Land-based Downwind Wind Turbine Optimization

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Downwind wind turbines may be advantageous at large scales because of the relaxed tower-strike constraint.
WISDEM: Wind-Plant Integrated System Design and Engineering Model

**Rotor**
- Rotor Perf
- Rotor Aero
- Section Aero

**Hub Struc**
- Rotor Struc
- Blade Struc
- Section Struc

**Nacelle**
- LSS/HSS
- Bearings
- Bedplate
- Yaw System

**Tower / Foundation**
- Tower Aero
- Tower Hydro

**Tower Struc**
- Jacket Struc
- Tower Soil

**Costs**
- O&M
- BOS
- TCC
- Finance

**Tower Hydro**
A coupled, multidisciplinary approach

<table>
<thead>
<tr>
<th>Discipline</th>
<th>Theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blade aerodynamics</td>
<td>Blade element momentum</td>
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<tr>
<td>Blade structures</td>
<td>Beam finite element, classical laminate theory</td>
</tr>
<tr>
<td>Tower aerodynamics</td>
<td>Power-wind profile, cylinder drag</td>
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<td>Tower structures</td>
<td>Beam finite element, Eurocode and GL</td>
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<tr>
<td>Nacelle</td>
<td>Physics-based component models, Univ. of Sunderland</td>
</tr>
<tr>
<td>Cost</td>
<td>mass-based TCC, new BOS</td>
</tr>
</tbody>
</table>
35 design variables

**Rotor**
- chord distribution
- twist distribution
- spar-cap thickness distribution
- aft panel thickness distribution
- blade precurve distribution
- tip-speed ratio in Region 2

**Nacelle**
- bedplate I-beam dimensions
- low speed shaft lengths

**Tower**
- tower diameters
- tower wall thicknesses
- tower waist location
- tower height
100+ constraints

- Natural Frequencies (resonance)
- Deflections (tower strike, ground strike, bedplate)
- Ultimate Stress/Strain (max wind and max thrust)
- Buckling (panel, shell, global)
- Fatigue Damage
- Max Tip-Speed
- Transportation
- Welding and Manufacturing
Several specific additions/modifications were made for this downwind study

- Converged aero/structural response
- Reductions in AEP due to blade curvature/deflection
- CurveFEM used to find natural frequencies of curved blades
OpenMDAO facilitates coupled gradients across 102 components
The dependence graph for the rotor contained the most complexity including nested solvers.
Analytic gradients allow for quicker and more robust convergence.

|  | Finite-difference | Analytic |
|----------------------------|--------------|
| Run time (hours)           | 5.43         | 1.11     |
Class I, 5-MW—negligible benefit for downwind designs

Blade mass savings was limited because survival wind speed was dominant constraint.
The cost savings for lighter blades were offset by a heavier tower
AEP was slightly lower for downwind designs
Class III, 5-MW—blade mass savings of around 30%
Class I, 7-MW—results were similar but tower design is limiting factor
Highly downwind precurved bladed did not appear to be advantageous

<table>
<thead>
<tr>
<th></th>
<th>Straight blade</th>
<th>Curved blade</th>
</tr>
</thead>
<tbody>
<tr>
<td>max strain at rated</td>
<td>1,336</td>
<td>841</td>
</tr>
<tr>
<td>(microstrain)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>max strain at survival</td>
<td>3,001</td>
<td>2,872</td>
</tr>
<tr>
<td>(microstrain)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1st flap freq (Hz)</td>
<td>0.961</td>
<td>0.848</td>
</tr>
<tr>
<td>1st edge freq (Hz)</td>
<td>1.15</td>
<td>1.08</td>
</tr>
<tr>
<td>AEP (MWh)</td>
<td>19,560</td>
<td>18,802</td>
</tr>
</tbody>
</table>
Conclusions

• Downwind rotors allowed for blade mass reductions of around 10-30%.

• Downwind configurations were potentially advantageous for sites with lower wind speeds, and for turbines with higher power ratings.

• For very large turbines, efficient tower design is critical.

• Optimal precurved blades were curved upwind.