Robust wind farm layout optimization using pseudo-gradients

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1 Wind energy systems

A wind energy system transforms wind into electrical power.

1.1 Wind turbines

Wind turbines (picture left) are the elementary wind energy systems. Important characteristics are its rated power, rotor diameter, and hub height. A high-level model consists of the power curve and the thrust curve, which map wind speed at hub height to power and force exerted on the wind (plot above right).

1.2 Wind farms

Wind farms are collections of wind turbines constrained to a specific site (picture left). The placement of turbines within a farm is its layout (drawing right). The layout influences the farm cost via the cabling and substructure cost, due to cable layout and depth & soil variations.

1.3 Wake losses

Wakes are regions of complexly perturbed wind behind turbine rotors (picture right). Computationally simple engineering wake models are used when calculating farm power output (simulation below right).

In a farm, wakes may reduce the wind speed at downstream turbines, causing lower power production, wake losses. Wake wind speed deficits for a given layout depend on the wind direction (plot above, corresponds to layout shown in Section 1.2).

2 Wind resources

A wind resource is the wind available at a wind farm site.

2.1 Wind direction & speed distributions

The minimal wind resource description required is a joint wind direction & speed distribution (plot left), there is a dependency between both components.

This joint is decomposed into the wind rose, the wind direction marginal (plot above right), and per-direction wind speed characteristics (plot right), for which Weibull distributions are often used.

2.2 Annual energy production of a wind farm

An essential quantity in the design of a wind farm is its annual energy production (AEP). The electrical energy produced by a farm for a given wind resource. Equivalent is the capacity factor, the ratio between the expected average power production and the farm's rated power. Also of interest is the power rose, the distribution over wind directions of relative wakeless power production (plot right).

2.3 Inter-year wind resource variation

We consider 35 yearly wind resources for a North Sea site from the Dutch meteorological institute’s "NMM atlas" (plot left: orange lower, blue average, and red upper wind roses for this set of distributions; plot right: corresponding power roses).

Note the substantial variation.

3 Wind farm layout optimization

3.1 Objectives

• AEP: Maximize for expected power production only (used in our study).
• LCoE: Minimize levelized cost of energy, the ratio between farm cost and power production (more realistic).

3.2 Constraints

Turbines in a farm must satisfy a distance constraint (drawing right, red circles) and site constraints (drawing right, red & blue lines).

3.3 Typical layout optimization algorithms

<table>
<thead>
<tr>
<th>type</th>
<th>gradient-based</th>
<th>steepest ascent</th>
<th>high-quality solutions</th>
<th>computationally expensive, can get stuck in local optima</th>
<th>heuristic (usually random search-based)</th>
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<tbody>
<tr>
<td>examples</td>
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<td>evolutionary, genetic, particle swarm</td>
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<td>flexible, does not use domain knowledge,</td>
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<td>low-quality solutions</td>
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Computational cost is crucial in robustness studies, so we developed a fast heuristic approach that uses domain knowledge and produces medium-quality solutions.

3.4 Pseudo-gradient-based optimization

For one wind direction (plot left), the power deficit of a downstream turbine due to an upstream one determines a vector. Average over all upstream turbines (plot right). Variant: vectors pushing upstream turbines 'back' (plot far right).

Taking the expectation over all directions (plot left) gives ‘pseudo-gradients’ usable in a local gradient ascent-type algorithm.

Applicable to all variants (plot right: ‘push down’; plot far right: ‘push back’).

We have created a layout optimization algorithm that each iteration:

• uses an adaptive step size,
• considers pseudo-gradients for each of the variants,
• greedily moves turbines according to the best one, and
• corrects constraint violations between steps by iteratively moving turbines to satisfying positions.

We obtain good convergence (plot above left, relative wake loss) and medium-quality layouts (drawing above right, turbine trajectories).

4 Inter-year variation robustness

A wind farm’s layout is usually optimized for one wind resource, the estimated average one over the farm lifetime. However, inter-year production stability is important for the financial attractiveness of a farm design. Making a farm robust against inter-year wind resource variation is therefore of practical interest.

4.1 Goals

• Quantify inter-year wind resource variation (done).
• Quantify inter-year AEP variation (done).
• Determine existence of robust farm layouts (partly done).
• Develop robust layout optimization algorithm (not yet done).

4.2 Setup

• Realistic test site.
• Realistic & extensive set of yearly wind resources.
• Create optimized layout for a degenerate wind resource (225°), the uniform wind resource, each wind resource in the set, their average, their lower & upper envelopes.

4.3 Results

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4.4 Conclusions

• Inter-year variation is substantial.
• Observed inter-year variation is larger than inter-layout differences.
• The set of layouts with undominated production profiles is relatively small.
• No real trade-off achieved yet between robustness and optimality.

4.5 Recommendations

• Create a more diverse set of layouts:
  • by varying the optimizer parameters,
  • by using different optimization algorithms.
• Try out ideas for robust optimization:
  • by each iteration using the maxmin solution over wind resources,
  • by following your suggestion.