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Turbine Wind Placement with Staggered Layout as a Strategy to Maximize Annual Energy Production in Onshore Wind Farms

Dwiana Hendrawati[1,2]*, Adi Soeprijanto[1], Mochamad Ashari[1]

[1]Departement of Electrical Engineering, Faculty of Electro Technology, Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia, [2]Department of Mechanical Engineering, Politeknik Negeri Semarang, Semarang, Indonesia. *Email: ana.hendrawati@gmail.com

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ABSTRACT

The wind energy potential of Indonesia based on the General Plan of National Energy is 60,647.0 MW at wind speeds of 4 meters per second or more. Considerable potential and untapped optimally, is a challenge that gives direction to the development and policy of the wind energy sector in Indonesia. The policy covers a wide range of activities including study technology for utilization of large-scale wind energy source or called Wind Farms. To achieve these targets, the initial policy that can be applied is the utilization of wind energy and technology development of land-based wind farm for onshore wind farm. Land limitations on onshore directs this research in the attempt to increase annual energy production (AEP) with a fixed land area. This is synonymous with minimizing the cost and is a Wind Farm Optimization (WFO) problem. The completion of WFO in this study was carried out by reconstructing the placement of wind turbines into a staggered layout. To test the performance improvement of the proposed design, by comparing the AEP of the proposed (staggered) layout and conventional (aligned) layout. The simulation shows that staggered layouts can reduce costs and increase AEP between 1.2% and 8.7%.

Keywords: Wind Farms, Aligned, Staggered Layout, Cost, Annual Energy Production
JEL Classifications: C61, C63

1. INTRODUCTION

According to the IEA, around 40% of the additional renewable energy comes from onshore wind, with commissioning around 60 GW of new integrated networks. This is in line with the Hybrid Wind Power Plant (WHyPGen) project launched by the Indonesian government and energy development projects (BP p.l.c 2016). The main target is the realization of the energy industry that generate electric energy technology based Wind of 18.115 GWh with an installed capacity of 9.4 MW.

The higher initial cost of renewable energy compared to conventional energy technology is often viewed as an obstacle in the development of renewable energy and so for wind energy (Giwangkara and Campen 2018). Therefore, efforts to reduce costs for renewable energy generation are needed so that the trust so that the confidence of industry players to invest in renewable energy increases. Of industry players invest in renewable energy increases. The trust in renewable energy investment will have a positive impact on Indonesia's electricity market (PwC, 2018).

Recently, converting wind energy into electricity by wind turbines has led to large-scale development, called wind farms. Furthermore, the main thing for optimal wind farms design is the wind speed deficits, which are the impact of interactions between wind turbines (Tian et al., 2015; Adaramola and Krogstad, 2011).

The velocity deficit is the wake effect phenomenon which is the decrease of energy production in wind farms. To overcome this phenomenon, many studies present the design of Wind Farm Optimization (WFO). WFO consists of Wind Farm Layout Optimization (WFLO) and Control Optimization (WFCO),

Figure 1. The WFLO determines the wind turbine positions and the WFCO determines the wind turbine operations.

When a wind farm development policy takes precedence on the onshore with limited land, the WFLO attempted to gain confidence in wind energy. WFLO is a factor that further affects the profitability of the installation (Gonzalez et al., 2010; Wang et al., 2016). The main concept in the WFLO design is the wind farm layout so that maximum energy production and minimal investment costs, within the framework of reducing the wake effect phenomenon (De-Prada-Gil et al., 2015; Sethi et al., 2011; Shakoor et al. 2016; Wei and Zhu, 2012; Hendrawati et al., 2016).

Ideally, the separation distance between wind turbines as far as possible in order that the wake effect being ignored, so that the Wind Farm energy is maximally possible. On the other hand, land use and wind turbine connection cost limits consideration of ideal conditions. The interesting calculation of this variable spacing is due to bring up two opposite effects. If the spaces between Wind Turbines too close will increase the wake losses and reduced power extraction, but minimize the land use that is identical to minimizing costs; and vice versa.

Therefore, the WFLO method is basically to put a number of wind turbines on wind farms. In the previous paper, almost all of the turbine placement uses the aligned layout, so further the research more directed to other layout modelling to explore the possibilities of improved energy production of a wind farm. This research will reconfigure the placement of wind turbines with aligned layouts into the pattern of placement with a staggered layout. So, the research will simulate for 2 layouts, i.e., the conventional (the aligned layout) and the proposed (the staggered) layout, Figure 2.

2. LITERATURE REVIEW

The economic model in WFLO's research is the energy costs generated by wind farms. Therefore, there are two objective functions in WFLO namely minimizing costs and maximizing energy (or power). The two objective functions are expressed in one unit of the objective function, which can be expressed by:

$$Max(G)\sum_{i=1}^{N}\frac{P_i(x,y)}{Cost_i(x,y)} \tag{1}$$

Or

$$Min(G)\sum_{i=1}^{N}\frac{P_i(x,y)}{Cost_i(x,y)} \tag{2}$$

Subject to

$$D_{pv(stagg)} \le D_{pv(align)}$$
$$2d_{pp(stagg)} \le d_{pp(align)}$$

Where (x, y) is the coordinate of a turbine placement, N is the number of wind turbines that will be installed on wind farms, d_{pv} and d_{pp} are the prevailing and the perpendicular spacing between wind turbines. The objective function is a maximized power or energy $P_i(x,y)$ and minimized $Cost_i(x,y)$.

Figure 1: Optimization system on Wind Farm Optimization

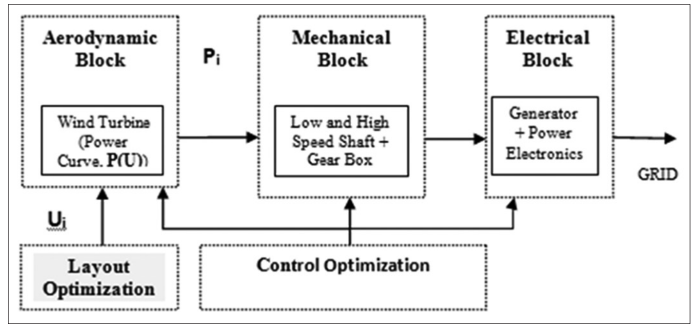
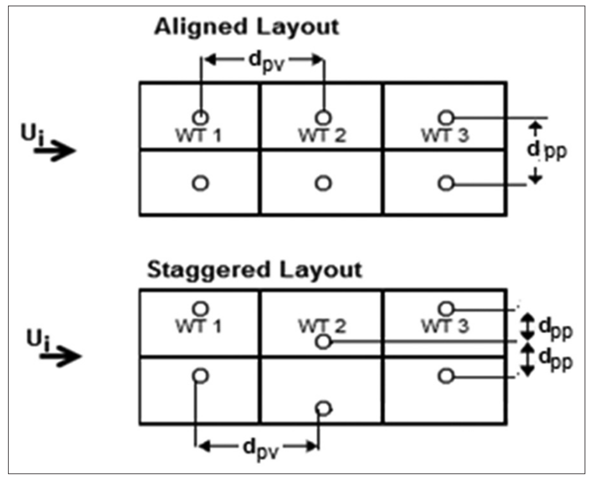


Figure 2: Wind turbine configuration with the aligned and staggered layout



This WFLO method arranges the placement of wind turbine on wind farms, set the distance or spacing between wind turbines, and determine the number of wind turbine installed on wind farms. Subsequently, the number of wind turbine determines the infrastructure cost in wind farms. Generally, infrastructure costs are modeled according to the number of wind turbines (Chowdury et al., 2013). If the cost/year of a single turbine =1 then the total cost/year of N wind turbine on the wind farm is expressed as Eq. 3).

$$Cost = N(\frac{2}{3}+\frac{1}{3}\exp^{0.00174}) \tag{3}$$

When reconfiguring means placing the wind turbine with the same amount in both layouts, the cost for Eq. 3) cannot be used as an optimization target. So the infrastructure costs in this optimization are identified by area:

$$Cost_i(X,Y) = \sum_{(X,Y)=1}^{N}(d_{pp}.X).(Y.d_{pv}) \tag{4}$$

For the aligned layout and

$$Cost_i(X,Y) = \sum_{(X,Y)=1}^{N} d_{pp}(2Y+1).(X.d_{pv}) \tag{5}$$

For the staggered layout.

3. METHODS

The steps of the proposed method are as follows:

- A number of turbines are arranged with the aligned layout at Wind Farm by utilizing all areas, so that a series of wind turbines are formed with certain prevailing and perpendicular spacing
- Calculate the energy per area and set it as the initial value
- Reconfigure the turbine into the staggered layout for the optimization process, so that the wind turbine is placed at certain prevailing (d2) and perpendicular (d) distances
- Compare the energy performance produced by the two layouts.

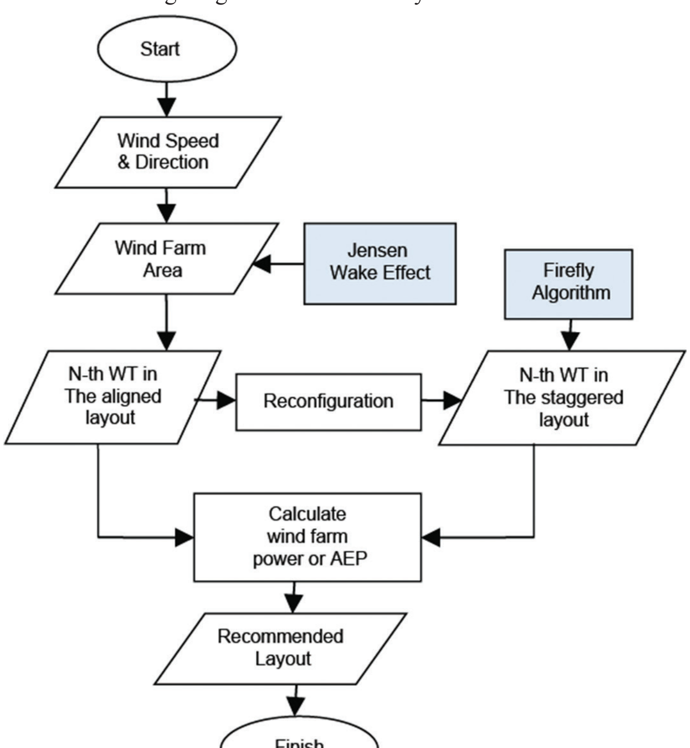
Figure 2 shows the reconfiguration flow chart.

The optimization with the proposed layout uses firefly algorithm (FA) because among all metaheuristic algorithms, FA excels in achieving global optimal values (Ali et al., 2014; Massan et al., 2015; Fister et al., 2013) (Figure 3).

3.1. Power and Annual Energy Production (AEP) Modelling

To calculate power or AEP in a wind farm, it is necessary to know the type of wind speed. Wind speed can be expressed as steady or variation. The wind turbine power when the steady wind speed is stated in the power curve. The power curve of a wind turbine model can be developed with the given cut-in speed, rated speed and cut-out speed. The power of each wind turbine in the wind farm is determined in Eq. 6.

Figure 3: Flow chart for wind farm layout optimization in reconfiguring the wind turbine layout at wind farms



$$P_i(U_i) = \begin{cases} 0; if\ U_i < U_{cut-in}\ \&\ U_i \geq U_{cut-out} \\ \frac{1}{2} C_p \rho A U_i^3;\ \ if\ U_{cut-in} \leq U_i < U_{rated} \\ P_{rated};\ \ if\ U_{rated} \leq U_i < U_{cut-out} \end{cases} \tag{6}$$

So that the wind farm power (P_F) is the power of the N wind turbines.

$$P_F = \sum_{i=1}^{N} P_i(U_i) \tag{7}$$

And AEP can be defined as the energy product for the 1 year period of time T

$$E = T.P_F \tag{8}$$

Steady wind speed cannot represent the true wind potential, so it is only used in simulation. Whereas to approach the actual wind potential, expressed in variations in wind speed. The modeling of wind variations typically uses a Weibull distribution that indicates a function of wind speed, with probability.

$$f(U) = \left[\frac{k}{c}\left(\frac{U}{c}\right)^{k-1}\right] e^{-\left(\frac{U}{c}\right)^k} \tag{9}$$

Where k is non dimensional of shape factor, c is the scale factor.

If $P(U)$ is the power curve of the wind turbine, then the expected power production:

$$P_{mean} = \int_{U_{cutin}}^{U_{cutout}} P(U) f(U) dU \tag{10}$$

In determining the wind farm energy, the wind speed distribution combined with the frequency distribution of wind speed from all directions which is a wind rose. Ordinarily, wind rose is divided into 12 wind classes (wind directions), for every 30°.

$$P_{mean} \approx \sum_{windclass} P(U) h(U) \tag{11}$$

The expected energy yield during the period T with the probability of occurrence of wind class U, $h(U)$, is

$$E = P_{mean} \times T \times \mu \tag{12}$$

In addition, if the determination of the AEP is per year, then $T = 365.25 \times 24$. Availability, μ, states the time per year when wind turbines are not produced and typically 98–99% for onshore and 93–95% for offshore.

4. JENSEN WAKE EFFECT MODELLING

The energy produced by wind turbines is determined by wind speed received. In wind farms, upstream wind turbines affect downstream wind turbines or the so-called wake-up phenomenon. Wind speed in downstream wind turbines is lower than the wind speed received by upstream wind turbines. And expressed as:

$$U_i = U_j - \Delta U_j \quad (13)$$

The velocity deficit at downstream wind turbine is determined by all upstream wind turbine i (N_{Up}) that affect it, thereby:

$$\frac{\Delta U_j}{U_j} = \sqrt{\sum_{j=1}^{N_{Up}} \left(\frac{\Delta U_{ij}}{U_j} \right)^2} \quad (14)$$

Based on Jensen's wake effect modeling, the analytical expression of the velocity deficit at downstream Wind Turbine i of a single upstream wind turbine j is

$$\frac{\Delta U_{ij}}{U_j} = (1 - \sqrt{1 - C_T}) \left(\frac{R}{R + kd_{pv}} \right)^2 \left[\frac{A_{ij}}{A} \right] \quad (15)$$

$$s.t: 0 \leq \frac{A_{ij}}{A} \leq 1$$

Where R is the radius rotor of the upstream wind turbine, C_T is thrust coefficient of wind turbine, k is wake decay (0.04 for offshore and 0.075 for onshore), d_{pv} is the prevailing distance between upstream and downstream wind turbines or d_1 in the aligned layout and d_2 in the staggered layout. A_{ij} is overlap area between the wake area of the downstream wind turbine A_w and sweep area of the upstream wind turbine A (Figure 4).

4.1. Optimization Algorithm

The completion WFLO optimization uses the FA to achieve the optimal spacing in the staggered layout. In the FA, the control variable is spacing in the prevailing and perpendicular of wind direction (d_2 and d) and as fireflies. Fireflies are released will look brighter and less light which indicates the amount of fitness function (G) with a certain d_2 and d. The less bright will approach the firmer fireflies, and the brightest presents the best value of the fitness function Eq. 1 or Eq. 2.

The basic movement of the firefly uses the basic algorithm. The best fitness function value remains in its position, while the remaining d_2 and d update their position with the FA parameters (α, β, and γ). Their position is updated until the criteria are met and d_1 and d_2 are optimally achieved.

$$x_k = x_{k-1} + \beta_0 e^{-\gamma r^2} (x_j - x_{k-1}) + \lambda \varepsilon_i \quad (16)$$

x_i and x_j represent the position of the less bright firefly i and the brighter firefly j. β_0 is a firefly attractiveness factor, γ represents a random vector, and α is the light absorption coefficient by a random vector ε_i generating from a Gaussian distribution.

5. RESULTS AND DISCUSSIONS

5.1. The Application of the Layout is Staggered

To apply the proposed staggered layout as a strategy that can improve AEP of Wind Farms, the optimization results were compared with the conventional aligned layout. On the area of X = 14 times diameter = 14 D and Y = 10D, installed 9 wind turbine with the aligned layout, Figure 5. The turbine used for the simulation is Vestas 80 onshore (2 MW), with specifications as in the Appendix Table 1.

Referring to this area, do the laying of the staggered, Figure 5. Then, the wind turbines position is rearranged using the FA until it reaches the optimization target (objective function) (Figure 6).

The distance between wind turbines on the aligned layout is 7D and 5D respectively, for prevailing and perpendicular spacing. Optimization with staggered layout obtains an optimal distance of 6.95D, 3.96D respectively, for prevailing and perpendicular spacing.

In addition, the simulation reviews 3 cases of different wind speeds:

Figure 4: Schematic of the overlap area between the wake area of the upstream wind turbine and sweep area of the downstream wind turbine

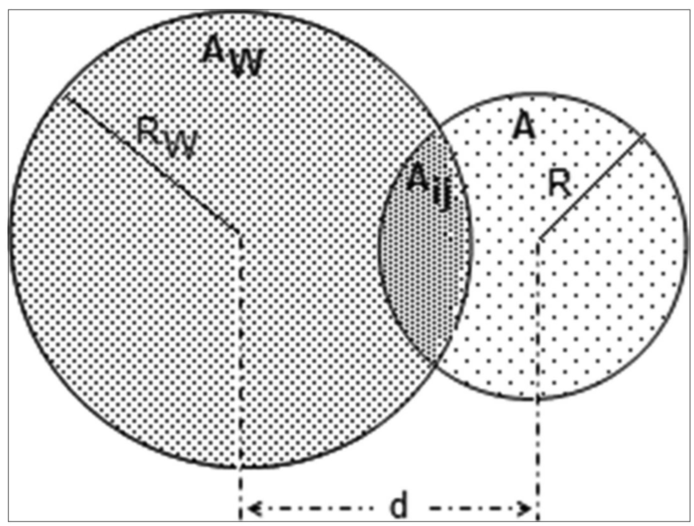


Table 1: AEP comparison between the aligned and staggered layout in a steady wind speed (case 1)

U (m/s)	AEP (GWh/year)		Enhancement (%)
	Aligned	Staggered	
3.50	29.54	32.11	8.70
4.50	78.40	81.58	4.06
5.00	111.86	116.13	3.82
5.50	151.45	156.97	3.65
6.00	197.27	203.79	3.31
6.50	253.03	259.86	2.70
7.00	318.36	324.55	1.95
7.50	391.57	399.14	1.93
8.50	570.01	581.01	1.93
11.40	1375.11	1401.61	1.93

AEP: Annual energy production

Figure 5: 9 Wind turbines on wind farm with aligned layout

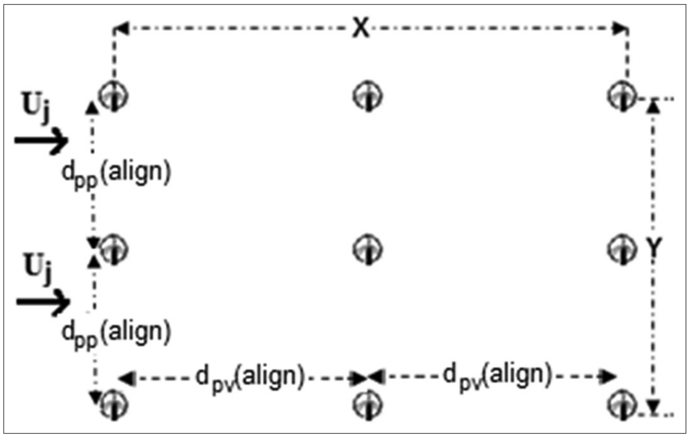


Figure 6: Nine wind turbines rearrangement on the staggered layout

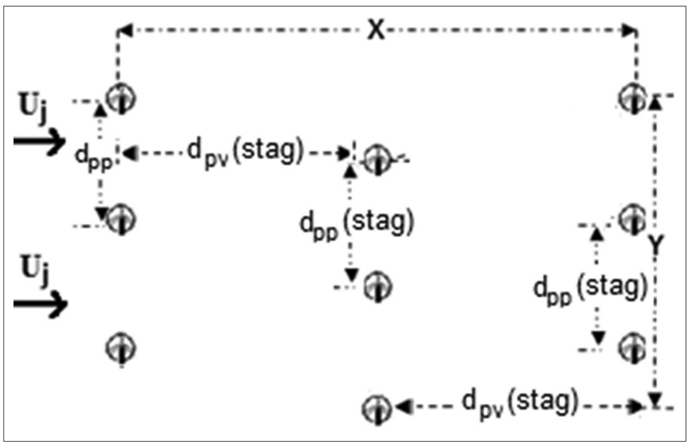
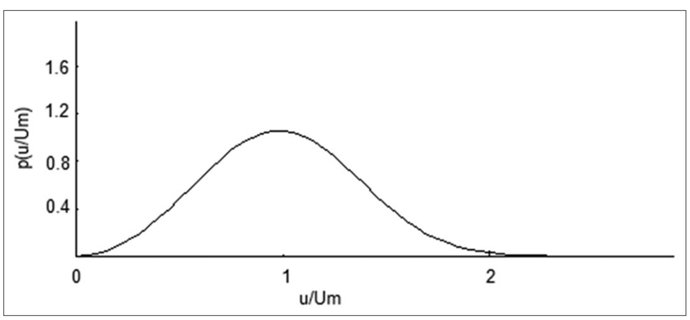


Figure 7: Model of a variable wind speed with the shape factor k=3 (case 2)



- Case 1: In a steady wind speeds of 3.50–11.4 m/s
- Case 2: In a variable wind speed with mean speed (Um) of 3.5–11.4 m/s and the shape factor k = 3.0
- Case 3: In a variable wind speed with average speed (Um) of 3.5–11.4 m/s and the shape factor k = 2.0

And the frequency is the same for the whole wind directions (in this case 12 wind classes). Tables 1-3 show the comparison of AEP before optimization (the aligned layout) and the results of the optimization (the staggered layout) respectively for cases 1–3.

Comparison of AEP in both layouts with three different wind speeds shows that staggered layouts can increase AEP between 1.20% and 8.70%. The higher the wind speed, the smaller the AEP increase. And conversely, if the wind speed is closer to the cut-in speed, the increase in AEP is greater. Because, when the layout is staggered, downstream wind turbines receive more free wind than the aligned layout (Figure 7).

Table 2: AEP comparison between the aligned and staggered layout in a variable wind speed with k=3.0 (case 2)

Um (m/s)	AEP (GWh/year)		Enhancement (%)
	Aligned	Staggered	
3.50	56.11	60.54	7.91
4.50	148.92	157.20	5.56
6.00	269.88	279.80	3.68
7.00	405.86	412.75	1.69
8.50	712.51	721.26	1.23
11.40	1705.14	1726.00	1.22

AEP: Annual energy production

Table 3: AEP comparison between the aligned and staggered layout in a variable wind speed with k=2.0 (case 3)

Um (m/s)	AEP (GWh/year)		Enhancement (%)
	Aligned	Staggered	
3.50	73.45	79.40	8.11
4.50	194.64	205.13	5.39
6.00	317.60	329.41	3.72
7.00	436.15	444.13	1.83
8.50	604.21	611.46	1.20
11.40	1430.11	1447.27	1.20

AEP: Annual energy production

Table 4: AEP comparison between the aligned and staggered layout in a real region

The Value of	Align.	Stagg (a)	Stagg (b)
Gross AEP	31.98	31.97	31.98
Net AEP	30.07	31.12	31.15
Wake losses (%)	5.97	2.66	2.59

AEP: Annual energy production

From the three results table also shows that when the speed is approaching rated, the increase in AEP is more likely to be constant. This is due to the power of the wind turbine being kept constant when the wind speed reaches a rated value (Figure 8).

5.2. Verify Simulation Results

To verify the simulation results, the wind turbine model as above is placed in the Lebak region, Indonesia, which has a wind potential that is described by the wind rose in Figure 8. While the wind turbine is placed in an aligned and staggered layout shown in Figures 9-11.

With the same type of turbine, the wind potential (Figure 9), and the distance of adjusting the simulation, are obtained AEP as in Table 4. The AEP increase is shown in the reduced wake losses in the staggered layout compared to the aligned layout. Table 4, shows that wake losses in the staggered layout Figure 11a becomes 2.66% or it can be said that the increase in AEP is 3.31%. Likewise with the staggered layout Figure 11b, wake losses decreased by 3.38% or in other words an AEP increase of 3.38%.

Figure 8: Model of a variable wind speed with the shape factor k=2

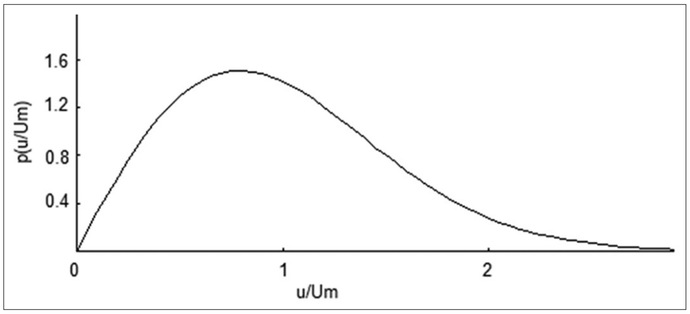


Figure 9: Wind rose of 12 wind classes with k = 3 and Um = 5.49 m/s

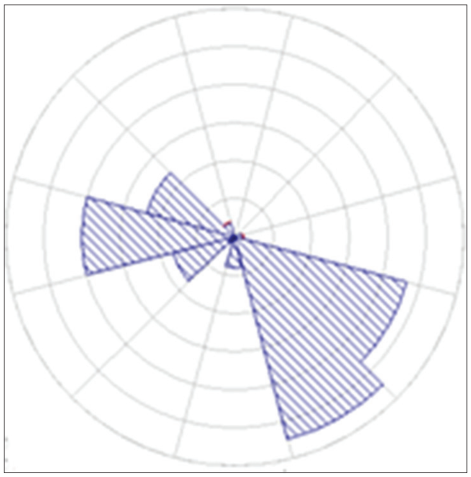


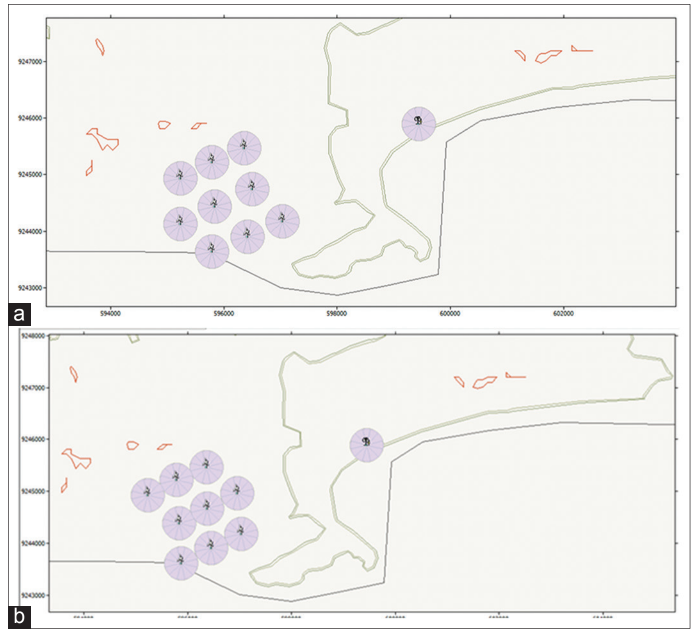
Figure 10: Placement of wind turbines with aligned layout

Considering the potential of wind energy in Indonesia is below 6 m/s, the staggered placement strategy can be expected to increase wind energy production by more than 3%. This AEP increase can be said without additional effort to increase wind energy, because the area that is identical to the cost of wind farms does not increase with this wind turbine placement strategy.

6. CONCLUSION

This paper presents a strategy to increase the AEP with the costs represented by the wind farm area. By reconstructing the placement of wind turbines into a staggered layout, AEP in an onshore wind farms can increase compared to conventional layouts. Determining the location of wind turbines with optimal distances is a determinant of improving AEP. This wind turbine placement can be a strategy for developing wind energy in the coastal region.

Figure 11: Placement of wind turbines with staggered layout



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APPENDIX

Appendix Table 1: Specification and power curve of wind turbine

VESTAS 80 (onshore)	
Rating	2 MW
Rotor orientation	Upwind, 3 Blades
Hub height	50 m
Cut-in wind speed	3 m/s
Rated wind speed	11.4 m/s
Cut-out wind speed	25 m/s
Rotor diameter	80 m