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Wind Turbine Blade Reference Model for the U.S. Low Wind Resource Regions

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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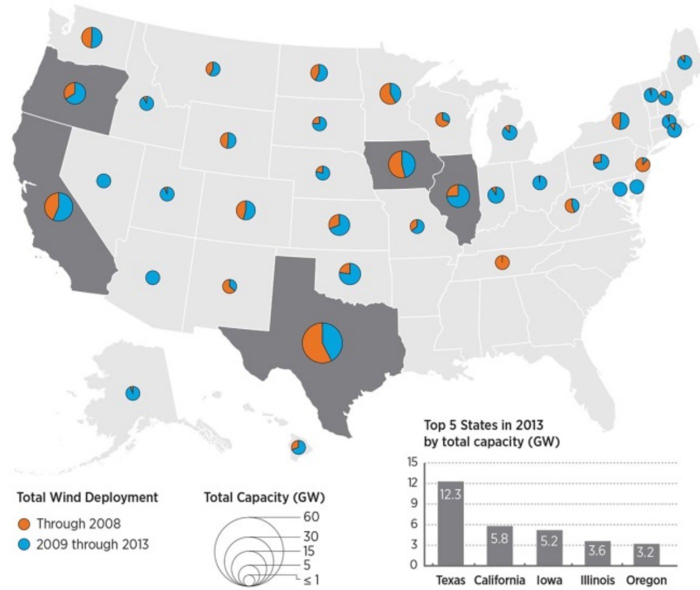
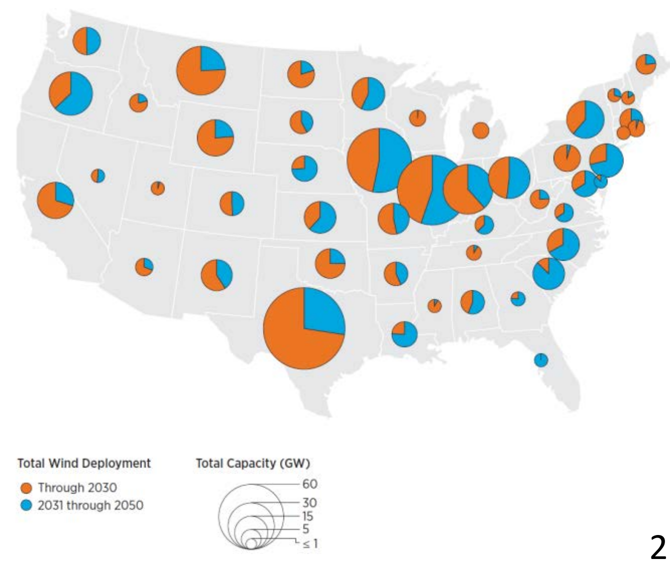
Wind energy sites are expanding

- The Department of Energy’s Wind Vision report explores scenarios where wind contributes to 35% of the U.S. energy demand by 2050
- The projections include wind energy installations in the low wind-resource southeast which are currently absent
- Significant wind energy generation is projected in the Midwest states, where many of the better wind resource sites have been utilized
- There is a need for improved technologies and designs targeted at energy capture in low wind conditions





Wind resource is too low for historical designs in parts of the U.S.

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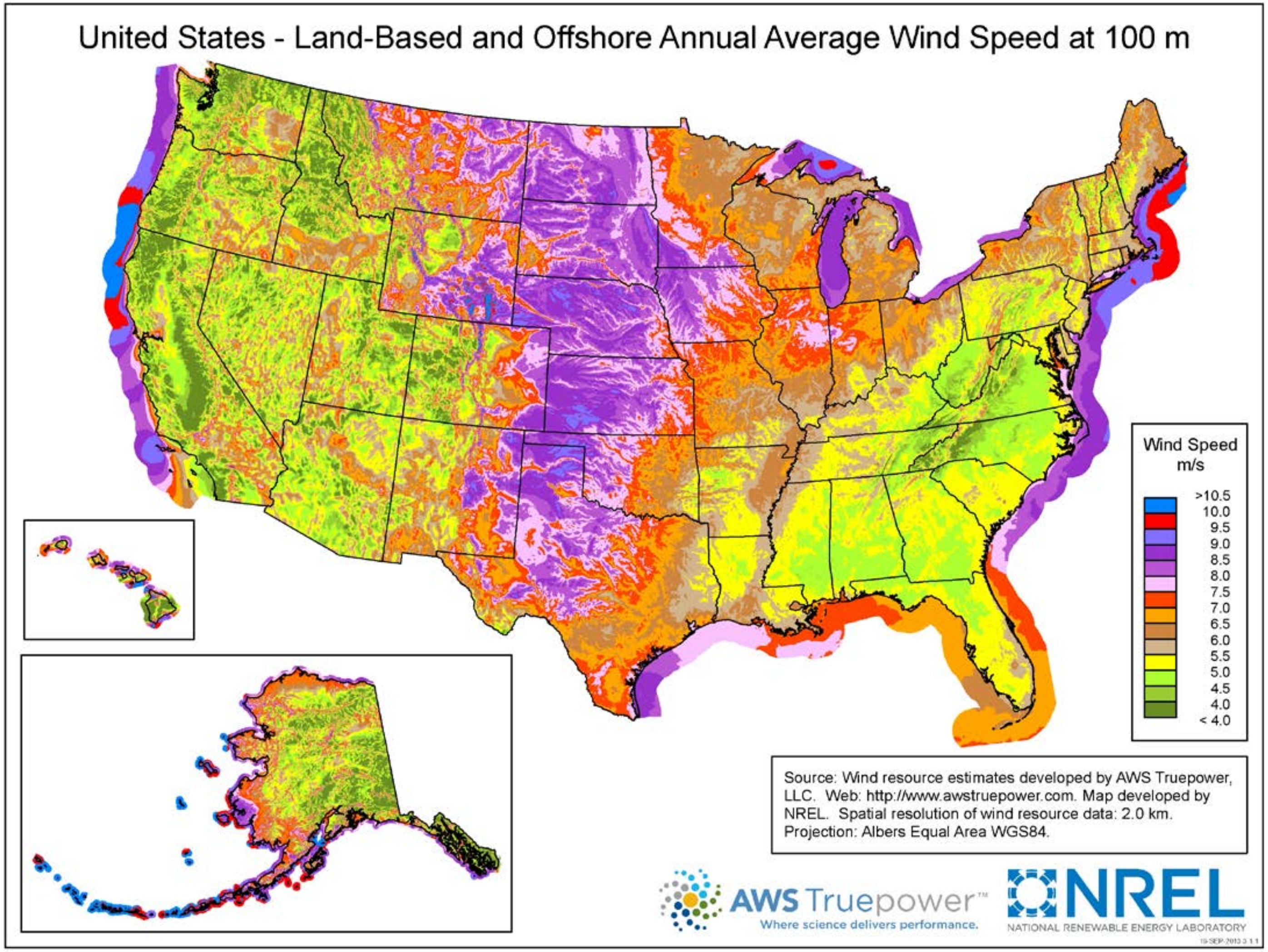
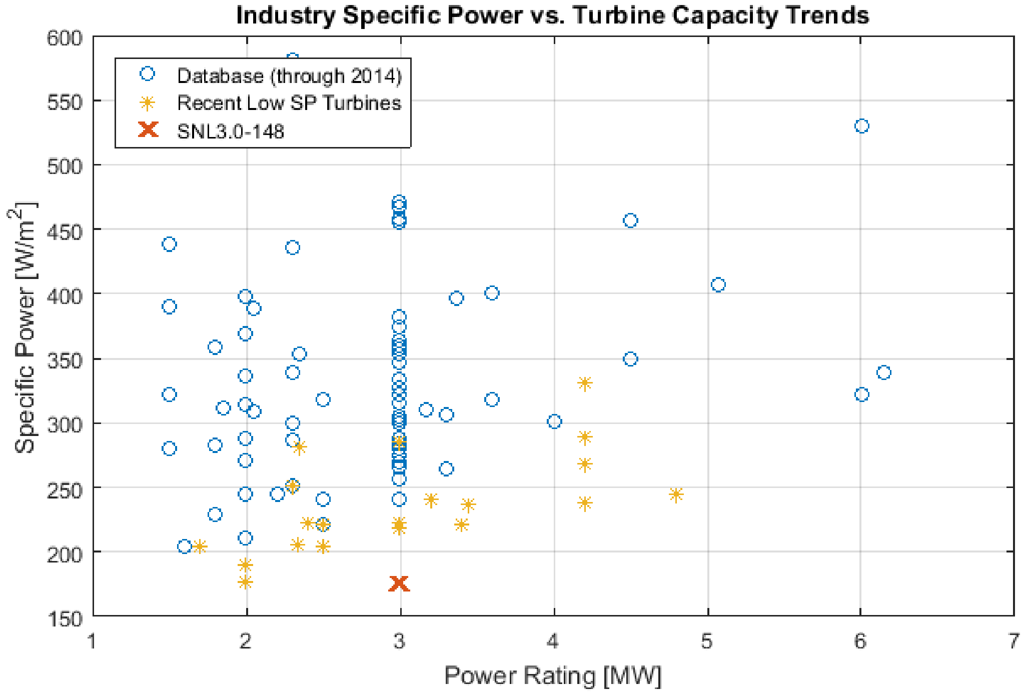


Midwest sites may have average wind speeds as low as 5.5-6.5 m/s

Interior southeast sites may have average wind speeds as low as 4.5-5.5 m/s

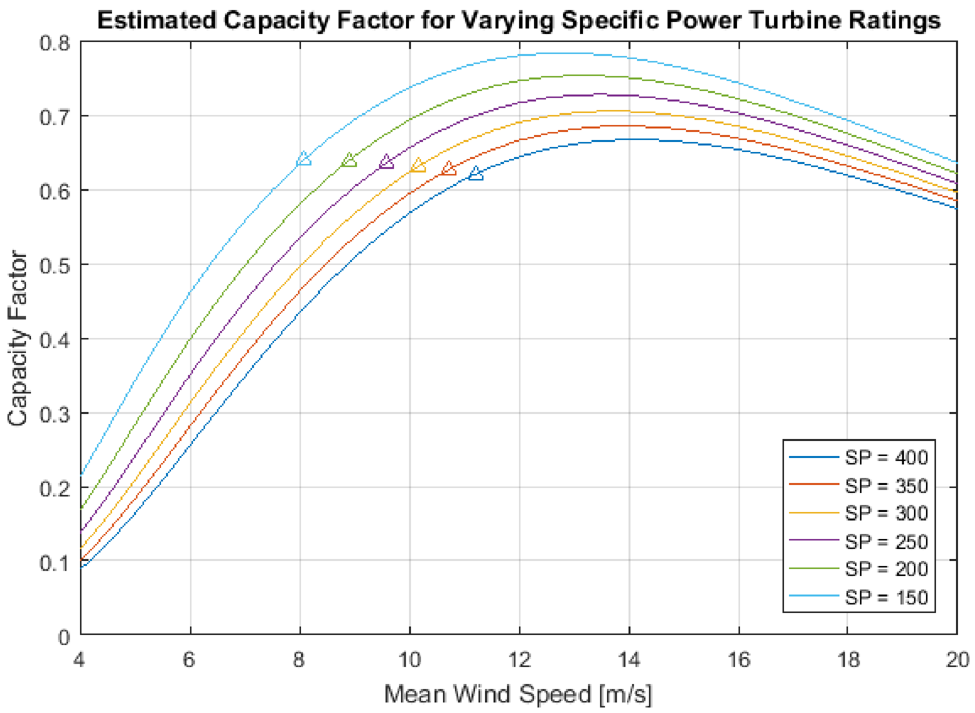
Industry trends for low wind sites

- The industry trend has been towards longer blades and lower specific power ratings for land-based wind turbines
- Vestas and GE both offer 2 MW turbines with specific power ratings below 200 W/m^2
- A blade reference model is needed to study the unique challenges for designing cost-effective low specific power wind turbines



Specific power and energy capture

- Wind turbine capacity factor is inherently higher for low specific power designs due to:
  - Increased energy capture at the same wind speed
  - Reduction in the turbine's rated wind speed
- At 6 m/s, the energy production is over 80% higher for a specific power design of 150 versus 400 W/m^2
- Can increase the energy capture while maintaining constant system loads



Effect on the cost of energy

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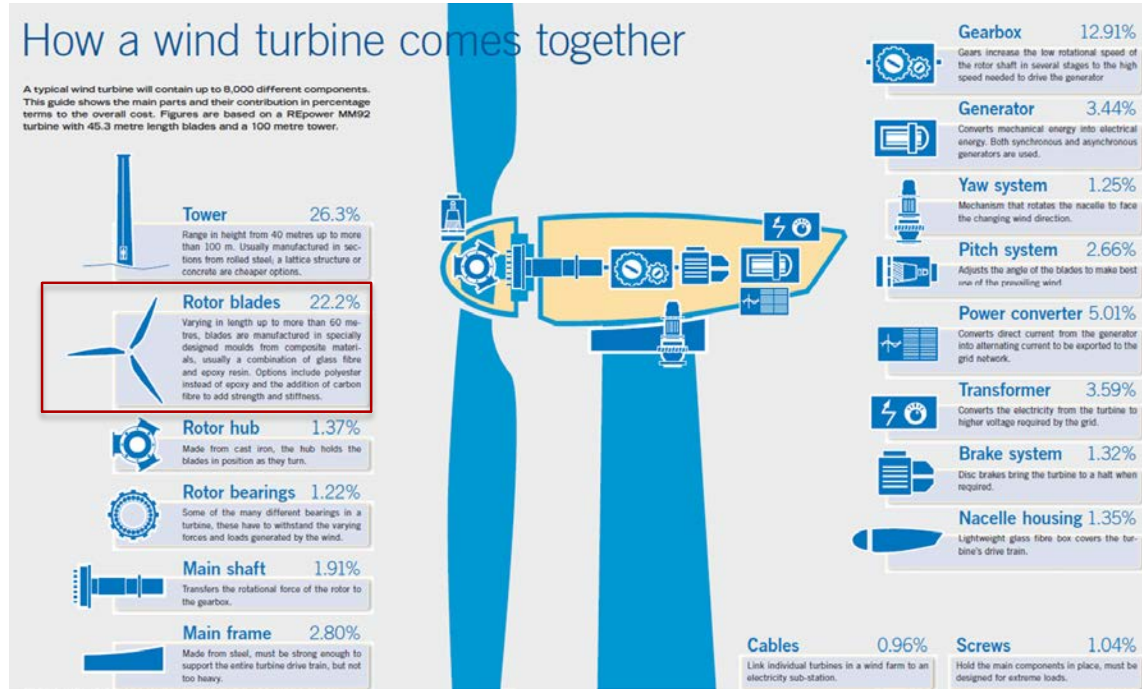
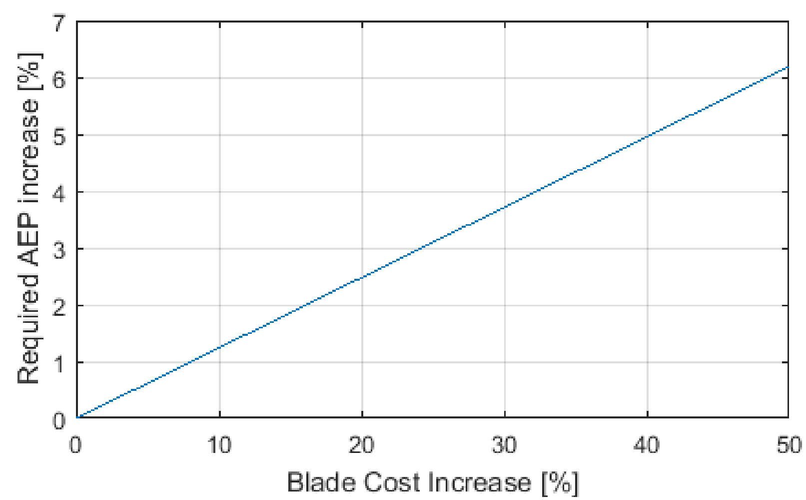
- Design decisions are not based on power or efficiency, but on cost of energy
- Blades contribute to 20-25% of the total turbine capital cost
  - A 25% increase in the blade cost only increases the turbine cost by ~5-6%
  - Assuming turbine capital costs are 55% of total costs, a 25% increase in blade cost is justified by a 3% increase in AEP to maintain LCOE



*Source: EWEA



SNL3.0-148 Reference Blade Model

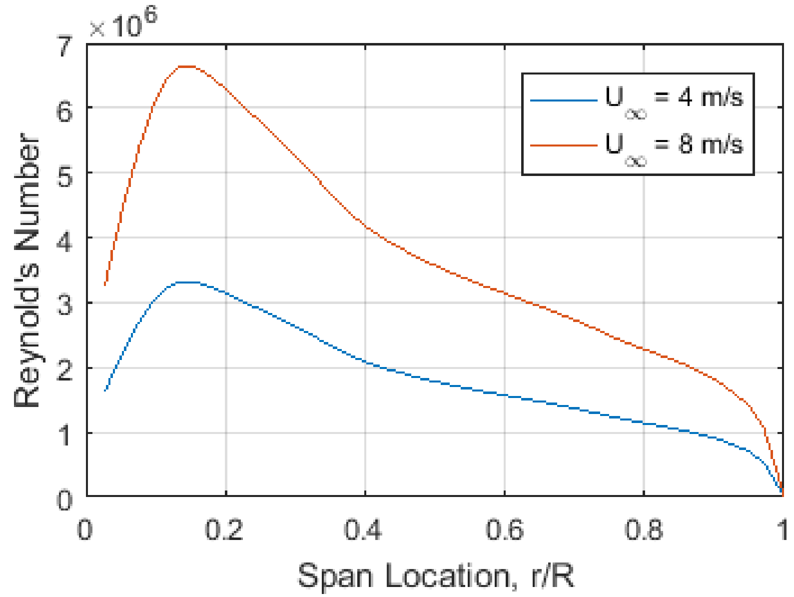
Publicly available reference model that is representative of the industry shift towards low specific power wind turbines for land-based sites. Can be used to identify and address the unique challenges faced for these machines, such as materials, controls, and aeroelastic coupling and tailoring.

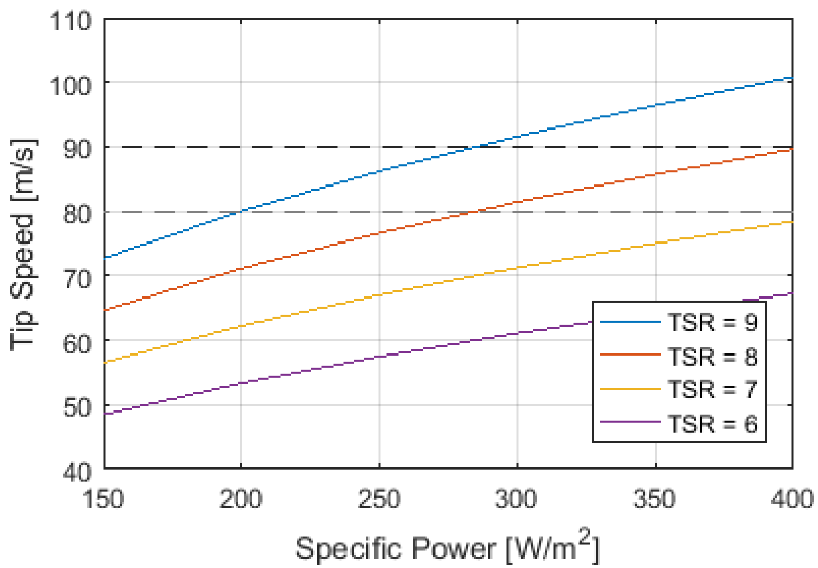
- 3 MW power rating
- 148m turbine diameter
- 72m blade length
- 175 W/m^2 specific power
- Three blade, upwind
- TSR = 9

- Lightly loaded tip
  - Matches the root bending moment of the “optimal” induction design (a=1/3) while increasing energy capture through a longer blade
- Tower and turbine reference models from IEA Task 37 will be used with the blade model

Interesting features of low Specific Power Turbines

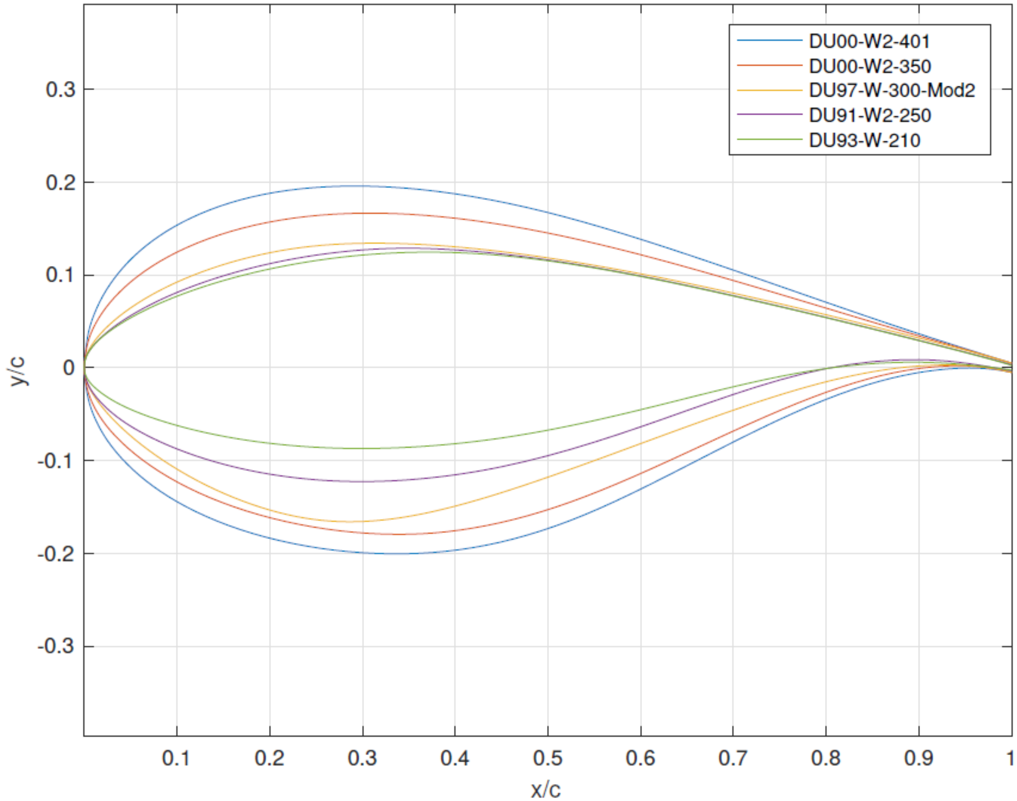
- High Reynold’s number
  - Thicker airfoils can be used outboard to increase structural efficiency
  - Improved airfoil performance
- No Region 2.5
  - The entire region below rated power can be operated at the design point, Region 2
  - Can operate at a lower design efficiency (a < 1/3) with an equivalent operational efficiency
- Reduced tip speed / noise





Airfoil selection and placement

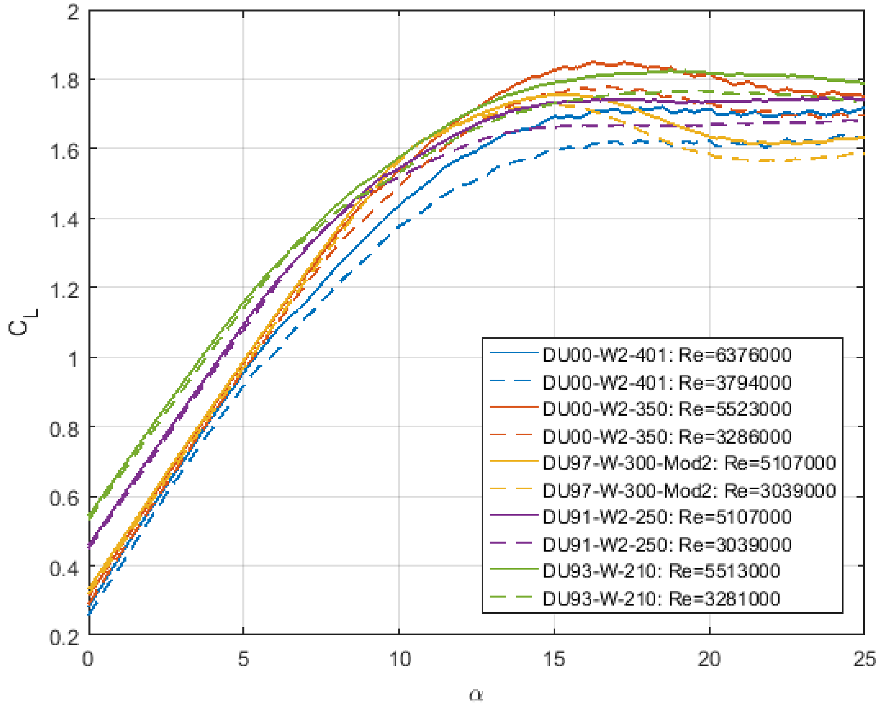
Airfoil Name	Percent Thick	Blade Span (r/R)
Circle	100%	0.00
DU00-W2-401	40%	0.12
DU00-W2-350	35%	0.23
DU97-W-300-Mod2	30%	0.40
DU91-W2-250	25%	0.74
DU93-W-210	21%	0.96

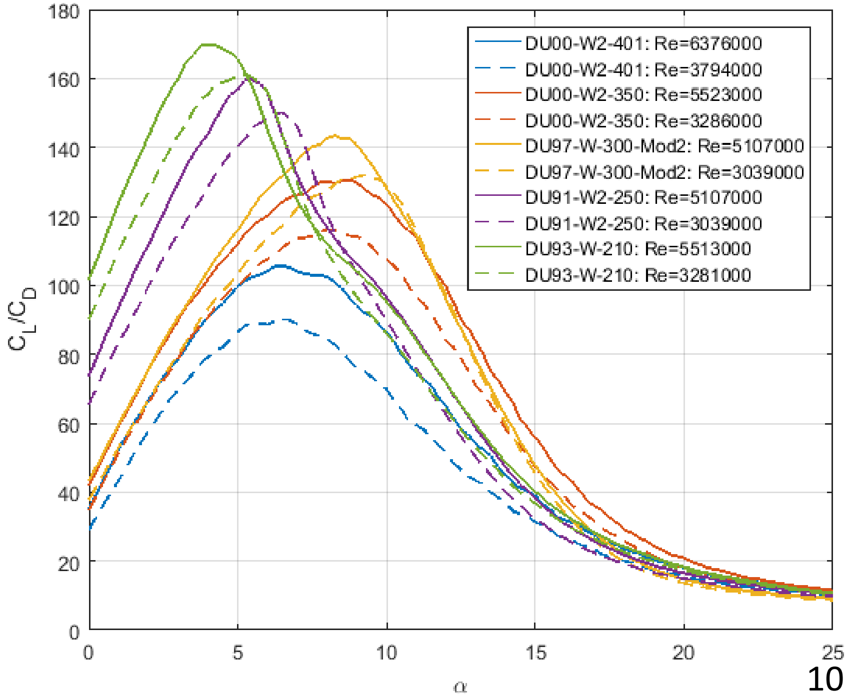


- DU-series airfoils were selected with similar shapes chosen that enable smooth transitions and lofting along the blade
- However, many of these airfoils were designed for stall-regulated machines and weren't designed to be an "airfoil family"

Simulated airfoil polars

- The absence of high Reynold's number experimental data forces the use of simulated airfoil polars in the design
  - There is a need for high Reynold's number designed and tested airfoils
- Design point chosen to operate at max lift to drag ratio
  - Produces an aerodynamically efficient blade, but a slender blade – may not be optimal from a cost of energy viewpoint





Low-induction rotor design

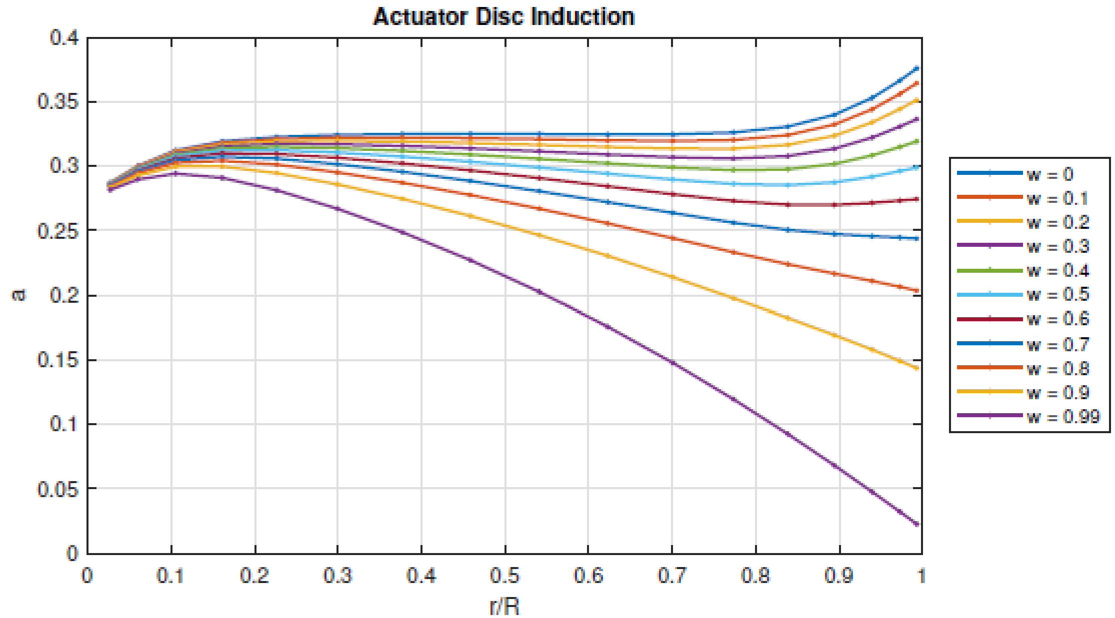
Optimization Parameters

$$\underset{a(r/R)}{\text{maximize}} \quad w\frac{AEP}{AEP_0} + (1-w)\frac{C_P}{C_{P_0}}$$

subject to
$$M_{\text{rated}} = M_{0_{\text{rated}}}$$
$$P_{\text{rated}} = P_{0_{\text{rated}}}$$
$$0 < a < 0.5$$
$$\lambda = 9$$
$$B = 3$$
$$\frac{L}{D} = 120, \quad \frac{r}{R} > 00.9$$
$$\frac{L}{D} = 160\frac{r}{R}, \quad \frac{r}{R} \leq 00.9$$

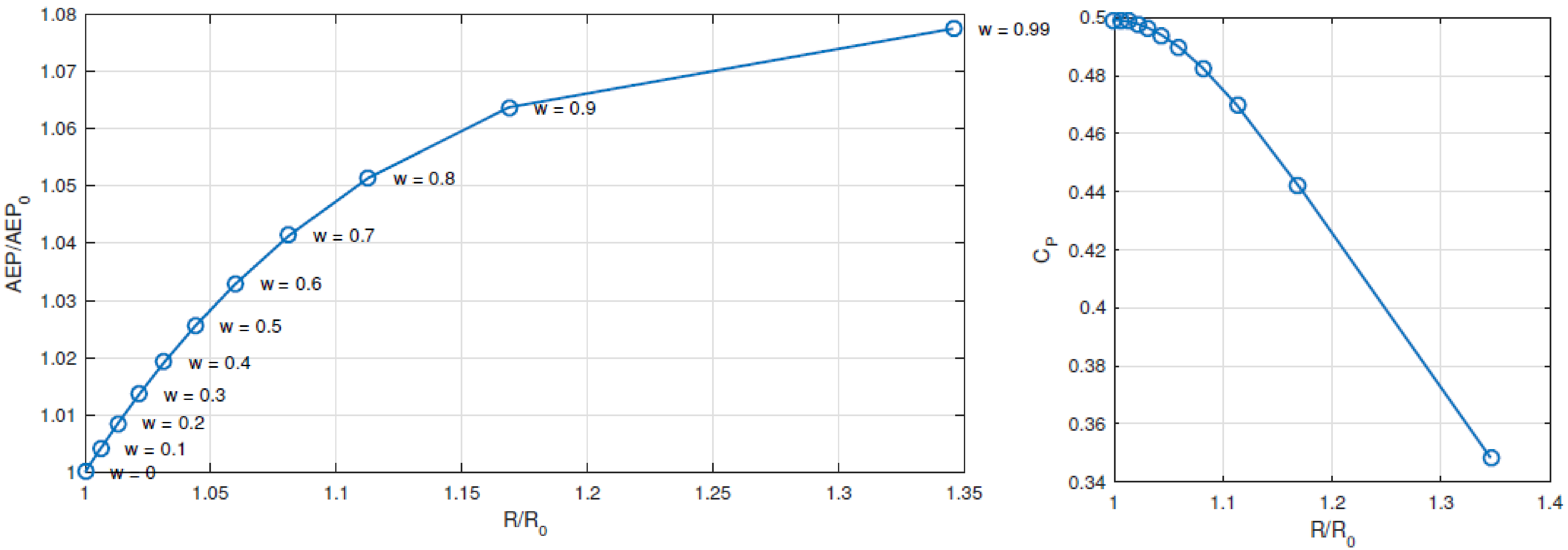
IEC Class III, Rayleigh Distribution, $U_{\text{mean}} = 7.5\text{m/s}$

Only Region 2 and 3, constant C_P until rated



*Christopher L. Kelley, presentation at WESC 2017

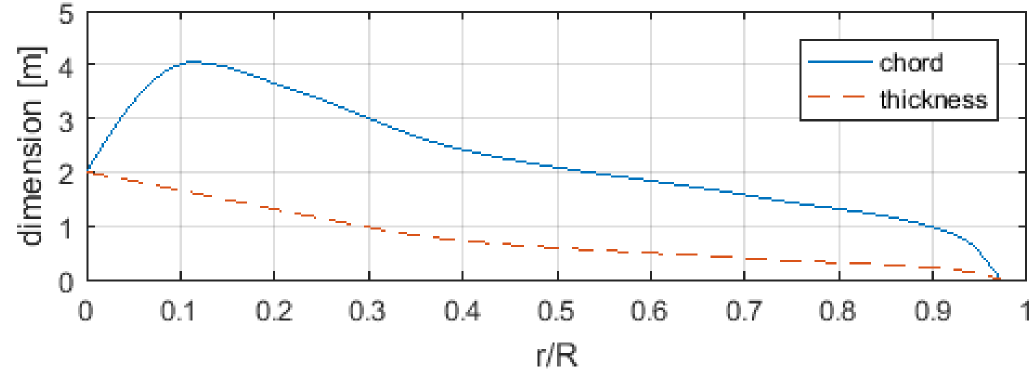
Low-induction rotor design

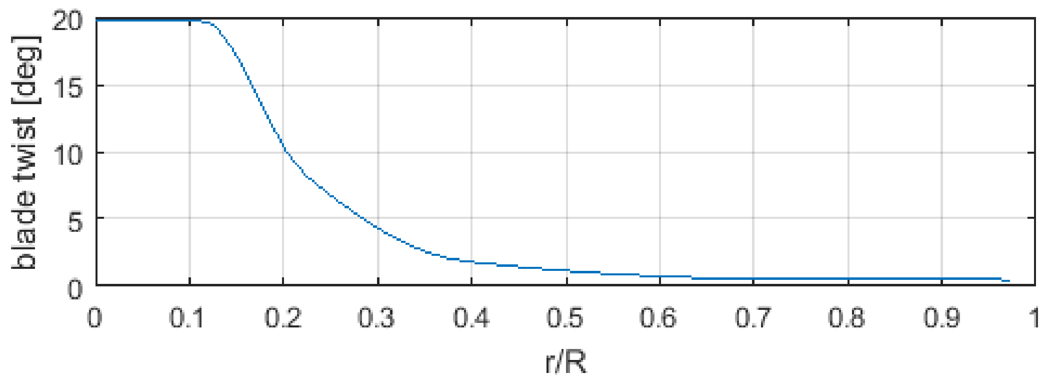


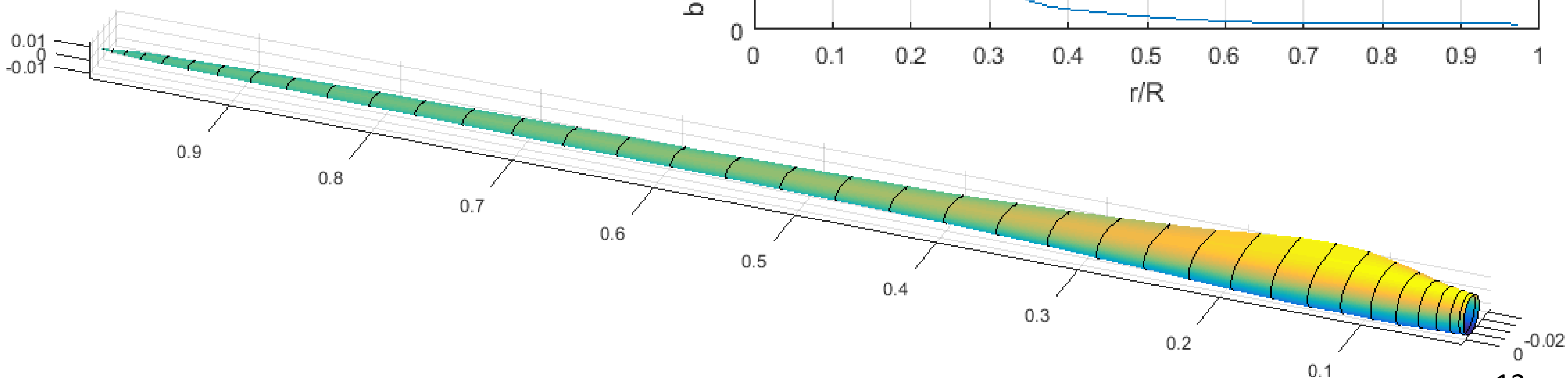
- Weighting factor of 0.8 (80% weight to AEP, 20% weight to Cp) was chosen for the SNL3.0-148 model as a good trade-off between energy capture and blade length
  - Compared with an optimally designed blade (a=1/3), it has an 11% increase in rotor radius and a 5% increase in annual energy production (AEP)

Initial blade design properties

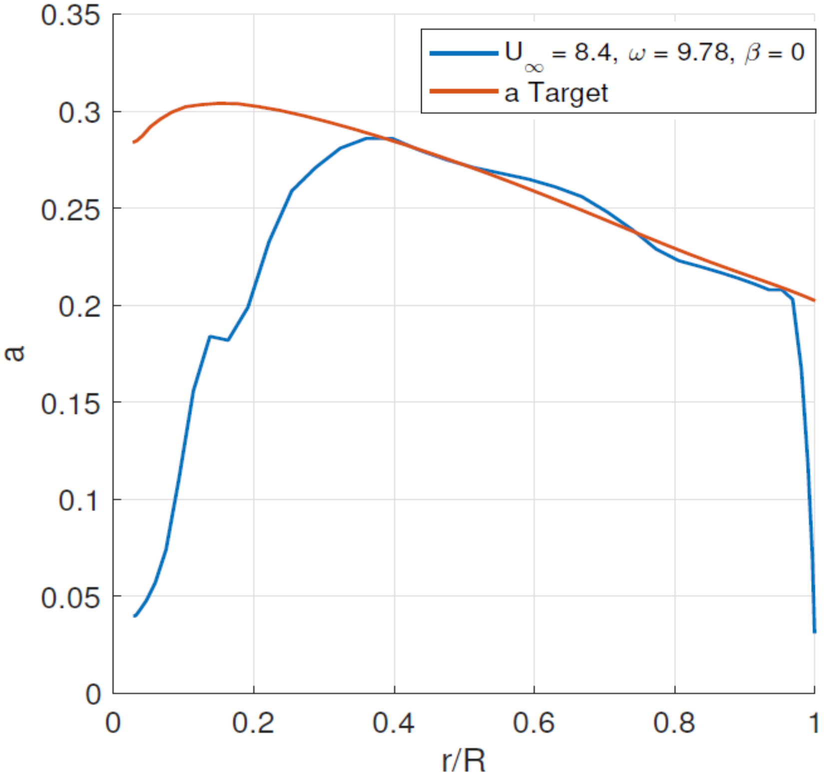
- Realistic chord and twist profiles were designed that produce the induction profile, with limitations included for manufacturability and transportation
- Blade solidity = 2.85%

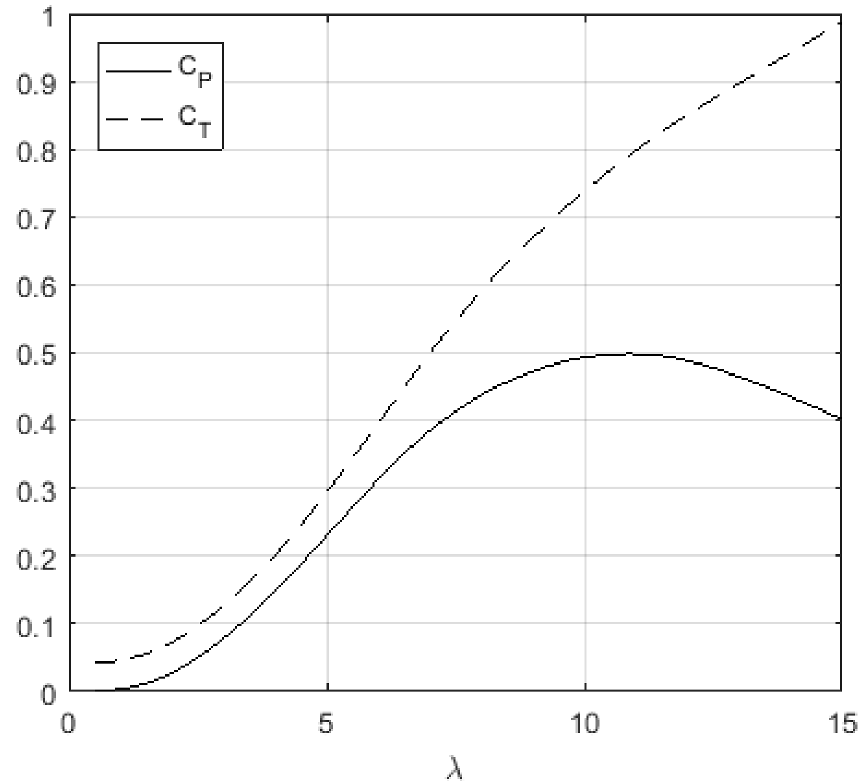






Initial blade design properties





- Initial aerodynamic design matches the desired induction profile from 40% span outboard, and is limited inboard due to the restrictive chord and twist limitations
- At the design point: Cp = 0.47, Ct = 0.67

Next steps

- Iterative process to produce the final aerodynamic and structural design (SNL3.0-148.s0)
  - All-fiberglass design
  - IEC III-A
- Blade models will be released publicly for use by the broader research community
- Aerodynamic design will be utilized to assess the usefulness of different carbon fiber materials in the spar cap from a blade cost analysis
  - Part of the DOE-funded SNL/ORNL/MSU optimized carbon fiber project