IEA Task 40. U.S. progress in downwind turbine R&D

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WP2.1: 10-MW Rotor Optimization

In Collaboration with Hitachi

Pietro Bortolotti, Chris Ivanov, Nick Johnson
Objectives

• Goal: Demonstrate Optimization Process for Downwind Rotor: Innovative 10-MW rotor design NREL-HITACHI
• Completed: March 2020
Wind turbine design framework WISDEM:

- Turbine and plant design
- Land-based and offshore design and cost models
- Implemented within the python-based framework OpenMDAO
- Fully opensource, available at [https://github.com/WISDEM](https://github.com/WISDEM)
- Historically comprised of low fidelity models, with ongoing work to add multi-fidelity capabilities
Optimization of Rotor of 10MW Downwind

**Redesign** of the **rotor** of the **10MW** offshore platform

- Blade mass reduced by 19%
- Blade cost reduced by 27%
- LCOE reduced by 1.3%
Comparison Upwind vs Downwind

NREL and Hitachi are submitting a journal paper in a few weeks

- Under loading, the downwind rotor generates a smaller swept area than an optimized upwind rotor
- The downwind design generates
  - Annual energy production $-1.2\%$
  - Capital costs $-1.7\%$
  - Levelized cost of energy $+0.9\%$
Sensitivity Studies

A first study looked at the impact of **rotor flexibility** on LCOE

- In upwind, increasing rotor flexibility lowers LCOE by decreasing rotor costs preserving AEP
- In downwind, the decrease in costs does not balance the loss in AEP
A second study looked at the impact of the center of gravity of the rotor nacelle assembly on tower and monopile mass.

The lower thrust of downwind generates mass savings only if the RNA COG is less than 1.5 m away from the tower axis.
A third study varied cone and tilt, no LCOE reduction could be identified.

A fourth study looked at the impact of passive yawing on LCOE. Reducing yaw mechanisms costs by 50% only reduces LCOE by 0.17%.
Opportunities of Downwind

The paper lists **four promising research areas** for downwind

1. Downwind optimized controller and distributed aerodynamic control devices
2. High tilt angles for wind park power maximization (maybe combined with negative cone angles?)
3. Simulations with higher fidelity aerodynamic solver, such as the NREL tools OLAF and SOWFA
4. Design of floating substructure, see X1Wind presentation
Conclusions

1. NREL is very active in the field of design optimization of wind turbines
2. A flexible design was found for Hitachi generating blade mass savings of 19.2% and LCOE savings of 1.3% compared to the baseline configuration
3. A comparison between upwind and downwind optimized designs showed blade mass savings of 4% for the downwind configuration, but lower AEP and higher LCOE
4. Four promising opportunities for downwind are highlighted
5. Journal paper is under submission
WP2.2: LCOE Updates

In Collaboration with Hitachi
LCOE Analysis Status – WP2

- Conduct LCOE estimate for a theoretical offshore commercial scale 10 MW Optimized Downwind Rotor (Completed)
- Assess load alignment in addition to tilt and wake dynamics to evaluate scalability benefits for downwind turbines and their impact on LCOE (Completed)
- The 2 MW baseline from WP1 will be compared to the 10 MW from this WP to illustrate scalability and impact on LCOE (Ongoing)
- LCOE of 2-MW & 5-MW Sample Wind Plants
  - 5MW from BAR project
- Assess load alignment and tilt-induced wake dynamics impact on LCOE
  - Assessment from SUMR
LCOE Roadmap

Baseline LCOE

• Assess LCOE for 2 MW & 5 MW theoretical commercial scale wind plant

10 MW LCOE

• Estimate LCOE for 10 MW theoretical commercial scale wind plant

Model Verification

• Compare modeling results with X1 Wind’s LCOE analysis
• Apply adjustments to modeling efforts based on verification exercise

Final LCOE metric used to assess 10 MW downwind rotor configuration and associated innovations

$$LCOE = \frac{(CapEx \times FCR) + OpEx}{AEPnet}$$
Big Adaptive Rotor (BAR) Status

Nick Johnson, Pietro Bortolotti, Scott Carron
What is BAR?

• Big Adaptive Rotor (BAR) is a 3-5 year research program that is analyzing 5MW land-based wind turbines
  – 100 m blades
  – 140 m hub height
  – IEC III A
  – Very flexible, transportable blade
  – Downwind rotors can be designed larger than upwind
## Rail Transport of Blades on U.S. Rail Lines

### Motivation:
The rotor-growth trend is currently constrained by blade transport logistics and costs.

### Solution:
The “R&D pathways for supersized wind turbine blades” by DNV-GL, 2019, identified controlled blade bending, as promising pathways for LCOE reductions.

<table>
<thead>
<tr>
<th>Route Type</th>
<th>Lateral curves (LC)</th>
<th>Vertical curves (VC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main routes Interior</td>
<td>8 deg</td>
<td></td>
</tr>
<tr>
<td>Secondary routes Interior</td>
<td>13 deg</td>
<td>2000 ft</td>
</tr>
<tr>
<td>Main routes other regions</td>
<td>13 deg</td>
<td>2000 ft</td>
</tr>
<tr>
<td>All lines</td>
<td>23 deg</td>
<td></td>
</tr>
</tbody>
</table>

*Sources: AWEA Trumower, National Renewable Energy Laboratory (NREL)*
- Rail transport module added to WISDEM to explore rail transportable blade designs.
- The new optimization module adjusts the blade root angle and the distributed load required to keep the blade within the rail clearance envelope while maximizing blade strains to just below allowable.
- Lateral and vertical wheel-rail contact forces due to blade bending are calculated by integrating the optimized distributed load along the blade span and checked against L/V.
- An optimized rail transportable, 100m, single-piece blade is developed, named BAR01 (highly flexible baseline blade).
A rail-transport module was implemented in WISDEM to enable design for rail transportable blades:

- Model flat cars and horizontal and vertical clearance envelopes
- Bend the blade to fit within the clearance envelope
- Verify that blade strains are within maximum allowable
- Check the flatcars do not tip over

Innovative approach to blade design by considering transportation constraints up front
Rail Transport Module in WISDEM

Fully integrated into WISDEM
- Paper submitted to TORQUE 2020
- TE points upwards, no prebend
- Up to 5 deg LC, 100m blades can be transported straight
- BAR00 flips the flat cars with 7 deg LC
- BAR01 and BAR02 designed to be rail-transportable up to 13 deg LC
- Optimizer finds viable solutions with 8-axle flat cars and counter-weights
Edge-wise blade bending strains do not exceed 3,500 ue in sag and summit vertical curves up to a 2000ft radius (~2.9 degrees).

Edge-wise blade bending forces do not indicate wheel lift or track damage in sag and summit vertical curves up to a 2000ft radius (~2.9 degrees).

Flap-wise blade bending strains do not exceed 3,500 ue in horizontal curves up to 13-degrees.

Flap-wise blade bending forces do not indicate wheel-rail derailment in horizontal curves up to 11-degrees with counterweights and 4-axle flatcars, and up to 13-degrees with counterweights and 8-axle flatcars.
WISDEM has enabled the design of an ultra-flexible, slender downwind rotor blade for the BAR project

BAR01 and BAR02 are flexible slender downwind rotors

We are now investigating their aeroelastic behavior in OpenFAST and conducting a detailed LCOE analysis

The turbine controller is the key. It is becoming a co-design study

<table>
<thead>
<tr>
<th></th>
<th>BAR01</th>
<th>BAR02</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orientation</td>
<td>Downwind</td>
<td>Downwind</td>
</tr>
<tr>
<td>Rail transport</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Mass [tons]</td>
<td>51.3</td>
<td>40.8</td>
</tr>
<tr>
<td>TSR reg II</td>
<td>11.5</td>
<td>11.5</td>
</tr>
<tr>
<td>Material spars</td>
<td>GFRP</td>
<td>CFRP</td>
</tr>
<tr>
<td>Pre-bend at tip</td>
<td>0 m</td>
<td>0 m</td>
</tr>
</tbody>
</table>
Aeroservoelastic Analysis

BAR01 and BAR02 push the boundaries in terms of blade slenderness and flexibility

• Necessarily downwind
• Highest blade deflections towards the tower during
  – DLC 1.x (power production) and 5.1 (e-stops) at high winds
  – DLC 1.4 (coherent gust with extreme change of direction) at low winds

Work with the Reference Open-Source Controller (github.com/NREL/ROSCO)
Downwind Controller

Shutdown maneuver during DLC 1.4:

• Below rated wind speed, stops are performed by pitching to stall (P2S)
• During P2S, blades are pushed away from the tower (positive deflections) without incurring into excessive flapwise blade root moments
• Pitch to feather (P2F) is still used at and above rated wind speed
Deflection Ranking
BAR01

Lower cut-out wind speed to reduce cone and tilt:
- We could derate power instead of shutting down above 19 m/s
- We could boost power above rated

Maximum deflection towards the tower for 2 deg cone and 4 deg tilt
Blade Cost Comparison

Blade cost model described in https://www.nrel.gov/docs/fy19osti/73585.pdf
Varying costs between 390 and 450 k$
Work-in-progress to optimize a design (BAR20) with heavy-tow CFRP (BAR-WP5)
Power Performance – Power Coefficient

- In downwind rotors, deflections reduce swept area and penalize power production
- CFRP helps adopting thinner and more efficient profiles, recovering power production

\[
C_p = \eta_{\text{gen}}\eta_{\text{drive train}} \frac{P_{\text{generator}}}{\frac{1}{2} \rho \pi (BL + HR)^2 V^3}
\]

- $BL$: blade length
- $HR$: hub radius
- $\eta$: efficiency
Low rated wind speed* limits the losses in AEP, computed from 6 turbulent seeds of DLC 1.1

<table>
<thead>
<tr>
<th></th>
<th>AEP [GWh]</th>
<th>Diff to BAR00 [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>BAR00</td>
<td>22.60</td>
<td>-</td>
</tr>
<tr>
<td>BAR01</td>
<td>22.56</td>
<td>−0.2</td>
</tr>
<tr>
<td>BAR02</td>
<td>23.82</td>
<td>+5.4</td>
</tr>
</tbody>
</table>

* and some inconsistencies in the tuning of the ROSCO controller
Conclusions

- Single-piece blade deployment lengths within the U.S. Interior Region can be increased from roughly 75m to 100m using low-cost rail infrastructure by switching from rigid blade transport to controlled blade flexing.
- Conversely, single-piece blade deployment length increases of roughly 33% could be realized throughout the US rail infrastructure using controlled blade flexing.
- The flexible, rail transportable, 100m BAR01 blade increase operational tip deflections by roughly 40% indicating transportation costs may drive downwind rotor technologies as blades get longer.
- BAR01 first iteration design completed and is a feasible solution for transportation and operation.
Ongoing Work and Proposed Next Steps Through Phase I

1. Complete design of downwind blade
   - Finalize rotor design with OpenFAST in the loop
   - Complete optimization w/ fatigue and buckling analysis in NuMAD
   - Run BeamDyn and/or vortex module for critical deflection cases
   - Complete LCOE comparison, including BOS analysis
   - Link work on distributed aerodynamic control (BAR10) as necessary
     • Determine design driving cases (e.g., ultimate/fatigue)
   - Complete flutter analysis
   - Detailed stability analysis (Campbell and damping plots)
   - Test blade-resolved CFD (Nalu-wind) for P2S shutdown

2. Consider fatigue during transportation
3. LCOE comparison to baseline
4. Develop catalog of open scientific / engineering challenges
5. Recommendations for Phase II
Thank you.