IEA Task 37 on System Engineering in Wind Energy

The Wind Farm Physics Model and Optimization Case Studies

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1 Introduction

In order to better understand the differences in Engineering Wake Model (EWM) selection and optimization algorithm implementation, this document defines two simple wind farm layout optimization (WFLO) case studies. These studies are designed to involve a broad spectrum of participants working on the WFLO problem.

Since two of the major factors contributing to superior wind farm turbine placement recommendations are 1) EWM characteristics and 2) optimization algorithm implementation, the two distinct case studies are designed in an attempt to quantify the effects of alterations in both variables. The first case study isolates optimization techniques for a single simplified EWM, the second observes the differences when combining variations in EWM selection and optimization method.[1]

To isolate optimization method variability, we have implemented a representative wake model, and permit participants to use any optimization strategy they think will achieve the maximum Annual Energy Production (AEP) for the specified wind farm. This collaboration will be called the Optimization Only Case Study, and is described below in Section 2.1.

Since an EWM's compatibility with gradient-based or gradient-free optimization methods dictate which algorithms can be applied, designing a case study which restricts participants to a single optimization algorithm would unnecessarily limit the scope of EWMs studied. With the aim of acquiring as much empirical data in order to determine best practices for the industry as a whole, our second case study will permit collaborating participant selection of not only EWM, but also implemented optimization algorithm. It will be called the Combined Physics Model/Optimization Algorithm Case Study, and is described below in Section 2.2.

The wind farm characteristics of these two cases are similar, and were selected to be both restrictive enough to maintain simplicity, yet general enough to aid in solving and interpreting the results of more complex and realistic problems.

2 Problem Definitions

2.1 The Optimization Only Case Study

The intent of this case study is to determine best optimization practices when given an EWM that permits both gradient-based and gradient-free methods to be used. As a representative EWM, we select a simplified version of Bastankhah's Gaussian wake model [1, 2, 3]. We supply a Python implementation of this wake model, as well as a description of the model in Appendix C for those who wish to implement it in another language.

With the wake model fixed, participants are free to use whichever computational optimization strategies they choose, with the objective of obtaining the maximum Annual Energy Production (AEP) for the defined farm. In this case study the wind farm boundaries, directional wind frequency, wind turbine attributes, and wake model physics are fixed—turbine locations are the only design variable participants are permitted to alter.

Since problem size strongly affects optimization algorithm performance, three wind farms of increasing size are specified in Section 2.1.1. These scenarios, roughly doubling in number of turbines, exist to avoid a bias towards algorithms optimized for wind farms of a specific dimension,

[1] Comparisons just between EWMs does not involve optimization and multiple studies already exist in this area.

and in order to observe how increased complexity correlates to algorithm performance. Perfect squares are used to permit grid turbine arrangements, if desired.

The goal of this collaboration is to compare participant results when using different optimization strategies under a single wake model, in order to understand the performance differences resulting from optimization algorithm selection in similar scenarios. While the provided wind farm scenarios are very simple, we expect the results to assist researchers in understanding the differences that occur in WFLO due to various numerical methods. A greater understanding of the trade-offs in algorithm selection for this simplified problem is expected to aid in solving and interpreting the results of more complex and realistic problems.

2.1.1 Wind Farm Definition

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

1. Wind farm of sixteen (16) turbines, boundary radius of 1,300 m.
2. Wind farm of thirty-six (36) turbines, boundary radius of 2,000 m.
3. Wind farm of sixty-four (64) turbines, boundary radius of 3,400 m.

For all wind farm sizes, the wind farm boundary is circular, as depicted Fig. 1. The origin is at the center of the farm, coincident with the depicted reference turbine, and the specified boundary radius for each farm is measured from the origin. The radii magnitudes were determined by evenly distributing the specified number of turbines in concentric circles, with no less than 5 diameter spacing between adjacent turbines, and rounding up to the nearest 100 m.

All wind farms will be populated with the IEA37 3.35 MW onshore reference turbine [4], whose main attributes are summarized in Appendix A.

Note that the farm boundary restricts only turbine hub locations. The blade radius is permitted to extend beyond, but hub locations must be on or within the boundary. Hub locations are further restricted from being placed closer to each other than two diameters apart.

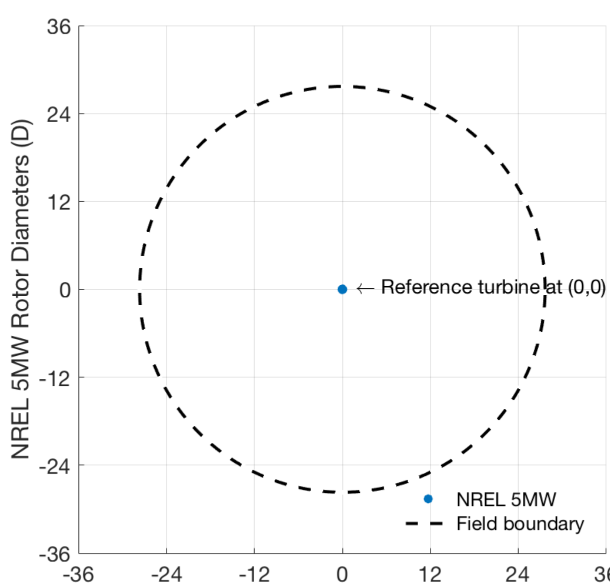
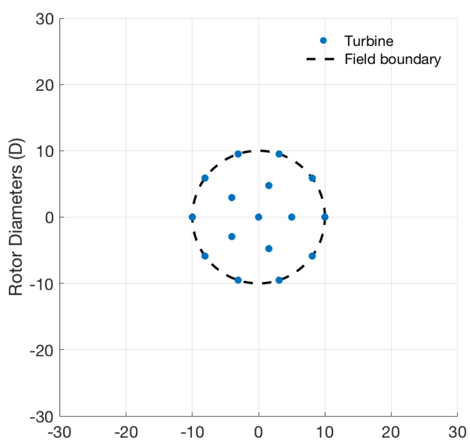


Figure 1: Depiction of circular farm boundary, reference turbine (to scale) placed at origin.

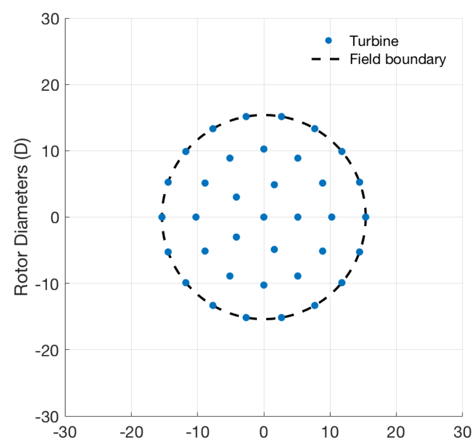
2.1.2 Baseline Layouts

To assist in validation, a baseline wind turbine layout is supplied as a check for each farm size. The AEP for these baseline layouts, as determined by our wake model implementation, is included in the `.csv` file for each size scenario, listed in the `.zip` file accompanying this document. If you choose to utilize your own implementation of the wake model and AEP functions described in Appendix C instead of the Python implementation provided, insure that your implementation reports the same AEP for these locations.

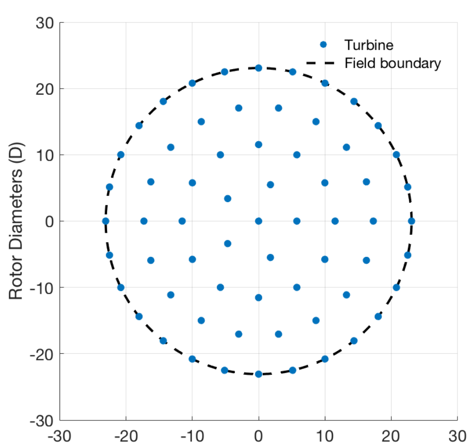
You are also to conduct a single baseline optimization from these baseline layouts, and report your resulting optimized turbine location and AEP values from these starting locations. You are not required to start *each* of your optimizations from these layouts, only report the results from a single run using these starting baselines. 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. The exact coordinates for the turbine locations in each of these baseline layouts are also included in `.csv` files listed in the `.zip` file accompanying this document. The format for these files is described later in Section 3.2.1. The baseline layouts are depicted graphically in Fig. 2



(a) 16 Turbine Farm



(b) 36 Turbine Farm



(c) 64 Turbine Farm

Figure 2: Baseline turbine locations, depicted with dashed wind farm boundaries and blue NREL 3.35 MW onshore reference turbines (to scale)

2.1.3 Wake Model and Code Description

The wake model implemented in this case study is Bastankhah's Gaussian wake model [1, 2, 3]. A description of the model's governing equations, data on the wind farm's wind speed and direction probability, and formulations for AEP calculations are included in Appendix C. The pertinent equations 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 turbine 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 Python code is permitted, if required to maximize optimizer effectiveness. Care must be taken, however, that the governing physics equations are not altered to deliver deviated AEP results. For this reason, baseline turbine locations and AEP calculations are described in Section 2.1.2, to be used for validation.

2.2 The Combined Physics Model/Optimization Algorithm Case Study

This case study closely matches the one described in Section 2.1, with the exception that no wake model is provided, and only a single wind farm size is to be optimized. Participants are free to chose their preferred EWM and optimization method. The objective is to obtain the maximum Annual Energy Production (AEP) for the defined turbine farm. Participants will adjust resultant AEP through choice of EWM utilized, and manipulation of turbine locations.

The intent of this case study is to determine best EWM selection and optimization practices for this representative wind farm scenario. Since different EWMs approximate the aerodynamic characteristics effecting power production differently, reported AEP from participants using different EWMs are not comparable. As a benchmark measuring tool for these case studies, we will run all participant results of optimized turbine locations through a Large Eddy Simulation (LES). Using LES as a tool for analysis, participant results will be analyzed based on which participant results (regardless of EWM used) give the highest LES-calculated AEP.

Like the previous case study defined in Section 2.1, the wind farm boundary for this case study is circular, and the number of turbines in the farm is a perfect square in order to permit a grid arrangement, if desired. To limit the LES computation time required for us to assess results, the wind farm size for this case study is limited to 9 turbines.

This study differs from the first, in that it assesses not only the optimization methods measured by previous case, but also the effects that different physics model approximations have on turbine location recommendations. While the provided wind farm is very simple, we expect the results to assist researchers in understanding the differences that occur in WFLO due to various aerodynamic approximations and optimization methods. A greater understanding of the trade-offs in EWM selection and optimization algorithm implementation for this simplified problem is expected to aid in solving and interpreting the results of more complex and realistic problems.

2.2.1 Wind Farm Definition

- The wind farm consists of nine turbines, boundary radius of 900 m.
- If necessary, the turbulence intensity is 0.075.
- Assume the freestream wind speeds given in this document are at hub height. If you need a wind shear, use a power law relationship with a shear exponent of 0.15.

The wind farm boundary is circular, as depicted in Fig. 3. The origin is at the center of the farm, coincident with the depicted reference turbine, and the specified boundary radius is measured from the origin. The radius magnitude was determined by evenly distributing the specified number of turbines in a circle, with no less than 5 diameter spacing between adjacent turbines, and rounding up to the nearest 100 m.

All wind farms will be populated with NREL 3.35 MW onshore reference turbine [4], whose main attributes are summarized in Appendix A

Note that the farm boundary restricts only turbine hub locations. The blade radius is permitted to extend beyond, but hub locations must be on or within the boundary. Hub locations are further restricted from being placed closer than two diameters apart from each other.

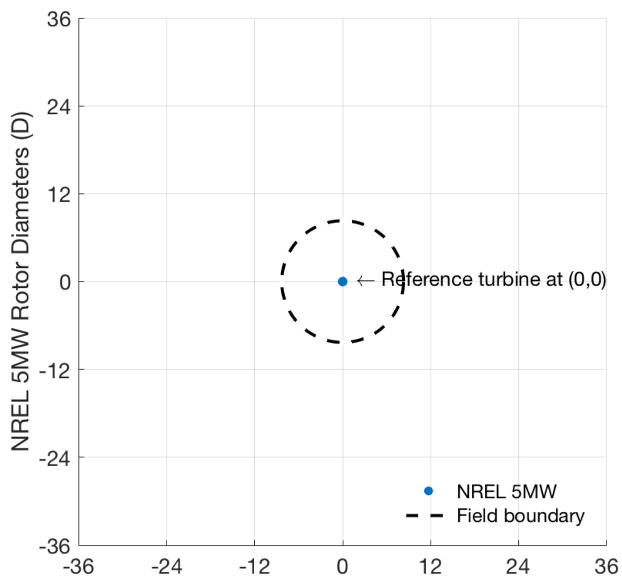


Figure 3: Depiction of circular farm boundary, reference turbine (to scale) placed at origin.

2.2.2 Baseline Layout

To better understand EWM characteristics and optimization methods, a baseline wind turbine layout is supplied. You are to conduct a single baseline optimization from this baseline layout, 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 this starting baseline. 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. The exact coordinates for the turbine locations in each of these baseline layouts are included in `.csv` files listed in the `.zip` file accompanying this document.

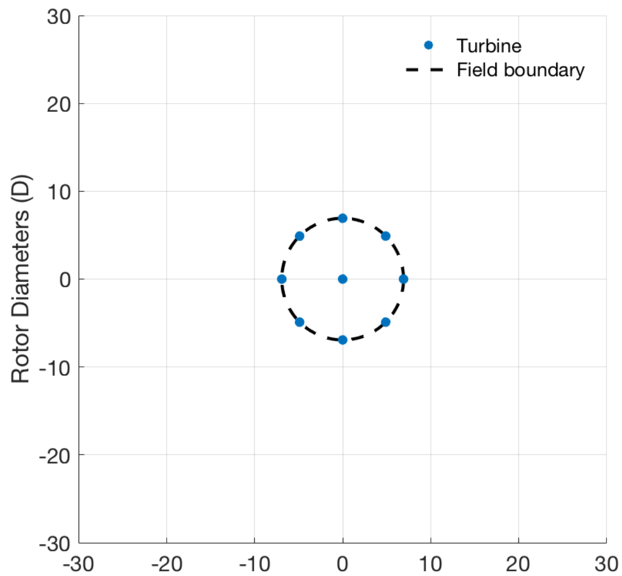


Figure 4: Baseline turbine locations, depicted with dashed wind farm boundaries and blue NREL 3.35 MW onshore reference turbines (to scale)

3 Reporting Results

In order to correctly process your results, as well as fairly compare them to results of other participants, all submissions must be in the proper format specified below. Exceptions will not be granted, and results submitted in incorrect format will be unable to be processed by our analysis tools.

3.1 Submission Contents

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

3.1.1 Method Description

The general intent with requesting a method description is to obtain sufficient information for us to reproduce your results. The `.txt` file containing a short description of the relevant details of your method/process should include (at a minimum):

- Wake Model (applicable only for the Combined Model/Algorithm Case Study)
  - Model name
  - Governing wake equations (if possible)
  - Description of general model shape (i.e. smooth, flat, Gaussian curve, presence of discontinuities, etc.)
  - What factors are accounted for by your model (i.e. partial wake, shear, turbulence, etc.)
  - Paper citation for description of model (if applicable)
  - Other relevant wake model details
- Optimization algorithm (including version and any non-default settings or modifications)
  - Algorithm name
  - General type of algorithm (e.g. gradient-free, gradient-based)
  - Specific algorithm type (e.g. particle-swarm, genetic-algorithm, sequential quadratic programming, etc)
  - Number of iterations
  - Number of AEP function calls
  - The level of convergence
  - How gradients were obtained (if applicable)
  - The number of gradient evaluations (if applicable)
  - The Lagrange multipliers for the constraints (if applicable)
  - The norm of the Kuhn-Karush-Tucker condition achieved in the final solution (if known)
  - Programming language(s) utilized
  - Other relevant algorithm details

- Computer hardware specifications
  - Manufacturer/Model/Speed of processor (GHz)
  - Number of cores utilized
  - System total RAM
- How you decided on the starting turbine locations for your final optimized results
- Time required for optimization convergence
- Links to relevant code(s) (if possible)
- Other details you consider relevant
- Bibliography

3.1.2 Turbine and AEP Data

Submitted in a separate `.csv` file for each wind farm layout, each file will list turbine locations and calculated AEP for that layout. The three (3) layouts to report for each size scenario are:

1. Overall optimal turbine layout your analysis discovered.
2. Initial turbine layout leading to this optimal layout.
3. The optimized layout reached using the supplied baseline layout as a starting point.

3.2 Submission Format

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

1. Two (2) `.txt` files of the method/process description (one for each case study) as described in Section 3.1.1.
2. Twelve (12) `.csv` files with the quantitative optimization results. There will be three (3) for each farm size:
   1) Optimized turbine locations (m) & AEP (MWh)
   2) Initial turbine locations (m) & AEP (MWh)
   3) Optimized turbine locations (m) & AEP (MWh) from baseline layouts

3.2.1 The `.csv` Format

A Comma-Separated Values (`.csv`) file is a simple text file that separates values by commas and linebreaks. You will have one (1) `.csv` file for each reported turbine layout. Each file will contain a single calculated AEP value, and a list of turbine x and y coordinates for each turbine's location. Baseline turbine layouts for each wind farm scenario will be supplied in this format as well. Please refer to Fig. 5 for an example.

```
# AEP (MWh)
AEP

x_coord(m), y_coord(m)
x0, y0
x1, y1
x2, y2
x3, y3
x4, y4
x5, y5
x6, y6
⋮,  ⋮
```

Figure 5: `.csv` file example for reporting turbine locations

Strict adherence to this format is required, as you will need to both formulate your own tools in such a way that you can read in grids supplied in this format to calculate AEP, and permit other participants to read your reported grids in this format, as explained in Section 3.3.

3.3 Cross Comparison for Combined Model/Algorithm Case Study

In order to gain a better understanding on comparison of different EWM physics approximations, you will run the other participants' reported optimal turbine locations through your implemented EWM.

After the call for results, we will send you the optimal turbine locations the other participants have found using their combined EWM selection and optimization algorithm. Turbine locations will be in a `.csv` format, explained previously in Section 3.2.1. You will report to us what your EWM calculates the AEP is for each layout we supply you. No optimization is needed for this cross comparison, simply your EWM's reported AEP number.

A Wind Turbine Definition

The wind turbine used for all wind farm scenarios in these case studies is the IEA37 3.35MW onshore reference turbine [4]. The important parameters are:

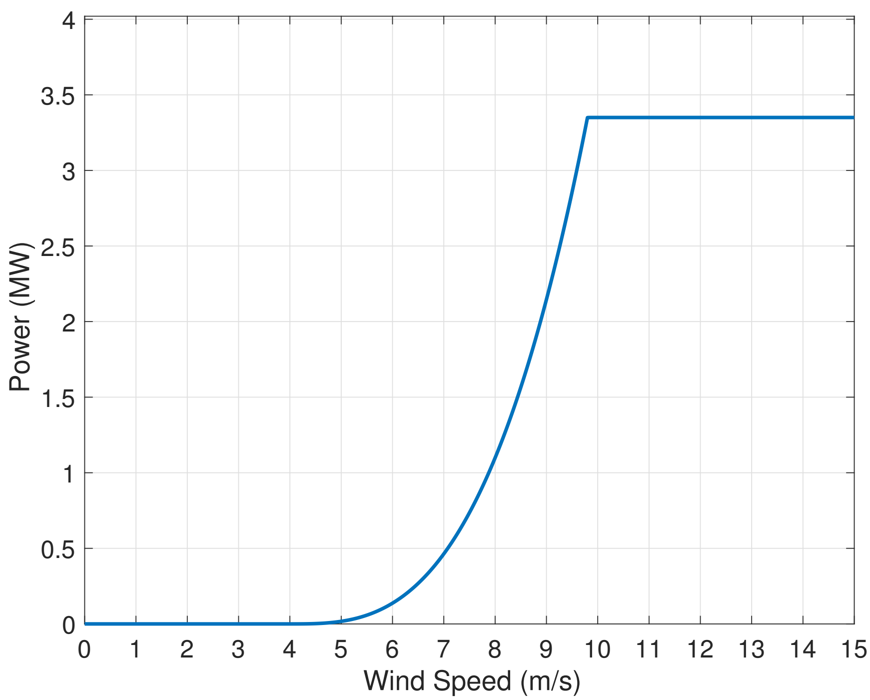
Table 1: IEA37 3.35MW Reference Turbine key attributes [4]

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

The power curve equation is given in Eq. (1) and graphed in Fig. 6.

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

Figure 6: Calculated IEA37 3.35MW onshore reference turbine power curve



B Wind Farm Data

B.1 Wind Speed

For this scenario, the freestream wind velocity will be constant throughout the farm at 9.8 m/s. This is the rated wind speed of the reference turbine described in Appendix A used in all farm scenarios, and will enable observation of wake effects.

B.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. (2) and the wind rose is shown below:

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

The variables for Eq. (2) are explained in Table 2:

Variable	Value	Definition
θ	-	Wind direction where north is $0°$, measured clockwise
μ_1	$180°$	First dominant wind direction
μ_2	$-10°$	Second dominant wind direction
μ_3	$350°$	Second dominant wind direction
σ_1	$20°$	First standard deviation
σ_2	$40°$	Second standard deviation
w_1	0.5	First distribution weight
w_2	0.5	Second distribution weight

Table 2: Variable definitions for wind direction probability in both case studies

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

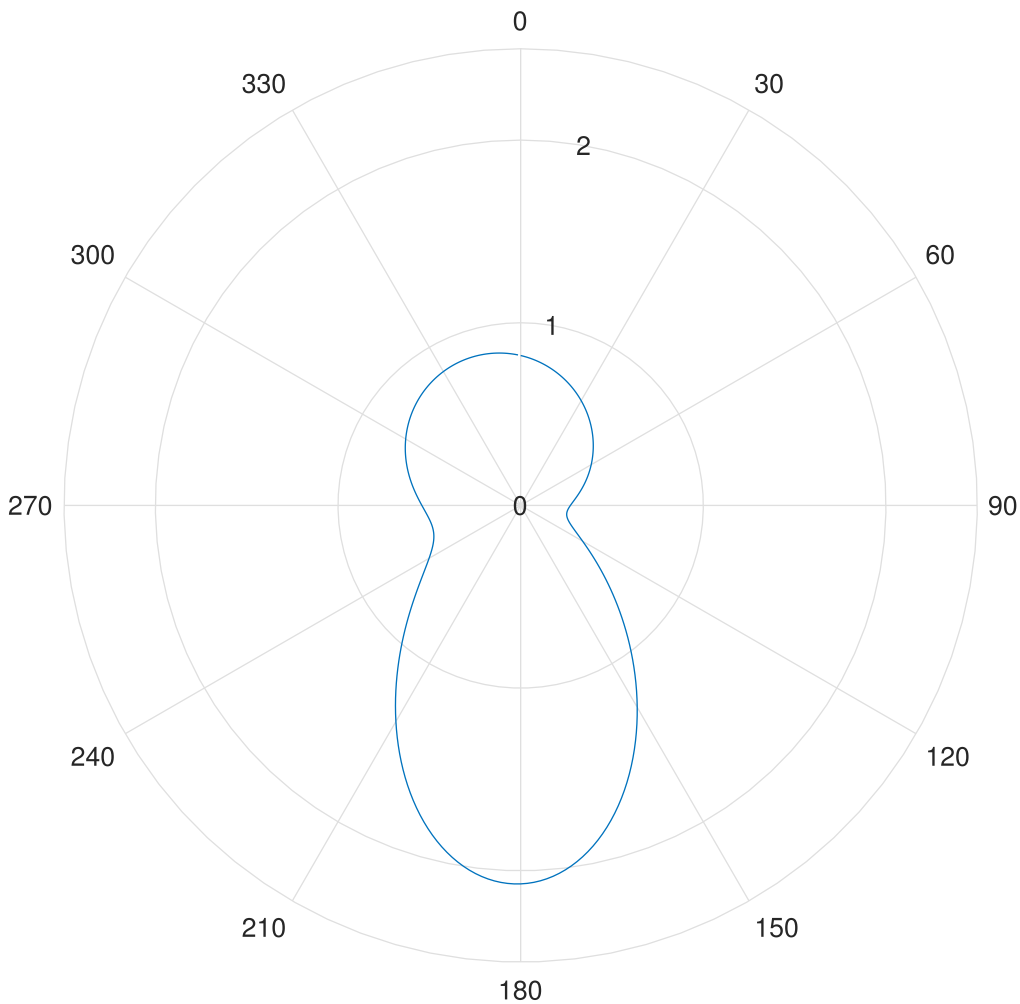


Figure 7: The wind frequency distribution; a bi-modal Gaussian distribution as defined in Eq. (2)

C Wake Model Data for Optimization Only Case Study

C.1 Wake Model

For the Optimization Only Case Study (described in Section 2.1), we implemented a simplified version of the Bastankhah Gaussian Wake Model [1]. The governing equations for the velocity deficit in the waked region, under this case study's implementation are:

$$\frac{\Delta U}{U_\infty} = \left(1 - \sqrt{1 - \frac{C_T}{8\sigma_y^2/D^2}}\right) \exp\left(- 0.5\left(\frac{y-\delta}{\sigma_y}\right)^2\right) \tag{3}$$

$$\sigma_y = k_y \cdot x + \frac{D}{\sqrt{8}} \tag{4}$$

The relevant variables for Eqs. (3) and (4) are defined in Table 3.

Variable	Value	Definition
$\frac{\Delta U}{U_\infty}$	-	Wake velocity deficit
C_T	$\frac{8}{9}$	Thrust coefficient
$y - \delta$	-	Dist. from point of interest to the wake center in cross-stream direction
D	130 m	Turbine diameter
σ_y	Eq. (4)	Standard deviation of the wake deficit
x	-	Downstream dist. from turbine generating wake to turbine of interest
k_y	0.0324555	Variable based on turbulence intensity [5, 1]

Table 3: Variable definitions for simplified Bastankhah Gaussian Wake Model

No partial wake is accounted for, and hub locations are used for velocity calculations. Turbines feeling multiple wake effects are calculated using the square root of the sum of the squares, as depicted in Eq. (5):

$$\left(\frac{\Delta U}{U_\infty}\right)_{cmbnd} = \sqrt{\left(\frac{\Delta U}{U_\infty}\right)_1^2 + \left(\frac{\Delta U}{U_\infty}\right)_2^2 + \left(\frac{\Delta U}{U_\infty}\right)_3^2 + \ldots} \tag{5}$$

C.2 AEP

Annual Energy Production (AEP) for the Optimization Only Case Study is calculated using Eq. (6), with variable descriptions in Table 4:

$$AEP = \omega(\theta) \cdot P(\theta) \cdot 8760 \frac{hrs}{yr} \tag{6}$$

Variable	Value	Definition
θ	$0 \leq \theta \leq 360$	Wind direction where north is 0°, measured clockwise
$\omega(\theta)$	$0 \leq \omega(\theta) \leq 1$	Wind frequency, for the given wind direction
$P(\theta)$	$0 \leq P(\theta) \leq 3.35$	Power (MW), for the given wind direction

Table 4: Variable definitions for AEP calculation

Increments of θ were taken to account for 16 'buckets', or samplings, around the compass. This number was picked since it proved to be past convergence within 1% of truth.

References

[1] Jared J. Thomas and Andrew Ning. A method for reducing multi-modality in the wind farm layout optimization problem. In *Journal of Physics: Conference Series*, Milano, Italy, June 2018. The Science of Making Torque from Wind.

[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.

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