IEA Task 37 on System Engineering in Wind Energy The Wind Farm Optimization Only Case Study

Nicholas F. Baker*, Andrew P. J. Stanley†, Jared Thomas‡, and Andrew Ning§

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1 Introduction

This document defines a simple wind farm layout optimization competition. Participants are directed to use whichever computational optimization strategies they choose, with the task of obtaining the maximum Annual Energy Production (AEP) for the defined turbine fields. Participants will adjust resultant AEP exclusively by manipulating turbine locations. In this case study the wind farm boundaries, wind turbine attributes, and wake model physics are fixed - turbine locations are the only design variable participants are permitted to alter.

In order to measure scalability of the methods utilized, three wind farm scenarios of increasing size are presented. They grow in both number of turbines and overall farm area.

The goal of this competition is to compare participant results when using different optimization strategies under a single wake model, in order to determine a set of "best practices" for optimization of similar scenarios. While this wind farm scenario is very simple, we expect the results to assist researchers in understanding the differences that occur due to optimizing wind farms with various numerical methods. A greater understanding of this simplified problem is expected to aid in solving and interpreting the results of more complex and realistic problems.

*Masters Student, Brigham Young University Department of Mechanical Engineering
†Ph.D. Candidate, Brigham Young University Department of Mechanical Engineering
‡Ph.D. Student, Brigham Young University Department of Mechanical Engineering
§Assistant Professor, Brigham Young University Department of Mechanical Engineering

2 Problem Definition

2.1 Wind Farm Definition

There are three (3) wind farm size scenarios which will be optimized:

1. Wind farm of sixteen (16) turbines, boundary radius of 2,000 m.
2. Wind farm of thirty-six (36) turbines, boundary radius of 3,000 m.
3. Wind farm of sixty-four (64) turbines, boundary radius of 4,000 m.

For all wind farm sizes, the wind farm boundary is circular, as depicted Fig. 1. The origin is at the center of the field, coincident with the depicted NREL 5MW reference turbine (whose attributes are summarize in Appendix A), and the specified boundary distance for each field is measured as a radius from the origin. Note that the entire turbine must be within the field boundary (taking into account rotor radius), and not just its hub location.

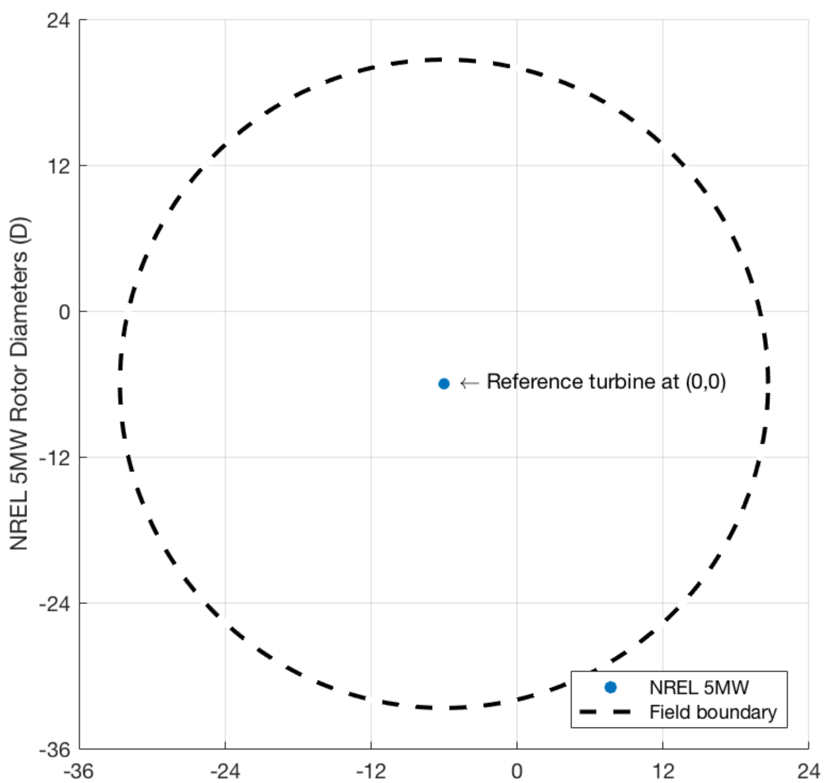
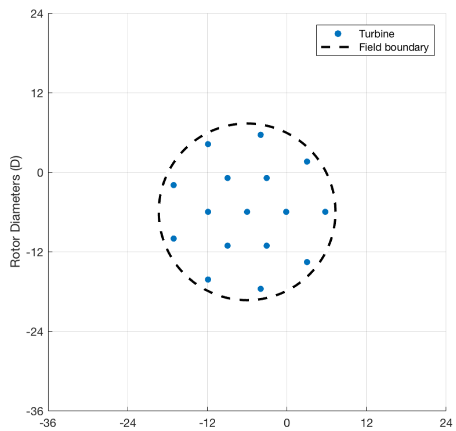


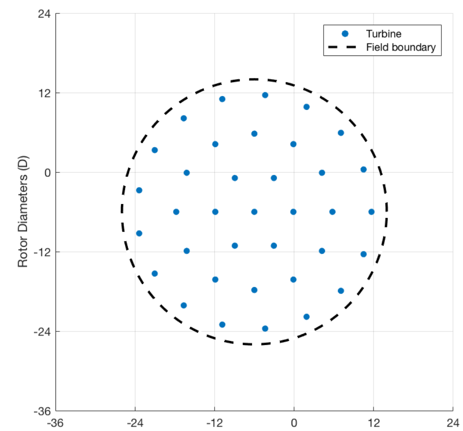
Figure 1: Depiction of circular farm boundary, reference turbine (to scale) placed at origin.

3 Baseline Layouts

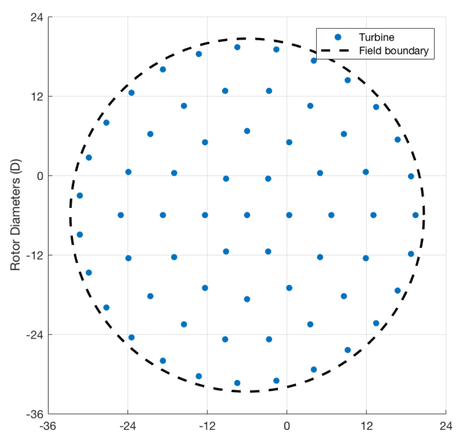
To assist in comparison of results, a baseline wind turbine layout is supplied for each field size. As explained in Section 4.1, you are to report the AEP calculated for each of these layouts for validation. You are also to conduct a single baseline optimization from these starting locations, and report your resulting optimized turbine location and AEP values. You are not required to start *each* of your optimizations from these layouts, only report the results from a single run using these starting locations. For your other optimization attempts, feel free to use random starts, warm starts, intuition, or any other selection method you choose to initialize turbine locations.



(a) 16 Turbine Farm



(b) 36 Turbine Farm



(c) 64 Turbine Farm

Figure 2: Baseline turbine locations (to scale)

The baseline layouts depicted are only to be used for a single optimization run, and will assist in results comparison. The exact coordinates are located in Appendix B, and you are to include in your report the optimized locations and AEP reached from a single run at these starting locations.

3.1 Wake Model and Code Format

The wake model implemented in this case study is Bastankhah's Gaussian wake model [1, 2, 3]. The model's governing equations, as well as data on the wind speed and direction probability used to formulate the code, are included in Appendix C.

The pertinent files are coded in Python, and are provided alongside this document in a `.zip` directory, in order for each participant to focus on the optimization aspect and apply their unique methods. The wake model routine takes a specified number of grid locations as inputs, and returns as output a single AEP value calculated from the input turbine locations.

Though not necessary, alteration to the released AEP calculation code is permitted, if required to maximize optimizer effectiveness. Care must be taken, however, that the governing physics equations are not altered to deliver different AEP results. For this reason, base case turbine locations are described in Section 4.1 and corresponding AEP calculations are to be used as validation.

4 Reporting Results

4.1 Submission Contents

You will submit both a `.txt` file with the requested turbine data, and a `.pdf` file containing a short description of your method/process. Both files are described below.

4.1.1 Turbine Data

Text file containing your:

- Baseline AEP
- Optimized AEP from baseline
- Initial AEP
- Optimized AEP

As well as:

- Optimized turbine locations from baseline
- Initial turbine locations
- Optimized turbine locations

The initial AEP and turbine locations should be from the starting point of your submitted optimized layout, whatever method you use. AEP values should be reported in Megawatt-hours. All turbine locations should be reported in meters.

The baseline locations were designed using a minimum dispersion of 5 rotor diameters between each turbine, in concentric circles. The turbine locations for the baseline value arrangements are given in Appendix B, and are depicted graphically in Fig. 2.

4.1.2 Method Description

The `.pdf` file containing a short description of the relevant details of your method/process should include (at a minimum):

- Optimization algorithm (including version and any non-default settings or modifications)
  - Name of algorithm

  - General type of algorithm (e.g. gradient-free, gradient-based)
  - Specific algorithm type (e.g. particle-swarm, genetic-algorithm, sequential quadratic programming, etc)
  - If you used a gradient-based method, how did you obtain the gradients.
  - Programming language(s) utilized
  - Other relevant algorithm details

- Computer hardware specifications
  - Manufacturer/Model/Speed of processor
  - Number of cores utilized
  - Amount of RAM allocated per core
- How you decided on the starting turbine locations for your final optimized results
- Time required for optimization convergence
- Modificiations made (if any) to the original wake model code
- Links to relevant code(s) (if possible)
- Other details you consider relevant
- Bibliography

4.2 Submission Format

All submission materials should be submitted in a single compressed `.zip` directory. The directory should contain:

1. A `.pdf` of the method/process description as described in Section 4.1.2
2. Three (3) `.txt` files with the quantitative optimization results, one (1) for each farm size, in the following format:

The text file for a given farm size should contain two sections: 1) for the baseline, optimized baseline, initial, and optimal AEP values and 2) for the turbine numbers and their corresponding optimized baseline, initial and optimized x and y locations. Entries in each row should be comma separated. All numbers should be in full double precision. Please see the example provided in Fig. 3.

```
# base AEP (MWh), opt base AEP (MWh), initial AEP (MWh), opt AEP (MWh)
AEP_base, AEP_base_opt, AEP_init, AEP_opt

# turb num, x_base_opt(m), y_base_opt(m), x_init(m), y_init(m), x_opt(m),
y_opt(m)
0, x0_base_opt, y0_base_opt, x0_init, y0_init, x0_opt, y0_opt
1, x1_base_opt, y1_base_opt, x1_init, y1_init, x1_opt, y1_opt
2, x2_base_opt, y2_base_opt, x2_init, y2_init, x2_opt, y2_opt
3, x3_base_opt, y3_base_opt, x3_init, y3_init, x3_opt, y3_opt
4, x4_base_opt, y4_base_opt, x4_init, y4_init, x4_opt, y4_opt
5, x5_base_opt, y5_base_opt, x5_init, y5_init, x5_opt, y5_opt
6, x6_base_opt, y6_base_opt, x6_init, y6_init, x6_opt, y6_opt
7, x7_base_opt, y7_base_opt, x7_init, y7_init, x7_opt, y7_opt
8, x8_base_opt, y8_base_opt, x8_init, y8_init, x8_opt, y8_opt
⋮,     ⋮,          ⋮,        ⋮,      ⋮,     ⋮,     ⋮
```

Figure 3: Optimization results text file example

A Wind Turbine Definition

The wind turbine used in this study is the NREL 5MW reference turbine [4]. The important parameters are:

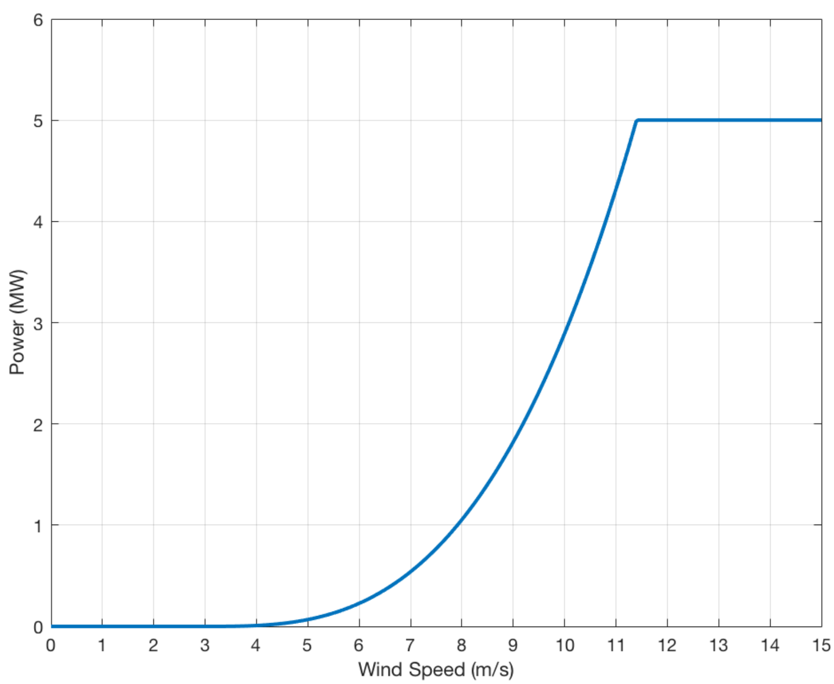
Table 1: NREL 5MW Reference Turbine key attributes [4]

Rotor Diameter	126.4	m
Turbine Rating	5	MW
Cut-In Wind Speed	3	m/s
Rated Wind Speed	11.4	m/s
Cut-Out Wind Speed	25	m/s

The power curve equation is given in Eq. (1) and graphed in Fig. 4.

$$P(U) = \begin{cases} 0 & U < V_{\textit{cut-in}} \\ P_{rated}\left(\frac{U - V_{\textit{cut-in}}}{V_{rated} - V_{\textit{cut-in}}}\right)^3 & V_{\textit{cut-in}} \leq U \leq V_{rated} \\ P_{rated} & U > V_{rated} \end{cases} \tag{1}$$

Figure 4: Calculated NREL 5MW reference turbine power curve



B Baseline Grid Coordinates

(16) Turbine Wind Farm		
#	x (m)	y (m)
0	0	0
1	884.80	0
2	442.40	766.26
3	-442.40	766.26
4	-884.80	0
5	442.40	-766.26
6	442.40	-766.26
7	1769.60	0
8	1355.59	1137.48
9	307.29	1742.72
10	-884.80	1532.52
11	-1662.88	605.24
12	-1662.88	-605.24
13	-884.80	-1532.52
14	307.29	-1742.72
15	1355.59	-1137.48

(36) Turbine Wind Farm		
#	x (m)	y (m)
1-5 same as (16) Farm		
⋮	⋮	⋮
6	1516.80	0
7	1313.60	758.40
8	758.40	1313.60
9	0	1516.80
10	-758.40	1313.60
11	-1313.60	758.40
12	-1516.80	0
13	-1313.60	-758.40
14	-758.40	-1313.60
15	0	-1516.80
16	758.40	-1313.60
17	1313.60	-758.40
18	2275.20	0
19	2138.00	778.16
20	1742.90	1462.50
21	1137.60	1970.40
22	395.08	2240.60
23	-395.08	2240.60
24	-1137.60	1970.40
25	-1742.90	1462.50
26	-2138.00	778.16
27	-2275.20	0
28	-2138.00	-778.16
29	-1742.90	-1462.50
30	-1137.60	-1970.40
31	-395.08	-2240.60
32	395.08	-2240.60
33	1137.60	-1970.40
34	1742.90	-1462.50
35	2138.00	-778.60

(64) Turbine Wind Farm		
#	x (m)	y (m)
1-35 same as (36) Farm		
⋮	⋮	⋮
36	3033.60	0
37	2938.30	754.43
38	2658.40	1461.40
39	2211.40	2076.60
40	1625.50	2561.40
41	937.43	2885.10
42	190.48	3027.60
43	-568.44	2979.90
44	-1291.60	2744.90
45	-1933.70	2337.40
46	-2454.20	1783.10
47	-2820.60	1116.70
48	-3009.70	380.21
49	-3009.70	-380.21
50	-2820.60	-1116.70
51	-2454.20	-1783.10
52	-1933.70	-2337.40
53	-1291.60	-2744.90
54	-568.44	-2979.90
55	190.48	-3027.60
56	937.43	-2885.10
57	1625.50	-2561.40
58	2211.40	-2076.60
59	2658.40	-1461.40
60	2938.30	-754.43
61	3792.00	0
62	-1896.00	3284.00
63	-1896.00	-3284.00

C Wake Model Data

The governing equation for the velocity deficit in the waked region, under this case study's implementation of the Bastankhah Gaussian Wake Model is:

$$\frac{\Delta U}{U_\infty} = \left(1 - \sqrt{1 - \frac{C_T}{8\sigma_y\sigma_x/d^2}}\right)\exp\left(-0.5\left(\frac{y-\delta}{\sigma_y}\right)^2\right)\exp\left(-0.5\left(\frac{z-z_h}{\sigma_z}\right)^2\right) \tag{2}$$

Where $\frac{\Delta U}{U_\infty}$ is the wake velocity deficit, C_T is the thrust coefficient. $y-\delta$ and $z-z_h$ are the distances of the point of interest from the wake center in the cross-stream horizontal and vertical directions respectively, and σ_y and σ_z are the standard deviations of the wake deficit in the cross-stream horizontal and vertical directions as defined in Eqs. (3) and (4):

$$\sigma_y = k_y(x - x_0) + \frac{D_r}{\sqrt{8}} \tag{3}$$

$$\sigma_y = k_z(x - x_0) + \frac{D_r}{\sqrt{8}} \tag{4}$$

In Eqs. (3) and (4), x is the downstream distance from the turbine generating the wake to the point of interest, x_0 is the length of the wake potential core, D_r is the diameter of the turbine generating the wake. k_y and k_z are determined as a function of turbulence intensity (I). In this case study, turbulence intensity will be neglected, therefore we shall use $k_{y,z} = 0.003678$ [5, 3].

C.1 Wind Speed

For this scenario, the freestream wind velocity will be constant throughout the farm, at 13 m/s, regardless of turbine location or time of day.

C.2 Wind Direction Probability

For the above specified wind speed, wind direction probability will mimic those found in a geographically linear canyon, using a bi-modal Gaussian distribution. This distribution is defined in Eq. (5) and the wind rose is shown below:

$$\begin{aligned} F =& w_1\left(\sqrt{\frac{1}{2\pi\sigma_1^2}}\right)\exp\left(-\frac{(\theta-\mu_1)^2}{2\sigma_1^2}\right) \\ &+ w_2\left(\sqrt{\frac{1}{2\pi\sigma_2^2}}\right)\exp\left(-\frac{(\theta-\mu_2)^2}{2\sigma_2^2}\right) \\ &+ w_2\left(\sqrt{\frac{1}{2\pi\sigma_2^2}}\right)\exp\left(-\frac{(\theta-\mu_3)^2}{2\sigma_2^2}\right) \end{aligned} \tag{5}$$

Where:

- θ: wind direction where north is 0°, measured clockwise.
- μ_1: first dominant wind direction (180°).

- μ_2, μ_3: second dominant wind direction (350° and −10°, respectively).
- σ_1: first standard deviation (20°).
- σ_2: second standard deviation (40°).
- w_1: first distribution weight (0.5).
- w_2: second distribution weight (0.5).

The wind rose shown below is a graphical depiction of the frequency from which direction on a compass (in degrees) the wind comes. A farther distance from the origin indicates a higher frequency.

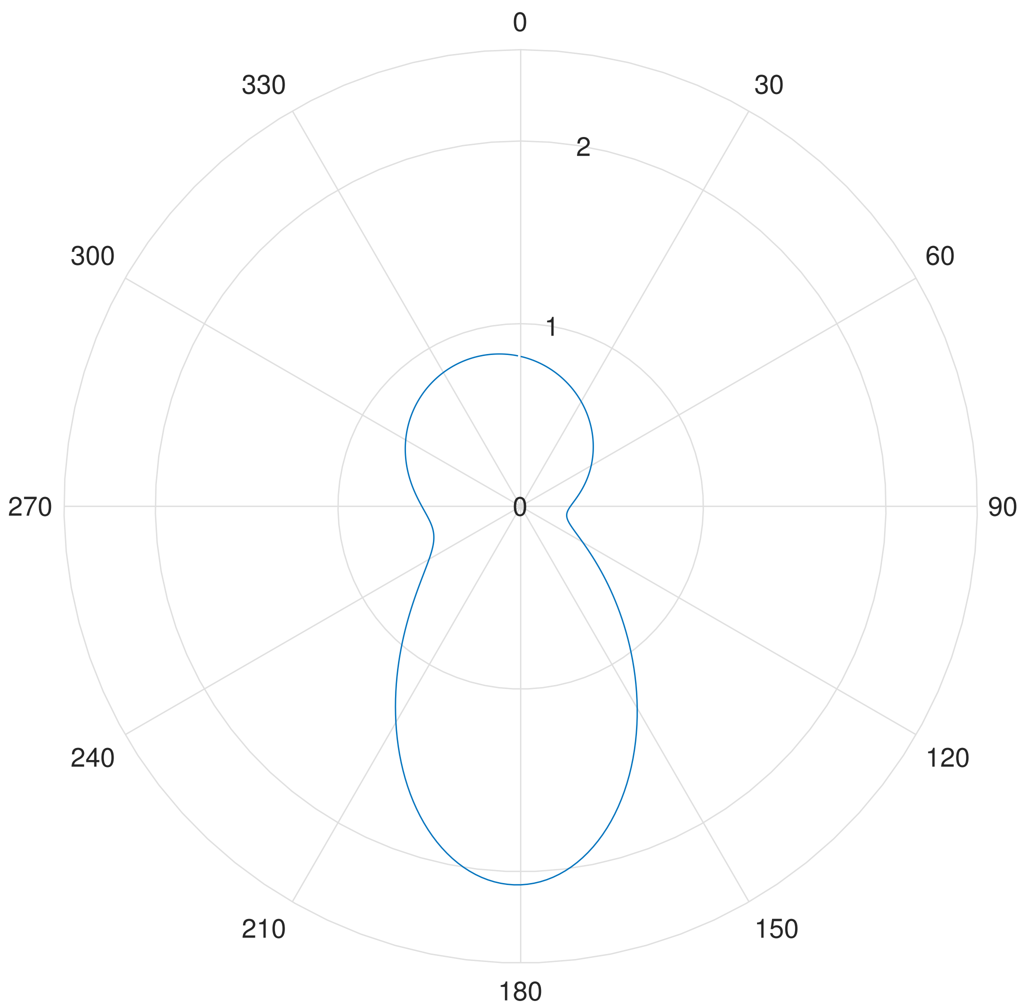


Figure 5: The wind frequency distribution; a bi-modal Gaussian distribution as defined in Eq. (5)

References

[1] Majid Bastankhah and Fernando Porté-Agel. A new analytical model for wind-turbine wakes. *Renewable Energy*, January 2014.

[2] Majid Bastankhah and Fernando Porté-Agel. Experimental and theoretical study of wind turbine wakes in yawed conditions. *J. Fluid Mech.*, 806:506–541, 2016.

[3] Jared Thomas and S. Ning. A method for reducing multi-modality in the windfarm layout optimization problem. Technical report, BYU, 2018.

[4] Jason Jonkman, Sandy Butterfield, Walter Musial, and George Scott. Definition of a 5-MW reference wind turbine for offshore system development. Technical report, National Renewable Energy Laboratory (NREL), Golden, CO., 2009.

[5] Amin Niayifar and Fernando Porté-Agel. Analytical modeling of wind farms: A new approach for power prediction. *Energies*, September 2016.