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[§]

May 2018

1 Introduction

This document defines a simple wind farm layout optimization problem of varying sizes, with the goal of comparing the results obtained when using different optimization methods for a single wake model. While the optimization problem is very simple, we expect the results to assist researchers in understanding the differences that occur due to optimizing wind farms using various numerical methods. The results are expected to serve as a benchmark for future wind farm layout optimization studies. The greater understanding of this simplified problem is expected to aid in solving and interpreting the results of more realistic problems.

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 1,500 m.

2. Wind farm of thirty-six (36) turbines, boundary radius of 2,500 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. The specified boundary distance is a radius from the origin.

2.2 Wind Turbine Definition

The wind turbine used in this study is the NREL 5MW reference turbine [1]. The important parameters are:

[*]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

- **Rotor Diameter:** 126.4 m

- **Turbine Rating:** 5 MW

- **Cut-In Wind Speed:** 3 m/s

- **Rated Wind Speed:** 11.4 m/s

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

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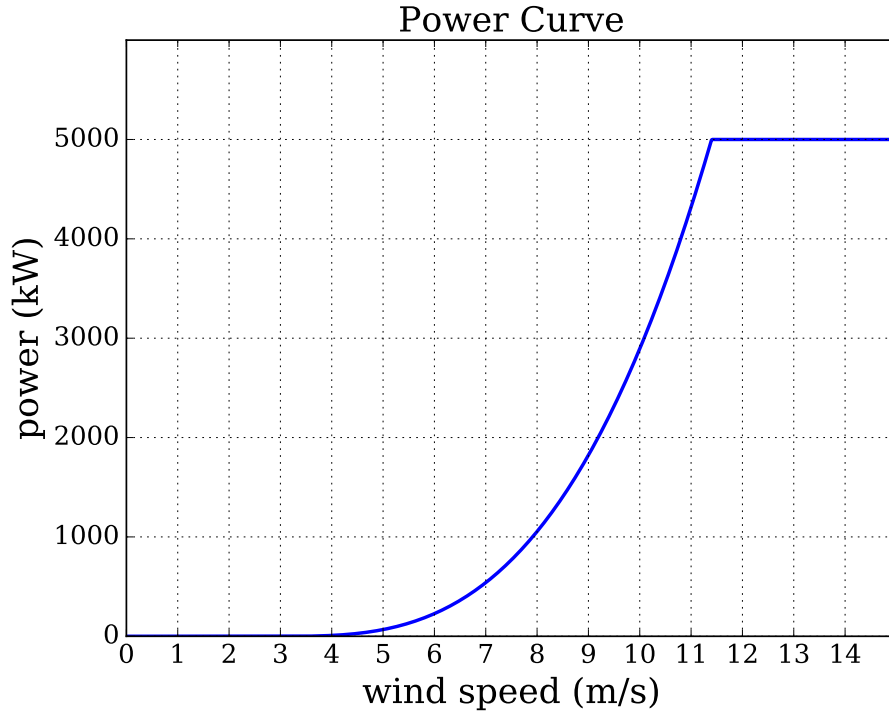

Figure 1: The wind turbine power curve.

2.3 Wake Model

The wake model utilized for this case study is Bastankhah's Gaussian wake model [2, 3]. The pertinent files are coded in Python, and are provided alongside this document in a `.zip` directory.

The governing equation under this model for the velocity deficit in the wake region is:

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

Where $\frac{\Delta U}{U_\infty}$ is the wake velocity deficit, C_T is the thrust coefficient, and γ is the upstream turbine's yaw angle with respect to the inflow direction (neglected in this study for simplicity).

$y - \delta$ 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):

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

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

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 also be neglected. Therefore we shall use $k_{y,z} = 0.003678$ [4, 5].

2.4 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.

2.5 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:

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

- θ: wind direction where north is 0°, measured clockwise.

- μ_1: first dominant wind direction (180°).

- μ_2: second dominant wind direction (350°).

- 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).
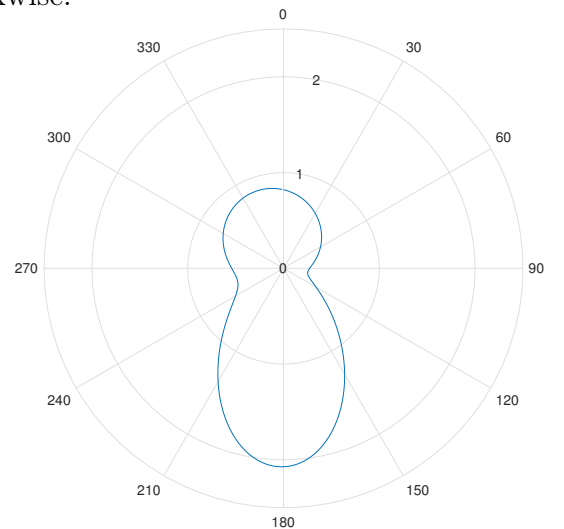
2.6 Code Format

The relevant code for the above formulas are pre-programmed in Python and released along with this document, in order for each participant to apply their unique optimization methods. The wake model routine takes a specified number of grid locations as inputs, and returns as output the AEP for the given turbine locations.

Though not necessary, alteration to the released AEP calculation code may be done, 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 3.1 and corresponding AEP calculations are to be used as validation.

3 Reporting Results

3.1 Submission Contents

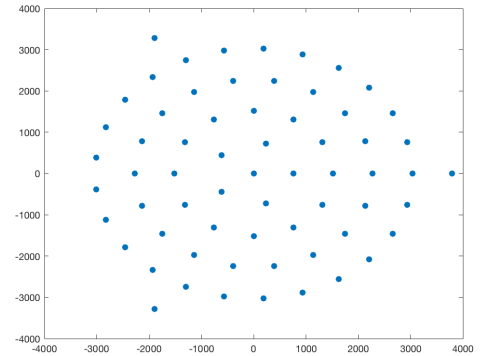The following information should be included in each submission:

- Text file containing your baseline, optimized baseline, initial, and overall optimal computed AEP values in Megawatt-hours, and your optimized baseline, initial and optimal turbine locations in meters. The initial AEP and layout should be from the starting point of your submitted optimized layout. This baseline is 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 A, and are depicted graphically in Fig. 2:
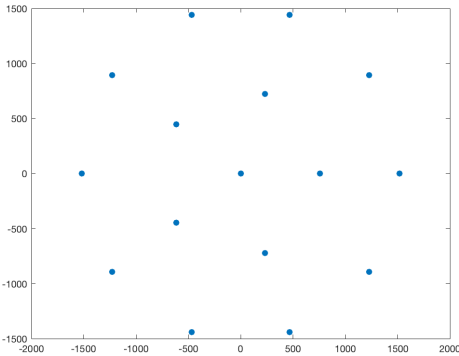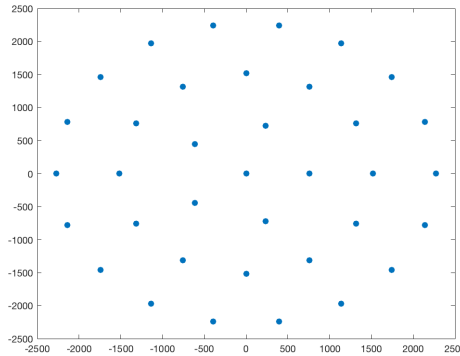
(a) 16 Turbine Farm   (b) 36 Turbine Farm   (c) 64 Turbine Farm

Figure 2: Baseline Turbine Locations

You are **NOT** required to start each of your optimizations from these layouts. Feel free to use random starts, intuition, warm starts, or any other selection method for initilizing the turbine locations for your optimizations. Simply report the AEP calculated at these base locations, and a resulting optimized wind farm from a single start using these layouts.

- Short description containing the relevant details of your method/process. This should include, at a minimum:

4

- 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
- Your computed initial and final AEP values
- 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

3.2   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 3.1

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), optimized base AEP, initial AEP (MWh), optimized 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   Baseline Grid Coordinates

(16) Turbine Wind Farm		
#	x (m)	y (m)
0	0	0
1	758.40	0
2	234.36	721.28
3	-613.56	445.78
4	-613.56	-445.78
5	234.36	-721.28
6	1516.80	0
7	1227.10	891.55
8	468.72	1442.60
9	-468.72	1442.60
10	-1227.10	891.55
11	-1516.80	0
12	-1227.10	-891.55
13	-468.72	-1442.60
14	468.72	-1442.60
15	1227.10	-891.55

(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

References

[1] 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.

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

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

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

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