DEVELOPMENTS IN LARGE BLADES

FOR LOWER COST WIND TURBINES

by

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Abstract

WindPACT scaling and concept studies have looked at identifying issues and constraints associated with growing turbines from 1-10 MW. As part of the WindPACT project, the Blade System Design Studies developed innovations in manufacturing, materials, and design that would alleviate issues and provide breakthroughs in constraints identified for large blade production. This paper describes the recent and predicted trends in blade-size growth and new COE goals developed by DOE's wind program. It also provides sample results from WindPACT studies and associated blade research activities that facilitate larger blade development in ways that reduce COE.

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Introduction

The recent growth rate of wind energy capacity is predicted to accelerate worldwide in the next few years. Europe is expected to double its installed capacity from 2003 to 2007 and the U.S. will grow significantly as well. WindPACT (Wind Partnerships for Advanced Component Technologies) scaling and concept studies have looked at identifying issues and constraints associated with growing turbines from 1-10 MW. Related to the recent growth in installed wind capacity is a companion drop in the cost of wind energy (COE). The current cost of wind-produced power is as low as 4-5 cents per kilowatt-hour (kWhr) in Class 6 (6.4-7.0 m/s at 10 m) sites. As part of the WindPACT project, Blade System Design Studies (BSDS) developed innovations in manufacturing, materials, and design that would alleviate issues and provide breakthroughs in constraints identified for large blade production. This paper describes the recent and predicted trends in blade-size growth and new COE goals developed by the Department of Energy (DOE) wind program. It also provides sample results from WindPACT studies and associated blade research activities that will facilitate larger blade development in ways that reduce COE.

Growth of Wind Capacity and New COE Goals

The recent strong worldwide growth of wind energy capacity is well documented and will likely continue. Europe is expected to double its installed capacity in the span from 2003 to 2007, and the U.S. is expected to grow significantly as well (Fig. 1, Ref. 1). [The U.S. growth rate is not as strong as that of Europe, partly due to the uncertainty of the FY 2004 energy legislation that would extend the Production Tax Credit (PTC).] In addition, Shell Global studies predict that all renewable forms of energy production will grow rapidly over the next 20 years with wind becoming the largest contributor relative to biomass, biofuels, solar thermal, geothermal, and solar photovoltaic (Fig. 2).

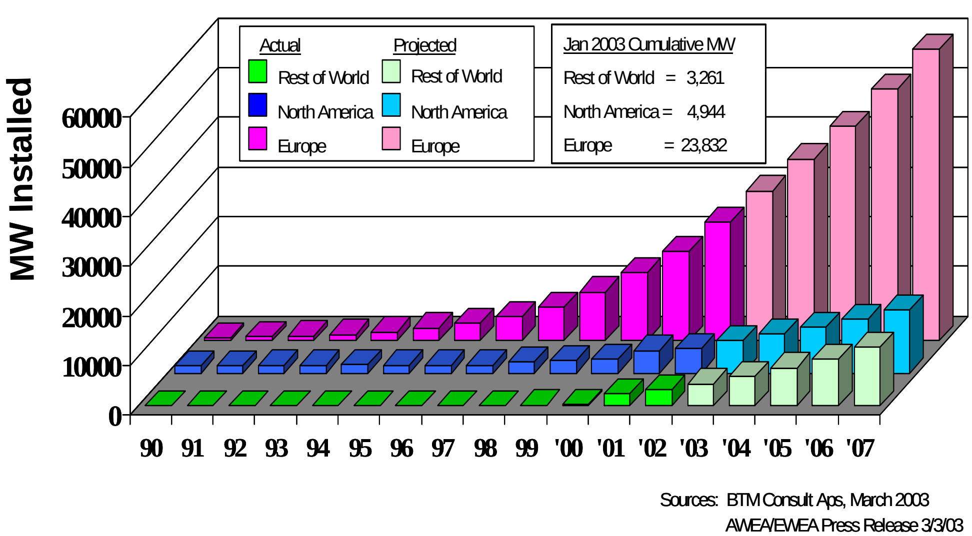

Fig. 1. Growth of Wind Energy Capacity Worldwide

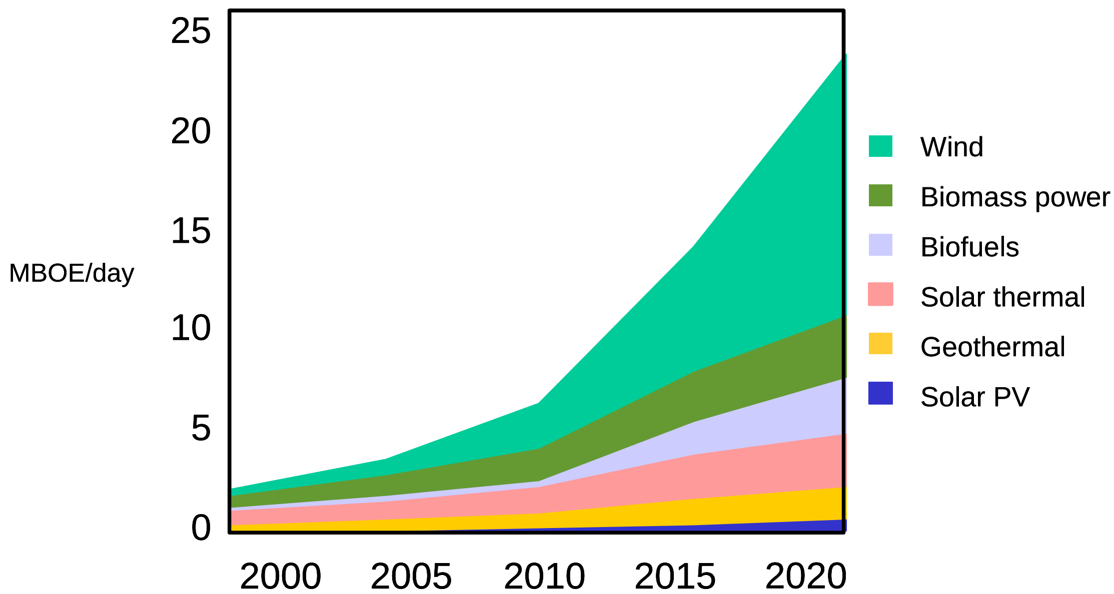

Fig. 2. Growth Prediction of Various Renewable Technologies to 2020
(Source: Shell Global Scenarios)

Associated with the recent growth in installed capacity is a companion drop in the cost of wind energy (Fig. 3). Wind produced power currently is as low as 4-5 cents per kWhr in Class 6 (6.4-7.0 m/s at 10 m) sites. This cost reduction can be attributed to advances in research and development and improvements in manufacturing, as well as increases in turbine size, where the current average utility-grade turbine is 1.5 MW, sits on towers 65 m high and spins with blades that are 34 m long (Fig. 4)

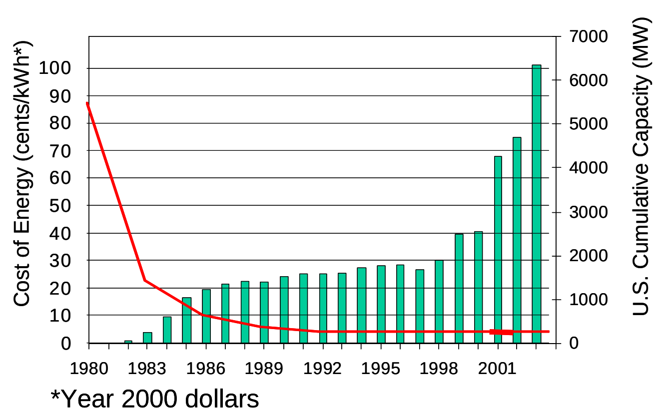

Fig. 3. Cost of Wind Energy is Falling and Capacity Growing
(Sources: Henry Dodd-SNL, BTM Consults, and AWEA)

The increase in commercial turbine sizes is expected to continue, as new prototype turbines have been built that are as large as 3.5-4 MW (5 MW on the drawing board) with towers up to 100 m tall and blades up to 50 m in length. Current costs of blades are usually less than $5/lb.

Figure 4. 1.5 MW Turbines and Hub

Figure 5 shows the approximate growth trend in blade lengths for utility-grade turbines over the past 25 years. This figure also indicates that 50 meter plus size blades are to be commercial in the near future.

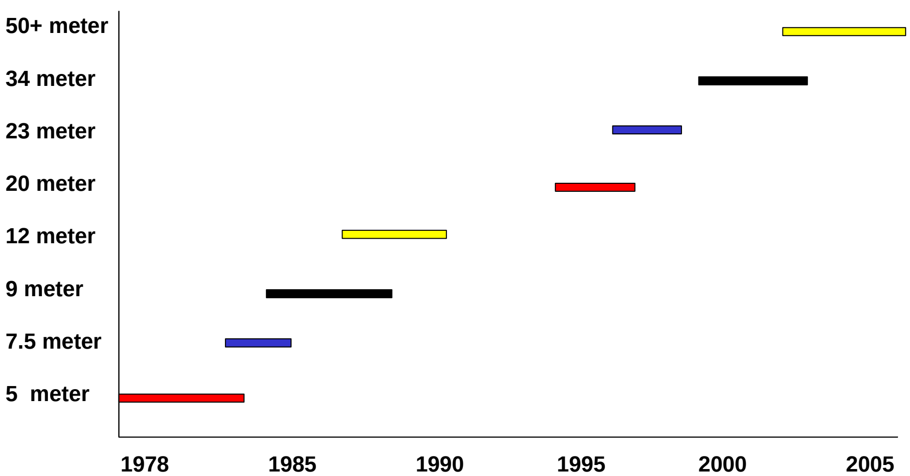

Figure 5. Approximate Utility-grade Blade Growth over Time

Figure 6 shows a GE 50.5 m prototype blade being transported by truck over a bridge in South America. Obviously, passers-by have noticed the action.

Figure 6. GE 50.5 meter Prototype Blade

Cost Goals

The DOE wind program, as part of its recently established Low Wind Speed Technology (LWST) project, has introduced new U.S. COE goals that when achieved will bring down production costs even further. By 2012, the goals are to reduce COE from large systems in Class 4 winds to 3 cents per kWhr onshore and 4 cents per kWhr offshore. [Class 4 sites average 5.6-6.0 m/s at a 10 m height] In 2003 when these goals were established, costs were approximately 5-6 cents per kWhr in Class 4 sites onshore (FY 2000 dollars). This is the first time that offshore goals have been established in the DOE Wind Energy program. It has been noted that offshore production has tremendous potential along the coasts of the U.S.

DOE and NREL (National Renewable Energy Laboratory) investigations have shown that improvements in several technology areas need to be made to achieve these goals. It is estimated that items such as advanced rotors and controls, advanced drive train concepts, new tower concepts, improved availability and reduced losses, manufacturing improvements, and site specific designs will provide up to 44% COE improvement (with a large plus or minus band of 32%). Table I lists these technology areas with the reductions in COE estimated for each. Blade-related areas such as advanced rotor developments and manufacturing improvements make up about 50% of the expected cost reductions. Work is continuing this year to establish a formal procedure to track the progress in each technology towards achieving these goals, using data points that largely result from LWST contracts.

•**Larger-scale 2 - 5MW -** (rotors up to 120m)	0% ± 5%
•**Advanced rotors and controls –** (flexible, low-solidity, higher speed, hybrid carbon-glass and advanced and innovative designs)	**-15% ± 7%**
•**Advanced drive train concepts –** (Hybrid drive trains with low-speed PM generators and other innovative designs including reduced cost PE)	-10% ± 7%
•**New tower concepts -** (taller, modular, field assembled, load feedback control)	-2% ± 5%
•**Improved availability and reduced losses -** (better controls, siting and improved availability)	-5% ± 3%
•**Manufacturing improvements -** (new manufacturing methods, volume production and learning effects)	**-7% ± 3%**
•**Region and site tailored designs** (tailoring of larger 100MW wind farm turbine designs to unique sites)	-5% ± 2%
TOTAL	**-44% ± 32%**

Table I. Estimates of Cost Reduction by Technology
(Source: Bob Thresher, NREL)

So, how can the development of larger blades contribute to the lowering of turbine costs and reduced COE? This question can be answered by studying the equation [1] used to calculate COE.

$$COE = (FCR \times ICC) / AEP + AOE \quad [1]$$

- ICC = Initial Capital Costs of turbine including rotor, tower, drive train
- AEP = Annual Energy Production
- AOE = Annual Operating Expenses
- FCR = Fixed Charge Rate

To affect ICC, lower the costs of components
To affect AOE, improve quality
To affect AEP, develop a larger rotor with same loads
–Edgewise – lighter (carbon, integrated design)
–Flapwise – adaptive or integrated design

COE is primarily a function of initial capital costs, annual energy production, and annual operating expenses. Larger blades can affect initial capital costs by becoming less expensive through economics of scale and more efficient designs. However, reductions in cost here are incremental in nature. If blade costs were reduced by 10% (a big number), full turbine costs would be reduced only by about 2% (because the blades makes up about 20% of full turbine capital costs) and COE by even less. Higher quality blades certainly can lower annual operating expenses, but this would affect COE by perhaps only a fraction of a percent.

A significant way to impact COE, however, can be made by increasing production (AEP) by developing larger blades that experience the same loads as the replaced blade. This would allow for larger blades to be placed on an existing turbine. Since energy captured by the turbine is directly related to rotor swept area (see Equation 2), a 10% increase in blade length increases energy by 20%. What can actually be realized if the rating of the turbine is kept the same is more on the order of a 10% increase in energy and a 10% reduction in COE.

$$P = (Cp)\ (0.5)\ (\rho)\ (A)\ (V^3) \qquad [2]$$

where, Cp = Coefficient of power (power capture efficiency)
ρ = air density
A = rotor swept area
V = velocity of wind

The idea of growing the rotor diameter (increasing blade length), but keeping loads constant is a fairly new concept. So how can it be done?

- Keeping blade loads the same in the edgewise direction can be accomplished by making blades lighter with the use of materials such as carbon and integrated designs that more efficiently use the structure.

- Keeping the loads the same in the flapwise direction can be accomplished by incorporating adaptive blade concepts or integrated designs.

Most importantly, from the designer's standpoint, the capital costs of larger blades could actual rise somewhat (due to the use of carbon for example) and COE could still be reduced. The challenge is for designers and fabricators to implement these concepts. We will discuss some of these solutions in the next section.

Developments in Large Blade Technology

A few years ago when average turbine sizes were around 750 kW, DOE, NREL, and Sandia National Laboratories (SNL) initiated a series of WindPACT scaling studies to determine what issues and constraints there might be in components such as the drive train, tower, rotor and blades when scaling turbines from 1 to 10 MW. Results from these blade-related studies and ongoing research efforts are now providing guidance for the development of larger, more efficient blades.

The WindPACT studies showed that there were only a couple of constraints identified for blades up to 70 m in length. Onshore transportation is limited to blades in the 52-55 m range due to restrictions in weight, length or height. (A blade with mid-span joints can overcome at least the length restriction, but with added cost and complexity.) For the offshore case, transportation constraints may disappear if the blade fabrication facility is close to shore.

Figure 7 shows the width and height constraints for overland trucking (Ref. 2). Figure 8 shows the blade weight constraints (Ref. 2).

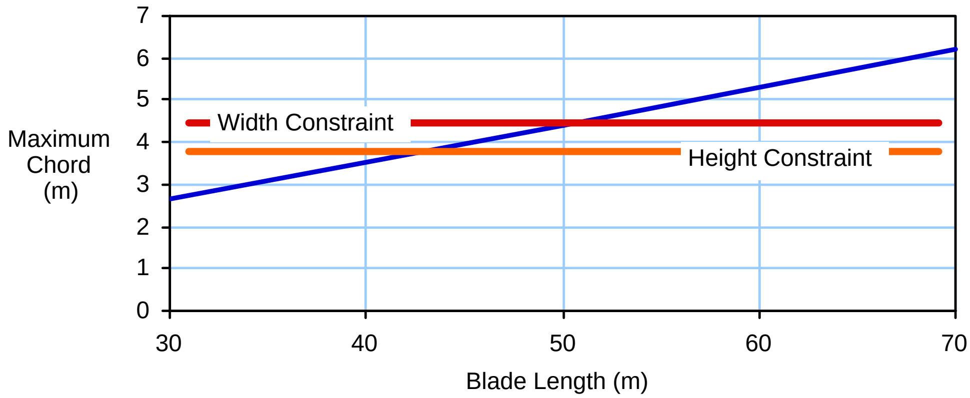

Figure 7. Width and Height Constraints for Blade Transportation

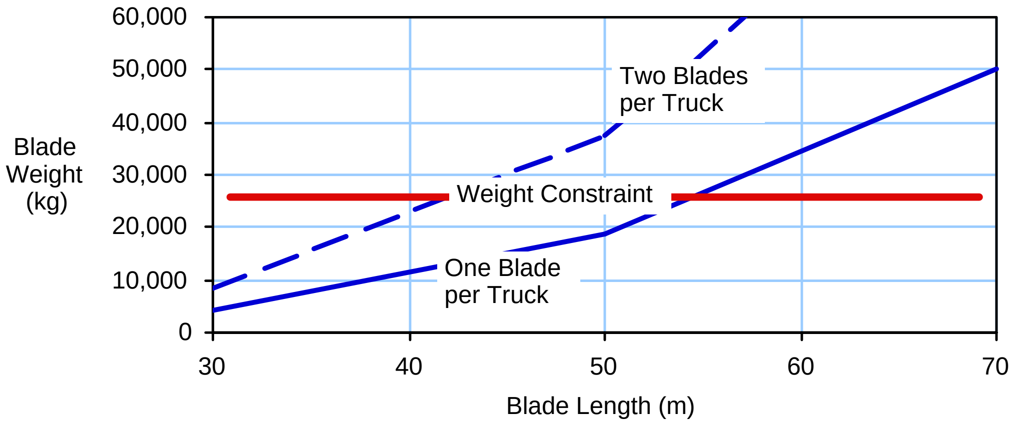

Figure 8. Weight Constraints for Blade Transportation

A second limitation is gravity itself. At some point, as blades grow in size, the oscillating loads due to gravity become prohibitive. It is hoped that making blades lighter and stronger can extend that limitation to even larger turbine sizes.

Commercial data show that current designs are keeping weight growth rate to less than that of earlier designs (Figure 9, Ref. 3). It is expected that under normal circumstances, blade weight grows as the blade length or rotor radius cubed (height times length times width). For earlier designs, that exponent of weight growth is slight smaller than three, at 2.9. For more recent designs the exponent is around 2.5. Recent designs are more efficient and sometimes include more modest wind sites with naturally lower loads (IEC Class III, for example). An alternate study (Figure 10, Ref. 4) shows a similar growth trend line (exponent = 2.3).

Designers and fabricators must continue to more efficiently produce blades and rotors to keep this trend from creeping back towards higher exponents. Primary areas in blade development where designers and fabricators can work to keep weight down are materials, manufacturing and design. A few trends, improvements and innovations in these areas coming out of the WindPACT studies and research efforts will now be briefly discussed.

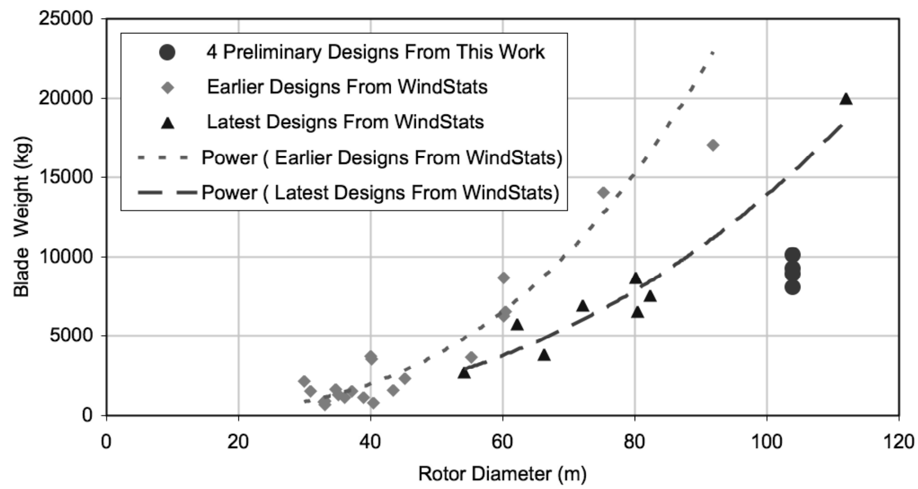

Figure 9. Blade Weight vs. Rotor Diameter from WindStats Data

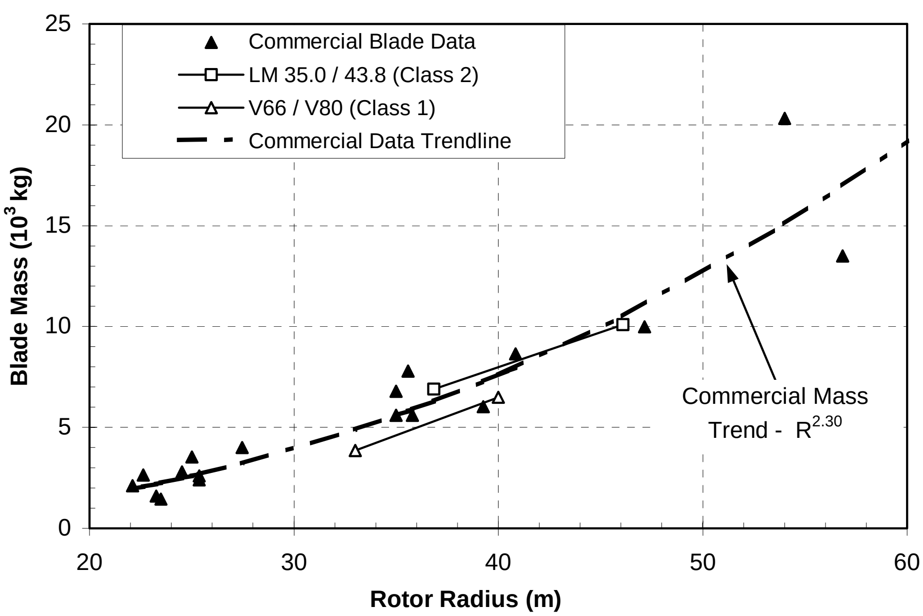

Figure 10. Blade Weight vs. Rotor Radius – Commercial Data

Trends in Manufacturing

It is expected that in the near future, manufacturing process improvements for large blade fabrication will include the optimization of the process around different material forms. For example, in the case of resin infusion, material-resin combinations will be chosen that infuse easily, achieve desired fiber content, and eliminate excess resin.

The automation of manufacturing will continue to become more widespread and is very important for large blades because of quality issues. The days of using primarily hand lay-up are gone. Resin infusion (Fig. 11) has become common because it reduces labor costs and improves part quality compared to hand lay-up. Automated lay-up and incorporation of pre-forms (especially in areas of thick build-up, like the root) will become more prevalent.

Increased reliability will be addressed for larger blades because it is so expensive to lose one, either on the manufacturing floor or in flight. Pre-preg processes tend to produce parts that are of high quality. Manufacturing blades with glass pre-preg has been incorporated by Vestas for some time now. Pre-preg carbon has traditionally been incorporated in aerospace structures but is very expensive. However, carbon fibers (pre-preg and infusion) will be incorporated more frequently because of the desire to move to lighter blades; the availability of larger tow, less expensive carbon fibers; and the concept of selective use in spar caps and areas of high stress.

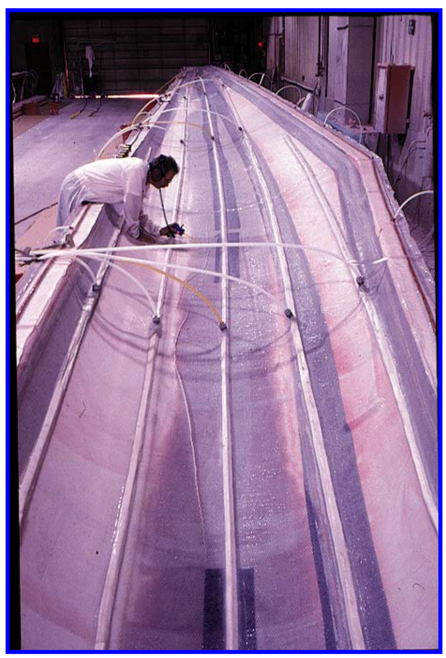

Figure 11. Resin Infusion of Blade at TPI Composites

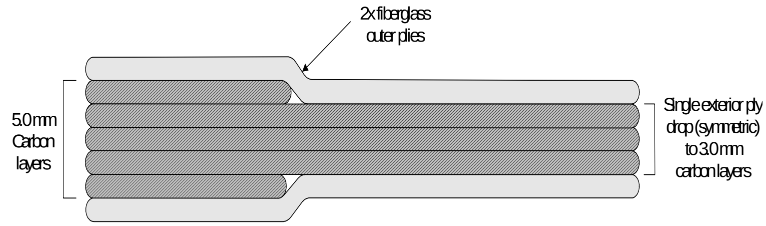

Figure 13.

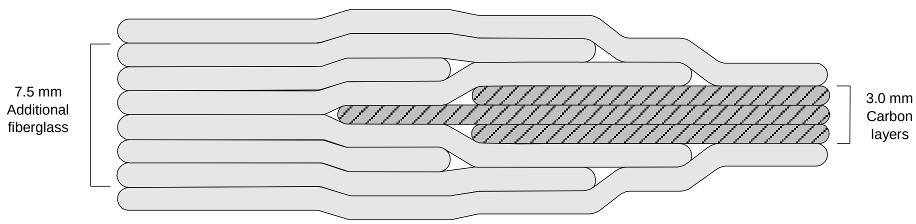

Figure 12.

Figure 14.

<u>New Materials and Innovative Ways to Incorporate into Large Blades</u>

The availability of new materials and new material forms is allowing more flexibility in design concepts and fosters not only the lowering of initial capital costs, but also lighter, stronger blades that reduce or resist loads.

The traditional forms of glass have been and continue to be woven, stitched, and bonded. Whenever there are new forms of bonding in glass forms usable for turbine structures, then they are added to the DOE/MSU fatigue base (Refs. 5-6) after performing coupon tests for strength and fatigue.

The incorporation of carbon was suggested by several of the WindPACT studies for use in larger blades to overcome gravity constraints. It is also efficient for the incorporation of passive bend-twist coupling – see next section. Compression fatigue of carbon is an area of concern (Fig. 12) and testing is continuous in this area at MSU (Montana State University) and under WindPACT contracts. Carbon pre-preg has traditionally been too expensive, but costs have dropped with the recent introduction of the so-called large and medium tow carbon fibers.

It would be too expensive to fabricate blades entirely of carbon, which means blades would be designed as carbon-glass hybrids. The interface of glass and carbon and how carbon fibers are dropped remain a challenge. Figures 13 and 14 provide examples of how carbon fibers can be dropped in a transition region to all-glass sections. See Reference 4. In addition, there are new fabrics, such as 3D weave, and new matrix materials, such as toughened resins, that show promise for more efficient blades.

The bar chart in Figure 15 (Ref. 7) shows the effects on shell blade weight when substituting alternate materials just in the spar cap. Blade weight is reduced by 15% when replacing e-glass with S-glass and 30% when replacing the e-glass with a carbon-glass spar cap.

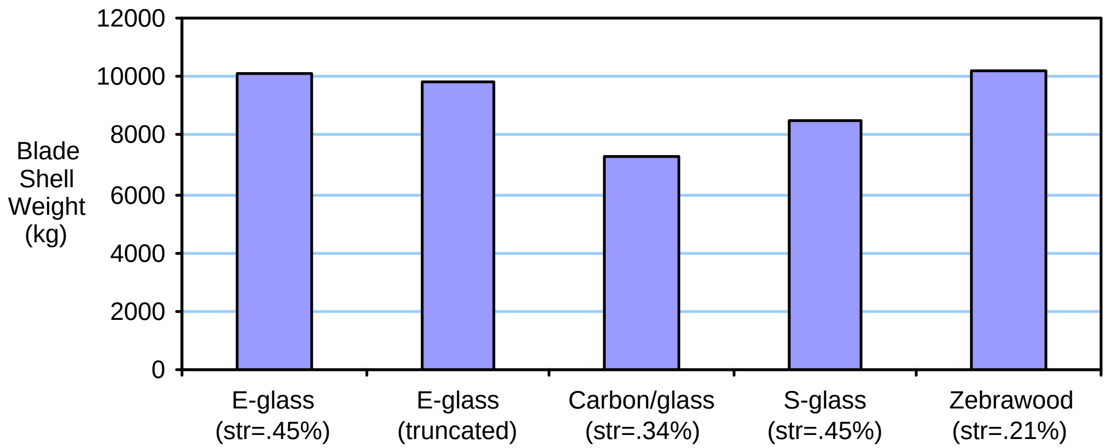

Figure 15. Effects on Blade Shell Weight When Substituting Alternate Materials

Innovations in Design

Some of the proposed design trends and innovations that have come out of the studies are:

- Integrated blade design
- Thicker airfoils
- Slender blades
- Adaptive blades – passive or active

1.) The integrated blade design process includes these features:

- design for simple structures before finalizing aerodynamic design
- use constant spar cap thickness and constant spar cap width design
- inboard – use high thickness flatback airfoils
- outboard – use high lift airfoils with modified thickness and shape for least complex and costly internal blade structure.

Fig. 16 shows a WindPACT preliminary design (Ref. 3) for a 50 m blade using the integrated design process where the spar cap is constant thickness for the entire span and constant width for much of the span.

2.) Thick airfoils would be used primarily in the inboard section of the blade and provide more flapwise stiffness.

3.)	Slender blades refer to the reduction of the typical large chords used inboard. This has the effect of reducing mass (good), but also reducing edgewise stiffness (not necessarily good). One airfoil family that can provide the necessary aerodynamic and structural requirements is the flatbacks. Flatback airfoils (Fig. 17) are truncated at the trailing edge, provide enhanced flapwise stiffness and lower weight, but have reduced edgewise stiffness. The trailing edge, however, can be strengthened with increased thickness or the use of carbon to maintain stiffness requirements.

Flatbacks tend to have high lift, but also high drag. It is predicted that 3D spanwise flow will reduce the higher drag. (Ref. 3). In a follow-on BSDS contract, 2D wind tunnel tests will be performed on several flatback airfoils to validate performance. 9-m prototype blades will then be built and flown to verify 3D effects.

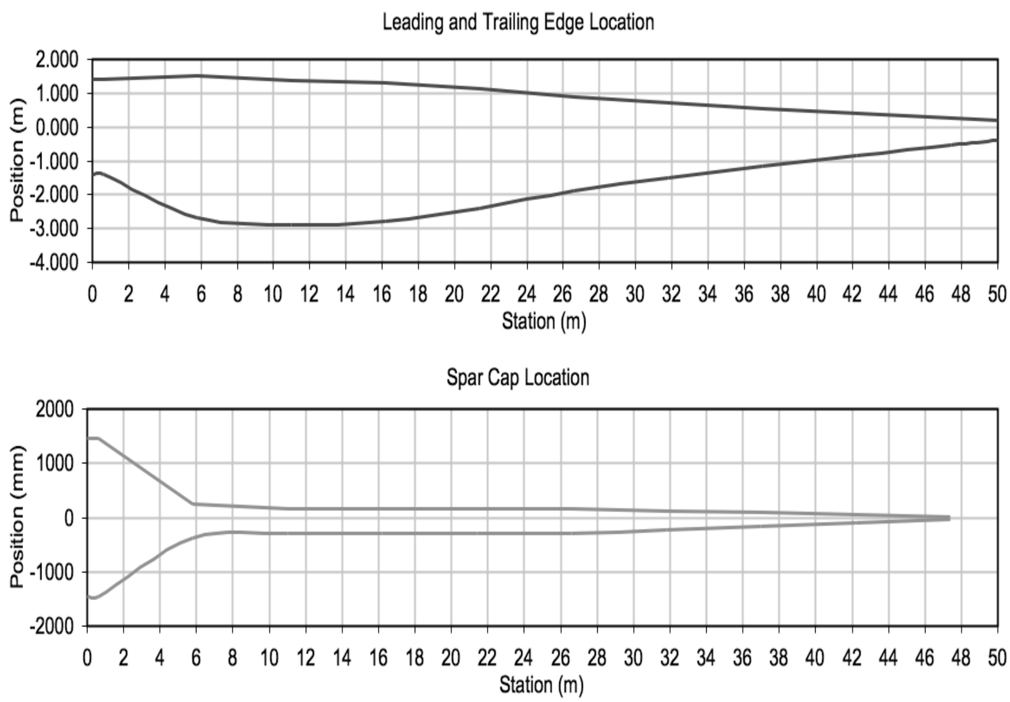

Figure 16. Preliminary Design of 50 m Blade Incorporating Integrated Design (Constant Spar Cap Thickness and Width for Most of Span)

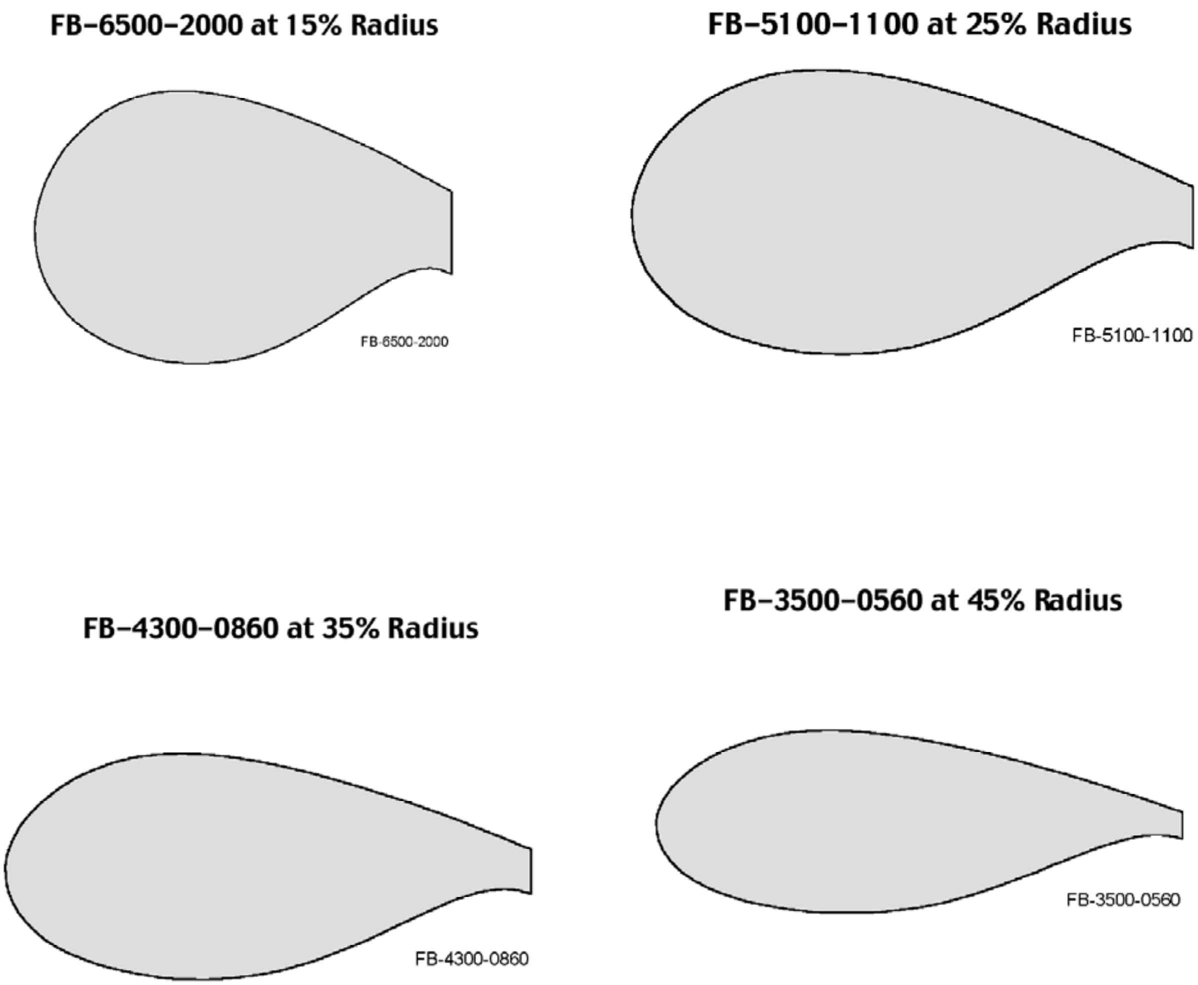

Figure 17. Use of Flatback Airfoils for Enhanced Structural Efficiency

4.) Adaptive blade concepts include both passive and active ideas. The goal is to affect blade response in ways that alleviate fatigue loads and enhance performance. Passively, blades can be designed in a couple of different ways. One is to sweep the blade along the span to create a moment that induces twist (Ref. 8). A second method is to align the primary load-carrying spanwise fibers in an off-axis manner by about 20 degrees, so as the blade bends, it twists more than normal allowing loads to be relieved (Fig. 18). Necessary goals are to maintain flapwise strength and maximum tip deflection. Studies have shown that this "bend-twist" coupling is maximized with the use of very stiff fibers, such as carbon (Ref. 9-10).

Actively, there are also several ideas. One concept is to incorporate micro-tabs in the trailing edge of the blade that are activated with low voltage several times in a rotation to reduce loads or enhance performance (Fig. 19). Other concepts involve ailerons, flaps, and pitch controls.

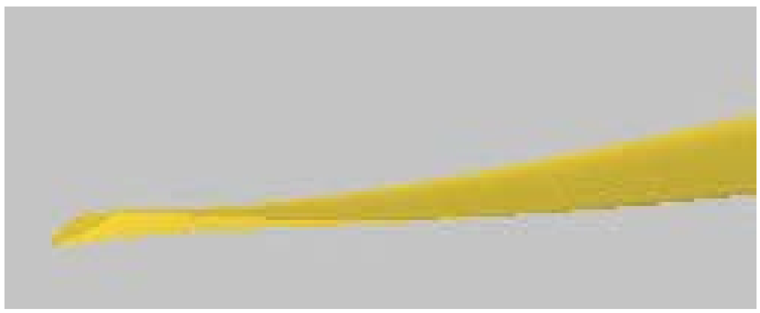

Figure 18. Bend-Twist Coupling of Blade for Passive Control

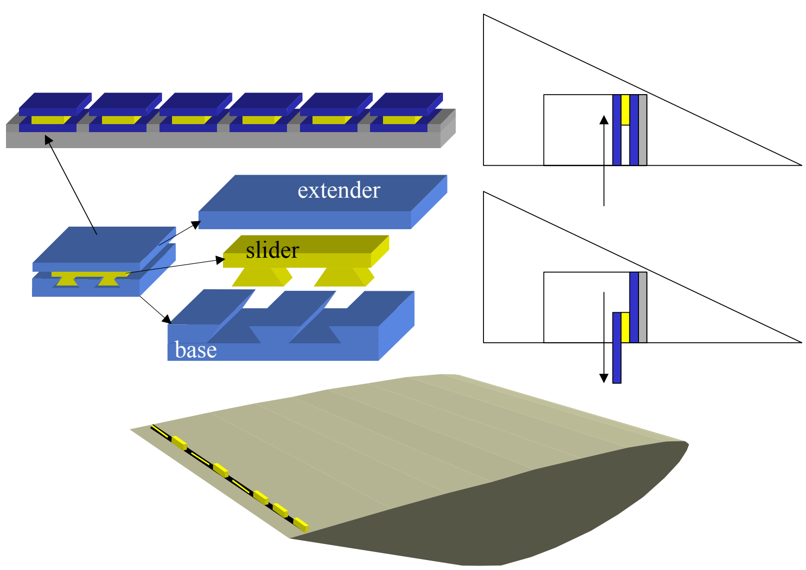

Figure 19. Microtabs on Trailing Edge of Blade for Active Control

Summary

WindPACT scaling and concept studies have looked at identifying issues and constraints associated with growing turbines from 1-10 MW. As part of the WindPACT project, the Blade System Design Studies developed innovations in manufacturing, materials, and design that would alleviate issues and provide breakthroughs in constraints identified for large blade production. This paper describes the recent and predicted trends in blade-size growth and new COE goals developed by DOE's wind program. It also provides a few results from WindPACT studies and blade research activities that facilitate larger blade development in ways that reduce COE.

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