Optimization Of Onshore Wind Farms

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Abstract

The present project was aimed at implementing a devised solution for the problem of onshore wind farms layout optimisation based on the maximization of the output power and the reduction of the wake effect.The proposed solution is based on a probabilistic basic search. This also assumes several parameters as ideal considering as variables the position of the turbines, the area of the farm, the cost of installing the turbines and the cost of wiring. The results obtained indicate trivial and expected values but not very realistic, so the model does not go beyond being a first approximation. In view of an improvement of the algorithm several suggestions are provided.

1 Introduction

The concept of renewable energy is related to the production of clean energy for the environment. There are many ways to produce clean renewable energy and wind farms are one of them. Due to the fact that they are cheaper to build than other ways of renewable energies in addition to being quite reliable because it only depends on the wind of a certain area, their construction has increased throughout the years. In 2019, wind supplied 1430 TWh of electricity, which was 5.3% of worldwide electrical generation [1, 2].

According to the German government, the portion of renewable energies in electricity generation should rise just over 30% to 40–45% in 2025 and 55–60% in 2035 [3, 4].

But still, the wind farm layout optimization problem is notoriously difficult to solve because of the large number of design variables, computationally expensive models for high fidelity simulations and extreme multi-modality of the design space [5]. Regardless of all the studies for the solution of such problem, a systematic wind farm layout optimization method has not yet been proposed.

The designing process refers basically to the optimal placement of each wind turbine in a limited area and its associated costs such as the wiring and installation of the turbines [6]. Then, The quality and quantity of the expected power output by a wind farm is dependent of loss sources. One of the most important loss sources is the called *Wake Effect* as seen in the Fig. (1) [7–9]. This effect is the product of the wind output of the turbine, which slows the free stream air passing through its face. It also increases the diameter of the affected wind volume, which decreases wind speed and increases turbulence in the medium. As a result, turbines placed in the wake-affected area experience a reduction in power (due to a wind deficit) and a shortened lifespan (due to the turbulence) [10, 11].

For this investigation, the proposed algorithm was based on a probabilistic basic search. The variables taken into account were the turbine positions for a discrete range of options limited by the position of a squared matrix respecting a minimum of 5D for spacing. In this sense, each matrix element or entry represents the position of the turbines. The area of the farm was also a variable in consideration since the dimension of the matrix was selected and varied. Nevertheless, the wind direction and velocity was considered constant.The land requirements were considered as ideal, which means, a complete flat terrain. The wake effect model used was a simplified version of the 3D Gaussian wake model developed by Bastankhah [12]. Finally, wind farm costs were based on the total costs for turbine installation and the total wiring length converging to a common line defined to be positioned in the middle of the matrix.

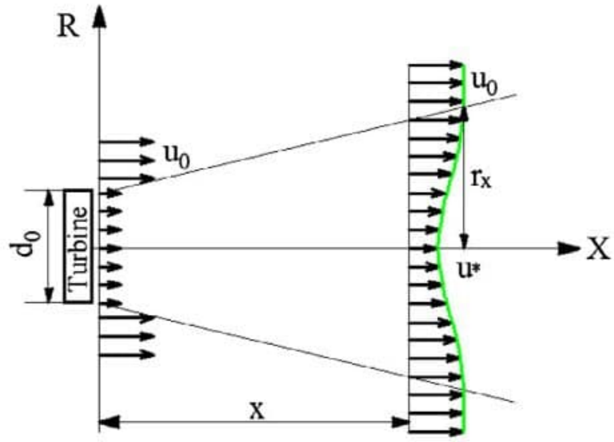

Figure 1: Jensen-Gaussian Wake Effect [9].

2 Algorithm

1. Samples creation

   a) Generate a matrix of 0's and 1's in a random pattern with probability of 0.3 of obtaining a 1 and 0.7 of obtaining a 0. Such a pattern would have the following shape:

```
array([ [0., 0., 0., 1., 1., 1., 0., 0., 0.,],
        [0., 0., 1., 0., 0., 1., 1., 0., 0.,],
        [0., 1., 0., 0., 0., 1., 0., 1., 0.,],
        [1., 0., 1., 0., 1., 0., 0., 1., 1.,],
        [1., 0., 1., 0., 0., 1., 0., 0., 1.,],
        [0., 1., 1., 0., 0., 0., 1., 1., 0.,],
        [0., 0., 1., 1., 0., 0., 1., 0., 0.,],
        [0., 0., 0., 1., 1., 1., 0., 0., 0.,]])
```

   Figure 2: Layout sample.

   Where each *1* corresponds to the location of a turbine and each *0* corresponds to an empty space.

   b) Assign each *1* to a coordinate *(x,y)* and store it as a *tuple* within the matrix.

2. Wind farm power computing:

   a) Compute the power of each turbine:

      1) Step on turbine *i* and establish a coordinate system relative to *i* with **+x** direction anti-parallel to the upstream wind direction.

      2) Compute distances between each turbine *i* and turbine *j*.

      3) Select turbine *j* affecting turbine *i* with the following conditions:

$$x_{ij} > 0 \tag{1}$$

$$\mid y_{ij} \mid \leq r_{d1} \tag{2}$$

Where r_{d1} is the radius of the *wake* at a distance *x* downstream of the turbine *j*. Assuming a linear dependence with *x*.

$$r_{d1} = \alpha \, x_{ij} + r_{d0} \tag{3}$$

Where the entrainment factor α is given by:

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

Now, r_{d0} is the downstream *wake* radius immediately after turbine *j*.

$$r_{d0} = r_r \sqrt{\frac{1-a}{1-2a}} \tag{5}$$

Where r_r is the radius of the rotor. Considering the maximum value of the rotor power coefficient at $a = \frac{1}{3}$, for which the *Betz limit* is $C_p = \frac{16}{27}$ [13].

      4) The *wake* deficit for the turbine *i* respect to the turbine *j* is computed by means of a simplified version of Bastankhah's Gaussian *wake* model [12].

$$\frac{\Delta V}{V_\infty} = \begin{cases} \left(1 - \sqrt{1 - \frac{C_T}{8\sigma_y^2/D^2}}\right) e^{-\frac{1}{2}\left(\frac{y_j - y_i}{\sigma_y}\right)^2} & (x_j - x_i) > 0 \\ 0 & otherwise \end{cases} \tag{6}$$

$$\sigma_y = k_y \cdot (x_j - x_i) + \frac{D}{\sqrt{8}} \tag{7}$$

Then, for a turbine *i* placed in multiple *wakes*, wind deficit will be given by

$$\left(\frac{\Delta V}{V_\infty}\right)_{total} = \sqrt{\sum_i \left(\frac{\Delta V}{V_\infty}\right)_i^2} \tag{8}$$

And the complete *wake* loss on the turbine *i* is given by

$$V_e = V_\infty \left[1 - \left(\frac{\Delta V}{V_\infty}\right)_{total}\right] \tag{9}$$

Lastly, for the turbines *i's* power in

$$P_{turb}(V_e) = \begin{cases} 0 & V_e < V_{cut-in} \\ P_{rated} \cdot \left(\frac{V_e - V_{cut-in}}{V_{rated} - V_{cut-in}}\right)^3 & V_{cut-in} \leq V_e < V_{rated} \\ P_{rated} & V_{rated} \leq V_e < V_{cut-out} \\ 0 & V_e \geq V_{cut-out} \end{cases} \tag{10}$$

Considering the following characteristics for the turbine model used

Table 1: Turbine Characteristics [14, 15]

Turbine Model	IEA37 3.35 MW
Rotor Diameter	130 m
Turbine Rating	3.35 MW
Cut-In Wind Speed	4 m/s
Rated Wind Speed	9.8 m/s
Cut-Out Wind Speed	25 m/s
Hub Height	110 m

5) Compute wind farm power

$$P_{farm} = \sum_{i=1}^{n} P_{turb,i} \tag{11}$$

3. Compute efficiency

$$Efficiency = \frac{P_{actual}}{P_{ideal}} \tag{12}$$

4. Compute costs
5. Compute objective function

$$Objectivefuntion = \frac{Efficiency * P_{farm}}{costs} \tag{13}$$

6. Generate *n* samples
7. Determine the most optimal sample based on the maximum value of the objective function
8. Print selected layout sample
9. Print total number of turbines, total power, layout efficiency, costs and objective function.

3 Results

The algorithm was tested for two different dimensions, with four different numbers of turbines. The objective function was the function to maximize in order to obtain the most efficient design according to this developed algorithm. The results showed an increase in the objective function inversely proportional to the number of installed turbines. This means that the optimized layout is considered to be the one with the fewest turbines. Nevertheless, note from Table 2 how for a bigger area considered, the objective function will be maximized but show minimal power for the case of the minimum number of turbines. It means that for a small area, a small number of turbines will lead to the most optimal layout but for a bigger area, the most optimal layout will have a small number of turbines and thus less power output but highest efficiency and minimal cost.

Now, in terms of the area considered for optimization, the results were as expected. This is, a larger design that will result in a more efficient wind farm but with minimal relative power compared to the rest. Finally, installation and wiring costs are directly affected by the number of turbines and the area determined, as expected.

In general, the algorithm did not return results outside the expected range. The solution presented could be considered trivial and therefore biased in the anticipated layout. Also, note that the results returned good values that should not be representative in general since all the simplifications taken into account. The simplistic presentation of the algorithm can foresee how these results would change considerably compared to more specific but practical approaches.

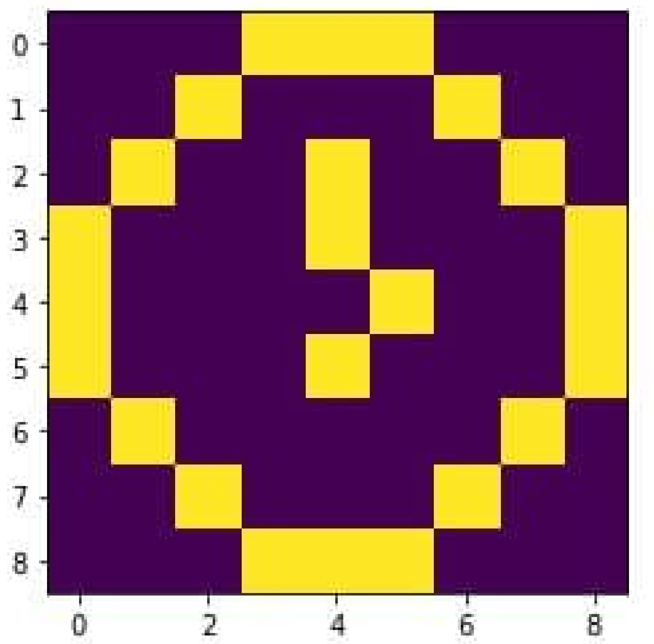

Figure 3: Example of the best layout obtained for 9x9 Matrix (34.2 km^2) and 24 turbines.

Table 2: Results for best selected sample runs.

Dimension	Turbines	Power (MWh)	Efficiency	Cost (M$)	Objective Function (MWh/M$
7	24	56.46	0.70	122.55	0.32
7	26	55.37	0.64	131.20	0.27
7	28	54.41	0.58	139.26	0.23
7	30	53.27	0.53	149.10	0.19
9	24	69.76	0.87	142.66	0.42
9	26	74.02	0.85	153.08	0.41
9	28	76.64	0.82	162.91	0.38
9	30	77.59	0.77	171.57	0.35

4 Conclusions and Suggestions

The simplicity of the proposed solution leads to good but unrealistic results classifying the algorithm as a good first approximation. On the other hand, the optimized layout can be improved in a number of ways:

1. Considering an adjustment on the turbine power just below its maximum. In this manner, the front rows of turbines facing the upstream wind would reduce the wake they produce and therefore the turbulence. A decrease in wake could allow to decrease the spacing between the turbines and thus increase the number of turbines in the farm which would lead to a higher total power.

2. It is possible, in principle, to redirect the *wake effect* generated by the turbine slightly away from its immediate rear. With this in mind, the turbines behind the front ones would not be immediately affected by the generated wake.

3. The matrix used in the model can consider continuous positions respecting the necessary distance, so the range of possible solutions would increase substantially

4. It is suggested to use methods based on gradients (genetic algorithms, cuckoo algorithm) and heuristics *(GWO)* which lean towards maximization in a more efficient manner. Thus it would be possible to consider more variables than those considered in the project.

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