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WIND FARM DESIGN THROUGH OPTIMAL WIND TURBINE POSITIONING USING GREEDY ALGORITHM

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ABSTRACT

Finding the optimal design method for offshore wind turbines in wind farms poses a challenge due to various optimization considerations. This study addresses the optimization problem of wind turbine placement using the Greedy Algorithm. The problem incorporates a linear wake model and a power output function, with an incremental computation method devised to account for the impact of additional turbines on existing ones, thereby enhancing the wind power assessment process. The objective function of the proposed study is the power output, factoring in the wake effect from nearby turbines. The optimal wind farm layout is determined through two optimization stages applied to the existing designs. The proposed wind farm aims to generate 3 MW of power from the turbines. Two scenarios with constant wind velocities and different rotor diameters were utilized to test the proposed method, employing Ansys 2022 as the simulation software. The findings demonstrate that the proposed Greedy Algorithm, coupled with repeated adjustments, yields more accurate results. By optimizing the placement of turbines while considering their mutual influence on power output, the proposed method validates the effectiveness of the Greedy Algorithm for wind turbine position optimization. The insights gained from this research can serve as a foundation for future work in large-scale offshore wind energy projects, contributing to the global transition toward sustainable energy solutions.

Keywords: Greedy Algorithm, Linear wake model, Optimal wind turbine, Wind turbine positioning, Wind farm optimization, Wind turbine placement.

1.0 INTRODUCTION

In recent years, the world has faced challenges with fossil fuel reliance, including increasing energy demands, depleting reserves, and environmental consequences. Therefore, there is a crucial need to seek an alternative to cater these issues. Wind energy is expected to contribute at least 30 % of global electricity by 2050. However, integrating wind power into the grid faces challenges due to its intermittent nature, varying wind velocities, and weather factors affecting output [1]. Different wind turbine models generate varying energy outputs due to their rotor size. The dominant design in the global wind turbine market is the Danish three-blade concept [2]. The rotor-swept area is crucial as it captures wind energy, and larger rotors can capture more energy [3]. Looking into wind energy alternative solutions, maximizing power output through optimal wind farm layout would be beneficial [4]. A crucial factor that affects power generation in the wind farm layout is the wake effects caused by wind turbines. For long term variability, study considering average wind speed, wind direction, and wind farm layout is essential [5].

Optimizing wind turbines placement in various wind conditions has been studied extensively, with irregular arrays showing better energy layouts. A Genetic Algorithm-based approach has been used to find optimal wind farm layouts, considering factors like electricity production and land coverage. However, the current model lacks a comprehensive wake-up model and fails to account for turbine accidents or oscillations in power curves caused by turbulence and other factors [6]. Wake effects downstream of wind turbines decrease wind speed, increase turbulence, and reduce energy output. Vortex wake models like the Jensen model estimate power production and losses by analyzing wind turbine vortices. Analytical tracking models such as WAsP, WindPro, and GH WindFarmer simulate wind resources and power losses in real wind farms [7]. Boundary conditions facilitate optimization convergence, and site restrictions ensure turbines remain within a designated area. Factors like aesthetics, environment, tourism, and legal authorization are considered in determining the wind farm's boundaries [8]. Multiple studies have explored wind farm optimization using different approaches, including Jensen's wake model and genetic algorithms. Researchers like Mosetti, Mora, Youjie, Acero, Turner, Emami, Noghreh, Mittal, Rahmani, Moreno, and Jonah have contributed to this field [9, 10]. For instance, Mosetti et al. conducted a test case in a 50Dx50D square field, dividing it into 100 cells with various turbine placement possibilities.

In this study, the objective has been focused on maximizing the wind energy generation through an optimal wind turbine sizing and placement for an offshore wind farm using Greedy Algorithm method. In this study, the maximum number of wind turbines has been limited to 25 turbines, in a 2 km x 2 km area to achieve a targeted load demand of 3 MW. ANSYS 2022 has been used to model and simulate the proposed layout, providing insights into the impact of turbine placement.

2.0 METHODS

2.1 Wind Speed Data

This study used a translated and extrapolated sample offshore wind data that has been used in [11] in which the data was collected using a measure-correlate-predict (MCP) technique. Short-term data was captured from a radio tower using cup anemometers. The long-term mean wind speed at the tower was determined to be 6.7 meters per second. Table 1 provides a summary of the wind data for various heights that will be considered under this study.

Table 1. Wind speed data

Location	Parameter	Mean wind speed	Derivation
Tower 1, 61 m	$U_{Waz,61}$	6.7 m/s	From MCP data
Tower 2, 80m	$U_{Waz,80}$	7.0 m/s	$U_{WBz,80} = U_{wBZ,61} \cdot (80/61)^{0.174}$
Coast, 80 m	$U_{KSL,80}$	7.1 m/s	$U_{K\&1,80} = U_{WBZ,80} \cdot 1.01$

2.2 Proposed Global Greedy Algorithm

By relocating each turbine, the maximum individual power output of each turbine can be determined [12-13]. The previous method was improved in [14] by applying a more effective relocation approach. In this study, a global Greedy Algorithm with repeated adjustments is used, whereby the incorporated cycle relocation optimizes the turbine placement for maximum power generation. The proposed global Greedy Algorithm under this study consists of two stages as explained below.

<u>Stage 1:</u>

1. The wind farm region of interest is selected on a Cartesian grid. In this study, a square grid with dimensions 2 km x 2 km was chosen for the wind farm region. Refer to Figure 1 for an illustration.
2. Select the coordinate cell in the grid area that is exposed to the highest wind speeds. For example,

choose T5 at cell (1,5) as turbine 1 (T1_stage1) if the wind speed recorded here is the highest. Then, install the first wind turbine at the selected coordinate cell. Refer to Figure 1(b) for an illustration.

3. Based on the first installed wind turbine, simulate the wake effect on it. Then, record the mechanical power generated by the turbine. For the next test, keep the first installed turbine fixed, and add the second wind turbine at another cell as turbine 2 (T2_stage1). For example, place it at T10 at cell (2,5). Record the mechanical performance value for this second turbine. Next, remove the second turbine and repeat this step by placing another wind turbine at different coordinate cells within the designated grid area. For instance, place it at T15 at cell (3,5). These relocations are illustrated in Figures 1(c) and 1(d), respectively. Repeat this process until all 25 wind turbines have been tested.
4. From the data obtained in step 3, select the wind turbines that demonstrate the highest power output and compute until the cumulative power value reaches 3 MW.

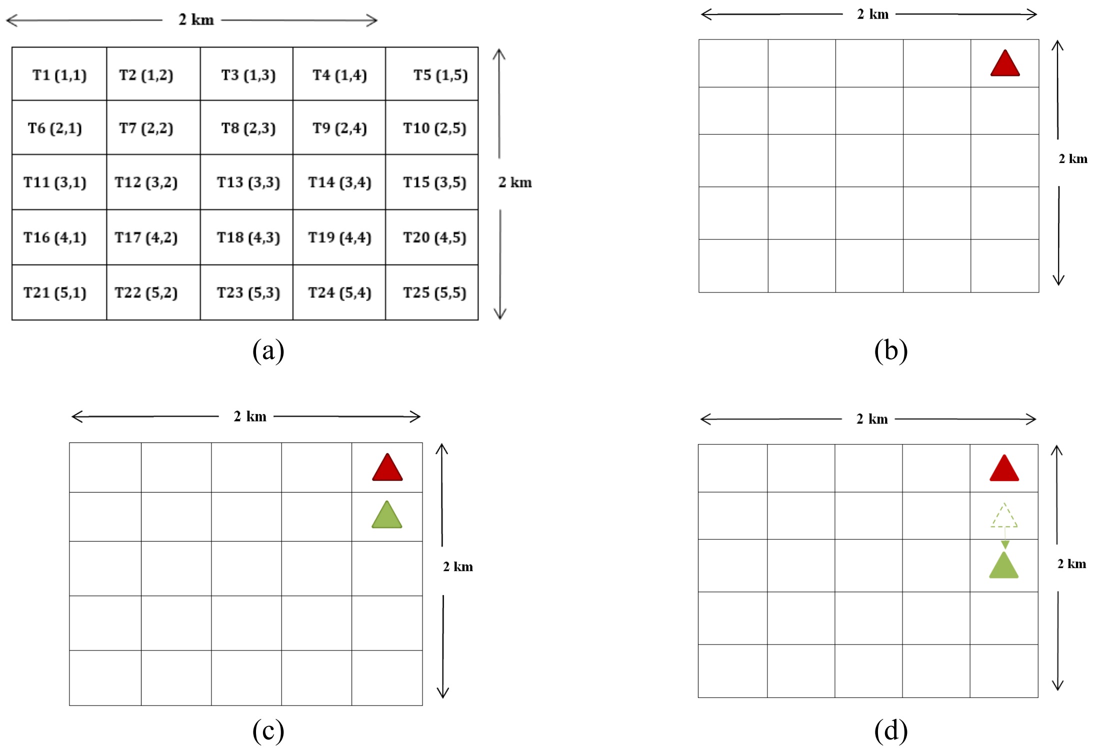


Figure 1. Illustration of the Algorithm Optimization Approach in Stage 1

Return to step 4 and resume the operation if necessary. Turbine placements in Stage 1 optimize each addition of a turbine, but they may not guarantee a globally optimal solution for the final wind turbine placement. Therefore, Stage 2 is necessary to enhance the predetermined layout of wind turbine placements. The steps undertaken for Stage 2 are outlined below:

<u>Stage 2:</u>

5. From the proposed placement method in Stage 1, the pre-optimal turbine placement can be obtained. As shown in Figure 2(a), suppose 11 turbines are placed in the figure, which have been found to generate a 3 MW power capacity. From this pre-optimal placement, select one turbine. For example, choose T1_stage2, located in T4 at cell (1,4), as shown in Figure 2(a).
6. Place the selected T1_stage2 in another empty grid cell, starting with cell (3,4), as shown in Figure 2(b). Compute the mechanical power evaluation value. Repeat the relocation and evaluation process, moving from one empty cell to another, until completed. Based on the highest power captured from the tested cells, choose the cell that presents the highest power. For example, if the optimized cell is at T14(3,4), name this optimized turbine T1_stage2(opt), as shown in Figure 2(b).
7. Repeat this process with T3. Continue until all pre-optimized wind turbines have been tested. However, if the power captured by the relocated turbine is lower than the power from its previous

location, the turbine should remain at its original position. If T2(1,2) presents the highest power, placed the turbine at this cell, as shown in Figure 2©.

8. When all turbines have undergone the relocation process and the final optimized position of each turbine has been determined, the complete cycle for Stage 2 is established. This process results in the optimal selection and placement of the turbines that together produce 3 MW of power, as an example as shown in Figure 2(d).

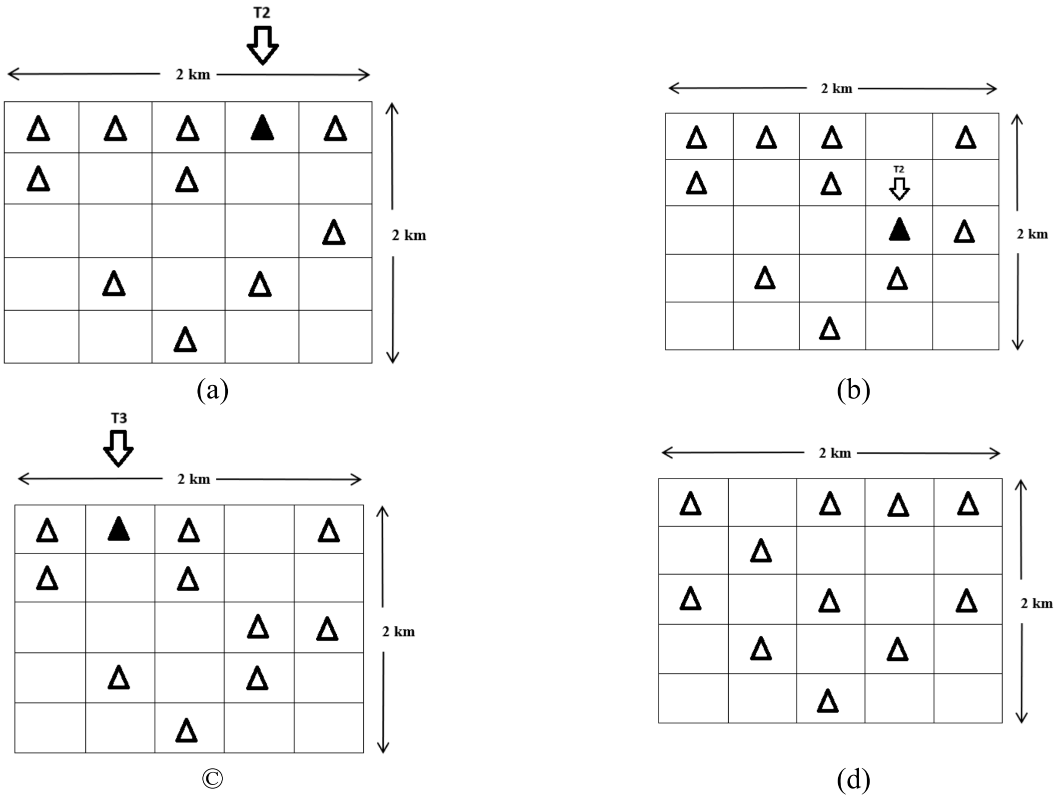


Figure 2 Illustration of the Algorithm Optimization Approach in Stage 2

The wake flow behind wind turbines can be computed using computational fluid dynamics (CFD), but it requires significant computational time. To optimize wind turbine placement, repeated modifications of turbine positions increase the total time to an unmanageable level. However, there is a popular alternative known as a wake model, which is typically used to estimate and visualize wake flow and is faster than CFD simulations [15]. In this study, the wake flow is computed using Mosetti et al.'s linear wake model, which assumes a conical wake zone with uniform speeds. Equation (1) expresses the downstream velocity of the turbine rotor.

$$u = u_0 \left[1 - \frac{2a}{\left(1+\alpha\frac{x}{r_1}\right)^2}\right] \tag{1}$$

where

$$a = \frac{1-\sqrt{1-C_T}}{2} \tag{2}$$

$$r_1 = r\sqrt{\frac{1-a}{1-2a}} \tag{3}$$

$$\alpha = \frac{0.5}{\ln(h/z_0)} \tag{4}$$

The equation represents the relationship between variables in the wake model. The variables include u_o (hub height entry velocity), x (distance downstream of the rotor), r_1 (radius of the downstream rotor), a and a (axial induction factor and entrainment constant), C_T (trust coefficient), r (rotor radius), h (tower height), and Z_o (height of the wind turbine and surface roughness of the site). The wake impacted radius R, defining the wake zone in the crosswind direction, is computed accordingly.

$$R = \alpha x + r \tag{5}$$

where R is directly proportional to x. In a wind farm with several turbines, the wake interference effect must be considered. The velocity of the ith turbine is computed using the following calculation:

$$u_i = u_0 - \sqrt{\sum_{j=1}^{N} \left[\left(u_0 - u_{ij}\right)^2 \right]} \tag{6}$$

where u_o represents the entrance velocity, u_{ij} represents the speed of the ith turbine in the wake zone of the jth turbine, and N represents the number of turbines. This wake model predicts a constant velocity throughout the same region of the wake zone [14] altered the model by displaying the area as

$$u_i = u_0 - \sqrt{\sum_{j=1}^{N} \left[\frac{A_{ij}}{\pi r_i^2} \left(u_0 - u_{ij}\right)^2 \right]} \tag{7}$$

where r_i is the radius of the rotor of the turbine. A_{ij} is the rotor region inside the jth turbine's wake?

The sum of the power produced by each turbine is the overall power output around the bladed area. The equation can be expressed as in Equation (8).

$$P_{\text{tot}} = \sum_{i=1}^{M} \left[p_i \int_0^{\infty} P_{\text{layout}}(u) f_i(u) \text{du} \right] = \sum_{i=1}^{M} \left[p_i \int_0^{\infty} \left(\sum_{j=1}^{N} P_{\text{e}}\left(u_{ij}\right) \right) f_i(u) \text{du} \right] \tag{8}$$

where P_{tot} is the total power output and M is the number of wind directions. P_i denotes the probability of the ith wind direction, while $P_{layout}(u)$ represents the power output of the ith wind direction at an arrival velocity of u. N denotes the number of wind turbines, $f_i(u)$ denotes the probability density function (PDF) corresponding to the wind speed in the ith direction, and P_e denotes the power output determined. To efficiently get the mechanical power of the WT, the following equation can be expressed as [16]:

$$\text{Power} = \text{k}C_p \ ½ \ \text{p} \ \text{A}V^3 \tag{9}$$

The power calculated is in kilowatts (KW), C_p is the maximum power coefficient, ranging from 0.25 to 0.45 [16], dimension less (theoretical maximum = 0.59), p is the air density, A is the rotor swept area, V is the wind speed in mph and k is a constant to yield power in kW which is 0.000133 [16]. Since the rotor is the component of a wind turbine that captures wind energy, the rotor swept area, A, is critical. As a result, the larger the rotor, the greater the amount of energy it can capture.

Typically, the anemometer and barometer installed at the meteorological mast are used to measure wind data. Therefore, the measured wind data must be height-adjusted in order to estimate the wind speed at a specific height. Wind velocity increases with tower height, which is determined by the surface roughness. Typically, the height effect is expressed by the power law or the logarithmic law, which can be uniformly stated [17] using Equation (10).

$$u = u_{\text{ref}} H(h) \tag{10}$$

where

$$\text{Exponential law: } H(h) = \left(\frac{h}{h_{\text{ref}}}\right)^{\alpha_u}$$

$$\text{Logarithmic law: } H(h) = \frac{\ln(h/z_0)}{\ln(h_{\text{ref}}/z_0)}$$

where U_{ref} is the wind speed at height h_{ref}, α_u is the wind shear coefficient, and Z_o is the ground's surface roughness. The probability density function (PDF) of wind speed at U_{ref} is $f(u)$ thus the PDF of wind speed at h is f(u/H(h))/H(h), which is inserted into the total power equation, as shown in Equation (11).

$$P_{\text{tat}} = \sum_{i=1}^{M} \left[p_i \int_0^\infty \left(\sum_{j=1}^{N} P_{\text{e}} \left(H(h) \left(u_{ij} \right)_{\text{ref}} \right) \right) f_i(u) \text{d}u \right] \quad (11)$$

The increase in tower height contributes to the rise in wind speed, which increases the amount of energy generated. The turbine's specifications are based on a reference in [18]. Table 2 presents the parameters used in the numerical calculations, with a focus on the horizontal-axis wind turbine (HAWT) for offshore farms.

Ansys is utilized to simulate the proposed wind farm layout and observe the effect of wind turbine placement on the wind farm's power output. Velocity streamlines, pressure, and wake effects for each wind turbine can be observed in the simulation. However, in this paper, the Ansys simulation is not included, as the main contribution here is focused on the implementation of the Global Greedy Algorithm for wind turbine placement in a wind farm. The Ansys work will be published elsewhere in the near future.

Table 2. Wind turbine specification

Property	Value
Rotor diameter (D)	40 m
Thrust coefficient ($C_s mT$)	0.88 m
Tower height	50 m
Cut-in	2 m/s
Cut-out	25 m/s
Rated speed	13.02 m/s
Rated power	680 kW

3.0 RESULTS AND DISCUSSIONS

Under this section, the results will be demonstrated and discussed in two subsections: Case 1 and Case 2. In Case 1, the results will be presented for a constant velocity of 9 m/s and a rotor diameter at a height of 40 meters. Meanwhile, in Case 2, the rotor diameter is reduced to 35 meters.

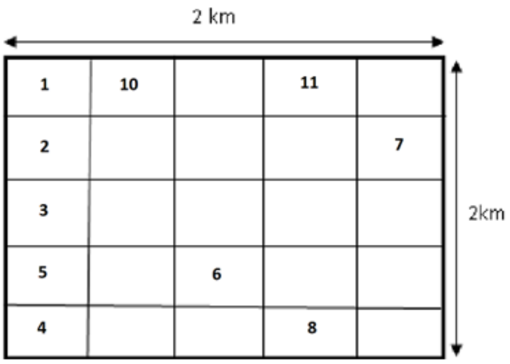
3.1 Case 1: Constant Velocity at 9 m/s and Rotor Diameter Is 40 m

3.1.1 Wind Turbines Placement Optimization for Case 1

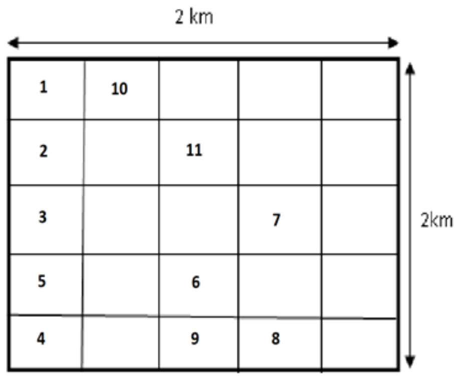
The wind blows constantly from north to south at 9 m/s, and the turbines are positioned across the wind direction from west to east, maintaining a safe distance of at least 10 times the rotor diameter. The turbine placement follows the Greedy Algorithm in two stages. In Stage 1, the turbine with the highest evaluation value, T1, is located at the top-left corner of the wind farm as an anchor turbine. Additional turbines are added one by one to calculate their power output, considering the wake effect of T1. From the calculated results, the front row of the wind farm yields the highest evaluation values, so the first five turbines are placed there to maximize power output.

Numerical calculations involve various data sets, including initial velocities U_o and wake velocities (U_{ij} and U_{oj}) obtained from Ansys simulation. The wake values (Wake 1,2,3,4) represent the impact of the front wind turbines on tested turbines. For instance, T25 at (25,5) is affected by the four wind turbines in front of it (at coordinates 21, 1; 22, 2; 23, 3; and 24, 4), while not affected by others due to narrow wake radii. Wake radii are calculated using Equation 3.5, and the final velocity of each turbine is computed using Equation 3.6, considering wake effects. Power output is computed using Equation 3.9, and each turbine's evaluation value is calculated on each grid. Turbines are selected in descending order of evaluation value to achieve a total power output of 3 MW, as shown in Figure 3(a). Stage 1 concludes with the determination of pre-optimized wind turbine placement based on high power production.

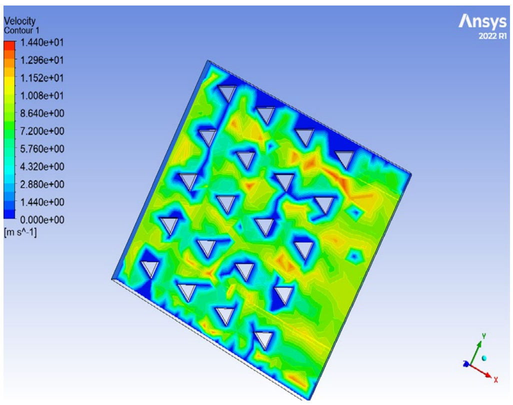
After Stage 1, Stage 2 of the Greedy Algorithm focuses on relocating the wind turbines to observe the new power output at empty grid locations. Each turbine is placed in an empty grid cell, and the evaluation value is computed. T7 and T11 are relocated to different coordinates as they produced higher power output compared to the previous optimal placement in Stage 1. The new optimal turbine placement is shown in Figure 3(b). The unoptimized layout is simulated in Ansys Fluent (Figure 3(c)), while the optimized layout is shown in Figure 3(d). The color represents wind velocity, with red indicating high velocity and blue indicating low velocity.



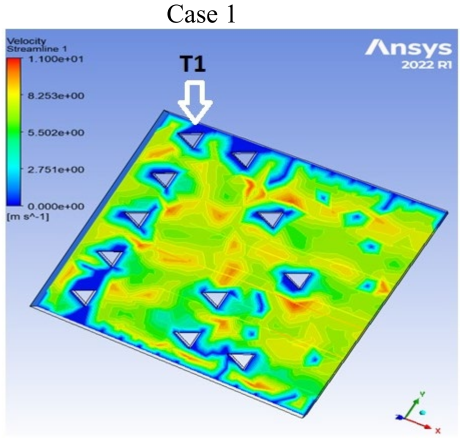
(a) Wind turbines placement after Stage 1 for Case 1



(b) Wind turbines placement after Stage 2 for Case 1



(c) Ansys simulation of the unoptimized layout for Case 1



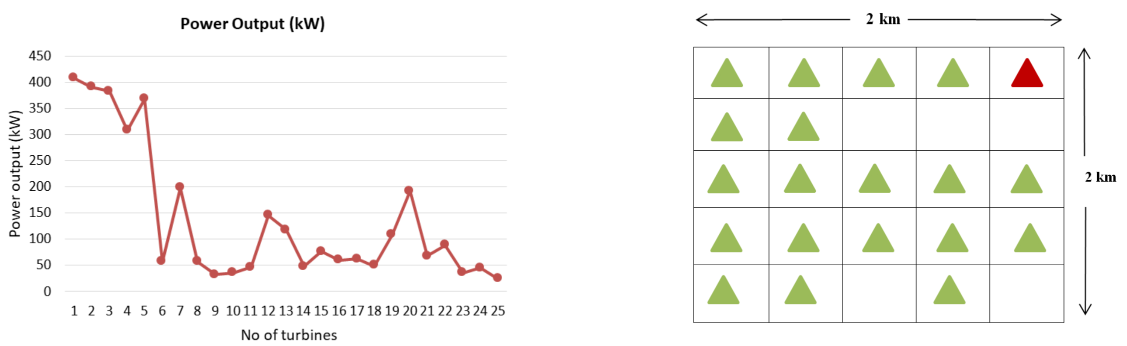
(d) Ansys simulation of the optimized layout for Case 1

Figure 3. Optimized, unoptimized wind turbine placement (Case 1)

3.1.2 Case 1: Constant Wind Speed at 9 m/s, Turbine Height at 40 m

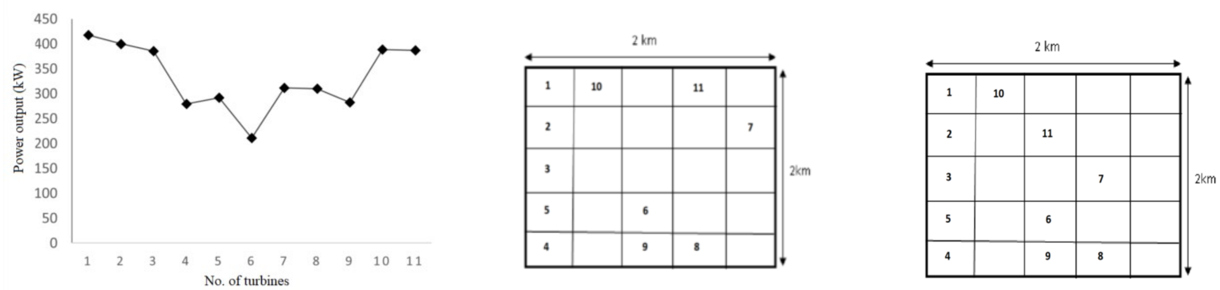
Figure 4(a) shows the generated power that can be captured by each of the 25 turbines when placed as shown in Figure 1(a). Without performing the Global Greedy Algorithm, 20 turbines are required to produce 3 MW of AC power. When applying the Global Greedy Algorithm, after going through the Stage 1 process and selecting the turbines that capture the highest power, it was found that 11 turbines were required to produce 3 MW of power capacity in the wind farm. The 11 turbines selected are T1, T2, T3, T4, T5, T7, T20, T12, T13, T19, and T22, as shown in Figure 5(a). These turbines should be arranged as shown in Figure 5(b). This result demonstrates that the proposed Greedy Algorithm provides significant benefits in determining the minimum number of wind turbines required for a wind farm. Clearly, the minimum number of wind turbines required can be economically determined. After optimization through Stage 1, as many as 9 turbine units can be eliminated. It is evident that this proposed method can greatly reduce the costs of installing wind turbines in a wind power plant.

After going through the Stage 2 process, during which turbines were relocated to other empty cells, it was found that the same 11 turbine units were needed to produce the same power capacity in the wind farm. However, to maximize the generated output, two turbines, named T7 and T11, needed to be moved to other cell positions. This was achieved by considering the wake flow model, in which the wake effects from one turbine to another were taken into account, as proposed in Equations (1) to (9).



(a) Output power from each turbine (b) 20 best turbines' selection to obtain 3 MW

Figure 4 Before Optimization approach



(a) No. of required turbines (b) After Stage 1: Optimized cells' location (c) After Stage 2: Optimized cells' location (3.1928 MW)

Figure 5 After Optimization using Global Greedy Algorithm

Table 3 summarizes the key values that significantly impact the optimal placement of wind turbines in the wind farm layout. It presents details on the generated power both with and without considering the wake effect, as well as the impact of optimization. The results show that, with the wake effect, the power generated is lower compared to when the wake effect is not considered. Moreover, optimization leads to higher energy generation compared to the pre-optimization scenario.

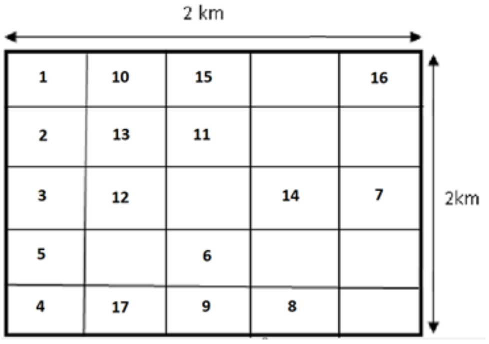
Table 3 Summary of CFD simulation results for Case 1

Layout	Average Power (kW)	Average Velocity (m/s)	Pout without wake effect (kW)	Pout with wake effect (kW)	Efficiency	Overall Energy Generation (kW)
Unoptimized	153.875	5.231	7167	3077.5	42.33%	3077.5
Optimized	296.981	6.106	3289.6	3192.8	97.6%	3192.8

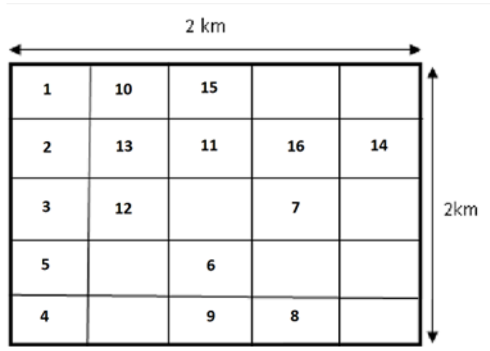
3.2 Case 2: Constant Velocity = 9 m/s and Rotor Diameter = 35 m

3.2.1 Wind Turbine Placement Optimization for Case 2

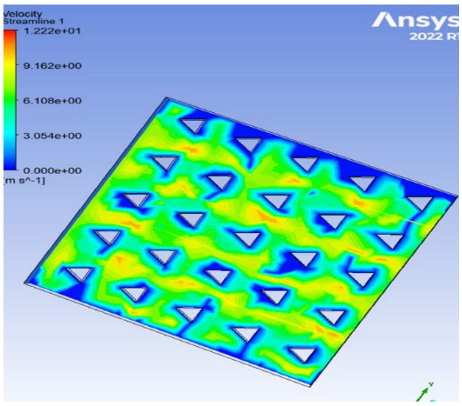
In Case 2, a smaller rotor diameter of 35 meters is used while maintaining a constant wind velocity of 9 m/s. The objective is to examine how the smaller rotor diameter affects the overall power output of the wind farm. As expected, the evaluation value decreases with the smaller rotor diameter since power output is directly proportional to the rotor diameter. The first five turbines are placed in the front row to maximize power output, as there are no obstructions from other turbines at this position. The placement of the remaining turbines is determined by selecting the grid with the highest evaluation value. In Stage 1, a total of 17 turbines are required to achieve 3 MW of AC power output. The order of turbine placement is based on their evaluation value. The pre-optimized layout of the wind farm can be obtained, as shown in Figure 6(a). In Stage 2 as shown in Figure 6(b), the relocation process further optimizes the wind farm layout. The number of turbines needed to achieve 3 MW of power is reduced by one compared to the first stage of optimization. T7, T14, and T16 are relocated to new grid locations to improve their performance, considering the wake effect of existing turbines. The unoptimized and the final optimized wind farm layout, given the case conditions, is shown in Figure 6(c) and Figure 6(d), respectively. The proposed layout is then simulated in Ansys to observe the wake effect and velocity contour of each turbine in the wind farm.



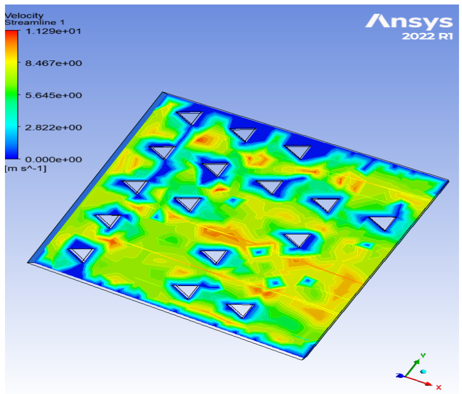
(a) Wind turbines placement after Stage 1 for Case 2



(c) Wind turbines placement after Stage 2 for Case 2



(d) Ansys simulation of the unoptimized layout for Case 2



(e) Ansys simulation of the optimized layout for Case 2

Figure 6 Optimized, unoptimized wind turbine placement (Case 2)

3.2.2 Wind Farm Power Production for Case 2

When the rotor diameter is reduced by 5 meters in Case 2, it was expected that the number of installed turbines would increase. However, the proportional reduction in turbine numbers could not be reliably determined. In the simulation conducted for this study, it was observed that without considering the Greedy Algorithm (Figure 7), 30 turbines were required to generate 3.09 MW of AC power. However, after optimization using the Greedy Algorithm (Figure 8), the total number of wind turbines was reduced to only 16. This represents a significant reduction, eliminating 14 turbines from the initial 30 to achieve the desired 3 MW of AC power output. Table 4 summarizes the key values for determining the optimal layout in Case 2, comparing the values between the unoptimized and optimized layouts.

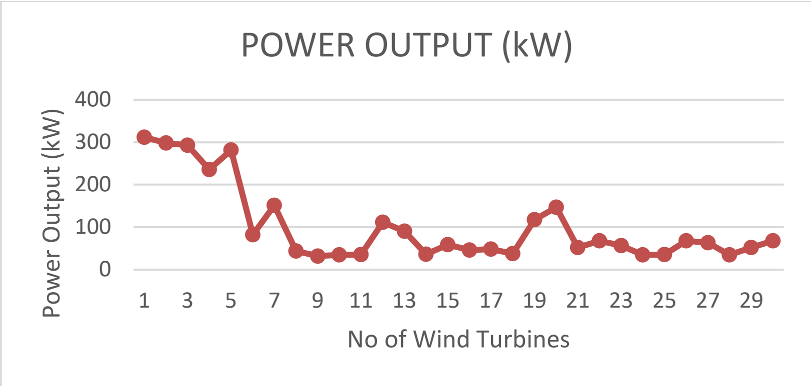


Figure 7. Power output for unoptimized layout (without Greedy Algorithm), 3.023 MW for 30 wind turbines

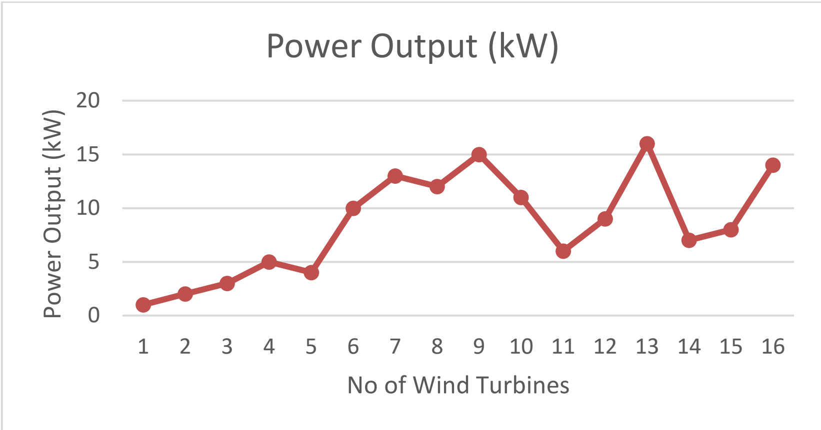


Figure 8. Power output for optimized layout (with Greedy Algorithm), 3.099 MW for 16 wind turbines

Table 4. Summary of CFD simulation results for Case 2

Layout	Average Power (kW)	Average Velocity (m/s)	Pout without wake effect (kW)	Pout with wake effect (kW)	Efficiency	Overall Energy Generation (kW)
Unoptimized	100.767	5.27	4108.28	3023.7	73.6%	3023.7
Optimized	193.718	6.11	3195.73	3099.5	97%	3099.5

The optimal wind farm layout is crucial for maximizing power output. Wind velocity and rotor diameter greatly influence the power generated. Higher wind velocity leads to increased turbine power. However, wind conditions vary across the grid due to factors like terrain. Larger rotor diameter allows for capturing more wind energy but reduces the maximum number of turbines in the limited area. The simulation validates the potential for turbines with larger rotors to achieve 3MW. It confirms that rotor diameter has a crucial impact on energy production and determines the number of turbines needed.

More computational time is required to determine the optimal wind farm layout when fewer turbines are needed to achieve the desired power output. The second stage of the Greedy Algorithm is particularly time-consuming because it involves evaluating each turbine's placement options in every available grid cell. For example, in Case 1, where 11 turbines are required to generate 3 MW of power, each of the 11 turbines must be tested in every empty grid cell, resulting in 154 total tests. In Case 2, with 16 turbines required for 3 MW of power, only 144 tests are needed in Stage 2, which is fewer than in Case 1. Both Case 1 and Case 2 require fewer iterations for turbine relocation in Stage 2.

4.0 CONCLUSION

This study proposes using the Greedy Algorithm with the linear wake model and the power-law power curve model to address the wind turbine placement problem in a wind farm. The incremental calculation method is employed to analyze power output by considering the wake effect of neighboring turbines and the wind's impact on power deficits in other turbines. The proposed technique is demonstrated through two test scenarios, highlighting its utility in determining the optimal wind farm layout. From the simulation study, it was found that the proposed method achieves the desired power output of 3MW while minimizing costs by identifying the minimum number of turbines in optimal positions.

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