Wind Power Plant Optimization
State-of-the-Art

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5th Wind Energy Science Workshop
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Outline

• ModSim Book

• Wind Plant Optimization - Background and Motivation

• Historical Developments in Wind Power Plant Optimization (2000 – 2015)
  • Manual Approaches
  • From AEP to LCOE

• Recent Trends (2015 – Present)
  • More advanced LCOE optimization
  • Multiple turbine types
  • Control strategies

• Current and Future Opportunities
  • High-fidelity / multi-fidelity
  • Optimization Under Uncertainty / Stochastic Optimization
  • Data-driven modeling
  • Site suitability and loads surrogates
  • The holy grail of reliability and O&M
  • Beyond LCOE & Hybrid power plants

• Collaboration Opportunities
  • IEA Wind Task 37

**Volume 1: Atmosphere and Plant**

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ModSim

• Systems Engineering and Optimization of Wind Turbines and Power Plants
  • Design-Based Optimization
  • Wind Turbine Design Optimization
    • Unique Challenges in Wind Turbine Optimization
    • Higher Fidelity Approaches and Unsteady Aeroelastic Modeling
    • Research and Industry Applications of Wind Turbine Optimization

• Wind Power Plant Design Optimization
  • Unique Challenges in Wind Power Plant Optimization
  • Higher Fidelity Approaches and Addressing Uncertainty
  • Research and Industry Applications of Wind Power Plant Optimization
Background and Historical Developments
Wind energy systems are complex and couple many sub-systems and components together, described by numerous physical phenomena and disciplines (from the atmosphere to the electrons).
Wind Plant Optimization

Background and Motivation

Plant designers addressed this complexity historically in various ways:

1. Skip optimization and rely on experience

2. Use optimization for basic design with emphasis on AEP (layout) and maybe some elements of LCOE (crude infrastructure models)

3. Develop strong dependence on optimization and include increasing levels of scope (more system elements) and fidelity (more accurate models)
   - Leveraging abundant computational resources and advanced multi-disciplinary design, analysis and optimization (MDAO) techniques
Historical Wind Plant Optimization

Manual Design Process

Energy Optimizers

1st Wind Energy Systems Engineering Workshop Presentation
https://www.nrel.gov/wind/assets/pdfs/se_workshop_oliver.pdf
Historical Wind Plant Optimization

Manual Design Process

Where the focus shouldn’t be

1st Wind Energy Systems Engineering Workshop Presentation
https://www.nrel.gov/wind/assets/pdfs/se_workshop_oliver.pdf
Historical Wind Plant Optimization

Manual Design Process

ENERGY OPTIMIZATION SOFTWARE: A bad idea in practice

- RES has developed various optimization software over the years
  - SIMPLEX ALGORITHM (>10 years ago)
  - GENETIC ALGORITHM (8 years ago)
  - SIMULATED ANNEALING (7 years ago)
  - SOFTWARE DISCONTINUED (2013)

- Why did we discontinue it?
  - Complex site constraints
    - Software could deal with this, but very time consuming entering all into software
    - Inevitably some ‘real world’ constraint missed (less value in the optimization)
      - Contractual: E.g. Landowner ‘A’ has stipulation of minimum MW
      - ALTA survey (late in dev. cycle) reveals pipelines, easements, microwaves, etc
      - Many times governed by noise constraints: Complex analysis in itself
  - Wake models and wind flow models don’t have required level of accuracy
    - See following slides: Can’t do an optimization if the inputs (models) aren’t correct
  - Many layouts end up ‘designing themselves’ and when they don’t ....
    - .... an experienced practitioner can get extremely close to the optimized solution

1st Wind Energy Systems Engineering Workshop Presentation
https://www.nrel.gov/wind/assets/pdfs/se_workshop_oliver.pdf
Historical Wind Plant Optimization (2000 – 2015)
From AEP to LCOE

- Slowly built trust in optimization with research and industry experience
- AEP optimization insufficient but cost models are cumbersome
- Compromise: simple models for major cost elements (electrical and road infrastructure)

<table>
<thead>
<tr>
<th>Objective Function</th>
<th>Net Energy [GW]</th>
<th>BOP Cost [$]</th>
<th>LCOE [$/MW]</th>
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<tbody>
<tr>
<td>AEP</td>
<td>1101 100%</td>
<td>51 100%</td>
<td>38.49 100%</td>
</tr>
<tr>
<td>COE</td>
<td>1096 99.6%</td>
<td>46 90.2%</td>
<td>38.3 99.5%</td>
</tr>
<tr>
<td>IRR</td>
<td>1094 99.4%</td>
<td>46 90.2%</td>
<td>38.38 99.7%</td>
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</table>
Recent, Current and Future Trends
Recent Wind Plant Optimization

More advanced LCOE optimization

• Optimization use in site design now widespread
• Emphasis shifts to more advanced modeling of LCOE components – and also addressing offshore sites

Example wind plant layout optimization workflow for an offshore reference wind plant (Source: Sanchez Perez-Moreno et al 2017)
Recent Wind Plant Optimization

Multiple Turbine Types

• Increasing trend towards modular turbine platforms with varied hub heights, rotor diameters and even power ratings


Recent Wind Plant Optimization

**Control strategies**

- As control paradigm shifts from turbine to plant, so do opportunities to consider plant control strategies in the upfront design process.

- **Baseline**: fixed (original) positions, turbines all yawed in mean wind direction.

- **Optimized yaw**: fixed (original) positions, turbines optimally yawed for each wind direction.

- **Optimized location**: position optimized, turbines all yawed in mean wind direction.

- **Combined optimization**: simultaneously optimized position and yaw for each wind direction.
Recent Wind Plant Optimization

Control strategies

- Considering wake steering strategies in the design process can increase AEP, reduce costs, or both

<table>
<thead>
<tr>
<th></th>
<th>Baseline</th>
<th>YawOpt</th>
<th>PosOpt</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean power (MW)</td>
<td>78.86</td>
<td>84.91</td>
<td>78.86</td>
<td>78.84</td>
</tr>
<tr>
<td>Area (km²)</td>
<td>14.53</td>
<td>14.53</td>
<td>12.45</td>
<td>8.96</td>
</tr>
<tr>
<td>Power density (W/m²)</td>
<td>5.43</td>
<td>5.84</td>
<td>6.33</td>
<td>8.80</td>
</tr>
<tr>
<td>AEP (GWh)</td>
<td>1040.3</td>
<td>1094</td>
<td>1055.8</td>
<td>1095</td>
</tr>
</tbody>
</table>

(+5.2%) (+1.5%) (+5.3%)

Final versus initial layout perimeter with higher power density

Current and Future Opportunities

*High / Multiple Fidelity Levels*

- Using higher fidelity models address more complex flow phenomena including influence of controls on flow, atmospheric stability, complex terrain, etc.

Full AEP Optimization (36 directions, 5 wind speeds)
Current and Future Opportunities

*Stochastic Optimization*

- Explicitly addressing uncertainty can lead to more robust plant design and operational / control strategies

Deterministic and OUU results for wake steering with uncertainty in the nacelle yaw sensor measurement

<table>
<thead>
<tr>
<th></th>
<th>Deterministic AEP</th>
<th>Expected AEP</th>
</tr>
</thead>
<tbody>
<tr>
<td>OUU Solution</td>
<td>173.7</td>
<td>168.2</td>
</tr>
<tr>
<td>Deterministic Solution</td>
<td>179.3</td>
<td>166.0</td>
</tr>
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</table>

Current and Future Opportunities

Data-driven modeling

• Using data from high-fidelity simulations or experimental data, we can improve accuracy of optimization models while preserving computational efficiency
Current and Future Opportunities

*Site suitability and loads surrogates*

- Using data and higher fidelity simulations to develop surrogates of loads to address site suitability concerns

Unpublished Topfarm results using IEA Wind Task 37 case study 19 turbine case.
Current and Future Opportunities

*The Holy grail of O&M and reliability*

- Long term assessment of reliability and associated costs includes high levels of uncertainty
- Leverage data-driven techniques and physics-based modeling together may hold the key
Current and Future Opportunities
Beyond LCOE & Hybrid Power Plants

• Shifting from fixed purchase price for renewable energy to participation in energy, capacity and service markets

Ahlstrom et al. 2017 IEEE Power & Energy Magazine

PJM market trends through 2017 (Source: PJM 2017)

Declining wind capacity credits (Source: MISO 2015)
Current and Future Opportunities

Beyond LCOE & Hybrid Power Plants

• Design wind power plants for shifting revenue streams
• Integrate solar and storage into hybrid power plant energy solutions
IEA Wind Task 37
IEA Wind Task 37

Overview

What model fidelity and disciplinary couplings must be captured in a design process? What is the best possible architecture of the design process?

IEA Wind Task 37

Overview

Project Objectives and Outcomes

• Improve quality of systems engineering by practitioners through development of best practices and benchmarking exercises
• Promote general knowledge and value demonstrations of systems engineering tools and methods applied to wind energy RD&D

Target audience

• wind turbine OEMs, developers, owner/operators, consultancies, and research community
IEA Wind Task 37

Case Studies

WP3.2 Plant MDAO case study

• **Phase 1**: participants provided with the same software workflow and asked to execute optimization for 3 different problems

• **Phase 2**: participants use their own software on high-simplified optimization problem and results compared to high-fidelity code
IEA Wind Task 37
Case Studies

WP3.2 Plant MDAO case study

• Main findings: Despite use of same exact model, part 1 of the case study still had a significant spread in results (which increased with increasing turbine number)

<table>
<thead>
<tr>
<th>sub#</th>
<th>Algorithm</th>
<th>Grad.</th>
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<tr>
<td>1</td>
<td>SNOPT</td>
<td>G</td>
</tr>
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<td>2</td>
<td>Preconditioned Sequential Quadratic Programming</td>
<td>G</td>
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<td>3</td>
<td>Full Pseudo-Gradient Approach</td>
<td>GF</td>
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<tr>
<td>4</td>
<td>SNOPT+WEC</td>
<td>G</td>
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<tr>
<td>5</td>
<td>fmincon</td>
<td>G</td>
</tr>
<tr>
<td>6</td>
<td>Simple Particle Swarm Optimization</td>
<td>GF</td>
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<td>7</td>
<td>Basic Genetic Algorithm</td>
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<td>Simple Pseudo-Gradient Approach</td>
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<tr>
<td>10</td>
<td>Multistart Interior-Point</td>
<td>G</td>
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IEA Wind Task 37

*Case Studies 3 and 4 – In Process*

Study: Realistic boundaries that gradient-based methods struggle with.

Case Study 3:
- Single region
- Non-uniform
- Concavities

Case Study 4:
- Multiple regions
- Discontinuities

https://github.com/byuflowlab/iea37-wflo-casestudies/tree/master/cs3-4
Summary and Outlook
Summary and Outlook

• We’ve come a long way!

• Still so much more to go... uncertainty, data, increased fidelity and scope, beyond LCOE and hybrids

• Join us in the journey!
  • IEA Wind Task 37 (contact me at kady@dtu.dk for info)
Thank you!

Past SE workshop materials can be found at:
https://www.nrel.gov/wind/systems-engineering-workshops.html

Other references:
https://www.nrel.gov/wind/systems-engineering-publications.html