SAND2014-1684C

INVESTIGATING THE EFFECTS OF FLATBACK AIRFOILS AND BLADE SLENDERNESS ON THE DESIGN OF LARGE WIND TURBINE BLADES

D. Todd Griffith
Sandia National Laboratories
Wind Energy Technology Department
dgriffi@sandia.gov

Phillip W. Richards
Sandia National Laboratories
Wind Energy Technology Department
pwricha@sandia.gov

Abstract:

Design and development of large blades is very challenging due to economics, logistics, and technical barriers. Regarding the technical barriers, designs must satisfy deflection, buckling, fatigue, and stability requirements. This is a very challenging design problem, and one that becomes more challenging to do cost-effectively as blades grow even longer. Sandia National Laboratories has been researching large blades for several years and identified several key design barriers for large blades in the course of this work, which include aeroelastic stability, panel buckling and gravitational fatigue loading. In this paper, we perform a series of parameter studies to evaluate design choices to address these technology barriers. The focus is on design of blades with varying slenderness using flatback airfoils with attention to aerodynamic, structural, and manufacturing trade-offs. This paper presents work in progress toward a finalized 100-meter design with flatback airfoils that meets all design loads requirements.

Keywords: Flatback airfoils, Sandia 100-meter blade, manufacturing cost model, panel buckling, flutter, blade solidity

1 OVERVIEW OF SANDIA 100-METER BLADE RESEARCH

Sandia National Laboratories Wind Energy Technology Department creates and evaluates innovative large blade concepts for horizontal axis wind turbines to promote designs that are more efficient aerodynamically, structurally, and economically. Recent work has focused on the development of a 100-meter blade for a 13.2 MW horizontal axis wind turbine and a series of large blade design studies for 100-meter blades. A link to the project website can be found in Reference [1]. Through this work, several key design barriers for large blades have been identified and documented including panel buckling, weight growth & gravitational fatigue loading, and aero-elastic stability [[2], [3]].

More recently, the focus has moved to blade geometry and airfoil effects through the use of flatback airfoils, in ultimately leading to a SNL100-03 design. This paper provides an overview of these design studies with focus on pathways to enable cost-effective large blade technology that is light-weight and aeroelastically stable. In the most recently completed design study for the SNL100-02 blade, new core material strategies were evaluated to address the technology barriers; of principal concern in that study were panel buckling requirements and weight reduction. An overview of the blade design studies in this project are as follows, which started with an all-glass baseline design in the initial study (SNL100-00; Reference [4]), followed by investigation of carbon fiber materials (SNL100-01; Reference [5]), then advanced core materials (SNL100-02; Reference [6]), and now advanced geometry effects (current paper):

All-glass Baseline Blade:	**SNL100-00**	***114 ton weight***	***Ref. 4***
Carbon Design Studies:	**SNL100-01**	***74 ton weight***	***Ref. 5***
Advanced Core Material:	**SNL100-02**	***59 ton weight***	***Ref. 6***
Advanced Geometry:	**SNL100-03**	***<50 tons***	***Present Study***

These designs are included in Figure 1 along with a survey of blade weights for commercial industry and research concept blades including the most recent data on new blades reported in the public domain. Note the Sandia SNL100-XX 100-meter series of designs (at 102.5-meter rotor radius in the figure), which demonstrates the weight reduction trajectory in this series of blade design studies. The industry survey includes recent large blades including the 73.5-meter (LM), 75-meter (Siemens), 83.5-meter (SSP/Samsung) and 81.6-meter (Euros/Mitsubishi) blades, which are plotted as diamonds in the figure. This data was gathered from web searches and is public domain. A few projections from 61.5-meter carbon blades are made in Figure 1 to project traditional and higher innovation weight growth to 102.5-meter rotor radius and beyond. The recent large blade data from industry indicates scaling between 2.0 and 2.5 being realized in actual designs, so a conservative projection for a 100-meter design with weight in the 50-60 ton range should be achievable although designs in the 40-50 ton range and lower should be possible through application of innovations.

The design conditions and materials are largely unknown for these industry designs, thus this data provides a broad perspective of the industry blade designs rather than one particular technology approach or set of design conditions. For example, IEC design load classes and choices for spar material (i.e. glass versus carbon) and core materials, which have a very large effect on blade weights, vary a great deal across the industry commercial and prototype designs. The SNL 100-meter designs include parasitic and coating weights in order to provide more realistic blade weights. Also, the more aggressive projections of weight reduction must assume that technical barriers can be overcome in design. The extent to which these barriers can be overcome in a cost-effective way while maintaining weight targets is an important motivation for these studies. Although not exercised in this paper, a blade manufacturing cost tool was developed within this program of study to aid in answering economics and manufacturing related questions for large blades, as documented in References [7] and [8].

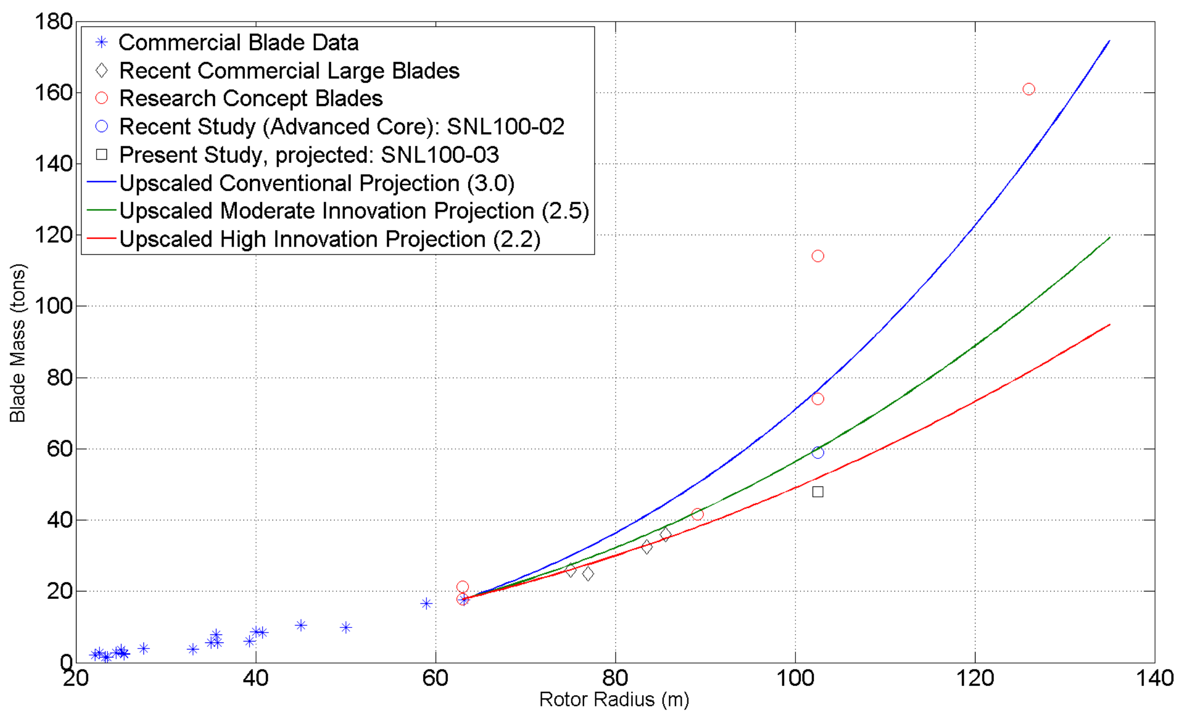

Figure 1. Blade Mass Survey and Projections Versus Rotor Radius

The pre-design work in the Upwind 20MW turbine study resulted in a design with 126-meter rotor radius and a blade mass of 161,000 kg (Reference [9]), which is also plotted in Figure 1. Similar to the Sandia All-glass Baseline Blade (SNL100-00) the Upwind 20MW blade design utilized only glass materials, and structural requirements on buckling necessitated a 3rd shear web. These choices contributed to both of these initial designs to have mass well above classical scaling exponent value of 3.0. A more recent concept design is the DTU Wind 10MW (at 89-meter radius in Figure 1) concept blade (Reference [10]), which shows a weight growth exponent just under 2.5.

One key point is that all design requirements for the SNL100-XX designs are satisfied according to international blade design standards (IEC and GL); these requirements or drivers include maximum strains, tip-tower clearance, buckling resistance, and fatigue life to demonstrate acceptance of the design concept to loads and safety factors from international design standards. The design safety factors and associated design standard are the same for this study as discussed in prior studies. NuMAD [[11], [12]] model files have been made publicly available for each of the SNL100-XX series detailed blade designs via the project website.

2 DESCRIPTION OF FLATBACK AIRFOILS FOR THIS STUDY

The FB-series of flatbacks utilized in the Sandia BSDS (Blade System Design Study) blade [13] are utilized in this study, as shown in Figure 2. The foils were selected based on the availability of their performance data, based on prior testing, as well as being previously published foils.

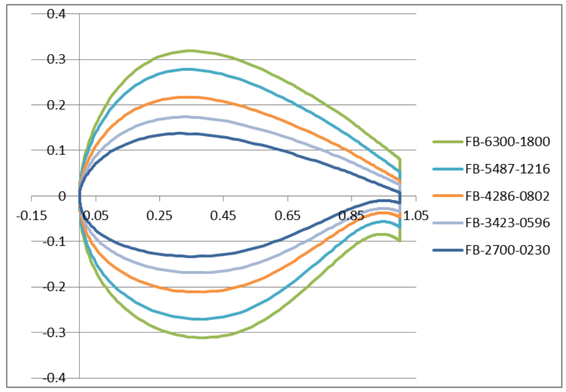

Figure 2. Family of BSDS Flatback Airfoils from 27% to 63% Thickness

3 PRELIMINARY AERODYNAMIC DESIGN OF SANDIA 100-METER BLADE WITH FLATBACK AIRFOILS

The National Wind Technology Center (NWTC) design code HARP_Opt (Horizontal Axis Rotor Performance Optimization) was used to optimize the 100-meter blade. HARP_Opt performs a dual-objective genetic algorithm optimization, where the objectives are annual energy production (AEP) and blade weight. The design variables for this optimization tool are control points for the twist and chord profiles of the blade along with variables to determine airfoil placement. For the aerodynamic model, HARP_Opt uses WT_Perf, which is a blade-element momentum theory wind turbine analysis code, also provided by NWTC. The airfoil data was provided to WT_Perf in the form of multiple Reynold's number data tables, with Reynold's numbers spanning the range of 7.5e5 to 20e6. A preliminary aerodynamic design was generated using this tool for the case of sharp trailing edge airfoils and is shown in Figure 3, along with the baseline design and two Betz optimum designs. The first Betz optimum design was created by matching the c_l distribution of the aero optimized design and calculating the optimum chord required to maintain a constant axial induction factor of 0.33 over the blade (using blade element momentum theory). The second design was created by using a design c_l of 0.9, which approximated the optimized c_l distribution over the last 50% of the blade. This figure shows the aero optimized profile produced using HARP-Opt has a reduced solidity and is very close to a "Betz optimum" design.

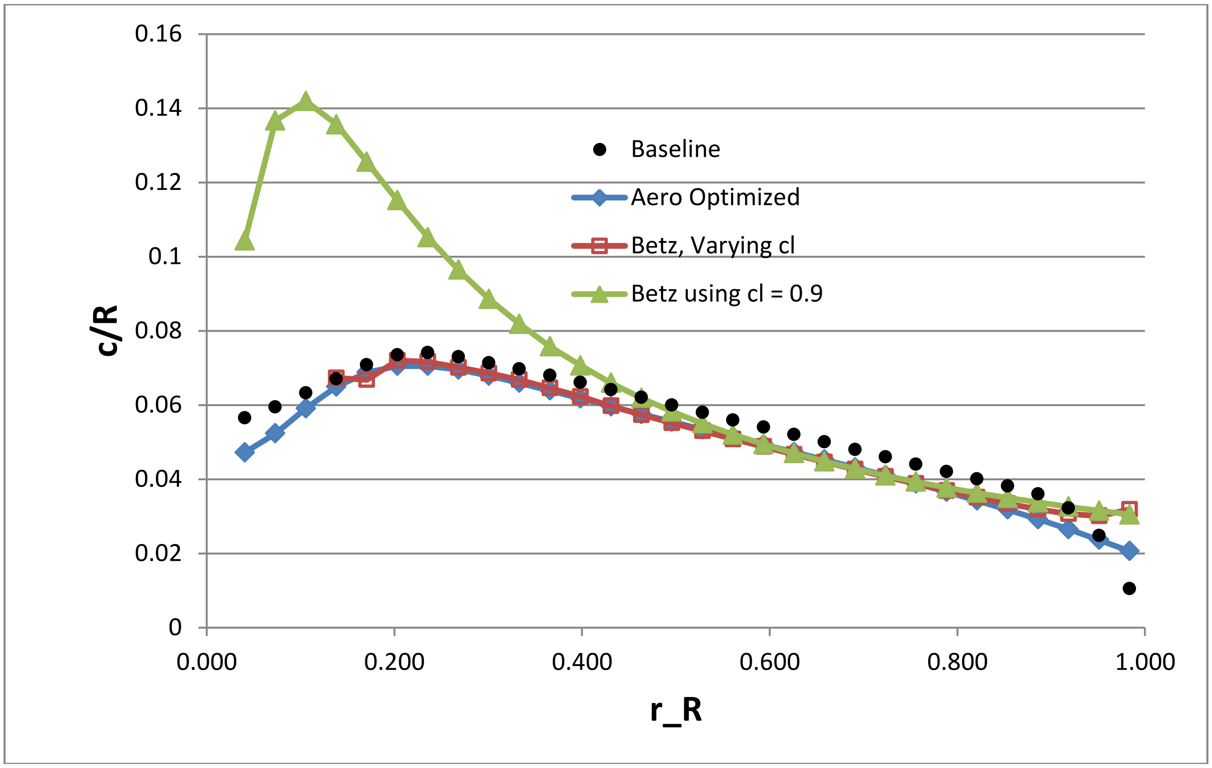

Figure 3. Comparison of Chord for SNL100m Baseline, Updated SNL100m (DU foils, pure Aero Optimization), and UpWind 123m Blades

The current design approach has the options to design the blade geometry considering only aerodynamic considerations or both aerodynamics and structural considerations simultaneously. Thus, one objective of this paper is to exploit and evaluate this capability in these design studies wherein the structural performance is also included with aerodynamic performance objectives in producing the external blade geometry definition. This can be a key step to meeting the stringent cost and structural performance objectives for large blades. Some of these initial calculations are described in the following section.

4 BLADE GEOMETRY: AERODYNAMIC-STRUCTURAL DESIGN PROCEDURE

The structural analysis aspect of the optimization tool HARP_Opt was integrated with Sandia National Laboratories NuMAD toolbox and an open source code for composite wind turbine blade structural analysis, CoBlade. In this way a consistent and accurate structural representation was available throughout the optimization process. Then, optimized structural designs were made with the baseline set of airfoils as well as the set of flatbacks shown above, while maintaining the same approximate thickness distribution for each blade. The root chord of the structurally optimized blades was reduced to 4.5m from 5.86m (scaled up from prior DOWEC 6MW blade studies) with the maximum chord at around 20% of the span. Preliminary and intermediate results identified the "extreme gust with coherent direction change" or ECD design load case as a design driver. Because the ECD analysis can take several seconds to run, an approximate deflection ratio between the ECD deflections and static deflections predicted by CoBlade was calculated, and the CoBlade static deflections were appropriately constrained throughout the optimization. The deflection ratio was updated at several stages of the process for each optimization. This novel approach to blade conceptual/preliminary design therefore captures aspects of aerodynamic performance, static structural performance, and aeroelastic performance. For each candidate aerodynamic evaluation, a parametric sweep of tip speed ratio (TSR) was performed in WT_Perf, and the speed controller scheduling for each candidate was adjusted to meet the optimum TSR for that candidate. In this way, TSR was allowed to vary throughout the optimization and the choice of TSR did not limit the design space.

Since the multi-objective genetic algorithm is used, each aero/structural optimizer run produced a Pareto front of candidates. The candidate from each optimization that has the same AEP as the baseline design was chosen. The geometry optimization with flatback airfoils resulted in two blade geometries for analysis. The first ("rev1") having a more slender planform than the second ("rev2"). Of course, both of these designs are significantly more slender than the initial Sandia 100-meter blades studies owing to the flatback airfoil choice. These designs are expected to provide insight into the appropriate degree of slenderness for blades of this size.

The optimization results for chord and twist are summarized in Figure 4. Table 1 gives more details about the optimized designs. Baseline refers to the upscaled DOWEC chord data to 100-meter blade length used in the earlier designs (SNL100-00 through SNL100-02) with DU-series airfoils. "DU Optimized Rev0" refers to the updated/refined chord and twist for 100-meter blade length using the same/original airfoil schedule. "Rev1" and "Rev2" are 100-meter blades with flatback airfoils from the series plotted in Figure 2. Polars for the maximum chord airfoils are shown in Figure 5.

Table 1. Details about the baseline and three new 100-meter design variants.

Design	AEP (kWh)	ECD Deflection (m)	Optimum TSR
Baseline	6.67e7	13.4	7.2
DU Optimized Rev 0	6.67e7	13.23	9.35
FB Series Rev 1	6.67e7	13.35	9.85
FB Series Rev 2	6.67e7	13.24	9.66

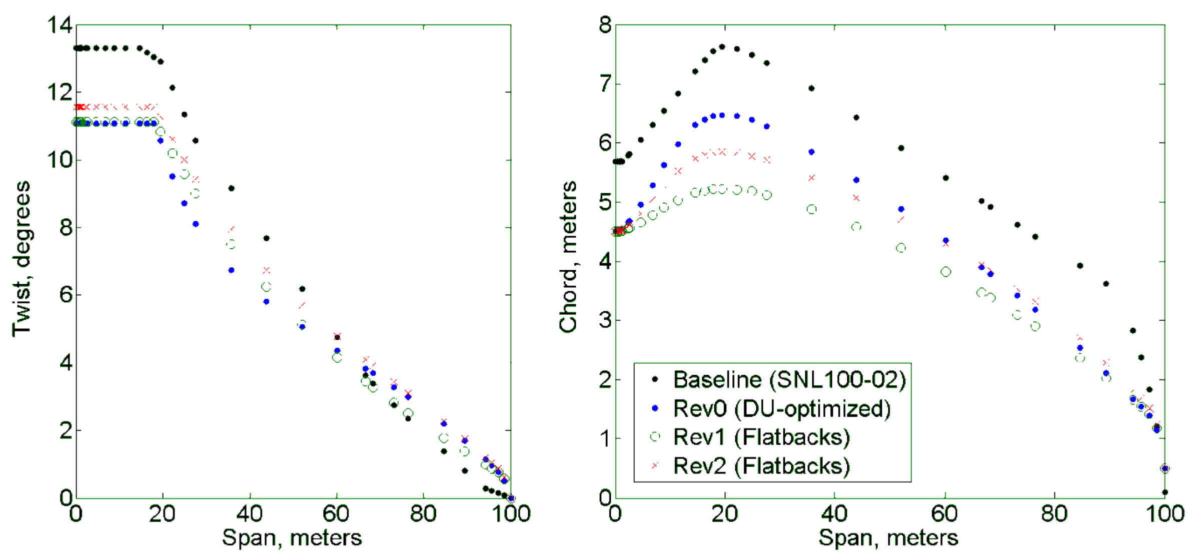

Figure 4. Chord and twist distributions for the baseline and three new 100-meter design variants.

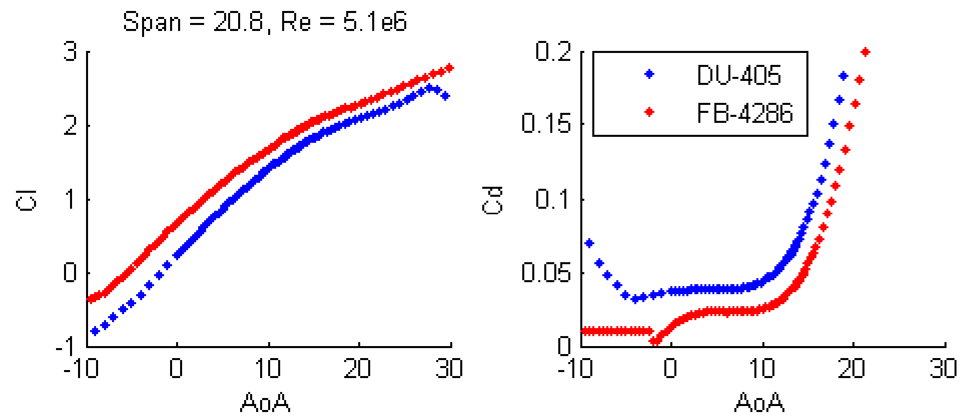

Figure 5. Polars for Maximum Chord Airfoils in this Study.

The optimized designs were able to produce the same AEP but at a lower solidity by increasing the optimum TSR of the design from 7.3 to around 9.6 (see Table 1). This was accomplished by altering the speed controller so that the optimum TSR is met at slightly lower wind speeds. Figures 6 and 7 show some details about the aerodynamic performance of the different designs compared with the baseline. Figure 6 shows the power coefficient, *Cp*, as a function of wind speed, showing that the optimized designs reach a higher maximum *Cp* than the baseline, and the maximum *Cp* is achieved over generally lower wind speeds. At and around the rated speed, where the loads are generally the highest, the maximum *Cp* is lower for the optimized than the baseline design. This has the effect of lowering the maximum loads the optimized blade will be expected to see. Figure 7, a plot of the root bending moment as a function of wind speed, shows the peak bending moment is reduced by ~25% for the optimized designs. The increased RPM also leads to a lower generator torque at the rated wind speed. Figure 8 demonstrates the difference in control schemes between the baseline and optimized designs.

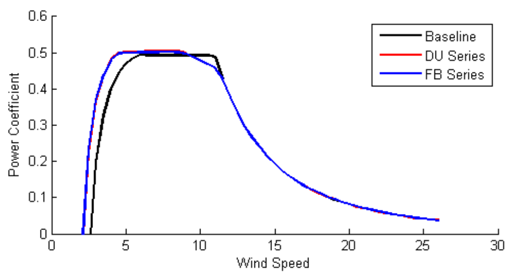

Figure 6. Predicted power output in terms of *Cp* from the designs.

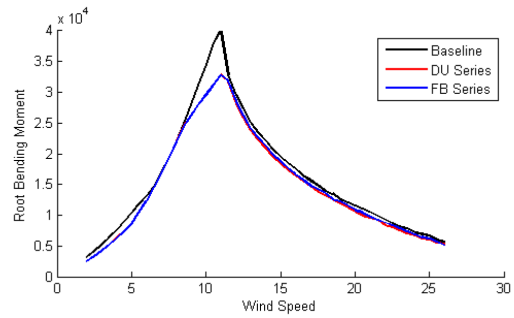

Figure 7. Root bending moment in kN for the designs as a function of wind speed.

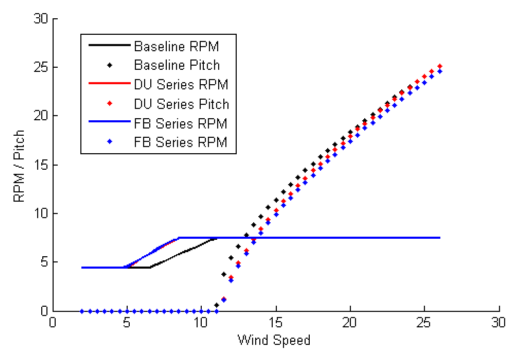

Figure 8. Design control scheduling for the designs. The speed control schedule is given in terms of RPM vs. wind speed, where the pitch control schedule is defined in terms of blade collective pitch angle vs. wind speed.

5 RESULTS: DESIGN STUDIES FOR 100-METER BLADE WITH FLATBACK AIRFOILS AND VARYING BLADE SLENDERNESS

Table 2 compares the four designs shown in Figure 4 from the highest solidity SNL100-02 design to the lowest solidity SNL-100-03 (rev1). In these results, each design has the same layup and internal spar geometry and spar placement based on the final SNL100-02 layup [6]. This initial comparison of designs was done in this manner to isolate the effect of the new geometry, although this layup is more optimized for the SNL100-02 design with larger chord and DU-series foils. Table 2 clearly shows the advantages of the new more slender designs (Rev0, Rev1, and Rev2) in terms of weight and loads reduction (Flap RBM refers to the flap-wise blade load root bending moment for the EWM50 (50-year occurrence wind speed) with pitch angle of zero degrees).

In comparing the three new designs, the most slender Rev1 design has lowest weight so it will be investigated first in the final series of design studies to come. Rev1 also has the largest excess buckling capacity indicating that core materials can be thinned and/or the design can utilize two shear webs versus the current three shear web architecture. Further, we consider the manufacturing labor operations on the blade surface such as sanding and painting. As noted in References 7 and 8, it is the area operations that grow in significance for large blades (e.g. Paint and Paint Preparation grows from 47% to 77% of the total blade finishing hours for a 40- to 100-meter blade length change). Such cost trends studies are useful to investigate and quantify the benefit of low blade solidity (lower surface area) with respect to labor hours cost and it motivates the inclusion of surface area (i.e. blade labor costs) as a variable for comparison in this study. The Rev1 design has 30% reduced surface area in comparison to the Baseline.

Some of the design loads requirements (e.g. fatigue life greater than 20 years) are not met in this set of designs, and additional work remains to quantify each design driver for final blade designs that satisfy design requirements. Flutter speeds were also computed (ratio of flutter predicted RPM to maximum RPM) and small reductions in flutter speed were noted [14].

These initial results demonstrate that a systematically optimized design for a 100-meter blade that would be considered highly innovative in relation to the projections in Figure 1 to likely be in the mid-40 ton range for weight. However, more work remains in meeting all design loads requirements while reducing blade weight further.

Table 2. Summary of Blade Performance and Cost Comparisons

	SNL100-02	SNL100-03: Rev0	SNL100-03: Rev1	SNL100-03: Rev2
Geometry Description	Baseline	DU-Optimized	More slender	Less Slender
Airfoil Family	DU	DU	Flatbacks	Flatbacks
Mass (kg)	59,047	53,146	50,530	53,671
Flap RBM (max) (kN-m)	111,900	87,410	74,930	92,600
Tip Deflection (m)	10.51	10.62	13.37	11.02
Spar Fatigue @ 15% (years)	646	4004	340	2641
Trailing Edge Fatigue @ 15% (years)	352	31.6	0.3	2.7
Lowest Panel Buckling Freq.	2.10	--	3.60	3.15
Flutter Speed Ratio	1.65	1.67	1.54	1.62
Surface Area (sq. meters)	1262	1021	886	979

REFERENCES

[1] "Offshore Wind: Sandia Large Rotor Development," Sandia 100-meter Blade Research Website: http://largeoffshorerotor.sandia.gov, Last modified 18-February-2013; accessed 01-October-2013.

[2] Griffith, D.T., Resor, B.R., and Ashwill, T.D., "Challenges and Opportunities in Large Offshore Rotor Development: Sandia 100-meter Blade Research," AWEA WINDPOWER 2012 Conference and Exhibition; Scientific Track Paper; Atlanta, GA; June 3-6, 2012.

[3] Griffith, D.T., "Large Rotor Development: Sandia 100-meter Blade Research," Invited Presentation: AMI Wind Turbine Blade Manufacture 2012, Dusseldorf, Germany, November 28, 2012, Slide Documentation: Sandia Technical Report Number: SAND2012-8790C.

[4] Griffith, D.T. and Ashwill, T.D., "The Sandia 100-meter All-glass Baseline Wind Turbine Blade: SNL100-00," Sandia National Laboratories Technical Report, SAND2011-3779, June 2011.

[5] Griffith, D.T., "The SNL100-01 Blade: Carbon Design Studies for the Sandia 100-meter Blade," Sandia National Laboratories Technical Report, SAND2013-1178, February 2013.

[6] Griffith, D.T., "The SNL100-02 Blade: Advanced Core Material Design Studies for the Sandia 100-meter Blade," Sandia National Laboratories Technical Report, SAND2013-10162, November 2013.

[7] Griffith, D.T. and Johanns, W., "Large Blade Manufacturing Cost Studies Using the Sandia Blade Manufacturing Cost Tool and Sandia 100-meter Blades," Sandia National Laboratories Technical Report, April 2013, SAND2013-2734.

[8] Johanns, W. and Griffith, D.T., "User Manual for Sandia Blade Manufacturing Cost Tool: Version 1.0," Sandia National Laboratories Technical Report, April 2013, SAND2013-2733.

[9] Peeringa, J., Brood, R., Ceyhan, O., Engels, W., and Winkel, G., "Upwind 20MW Wind Turbine Pre-Design: Blade Design and Control," Energy research Centre of the Netherlands (ECN) Technical Report, ECN-E—11-0017, December 2011.

[10] Bak, Christian et al. "Light Rotor: The 10-MW reference wind turbine". *Proceedings of EWEA 2012 - European Wind Energy Conference & Exhibition.* EWEA - The European Wind Energy Association. 2012.

[11] Laird, D. and T. Ashwill, "Introduction to NuMAD: A Numerical Manufacturing and Design Tool," *Proceedings of the ASME/AIAA Wind Energy Symposium*, Reno, NV, 1998, pp. 354-360.

[12] Berg, J.C. and B.R. Resor, "Numerical Manufacturing And Design Tool (NuMAD v2.0) for Wind Turbine Blades: User's Guide," Sandia National Laboratories Technical Report, SAND2012-7028.

[13] Berry, D.S., "Blade System Design Studies Phase II: Final Project Report," Sandia National Laboratories Technical Report, SAND2008-4648, July 2008.

[14] Owens, B.C., Griffith, D.T., Resor, B.R., and Hurtado, J.E., "Impact of Modeling Approach on Flutter Predictions for Very Large Wind Turbine Blade Designs," Proceedings of the American Helicopter Society (AHS) 69th Annual Forum, May 21-23, 2013, Phoenix, AZ, USA, Paper No. 386.

ACKNOWLEDGEMENT

Sandia National Laboratories is a multi-program laboratory operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.