Wind Farm Layout Optimization Case Studies 3 & 4

IEA Task 37 on System Engineering in Wind Energy

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1 Introduction

Two major factors that affect wind farm layout optimization are 1) the optimization approach and 2) the wake model. We have thus far conducted two case studies to analyze differences in these variables, this document defines a third and fourth case study to further study these factors when given more realistic wind farm boundary and wind resource. Case study 3 (cs3) presents a scenario with a concave boundary. Case study 4 (cs4) presents a scenario with boundaries that are discontinuous and contain concavities. For cs3 a wake model is provided, participants need only optimize turbine locations. For cs4 users are free to choose both optimization approach and wake model.

Participants will (1) optimize turbine locations to maximize annual energy production, (2) submit solutions with details regarding their optimization convergence and methodology. After all submissions are received, participants of cs4 will be expected to perform a cross comparison of other participant solutions. Data will be consolidated, processed, and made available to all participants.

2 Problem Definition

Objective

The objective of each scenario is to maximize annual energy production (AEP), which we define simply as the expected value of aerodynamic power multiplied by the hours in a year. In other words:

$$AEP = 8760 \frac{\text{hrs}}{\text{yr}} \sum_{i=1}^{n} \sum_{j=1}^{m} f_i w_j P_{i,j}$$

where $P_{i,j}$ is the power produced for wind direction i at wind speed j, n is the number of wind directional bins, f_i is the corresponding wind direction probability, m is the number of wind speed bins for each direction, and w_j is the probability each speed bin will occur.

For cs3 and cs4, the wind resource is supplied in 60 bins. Each bin has a specific directional probability and continuous wind speed distribution derived from Weibull parameters. For their optimizations, participants are free to use all, fewer, or interpolate more n directional bins if they wish. However final evaluations will use the 60 supplied bins, with wind speeds partitioned in 5 m/s increments from $0 - 25$ m/s.

Design Variables

The design variables are the (x, y) locations of each turbine, all hub heights (z values) will be the same in cs3 and cs4. Every turbine in the farm is identical and is defined below in Parameters.

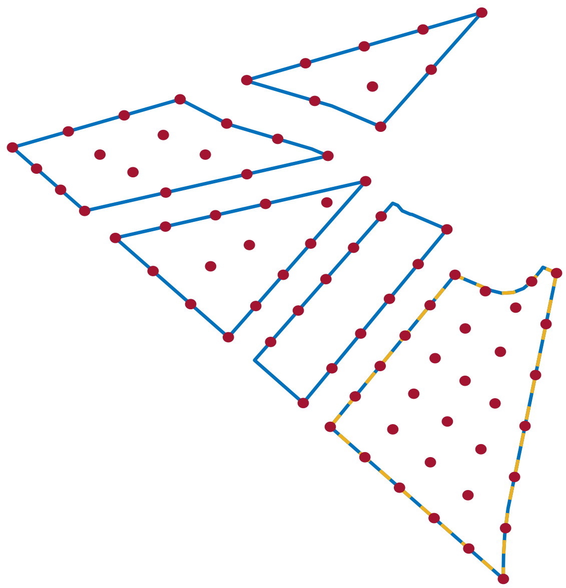


Figure 1: The wind farm boundary for cs3 (outlined in yellow) and cs4 (outlined in blue). A provided baseline turbine layout for cs4 is overlaid in red, with rotor radii to scale.

Constraints

In case studies 1 and 2, all farm boundaries were circular. To make cs3 and cs4 more realistic, all boundaries are non-uniform. The cs3 and cs4 boundaries are based on the Borselle III and IV wind farms, our version is depicted graphically in Figure 1. The coordinates for the boundary vertices are given in `iea37-boundary-cs3.yaml` and `iea37-boundary-cs4.yaml`. All turbine hub coordinates must remain on or within these boundaries. The turbines are further constrained such that no hub can be less than two rotor diameters from any other hub.

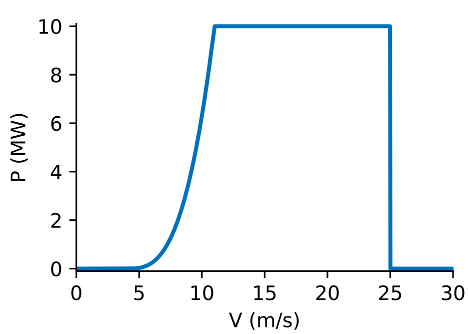
Parameters

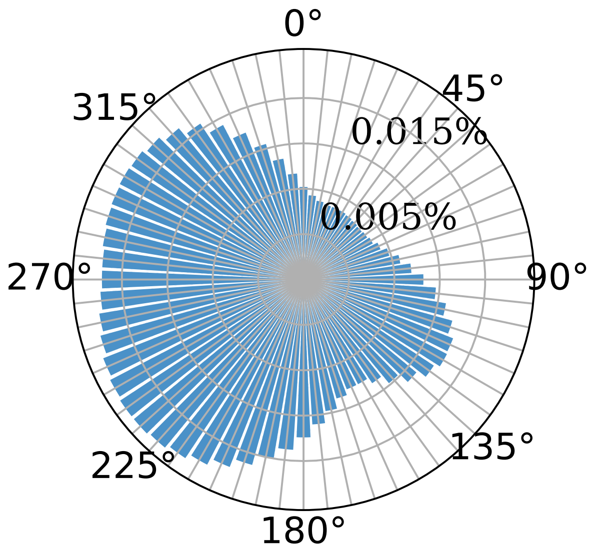
The wind turbine is the IEA37 10 MW offshore reference turbine [1] with the following characteristics:

Rotor Diameter	198.0	m
Hub Height	119	m
Turbine Rating	10	MW
Cut-In Wind Speed	4	m/s
Rated Wind Speed	11	m/s
Cut-Out Wind Speed	25	m/s

All turbine data are also contained in the enclosed `iea37-10mw.yaml`. The power curve is defined as:

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





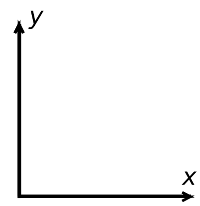


Figure 2: Wind frequency distribution over the 60 bins for the windrose used in cs3 and cs4.

The wind speed for each bin is given as a continuous distribution derived from provided Weibull parameters. The distribution is calculated as:

$$w = \frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{k-1} e^{-(x/\lambda)^k}$$

Where x is the wind speed in m/s and w is the probability of that wind speed to occur. The variable k is the Weibull shape parameter and λ is the Weibull scale parameter. Note that the associated λ is also the dominant wind speed for that binned direction.

Figure 2 depicts the wind frequency distribution used in cs3 and cs4. The `+y` axis is coincident with 0°, and the clockwise wind rose is tabulated in `iea37-windrose-cs3.yaml`.

2.1 Case Study 3

This wind farm scenario consists of twenty-five (25) turbines with a boundary containing concavities. Participants will optimize the wind farm layout for maximum AEP with the provided Gaussian wake model, wind rose, turbine, and boundary. The wake model is supplied (coded in python) as `iea37-aepcalc.py`. Alterations to this implementation are permitted, as long as the governing physics equations are not altered. Participants may use other programming languages, but must use the same physics equations. To aid with this, the relevant equations are defined in a separate document (`iea37-wakemodel.pdf`), and baseline wind farm layouts with corresponding AEP values are provided in the `iea37-ex-opt#.yaml` files to verify implementations.

2.2 Case Study 4

This scenario consists of eighty-one (81) turbines with a boundary containing concavities and discontinuities. The user is free to choose both the optimization algorithm and wake model. There is no region-turbine apportionment criteria, the participant or their optimization algorithm is to determine placement of all eighty-one turbines across the five boundary regions.

3 Reporting and Evaluation

3.1 Baseline Layouts

Baseline turbine layouts for both case studies are supplied. These are provided in part to give examples of our precise reporting format. They are called `iea37-ex-opt3.yaml`, `iea37-ex-opt4.yaml`, and `iea37-ex-log3.yaml`. Like the example layouts provided for case studies 1 and 2, these baseline layouts are also meant to provide a reasonable minimum output against which results can be measured. Participants are not required to use the baseline layouts as starting points for their optimizations, though they are permitted to do so.

3.2 Reporting

Submissions must adhere to the `.yaml` format in order to enable easy and fast analysis of participant results. You will submit two (2) files per case study: one with your optimized turbine layout, the second a log of your optimization convergence data. Your submitted files should be named:

```
iea37-yourname-opt#.yaml
iea37-yourname-log#.yaml
```

Where "`yourname`" is your personal or organizational name, all lowercase with no spaces or punctuation, `-opt#.yaml` describes the (x,y) coordinates for your optimal turbine layout, `-log#.yaml` contains information regarding your hardware and optimization algorithm's performance, and "`#`" is the case study number of the submission (i.e. "`-opt3.yaml`" contains optimized results for cs3).

As shown in the example log given in `iea37-ex-log3.yaml`, participants must report both: (1) number of total target function calls, and (2) AEP calculation at each chronological function call. This means participants must log the intermittent AEP calculations at **each** function call occurring during the optimization process, in order for us to study trends regarding time to convergence.

3.3 Evaluation

Evaluations for cs3 will be made using the wake model target function supplied in `iea37-aepcalc.py` and convergence data reported by each participant.

Because the participant wake models in cs4 are intended to differ, determining a "best" solution is generally not possible. Evaluations will be made using a cross-comparison approach. Every participant will evaluate every other participant's solutions using their own wake model(s). It is essential that the `.yaml` format is adhered to so that cross-comparisons are painless.

4 Enclosures

Files included with this document, needed for full participation in the case studies are:

- `iea37-10mw.yaml` - data for the reference turbine used in both cs3 and cs4
- `iea37-aepcalc.py` - target AEP calculator using a simplified Gaussian wake model
- `iea37-boundary-cs3.yaml` - the vertices for cs3's wind farm's boundary
- `iea37-boundary-cs4.yaml` - the vertices for cs4's wind farm's boundary
- `iea37-ex-log3.yaml` - example of optimization results, denoting timing and iteration analysis
- `iea37-ex-opt3.yaml` - baseline layout for cs3, template for your submitted optimal turbine layout
- `iea37-ex-opt4.yaml` - baseline layout for cs4
- `iea37-wakemodel.pdf` - description of the AEP algorithm used in cs3
- `iea37-windrose-cs3.yaml` - 60 bins, wind speeds given as Weibull distributions, for cs3 and cs4

References

[1] Bortolotti, P., Dykes, K., Merz, K., Sethuraman, L., and Zahle, F., "IEA Wind Task 37 on System Engineering in Wind Energy, WP2 - Reference Wind Turbines," Tech. rep., National Renewable Energy Laboratory (NREL), Golden, CO., May 2018.