind turbine [W], ρ is the density of the air [kg/m³], A is the swept area by the turbine rotor [m²], V is the wind speed that impinges on the wind turbine [m/s], C_p is the turbine power coefficient, which is a function of the maximum speed rate λ and the blade pitch β [°]. On the other hand, θ represents the angle between the wind direction and the normal direction of the rotor [°].

The closer the wind is aligned in relation to the direction of the horizontal axis of the turbine, the greater the ability to capture wind energy and, therefore, the capture is maximum when the rotor plane is perpendicular to the wind direction (Bu et al., 2009).

As exposed by Manwell, McGowan and Rogers (2009), due to the wake effect, the first turbines to come into contact with the wind incident in the wind farm will start to produce energy if the speed reaches the cut-in speed of its power curve and the downstream turbines are not necessarily activated. However, as the wind speed increases, the next lines of turbines will receive their interference and start producing energy, as long as the speed of the wind reaching them is greater than the cut-in speed. As the downstream turbines are generally in the wake of the upstream turbines, the farm will produce less energy compared to the same amount of isolated turbines. This makes the power curve of the farm in this comparative situation different from the hypothetical power curve of an isolated turbine multiplied by the number of turbines in the farm, as illustrated in Figure 2.

2.2 Wake effect and its mitigation

As explained by Manwell, McGowan and Rogers (2009), despite a possible concentration of a large number of turbines in the same location, a wind farm will never produce the same amount of energy in which the same number of isolated turbines would produce exposed to the predominant wind in the region. So even if the installation costs of a farm are reduced, the level of loss of energy production is increased due to the wake effect, which occurs as a result of the trail of turbulence and decrease in the speed of the winds after the passage through the rotor of the upstream turbines, which directly influences the energy production of the downstream turbines (Pardalos et al., 2013).

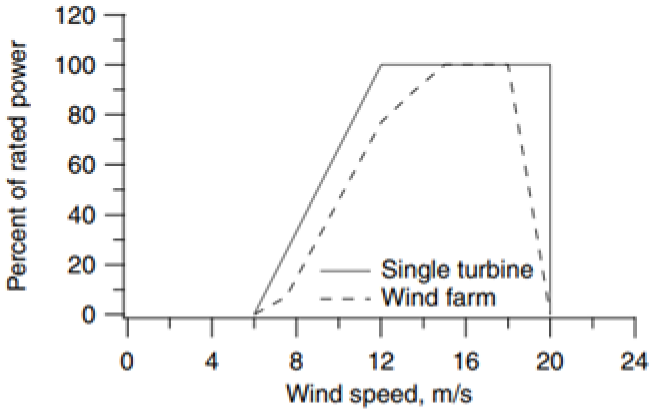

Figure 2. Comparison of the power curve of isolated turbines and a wind farm. Extracted from: Manwell, Mcgowan e Rogers (2009).

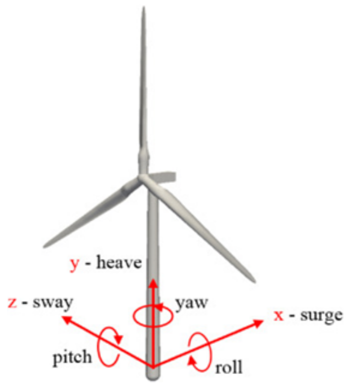

Figure 3. Degrees of freedom of a floating turbine. The yaw motion is the rotation of the rotor around the longitudinal axis of the turbine tower. Extracted from: : Kyle, Lee e Früh (2020).

This power decrease can lead to considerable losses in large wind farms, making it interesting to use strategies that can minimize them, in order to maximize energy production and minimize its cost. There are a few methods to mitigate the wake losses, for example the optimization of the layout of wind farms, increasing the spacing between the turbines, and the regulation of the operating point of each one of them. In addition to the strategies mentioned, the process of misalignment of the wakes through the angle in relation to the direction of incidence of the wind caused by the yaw movement (Figure 3), is one of the methods that could be implemented in farms to improve energy production (Dou et al., 2020).

The yaw angle optimization method performs the individual control of the rotor yaw of specific turbines in a way that misalignment with the direction of incidence of the wind decreases its produced power, but allows the displacement of the wake, increasing the energy production of turbines downstream and, consequently, the production of the farm as a whole (Dou et al., 2020).

3. METHODOLOGY

To carry out this work, the FLORIS software was used to perform simulations to estimate the energy produced by a wind farm described in the literature and a real farm located on the coast of northeast Brazil, optimizing the yaw angles for a single wind direction. and calculating the AEP (Annual Energy Production) using their respective wind roses.

Comparison with the literature was performed according to the data provided by King et al. (2020) regarding the layout of the wind farm, the values of TI (Turbulence Intensity), wind direction, turbine model (5 MW NREL) and wake model used, composed of the Gaussian model and GCH (Gauss Curl Hybrid) presents the construction of the latter, which offers modeling improvements over the Gaussian model. This new model combines features relevant to the Gaussian model and the Curl model. Its main feature is the introduction of counter-rotating vortex elements in the wake, in order to develop a faster effect on its recovery due to turbulence, generating results in the optimizations closer to those presented by the highest fidelity simulations (using LES – Large Eddy Simulations). The wake flow produced in the circular farm simulations tested by King et al. (2020) is shown in Figure 4.

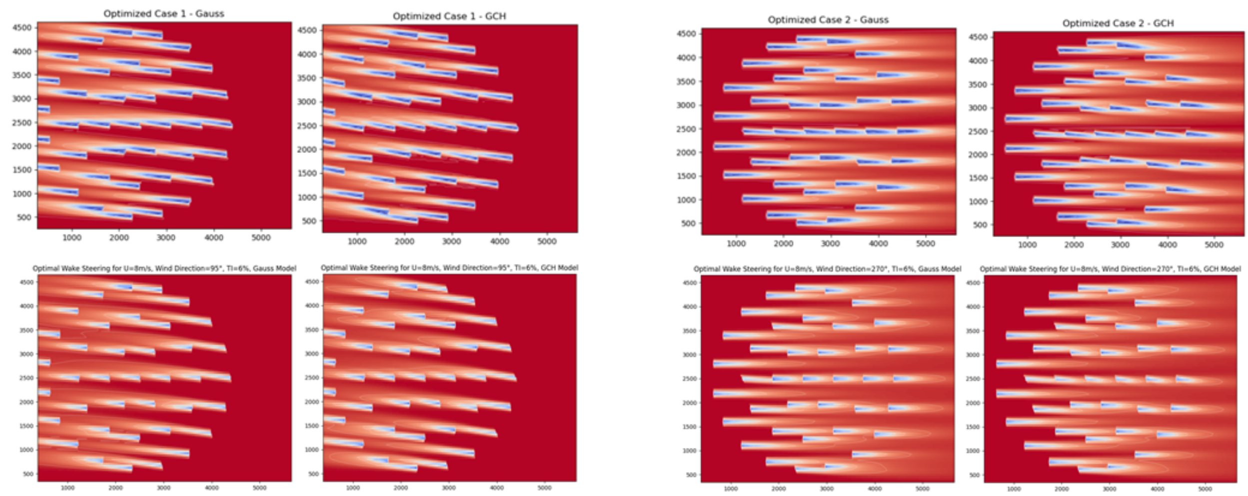

Figure 4. Comparison of simulations with the literature with circular farm with wind direction at 95° and 270°, using Gaussian wake models and GCH. Upper line simulations performed by King et al. (2020). Current simulations in the bottom row.. Available from: Author (2022).

Table 1. Comparison of energy gain of the circular farm with the literature.

TI	Wind Direction	(KING *et al.*, 2020)			Current Simulations	
		SOWFA	Gauss	GCH	Gauss	GCH
6%	95°	8%	4,7%	8,5%	4,9%	7,4%
	270°	4,3%	1,7%	5,8%	1,8%	4,5%
10%	95°	4,5%	1,6%	5,8%	2%	3%
	270°	3,1%	0,0%	3,3%	0,5%	2%

The gain values produced by the integrated yaw optimization in each IT situation and wind direction can be seen in Table 1, where we observe that the percentages of the current simulations have smaller deviations in the Gaussian model (it is already well established) than in the hybrid model GCH in relation to King et al. (2020). Possible explanations regarding this fact can be raised in relation to the constant advances in the development of the FLORIS tool. However, it appears that the percentages of gain in current simulations using the GCH wake model are closer to the results obtained with LES using SOWFA, as described in King et al. (2020). Due to this better agreement of the gains of the GCH model with those obtained with SOWFA, the other simulations were performed using this wake model

After these simulations, which are used as a way of evaluating the adherence of the simulations performed by other authors, simulations were carried out in different conditions of wind direction and speed, and TI for a real farm, comparing the total power produced instantly, the individual powers of each turbine and the speeds in the rotors of each one of them with real data from the farm, observing the existence of possible trends according to the simulation conditions. For such simulations, the possible gains in production with the implementation of integrated yaw control on the farm were also analyzed.

In addition, the calculation of AEP was carried out for a specific period that includes the observance of minor intercurrences in the operation of the turbines. In this simulation, the local wind rose of the specified period is used, comparing it with the real data of the farm and also calculating its optimization over time of the energy produced by the farm.

4. RESULTS

The results of the numerical simulations developed for the real park in different wind conditions can be seen in Figures 5 to 8. The percentage differences in the total power produced by the wind farm according to each wind speed measured with anemometers installed in the farm met mast at certain time instants can be observed in Figure 5. Among the results, only one presented higher power in the FLORIS simulation in relation to the real farm data. In addition, there is a tendency to decrease percentage differences in higher values of wind speed, especially that which is close to the rated power of the turbine in the farm.

The power produced instantaneously by each turbine referring to the simulations shown in Figure 5 are found in Figure 6. The relative behaviour of large differences observed in turbines 16 to 24 are related to their downstream positioning in relation to the other turbines in the farm, indicating the overestimation of production losses due to the wake effect by

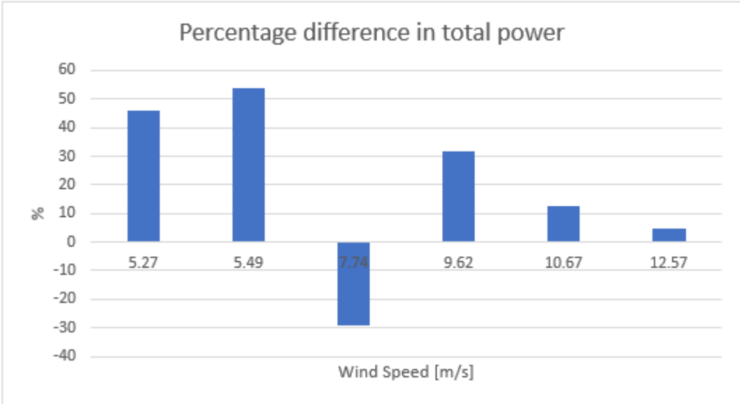

Figure 5. Percentage differences between the real farm and FLORIS in simulations under different wind conditions.

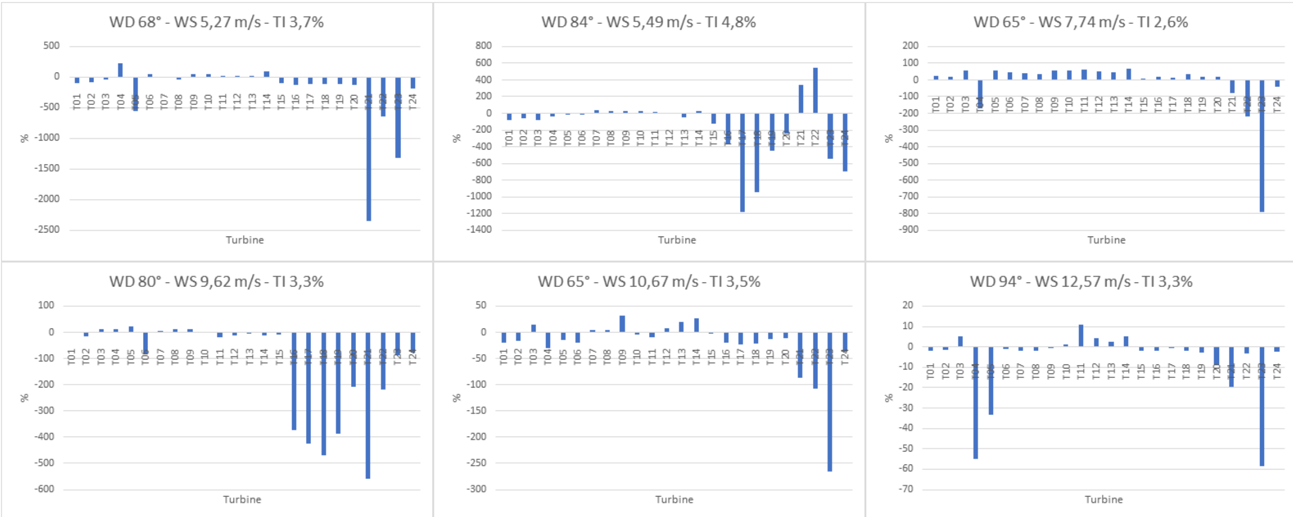

Figure 6. Percentage difference between the power produced by each turbine in the real farm in relation to the power calculated in FLORIS.

FLORIS, mainly at lower speeds of wind, having better adhesion of results when superior to 12 m/s. The turbine number 15 is actually at a favourable position to the wind, which should be better investigated the possible causes of relevant differences with the farm data.

The wind speeds at the rotor of each turbine are relevant to the power produced, and the percentage differences between the simulations and the farm data are shown in Figure 7. Again, we can see that the model is not yet capable of reproducing the flow field within a reasonable level of agreement.

Despite the disagreement between the field data and simulation results for some turbines and some wind speeds, we decided to proceed to the study of yaw optimization. The power gain generated by the integrated yaw control is shown in Figure 8, and it was not possible to identify a clear trend in relation to wind speed.

Finally, the results of the AEP simulations for the farm are shown in Figure 9, showing proximity with the real data for the stipulated period and also verifying the possibility of a 6 percent gain in the use of the integrated yaw control as a mitigation of the wake effect produced by the farm over the period.

5. CONCLUSION

According to the results obtained, there is a greater tendency to adapt to the wake model used the closer the wind speed is to the rated speed of the turbine, requiring more simulations at speeds similar to those presented here to enable the statement or verification of other incumbent factors.

As a low-fidelity tool, FLORIS exhibits a tendency to underestimate the farm's gain potential in instantaneous simulations, coming into direct conflict with AEP simulations, which have higher power trends than the farm's data, and should be better verified.

Regarding the optimization, it can be seen that the integrated yaw control adds important gains in complex layout farms as shown by King et al. (2020) in low turbulence situations, and in some situations in the real farm reported throughout the

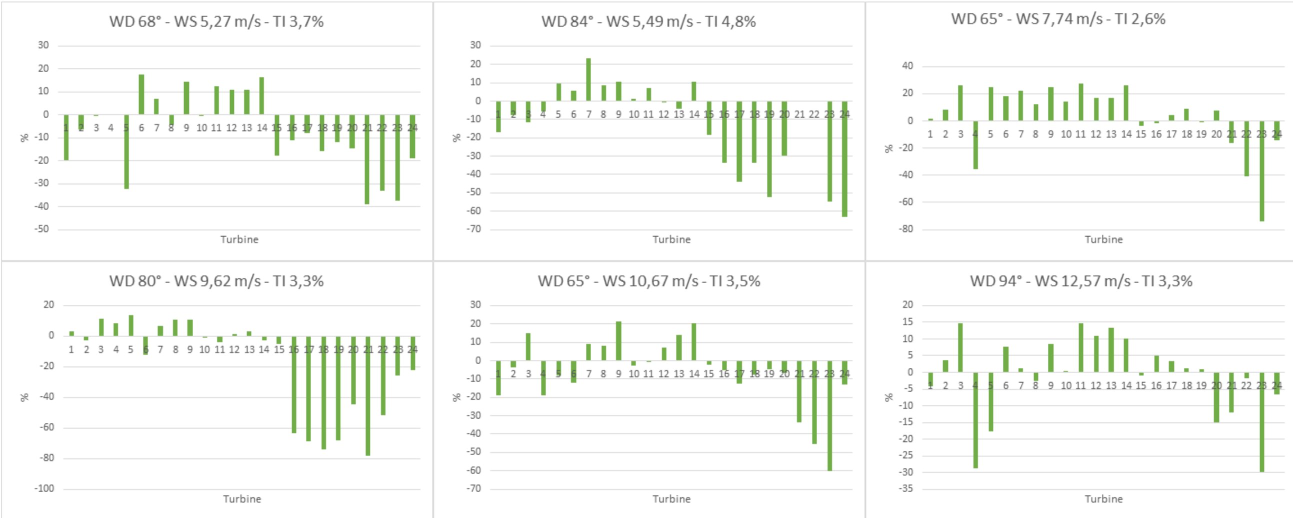

Figure 7. Percentage difference between the speeds in the rotors of the turbines of the real farm in relation to the speeds in FLORIS. Available from: Author (2022).

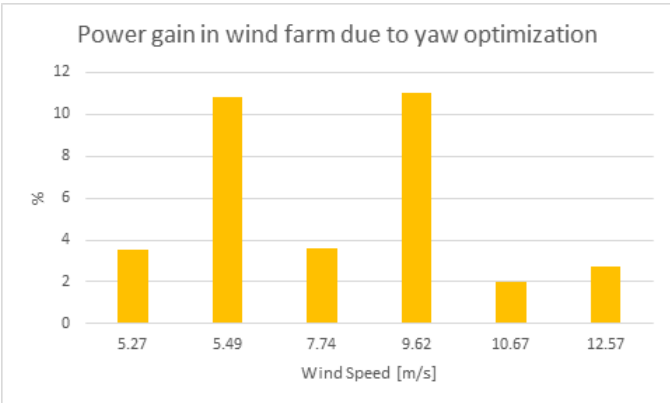

Figure 8. Optimization of the power produced by the integrated yaw control. Available from: Author (2022).

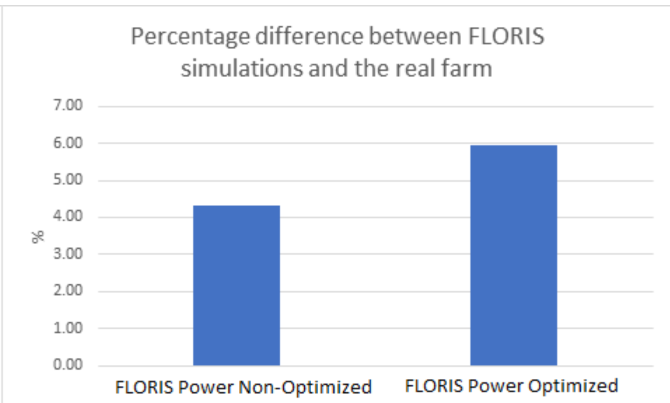

Figure 9. Percentage difference of AEP of the real farm in relation to the FLORIS in the conditions of initial power generated and power optimized by the integrated yaw control of the turbines.

work, which can be seen as an interesting strategy for mitigating the wake effect in existing farms with limited territorial spacing and layout.

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