Effects of Increasing Tip Speed on Wind Turbine Rotor Design

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Background

- Modern land-based wind turbine rotors operate up to tip velocities of 75 to 80 m/s—limited by noise constraints.
- System benefits of high speed rotors have been the subject of discussion over many years.

  Rotor torque decreases as tip speed increases and rotor size and power rating are held constant.
  A reduction in rotor torque translates into a gearbox that is lighter weight and less expensive.
  The less expensive gearbox yields a decrease in the turbine cost and ultimately an improvement in the ability for the turbine to deliver cost competitive electricity.
  However, resulting changes in loads on the rotor, as well as the rest of the turbine system, can have a strong effect on the sizing and cost of other components in the system.
  The magnitude of these costs and benefits were not well quantified.

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The full problem of wind turbine system optimization is complex. Singular focus on investigation of tip speed was helpful in that it

1. demonstrated of a preliminary rotor optimization framework on a relatively simple multidisciplinary design problem and
2. provided a preliminary quantitative assessment of tip speed increase effects to help prioritize research investments.

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Scope Constraints I

The following were outside the scope of work for the current study. However, each is an important area for follow-on investigations:

- **Rotor size.** Tip speed increases on commercial turbines are driven by the need for larger swept area while allowing only minimal changes to the rest of the turbine system.
- **Turbine wind speed class.** The Turbine class for these designs is IEC I-B. Investigations at lower turbine classes could exhibit different results.
- **Blade materials.** Comparison studies on the use of carbon fiber or glass fiber in the construction of the blades was not included in this work.
- **Innovative airfoils.** Innovative airfoils, i.e. flatback airfoils, were not included as design options in this work.

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Scope Constraints II

- **Aeroelastic tailoring.** Aeroelastic tailoring, i.e. bend-twist coupling, is a rotor design feature that enables larger swept area with minimal cost to the system in terms of increased rotor loads.
- **Two-bladed rotor.** Individual blade thickness, and therefore structural efficiency, is higher for a two-bladed rotor than a three-bladed rotor with equal solidity.
- **Controls.** The investigation only includes tuning of the Region 2 control constant. Implementation of tuned constants for Region 2.5 and Region 3 are more complicated and were not automated in the optimization framework used for this investigation.

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Basic Process

Rotor designs for this work were created using a two-step process.

1. An aero-structural optimization process was used to identify the blade geometry which yields the highest annual energy production (AEP) for the potentially lightest blade structural design.
2. The most promising generic blade structural designs were used to initialize a detailed structural optimization in which spar cap, panels and trailing edge reinforcements were sized such that the blades met the intent of design standards.

The targeted outcomes of the analysis include aerodynamic-structural rotor designs which:

- were as light as possible,
- met a consistent set of design criteria, and
- captured as much energy as possible.

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Designs
80 m/s Tip Speed Optimized Design

- 5MW NREL reference model components with newly optimized rotor.
- The redesign included tightly coupled effects of blade aerodynamic geometry and structural design.
- The generator speed control constants were recomputed to align with the new rotor performance but the blade pitch controller remained unchanged from the 5MW reference model.
- Both the fine pitch setting in Region 2 as well as the Region 3 time constants for the pitch controller were unchanged from baseline values.

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Designs
Two 100 m/s Tip Speed Designs

- 5MW NREL reference model components with newly optimized rotor and modified gearbox ratio.
- Optimized for tip speed increase of 25% to 100 m/s and a three bladed rotor.
- Region 2 control recomputed to align with the new rotor performance but Region 3 control remained unchanged from the 80 m/s 5MW reference model.
- Drivetrain input speed increased and torque capacity was reduced.
- Significant cost saving for the drivetrain was anticipated for this configuration by virtue of the torque reduction.
- Two different rotor approaches pursued:

  High solidity & low TSR. Practically the same as Design 80, but operated to higher rotor speeds.

  Low solidity & high TSR. A rotor which is more aerodynamically ideal, but structurally very challenging.

  Both designs are discussed—they contrast isolated component design versus system integrated component design.

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Baseline Rotor Blade Design

- The starting point for rotor designs was the Sandia 61.5 m blade concept [[**?**]].
- The 61.5 m blade concept represents the exact aerodynamic design of the NREL 5MW reference turbine
- The 61.5 m blade includes a layup created to meet basic IEC design standards while also matching the basic mass properties of the original NREL 5MW reference turbine blades.
- The current work improves beyond that rotor by seeking a new optimal aerodynamic and structural design.

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Blade Details–Airfoils

- Same as the NREL 5MW reference rotor design; a combination of DU and NACA airfoils.
- Rotor optimization allowed relocation of the airfoils to achieve new optimal thickness distributions.
- Airfoil polar data from the official file archive for the NREL 5MW reference turbine were used without modification.

Airfoil names and maximum thickness ratios

Airfoil Name	t/c ratio
DU99-W-405	40%
DU99-W-350	35%
DU97-W-300	30%
DU91-W2-250	25%
DU93-W-210	21%
NACA 64-618	18%

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Blade Details

- Materials

  Taken from the Sandia 100m Blade design [[**?**]] and in the Sandia 61.5m structural concept [[**?**]].

- Blade Root Hardware–

  Blade root hardware (e.g. carrots, t-bolts, embedded studs) were not included in this simplified structural model.

  The root diameter and root buildup material and layer schedule were the same for all designs.

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Design Tools Integration

Three publicly available tools from the wind energy community were combined to perform the initial aero-structural optimization:

Public tool	Strength	Weakness
HARP_Opt v2.00.00 [?]	A multi-objective rotor optimization tool geared to maximize AEP while minimizing blade mass.	Structural representation of blades is limited to a shell of uniform wall thickness.
Co-Blade v1.23.00 [?]	A computationally efficient structural design and analysis tool based on 2D cross section analysis.	Buckling computations are fast, but uncertainty on the level of conservatism may be high.
NuMAD v2.1 [Sandia]	A blade structure design tool that includes abilities to represent blade layup and architecture parametrically in an optimization framework and to use ANSYS for high fidelity buckling analysis.	Requires time intensive buckling computations in ANSYS.

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Design Variables

20 total design variables available to the multi-objective genetic algorithm.

- 5 points shaped the entire chord distribution
- 5 points shaped the entire twist distribution
- 8 airfoil locations; a variable represented airfoil location for each of the following airfoil thicknesses: 18, 21, 21, 25, 25, 30, 35 and 40%
- 2 points shaped the distribution of materials in the spar cap

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Objective Function

The genetic algorithm used a multi-objective fitness function $F(x)$ to assess the quality of the blade design represented by the set of design variables.

$$F(x) = [F1(x), F2(x)] \tag{1}$$

The two dimensions of the fitness function were as follows

$$F1(x) = AEP(x) * (-1) \tag{2}$$

$$F2(x) = M(x) * P \tag{3}$$

$$P = \begin{cases} \frac{\delta(x)}{\delta_{target}}, & \text{if } \delta(x) > \delta_{target} \\ 1, & \text{otherwise} \end{cases} \tag{4}$$

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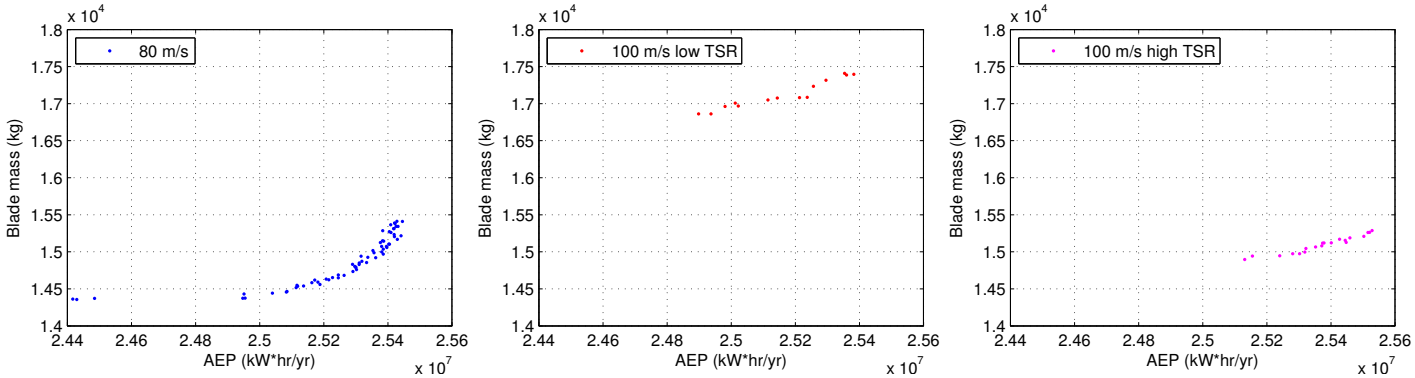
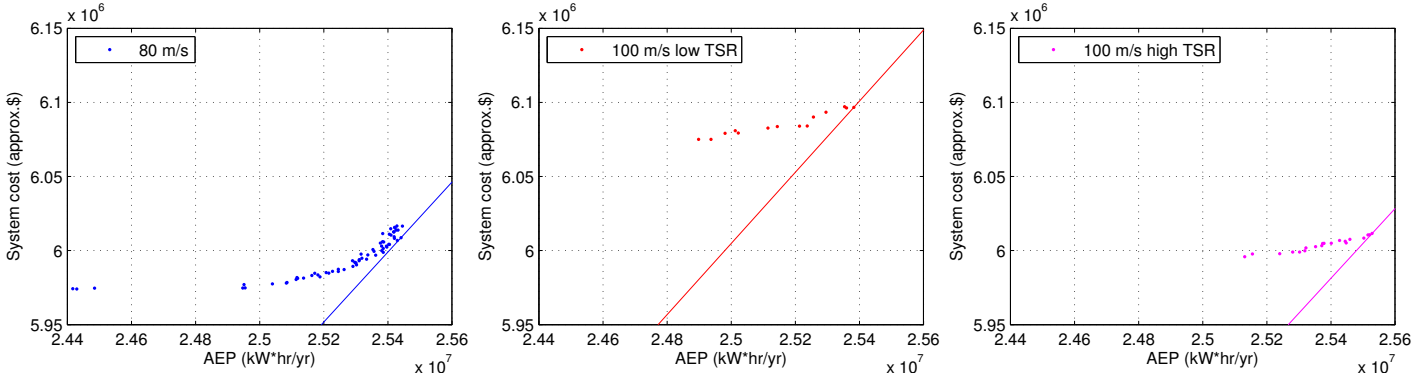
Approximately 30,000 designs were evaluated for each rotor (200 generations each with a population of 150).



Pareto fronts showing the sets of noninferior designs. Points shown only for designs that meet tip deflection requirement, $P = 1$



Pareto fronts expressed in terms of approximate system cost

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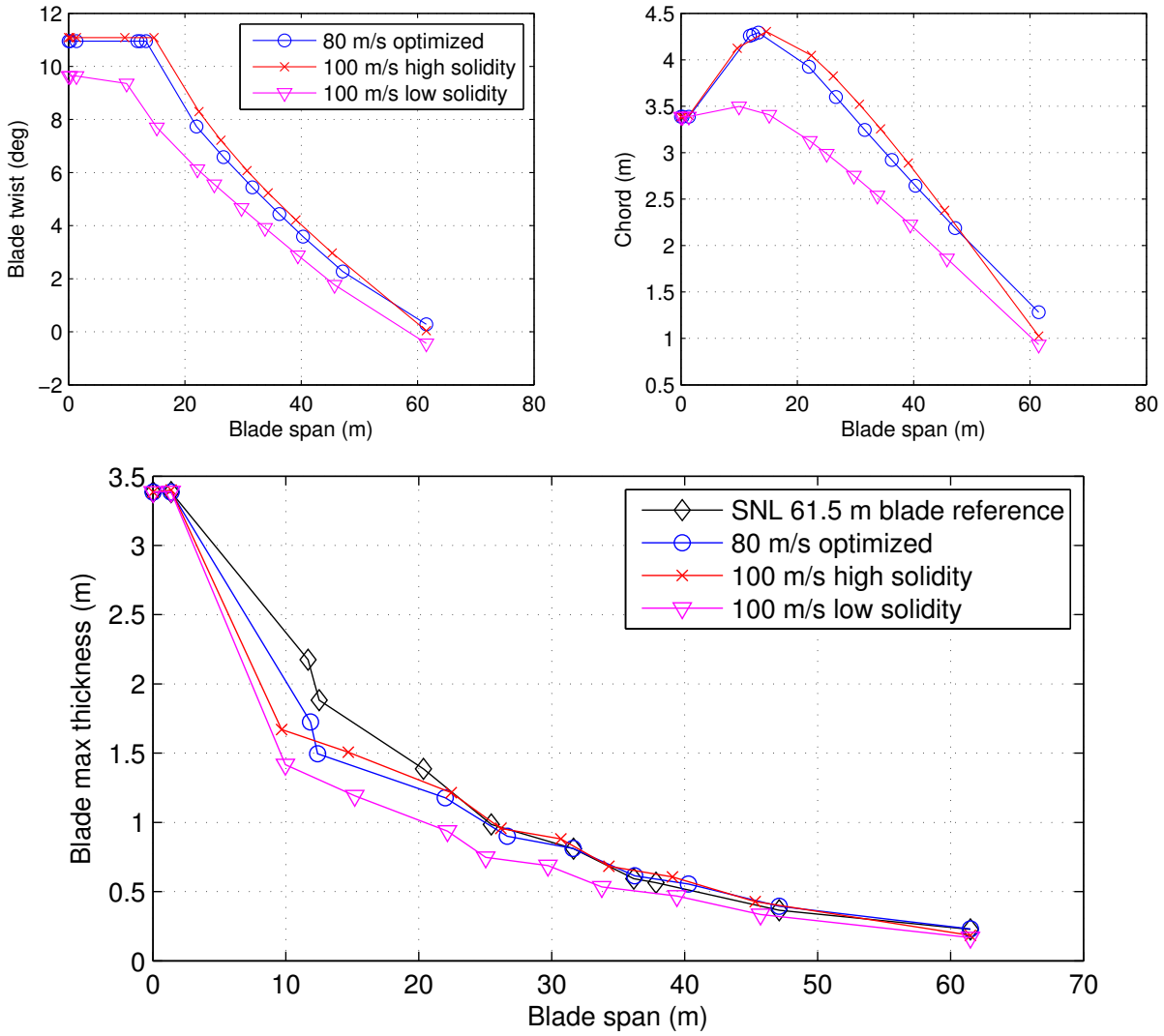
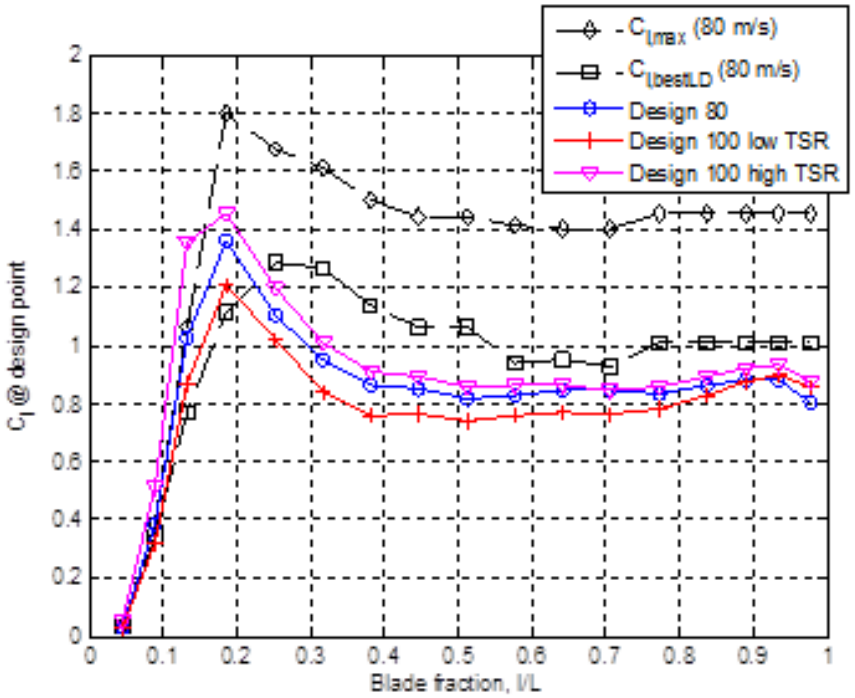
Designs Selected from Pareto Fronts



Aerodynamic Performance of Selected Designs



	TSR	$C_{p,max}$	Rotor C_T	Rotor solidity (%)
NREL 5MW Reference	7.55	0.482	-	5.16
80 m/s Optimized Design	8.9	0.499	0.743	4.53
100 m/s High Solidity Design	9.1	0.493	0.720	4.60
100 m/s Low Solidity Design	9.9	0.503	0.761	3.76

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Structural Optimization

Aero-structural optimizations used preliminary layups. Selected designs from aero-structural optimization proceeded to detailed structural optimization.
Structural optimization goals included:

- **Panel sizing.** Determine the thickness of aft panels, especially near maximum chord where panel span is greatest. The thickness of these panels determines their resistance to buckling.
- **Spar cap sizing.** Determine both the width (constant width) and spanwise layer schedule for the spar cap. The spar cap design affects the overall blade flapwise stiffness and flapwise frequency.
- **Trailing edge reinforcement sizing.** The amount of trailing edge reinforcing material is used to affect the edge stiffness and frequency of the blade.
- **Root buildup.** Constant throughout the study.

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Structural Optimization Method

A simple genetic algorithm was used to manage the structural optimization process. The optimization goal was to minimize the penalized blade mass, F_{struc}.

$$F_{struc}(x) = M(x) * P_\delta * P_{buckle} * P_{fatigue} * P_{flap} * P_{edge/flap} \quad (5)$$

Penalties P are applied to the blade mass M for exceeding:

- tip deflection criteria, P_δ
- buckling criteria, P_{buckle}
- 20 year fatigue damage, $P_{fatigue}$
- flap frequency criteria, P_{flap}
- edge-flap frequency spacing criteria, $P_{edge/flap}$

Design variables, x, included

- (2 variables) panel foam thicknesses in the aft panels
- (2 variables) spar cap thicknesses at 20% & 50% span
- (1 variable) spar cap width
- (1 variable) maximum thickness of trailing edge reinforcement

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Aeroelastic Simulations

FAST and AeroDyn were used to perform aeroelastic simulations to evaluate designs w.r.t. IEC Design Load Cases.

IEC DLC's used to check rotor design

DLC 1.2 (NTM)	Fatigue damage evaluation during normal power production in normal turbulence
DLC 1.3 (ETM)	Ultimate loads evaluation during normal power production in extreme turbulence
DLC 1.4 (ECD)	Ultimate loads evaluation during normal power production with an extreme coherence gust with change in wind direction
DLC 1.5 (EWS)	Ultimate loads evaluation during normal power production with the presence of extreme wind shear
DLC 6.1 (EWM50)	Ultimate loads evaluation while in a parked configuration during a 50-year extreme steady wind event
DLC 6.3 (EWM01)	Ultimate loads evaluation while in a parked configuration during a 1-year extreme steady wind event with extreme yaw misalignment

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80 m/s Optimization Results

The optimized 61.5 m blades for the 5MW rotor were different in several ways from the original 5MW baseline:

- lower solidity,
- TSR for optimal C_p was higher,
- lower blade mass.
- Also, the blade is stiffness driven; driven by out-of-plane blade deflection.

Airfoil placement:

- Initial expectations were that the low solidity rotor design would take advantage of the structural efficiency by locating thick airfoils further outboard.
- However, use of thicker airfoils outboard incurred the cost of increased blade drag, decreased blade lift-to-drag ratio, and decreased rotor AEP.
- High performing thick airfoils would enable more effective rotor systems across the entire design space.

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Ideal high speed rotor design

Explanation of an ideal scenario for aerodynamic design of a high tip speed rotor is helpful in understanding results of this investigation.

- From a purely aerodynamic perspective, an increase in tip speed from the baseline 80 m/s to 100 m/s would translate to an increase in rotor design tip speed ratio of 100/80, or 25%.
- Aerodynamic rotor loads on the rest of the turbine system remain unchanged, with the exception of the 20% decrease in rotor torque.
- Design TSR increases; it increases from a value of 8.9 for baseline Design 80 to $8.9 * 1.25 = 11.125$.
- Optimal airfoil design lift coefficients remain unchanged.
- Rotor solidity decreases from 4.53 for baseline Design 80 to $4.53/1.25 = 3.624$.

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What really happens

Structures are adversely affected by the low solidity of an ideal high speed rotor design.

- As the ideal rotor solidity and blade thickness decrease with increased rotor speed, the blades' spar caps become disproportionately heavy because they are stiffness driven.
- Even though the decrease in solidity also leads to lighter weight blade skins, the overall blade weight increases because of the larger spar caps.
- There are options:

  Pursue two-bladed rotors, thus increasing the thickness and structural efficiency of the individual blades; two-bladed rotors were beyond the scope of this work

  Utilize an airfoil family which exhibits lower design lift coefficients (L/D will suffer).

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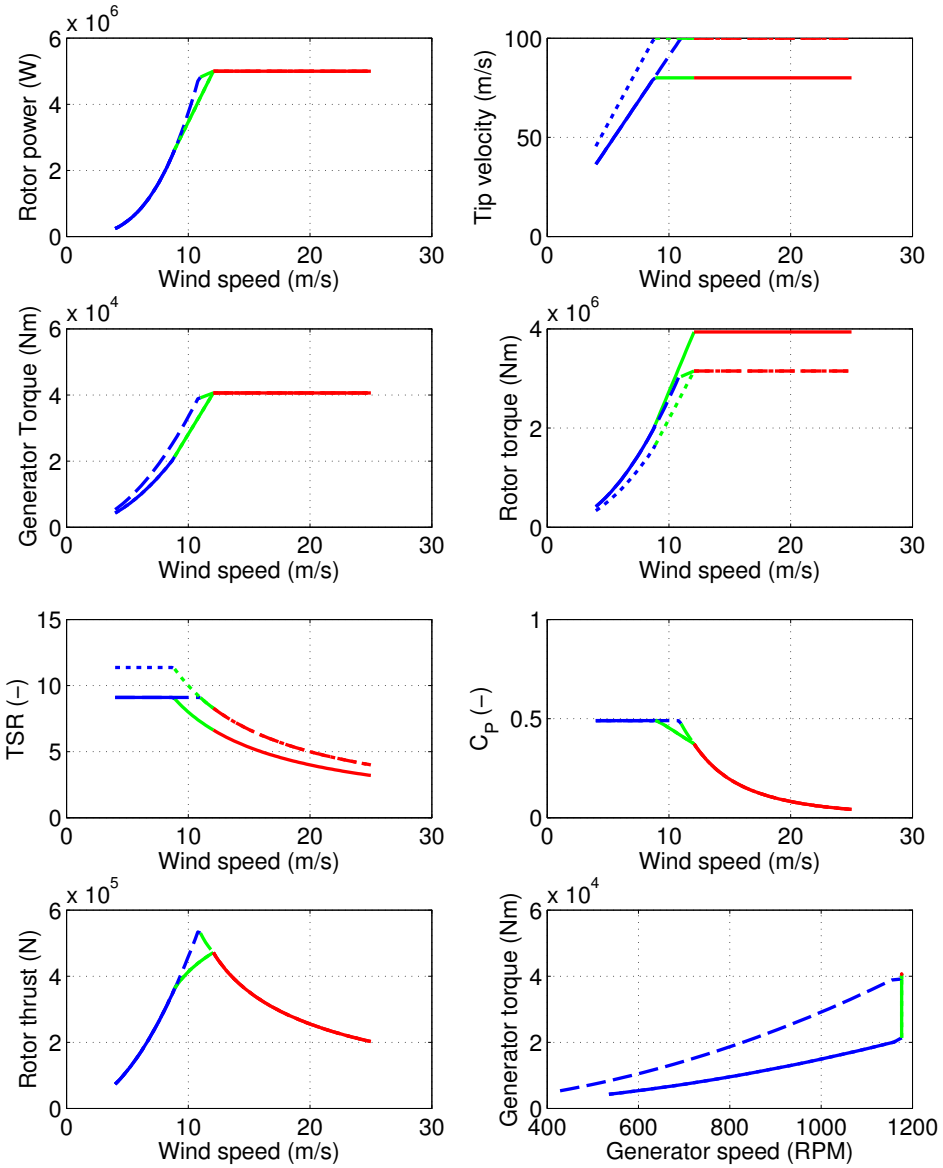
Controls Implications

Illustration of turbine control regions showing three different rotor design approaches: solid–low speed, high solidity, low TSR; dotted–high speed, low solidity, high TSR; dashed–high speed, high solidity, low TSR



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100 m/s Design Results

Design 100 low TSR (large planform)

- Solidity was roughly same as Design 80.
- Its thrust loads were highest.
- Lightest of the high speed designs because its high solidity allowed for a thick blade and lighter weight spar caps.
- It had the most adverse effect on the sizing of the rest of the system because its thrust loads were highest.

Design 100 high TSR (small planform)

- Solidity was lowest, but not as low as was anticipated for the ideal aerodynamic design.
- Thrust loads were increased above the baseline, but not as high as the high speed high solidity design.
- Heaviest of the high speed designs because its lower solidity and lower blade thickness required much heavier spar caps to meet stiffness requirements.
- It had a much smaller adverse effect on the sizing of the rest of the system because its thrust loads were only moderately higher than Design 80.

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Summary of rotor designs

	Design 80	Design 100 low solidity	Design 100 high solidity
TSR, λ	8.9	9.9	9.1
Rotor $C_{p,max}$	0.499	0.503	0.493
Rotor C_T	0.743	0.761	0.720
Rotor solidity (%)	4.53	3.76	4.60
Max characteristic rotor thrust (kN)	933 DLC1.3, ETM	1,059 DLC1.3, ETM	1,148 DLC1.3, ETM
Spar cap width (mm)	575	587	496
Max T.E. panel thickness (mm)	68	30	57
Max spar cap thickness (#)	90	196	120
Max T.E. reinf. thickness (#)	47	122	58
Max characteristic blade tip defl. (m)	7.05 DLC1.4, ECD	7.02 DLC1.4, ECD	6.99 DLC1.4, ECD
Min blade fatigue life (yrs)	17,788 Spar cap	111,682 T.E. reinf.	4,371 Spar cap
Buckle driving DLC	50yrEWM	50yrEWM	50yrEWM
Blade mass (kg)	16,097	17,590	16,423

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Future Improvements

- Blade cost models are important. Optimization should minimize system cost, not rotor mass—especially useful with carbon fiber.
- A higher fidelity structural model should be utilized during the aero-structural optimization.
- Computationally fast and accurate buckling models are needed in order to include panel sizing in the aero-structural optimization loop.
- Include analysis of loads during extreme winds—inclusion of parked storm loads encourage blades with lower solidity.
- Careful definition of structural and aerodynamic design variables—e.g. rotor TSR should be a design variable not a side effect of random chord and twist distributions.
- Controls design should be included in the optimization—perhaps not so easy.