Optimized Design of Wind Farm Configuration: Case Study

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ABSTRACT— ***The initial result of wind energy study conducted in onshore Purworejo in one year (October 2004 ~ September 2005) shows that potential wind speed on the heights of 100 m with the Weibull shape parameter is 1.74 and the Weibull scale parameter is 6.93 m/s. The research is located near fishery industrial activity, fish auction market and transmission network electric. Study for the development of potential wind energy into wind farm in coastal area of South Purworejo is strategic for Central Java Province, Indonesia. In numerical procedure, two-numerical phases are conducted, and they cover (i) numerical based on capacity factor and (ii) numerical based on wind farm configuration design. From result and discussion can be concluded that wind farm configuration with size L_{row} = 4000 m and L_{col} = 1000 m, wind turbines with a diameter of 113 m with 42 turbines, produced total energy about 363382.71 MWh per year with ratio cost per energy about 0.000079, and it has the most optimal result.***

Keywords— Potential, wind farm, optimized design, ratio cost per unit energy

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1. INTRODUCTION

Wind energy potential in Indonesia is generally located along southern coastal area of Java reaching to eastern part of Indonesia. The result of wind energy study conducted especially in coastal area of South Purworejo which employs measurement point in one tower containing record of mean for every five second. The record is continuously taken for one hour during one year (October 2004 - September 2005) [1]. Measurements have been taken in coastal area of South Purworejo by placing an anemometer at three positions. Anemometer is placed at the heights of 100 m, 80 m and 60 m. The measuring instrument used to measure air temperature, air pressure, and air humidity is placed on the height of 6 m which shows that each element have the annual average equal to 29.18 ^{0}C, 1002.4 mbar, and 81.025 %RH. The dominant direction of wind measured by anemometer and wind vane in height of 100 m is from south east [1]. Potential in coastal area of South Purworejo is near fishery industrial activity, fish auction market and transmission network [2]. Study for the development of potential wind energy into a wind farm in coastal area of South Purworejo is strategic for Central Java Province, Indonesia.

The development of a wind farm is a complex task involving a wide range of engineering and scientific skills [3]. The challenge for the wind farm designer is to maximize the energy capture within the given restrictions [4]. The investigations on wind energy essentially consist of four principal topics [5]. The first one deals with the sensors and instrumentation used for wind measurements. The second one is the evaluation of wind energy potential for particular region using various statistical approaches. The third focuses on the design and characterization of wind energy turbines. The fourth is the design and development of wind farms [5].

The current study deals with the fourth topic which concerns the design of wind farms. A numerical simulation of combined model for wind farm configuration by taking account on requirements and restrictions needs to be developed. The wind farm investment costs and the total power of wind turbine types and number are used to determine an optimum relation between them [3].

2. WIND FARM CONFIGURATION DESIGN MODELLING APPROACH

At the early stage a suitable wind farm site is identified by its geographical location, and based on long-term wind record for annual wind speed variation [4]. The determination of the wind turbines number in the designed wind farm is restricted by the necessity to be placed within a limited geographical area [3]. The separation distance between the turbines is among the other things to be considered when defining the wind farm layout and depends on the needed recovery of wind energy behind the neighbouring turbines [7,8]. The optimum solution should define the wind turbines number and type and also their placement in the given geographical area [3]. Different profit-to-cost ratio could be used as performance metrics of investment [9]. In this study case use wind farm configuration in an area dimension broadly area about 4 km^2. A schema wind turbine is placement for dominant wind direction as shown on Fig. 1.

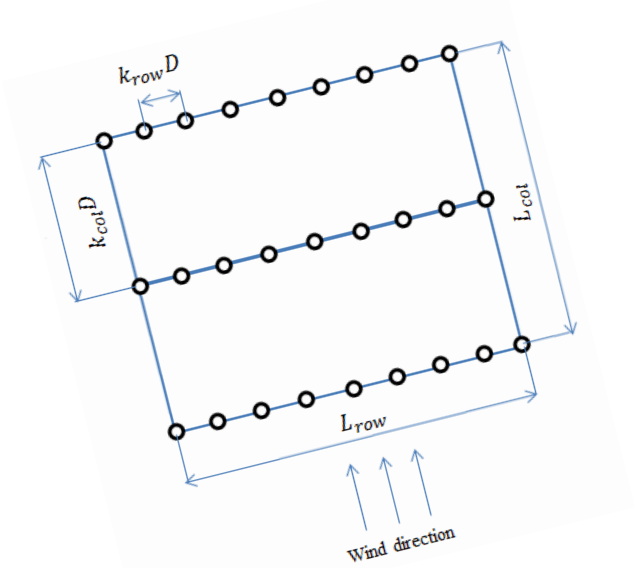

Figure 1: Schema wind turbines placement for dominant wind direction

Based on wind farm configuration design should conform to a preliminary chosen geographical area with known parameters wind conditions and area size. The main goals of determining the optimal wind turbines type and wind farm configuration are to obtain maximum power output and to minimize the investment costs. In this case, wind direction is assumed as dominant wind direction. The spacing of wind turbines cluster in a wind farm depends on the terrain, the wind direction and speed, and the turbine size [3].

Capacity factor is one of the parameters which determines maximum power output wind turbine. Wind turbine capacity factor is expressed in the following Eq. (1) [9]:

$$CF = \frac{exp\left[-\left(\frac{V_c}{c}\right)^k\right] - exp\left(\frac{V_R}{c}\right)^k}{\left(\frac{V_R}{c}\right)^k - \left(\frac{V_c}{c}\right)^k} - exp\left[-\left(\frac{V_f}{c}\right)^k\right] \quad (1)$$

Where V_c is cut in wind speed, V_R is rated wind speed, V_f is furling wind speed, k is the Weibull shape parameter, and c is the Weibull scale parameter. The Weibull distribution is one of the statistical methods useful for finding distribution from a various number of data of wind speed. The Weibull distribution consist of two distribution parameters, those are, the Weibull shape parameter k (dimensionless) and the Weibull scale parameter c (m/s). To determine parameter k value if middle value and variant can be measured from following Eq. (2) [9]:

$$k = \left(\frac{\sigma}{\bar{u}}\right)^{-1,086} \quad (2)$$

where σ is the standard deviation wind speed, n is the number of measured values, $\bar{u}$ is mean of wind speeds, and u_i is a set of measured wind speeds, The standard deviation is then defined in the following Eq. (3) [9]:

$$\sigma^2 = \frac{1}{n-1}\sum_{i=1}^{n}(u_i - \bar{u})^2 \qquad (3)$$

The mean of wind speed is defined as Eq. (4) [9]:

$$\bar{u} = \frac{1}{n}\sum_{i=1}^{n} u_i \qquad (4)$$

The Weibull scale parameter can be obtained from Eq. (5) [9]:

$$c = 1{,}12\,\bar{u} \qquad (1.5 \le k \le 3) \qquad (5)$$

The distribution function from distribution probability of Weibull f(u) can be defined using following Eq. (6) [9]:

$$f(u) = \frac{k}{u}\left(\frac{u}{c}\right)^{k-1} exp\left[-\left(\frac{u}{c}\right)^{k}\right] \qquad (k > 0, u > 0, c > 1) \qquad (6)$$

Maximum power output is maximum power output to one the wind turbine expressed in the following Eq. (7) [9]:

$$P_{wt} = P_{rated}CF \qquad (7)$$

Where P_{rated} is rated power output of wind turbine manufacturer.

Wake effects model developed by N.O Jensen is shown at Fig. 2 [6,10,11,12,13]. After the use of momentum balance and Betz theory to determine the wind speed immediately behind the rotor, the following expression can be derived to describe the downstream wind speed of the turbine in the following Eq. (8) [6,10,11,12,13]:

$$u_{down} = u_{up}\left[1 - \frac{2a}{\left(1 + \alpha\left(\frac{k_{col}D}{r_1}\right)\right)^2}\right] \qquad (8)$$

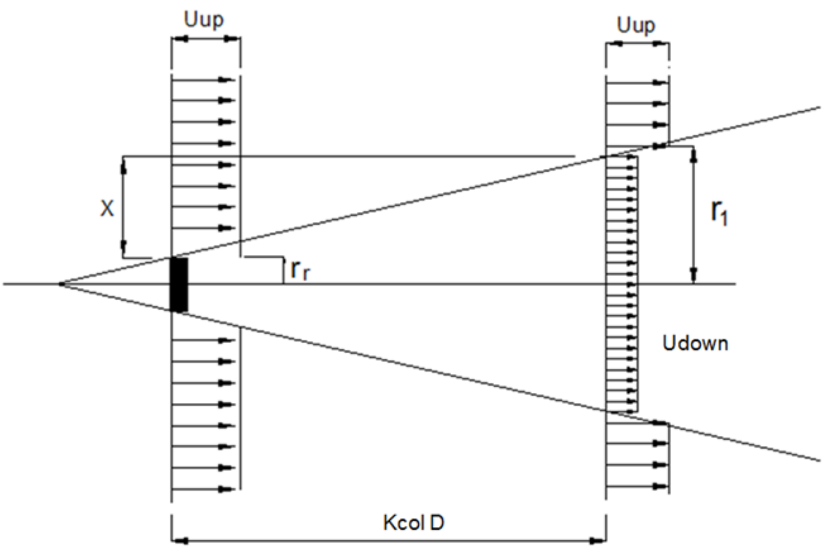

Figure 2: Schematic of Jensen wake effects model

Where u_{up} is upstream wind speed, a is the axial induction factor, r_1 is the downstream rotor radius, α is entrainment constant, and $k_{col}D$ the separation distances in a column between turbines.
The downstream rotor radius expressed in the following Eq. (9) [6,10,11,12,13]:

$$r_1 = r_r\sqrt{\frac{1-a}{1-2a}} \qquad (9)$$

The turbine thrust coefficient C_T and power coefficient C_p is related to the axial induction factor in the following Eq. (10) [6,10,11,12,13]:

$$C_T = 4a\,(1-a) \quad \text{and} \quad C_p = 4a\,(1-a)^2 \tag{10}$$

The entrainment constant is empirically given as Eq. (11) [6,10,11,12,13]:

$$\alpha = \frac{0,5}{ln\left(\frac{z}{z_0}\right)} \tag{11}$$

z is the hub height of the wind turbine, and z_0 is the site surface roughness.
By using the turbines placement layouts from Fig. 1, the total number of turbines N can be defined as multiplication of rows and columns turbines numbers in Eq. (12) [3]:

$$N = N_{row}N_{col} \tag{12}$$

The number of wind turbines in a row can be determined as Eq. (13) [3]:

$$N_{row} = \frac{L_{row}}{k_{row}D} + 1 \tag{13}$$

Analogically, the number of wind turbines in a column can be determined as Eq. (14) [3]:

$$N_{col} = \frac{L_{col}}{k_{col}D} + 1 \tag{14}$$

The energy produced by wind turbine in row per year is calculated in Eq. (15):

$$E_{row} = N_{row}h_y\, P\, CF \tag{15}$$

Where P is power design of wind turbine manufacturer (power curve), h_y is the number of the hours during one year, value h_y is 8760 h (365 x 24). The total energy produced by wind farm per year is from Eq. (15) into Eq. (16):

$$E_{total} = \sum_{i=1}^{N_{col}} E_{row\,(i)} = N_{row(1)}h_y\, P_{(1)}CF + N_{row(2)}h_y\, P_{(2)}CF + \cdots N_{row(N_{col})}h_y\, P_{(N_{col})}CF \tag{16}$$

In general, the widely accepted equation for counting annual cost used for wind farm as function of the turbines number N in the following Eq. (17) [3,6,10,14]:

$$Costs = N\left\{\frac{2}{3} + \frac{1}{3}e^{-0,00174N^2}\right\} \tag{17}$$

For minimum cost per unit energy produced expressed in the following Eq. (18) [6,14]:

$$min\left(\frac{Costs}{E_{total}}\right) \tag{18}$$

The chosen objective function defines the profitability of the wind farm design which involves minimization of the investment and maximization of the power generation. Therefore, the optimum solution will be a compromise between the wind farm investment costs and wind turbines installed power. Both depend on the type and price of wind turbines and on their number. The number of the wind turbines is directly connected with the size of the wind farm. It also depends on the dominant wind direction. The power generation is the function of the number of installed turbines, their rated power and wind conditions.

3. NUMERICAL PROCEDURE

Numerical used data measurement of speed in one year (October 2004 - September 2005) in Purworejo. To determine value, the Weibull shape parameter and the Weibull scale parameter used Eqs. (2), (3), (4), and (5). Based on data source from BTM Consult ApS [16], division of turbine producer market in world in 2010 based on attached capacities shows following percentage shown in Fig.3. Commercial wind turbines parameters serve as data from selection resulted from using hub high constraint of minimum 100 m. This condition happens since wind measurement is conducted in height of

100 m, and then limit used based on turbine thrust coefficient and power coefficient [16, 17, 18, 19, 20] that can be accessed.

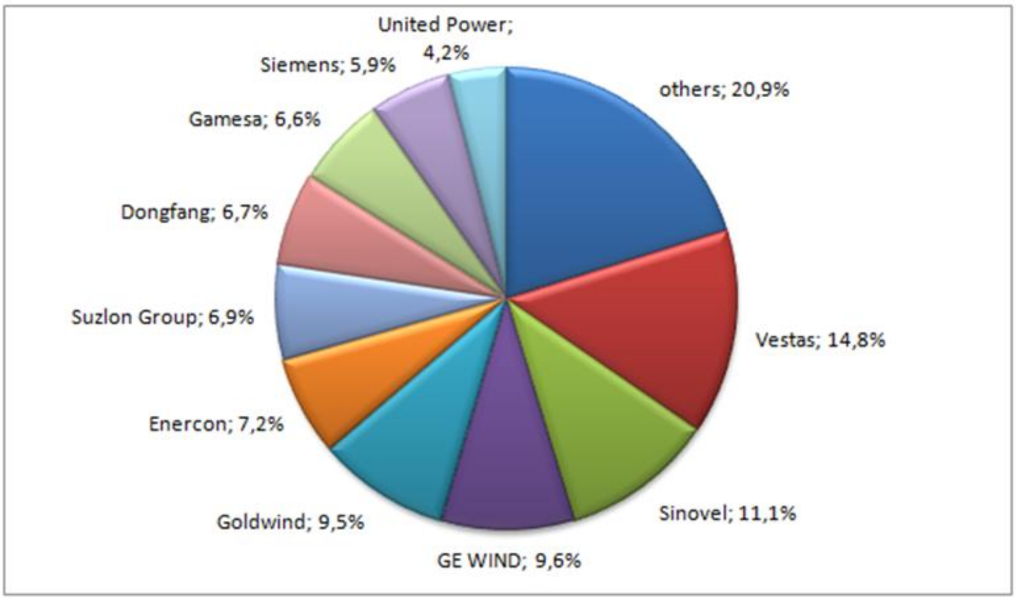

Figure 3: Worldwide market share in 2010 based on installed capacity (Source: BTM Consult Aps)

Value capacity factor is determined from value the Weibull shape parameter and the Weibull scale. Data on commercial wind turbines parameters are used as; cut in wind speed, rated wind speed, and furling wind speed. Value capacity factor used Eq. (1). This article discusses dominant wind direction with by using an area constraint 4 km^2. The first data use an area square with size L_{row} = 2000 m and L_{col} = 2000 m, the second data use area rectangular horizontal with size L_{row} = 4000 m and L_{col} = 1000 m, and the third use area rectangular vertical with size L_{row} = 1000 m and L_{col} = 4000 m.

Wind turbine data are used in simulation such as: rotor diameter, hub height, power curve and thrust coefficient curve. The downstream wind speed of the turbine use Eqs. (7) (8), (9), (10), and (11). For constant dominant wind direction exists, the recommended wind turbines spacing are 8–12 rotor diameters in rows apart in the windward direction and 1.5–3 rotor diameters apart in the crosswind direction [3,6,14,15]. The total number of turbines of wind farm use Eqs. (12), (13), and (14). The total energy produced per year of wind farm use Eq. (16). For minimum cost per unit energy produced of wind farm Eq. (18), minimum value is the most optimal result.

4. RESULTS AND DISCUSSION

From data measurement of speed in one year (October 2004 - September 2005) in Purworejo, calculation used Eqs. (2), (3), (4), and (5) result shows that value k = 1.74 and value c = 6.93 m/s. Fig. 4 shows distribution wind speed in Purworejo for one year by using Eq. (6). Parameters and commercial wind turbines types are shown in Table 1. Numerical is done at first phase by calculating the capacity factor from each commercial wind turbine by using Eq. (1). Results of calculation of capacity factor are shown on Table 2.

Numerical simulation used wind turbine data with rotor diameter is about 113 m with cut rate wind speed 11 m/s, and is placed on the hub heights of 100 m. The site surface roughness is about 0.3 m [6,10]. This article discusses dominant wind direction by using constraint 4 km^2, the first data using an area square wind farm with size L_{row} = 2000 m and L_{col} = 2000 m, the second data uses area rectangular horizontal wind farm with size L_{row} = 4000 m and L_{col} = 1000 m, and the third uses area rectangular vertical wind farm with size L_{row} = 1000 m and L_{col} = 4000 m. For constant dominant wind direction exists, the recommended wind turbines spacing is 8–12 rotor diameters in rows apart in the windward direction and 1.5–3 rotor diameters apart in the crosswind direction [3,6,14,15].

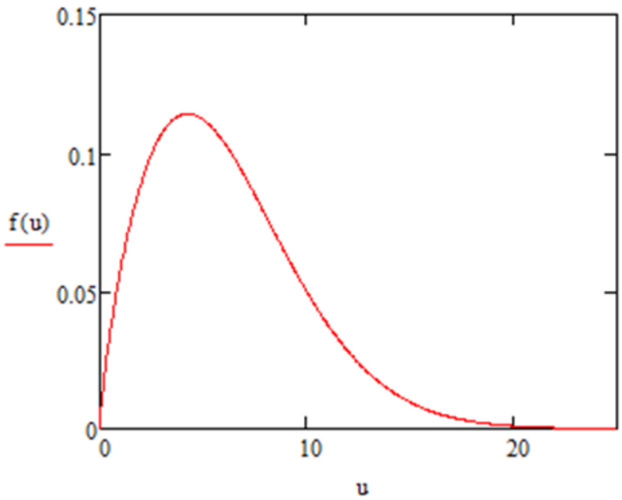

Figure 4: Distribution of wind speed in Purworejo during one year with value k = 1.74 and value c = 6.93 m/s

Table 1: Commercial wind turbine parameters [16, 17, 18, 19, 20]

No	Type wind turbine	Rotor diameter	Hub height	Rated Power Output	Cut in	Cut Rate	Cut Off
(i)		(m)	(m)	(MW)	m/s	m/s	m/s
1	Enercon E-70/2300	71	Min : 57 Max : 113	2.3	2	15	34
2	Enercon E-82/2300	82	Min : 78 Max : 138	2.3	2	14	34
3	Enercon E-82/3000	82	Min : 78 Max : 138	3	2	17	34
4	Enercon E-101/3000	101	Min : 99 Max : 135	3	2	13	34
5	Vestas V-80/2000	80	Min : 60 Max : 100	2	4	17	25
6	Vestas V-90/2000	90	Min : 95 Max :125	2	4	13	25
7	Vestas V-100/3000	100	Min : 82 Max: 119	3	3	11.5	20
8	Vestas V-112/3000	112	Min : 84 Max : 119	3	3	13	25
9	Sinovel SL 1500/89	89	Min : 65 Max : 100	1.5	3	11.5	20
10	Sinovel SL 3000/113	113	Min : 90 Max : 110	3	3	11	25

Table 2: Results from calculating capacity factor with value k = 1.74 and c = 6.93 m/s

No	Type wind turbine	Rotor diameter	Rated Power Output	Capacity factor
(i)		(m)	(MW)	%
1	Enercon E-70/2300	71	2.3	23.39
2	Enercon E-82/2300	82	2.3	26.12
3	Enercon E-82/3000	82	3	18.98
4	Enercon E-101/3000	101	3	29.27
5	Vestas V-80/2000	80	2	15.33
6	Vestas V-90/2000	90	2	24.20
7	Vestas V-100/3000	100	3	32.04
8	Vestas V-112/3000	112	3	26.92
9	Sinovel SL 1500/89	89	1.5	32.04
10	Sinovel SL 3000/113	113	3	34.22

4.1 Results area square wind farm with size L_{row} = 2000 m and L_{col} = 2000 m

Area square wind farm used data with size L_{row} = 2000 m and L_{col} = 2000 m by spacing wind turbines in rows apart in the windward direction k_{col} = 1000 m and apart in the crosswind direction $k_{row}D$ = 200 m. Calculation use Eqs. (8) up to (18), use Table 2, turbine thrust coefficient and power coefficient. Results on area square wind farm with size L_{row} = 2000 m and L_{col} = 2000 m as shown on Table 3.

Result wind farm configuration design shows that area L_{row} = 2000 m and L_{col} = 2000 m, have total energy of 265599.14 MWh per year with ratio cost per energy about 0.000089 with 33 turbines and percentage total deficits energy is about -11%.

Table 3: Results area square wind farm with size L_{row} = 2000 m and L_{col} = 2000 m

Wind turbine type	Turbines number (N)	Total produced energy, (MWh)	Separation Cofficients	Separation distances (m)	Cost per unit of energy
Square wind farm with size L_{row} = 2000 m and L_{col} = 2000 m					
Enercon E-70/2300	N = 63	294753.21	k_x = 1.41	k_xD = 100	0.000143
	N_x = 21		k_y = 14.08	k_yD = 1000	
	N_y = 3				
Enercon E-82/2300	N = 63	335235.18	k_x = 1.22	k_xD = 100	0.000125
	N_x = 21		k_y = 12.12	k_yD = 1000	
	N_y = 3				
Enercon E-82/3000	N = 63	314875.75	k_x = 1.22	k_xD = 100	0.000133
	N_x = 21		k_y = 12.12	k_yD = 1000	
	N_y = 3				
Enercon E-101/3000	N = 51	398137.47	k_x = 1.24	k_xD = 125	0.000086
	N_x = 17		k_y = 9.9	k_yD = 1000	
	N_y = 3				
Vestas V-80/2000	N = 63	169192.86	k_x= 1.25	k_xD = 100	0.000248
	N_x = 21		k_y = 12.5	k_yD = 1000	
	N_y = 3				
Vestas V-90/1800	N = 51	196121.52	k_x = 1.39	k_xD = 125	0.000174
	N_x = 17		k_y = 11.11	k_yD = 1000	
	N_y = 3				
Vestas V-100/1800	N = 51	259327.66	k_x = 1.25	k_xD = 125	0.000132
	N_x = 17		k_y = 10	k_yD = 1000	
	N_y = 3				
Vestas V-112/3000	N = 33	239050.85	k_x = 1.78	k_xD = 200	0.000099
	N_x = 11		k_y = 8.93	k_yD = 1000	
	N_y = 3				
Sinovel SL-89/1500	N = 51	214107.12	k_x = 1.4	k_xD = 125	0.000160
	N_x = 17		k_y = 11.23	k_yD = 1000	
	N_y = 3				
Sinovel SL-113/3000	N = 33	265599.14	k_x = 1.77	k_xD = 200	0.000089
	N_x = 11		k_y = 8.85	k_yD = 1000	
	N_y = 3				

4.2 Results area rectangular horizontal wind farm with size L_{row} = 4000 m and L_{col} = 1000 m

Area rectangular horizontal wind farm used data with size L_{row} = 4000 m and L_{col} = 1000 m by spacing wind turbines in rows apart in the windward direction k_{col} = 1000 m and apart in the crosswind direction $k_{row}D$ = 200 m. Calculation use Eqs. (8) up to (18), use Table 2, turbine thrust coefficient and power coefficient. Results on area rectangular horizontal wind farm with size L_{row} = 4000 m and L_{col} = 1000 m as shown on Table 4.

Result wind farm configuration design shows that area L_{row} = 4000 m and L_{col} = 1000 m, have total energy of 265599.14 MWh per year with ratio cost per energy about 0.000089 with 33 turbines and percentage total deficits energy is about -11%.

Table 4: Results area rectangular horizontal wind farm with size L_{row} = 4000 m and L_{col} = 1000 m

Wind turbine type	Turbines number (N)	Total produced energy, (MWh)	Separation Cofficients	Separation distances (m)	Cost per unit of energy
Rectangular horizontal wind farm with size L_{row} = 4000 m and L_{col} = 1000 m					
Enercon E-70/2300	N = 82	385094.74	k_x = 1.41	k_xD = 100	0.000142
	N_x = 41		k_y = 14.08	k_yD =1000	
	N_y = 2				
Enercon E-82/2300	N = 82	438712.48	k_x = 1.22	k_xD = 100	0.000125
	N_x = 41		k_y = 12.12	k_yD = 1000	
	N_y = 2				
Enercon E-82/3000	N = 82	410808.24	k_x = 1.22	k_xD = 100	0.000133
	N_x = 41		k_y = 12.12	k_yD = 1000	
	N_y =2				
Enercon E-101/3000	N = 66	515712.21	k_x = 1.24	k_xD = 125	0.000085
	N_x = 33		k_y = 9.9	k_yD = 1000	
	N_y = 2				
Vestas V-80/2000	N = 82	220228.25	k_x = 1.25	k_xD = 100	0.000248
	N_x = 41		k_y = 12.5	k_yD = 1000	
	N_y = 2				
Vestas V-90/1800	N = 66	253878.24	k_x = 1.39	k_xD = 125	0.000173
	N_x = 33		k_y = 11.11	k_yD = 1000	
	N_y = 2				
Vestas V-100/1800	N = 66	335989.65	k_x = 1.25	k_xD = 125	0.000125
	N_x = 33		k_y = 10	k_yD = 1000	
	N_y = 2				
Vestas V-112/3000	N = 42	304489.77	k_x = 1.78	k_xD = 200	0.000094
	N_x = 21		k_y = 8.93	k_yD = 1000	
	N_y = 2				
Sinovel SL-89/1500	N = 66	277546.97	k_x = 1.4	k_xD = 125	0.000159
	N_x = 33		k_y = 11.23	k_yD = 1000	
	N_y = 2				
Sinovel SL-113/3000	N = 42	363382.71	k_x = 1.77	k_xD = 200	0.000079
	N_x = 21		k_y = 8.85	k_xD = 1000	
	N_y = 2				

4.3 Results area rectangular vertical wind farm with size L_{row} = 1000 m and L_{col} = 4000 m

Area rectangular vertical wind farm used data with size L_{row} = 1000 m and L_{col} = 4000 m by spacing wind turbines in rows apart in the windward direction k_{col} = 1000 m and apart in the crosswind direction $k_{row}D$ = 200 m. Calculation use Eqs. (8) up to (18), use Table 2, turbine thrust coefficient and power coefficient. Results on area rectangular vertical wind farm with size L_{row} = 1000 m and L_{col} = 4000 m as shown on Table 5.

Result wind farm configuration design shows that area L_{row} = 1000 m and L_{col} = 4000 m, have total energy of 265599.14 MWh per year with ratio cost per energy about 0.000089 with 33 turbines and percentage total deficits energy is about -11%.

Table 5: Results area rectangular vertical wind farm with size L_{row} = 1000 m and L_{col} = 4000 m

Wind turbine type	Turbines number (N)	Total produced energy, (MWh)	Separation Cofficients	Separation distances (m)	Cost per unit of energy
Rectangular vertical wind farm with size L_{row} = 1000 m and L_{col} = 4000 m					
Enercon E-70/2300	N = 55	254941.85	k_x = 1.41	k_xD = 100	0.000144
	N_x = 11		k_y = 14.08	k_yD = 1000	
	N_y = 5				
Enercon E-82/2300	N = 55	288923.02	k_x = 1.22	k_xD = 100	0.000127
	N_x = 11		k_y = 12.12	k_yD = 1000	
	N_y = 5				
Enercon E-82/3000	N = 55	273502.35	k_x = 1.22	k_xD = 100	0.000134
	N_x = 11		k_y = 12.12	k_yD = 1000	
	N_y = 5				
Enercon E-101/3000	N = 45	347953.49	k_x = 1.24	k_xD = 125	0.000087
	N_x = 9		k_y = 9.9	k_yD = 1000	
	N_y = 5				
Vestas V-80/2000	N = 55	147695.35	k_x = 1.25	k_xD = 100	0.000249
	N_x = 11		k_y = 12.5	k_yD = 1000	
	N_y = 5				
Vestas V-90/1800	N = 45	172782.27	k_x = 1.39	k_xD = 125	0.000176
	N_x = 9		k_y = 11.11	k_yD = 1000	
	N_y = 5				
Vestas V-100/1800	N = 45	226686.98	k_x = 1.25	k_xD = 125	0.000134
	N_x = 9		k_y = 10	k_yD = 1000	
	N_y = 5				
Vestas V-112/3000	N = 30	215203.94	k_x = 1.78	k_xD = 200	0.000103
	N_x = 6		k_y = 8.93	k_yD = 1000	
	N_y = 5				
Sinovel SL-89/1500	N = 45	187164.14	k_x = 1.4	k_xD = 125	0.000163
	N_x = 9		k_y = 11.23	k_yD = 1000	
	N_y = 5				
Sinovel SL-113/3000	N = 30	191670.72	k_x = 1.77	k_xD = 200	0.000115
	N_x = 6		k_y = 8.85	k_yD = 1000	
	N_y = 5				

5. CONCLUSIONS

From result and discussion can be concluded that rectangular horizontal wind farm with size L_{row} = 4000 m and L_{col} = 1000 m, wind turbine with a diameter of 113 m with 42 turbines, produced total energy about 363382.71 MWh per year with ratio cost per energy about 0.000079, and it has the most optimal result.

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