SAND2018-9682C

DOE Optimized Carbon Fiber Project

Sandia Blade Workshop

August 29, 2018

Brandon Ennis, Chris Kelley, Brian Naughton (SNL)

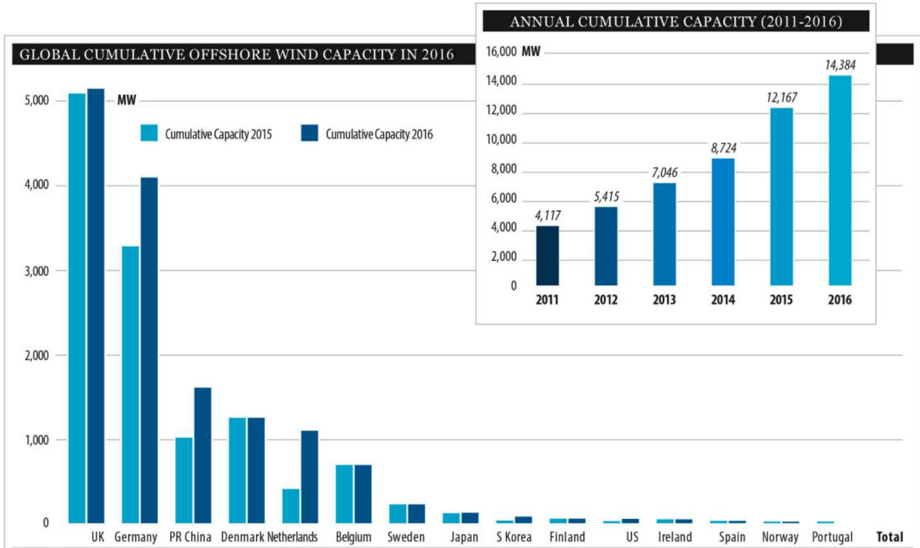
Bob Norris, Sujit Das, Dominic Lee (ORNL)

David Miller (MSU)

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Wind Energy Industry Trends

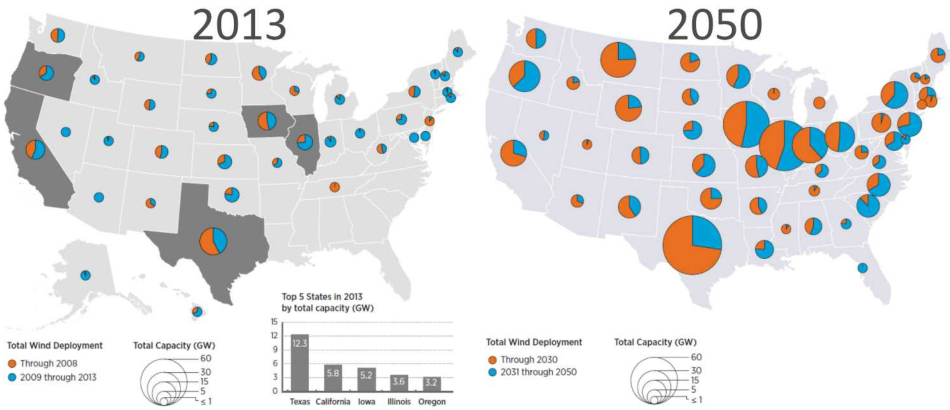
- New markets are opening as land and resource restrictions are faced across the world
- Offshore wind energy industry is growing globally
  - In 2016, the first offshore wind plant was installed in the U.S.
  - China has been installing offshore wind plants to access better wind resources
  - The first floating offshore wind plant was installed off the coast of Scotland to access deep-water sites
- Land-based wind turbines are being designed for lower wind resource sites as the better sites have been developed



	UK	Germany	PR China	Denmark	Netherlands	Belgium	Sweden	Japan	S Korea	Finland	US	Ireland	Spain	Norway	Portugal	Total
Total 2015	5,100	3,295	1,035	1,271	427	712	202	53	5	32	0.02	25	5	2	2	12,167
New 2016	56	813	592	0	691	0	0	7	30	0	30	0	0	0	-2	2,219
Total 2016	5,156	4,108	1,627	1,271	1,118	712	202	60	35	32	30	25	5	2	0	14,384

Source: GWEC

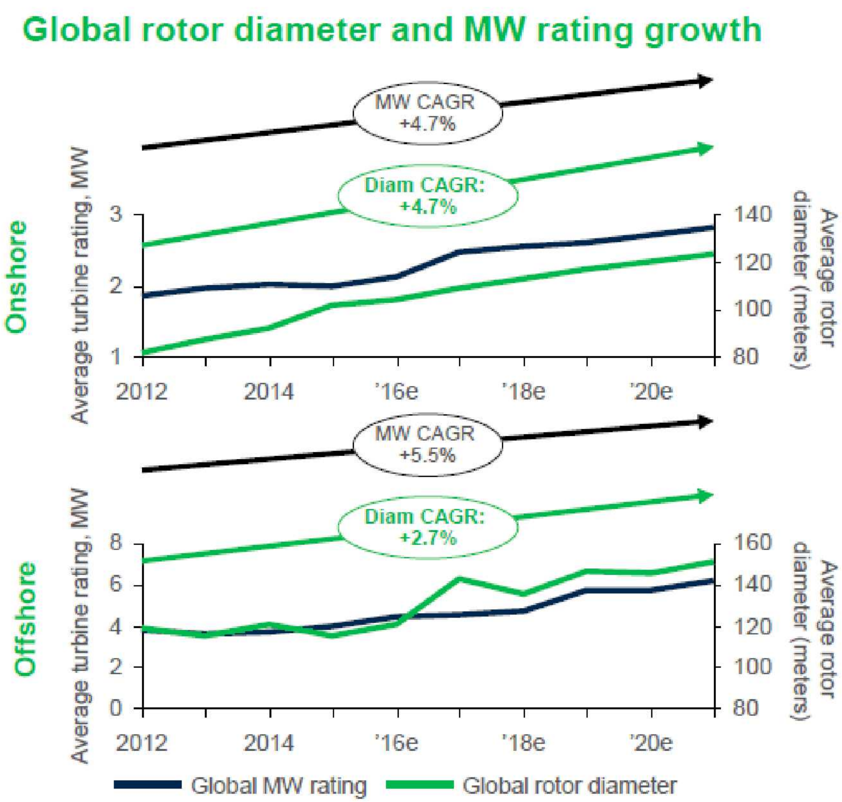
Source: Global Wind Energy Council

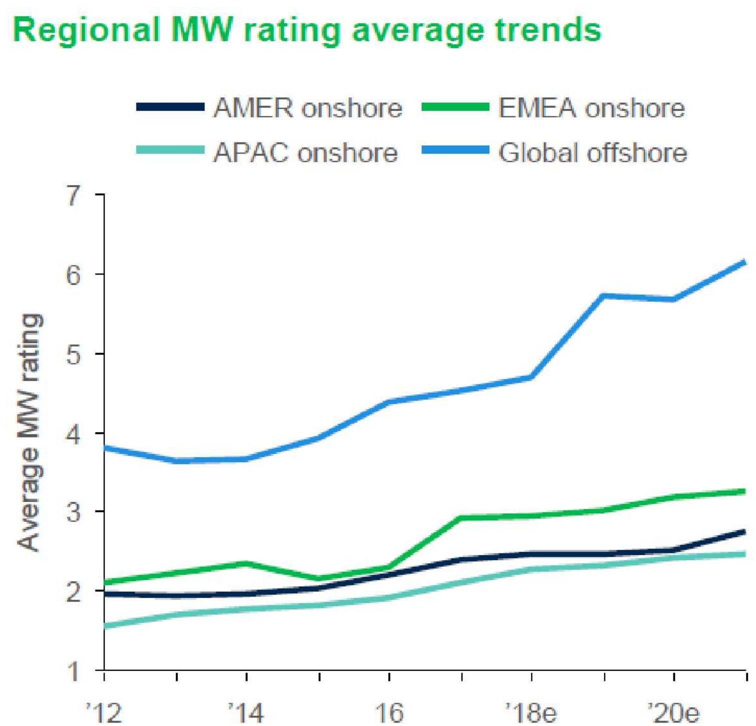


Scenario projections of U.S. wind energy installation through 2050
Source: DOE Wind Vision Report

Wind Turbine Blade Trends

- Wind turbines are getting larger, and blades are getting longer
- The growing offshore wind industry is enabling very large wind turbines
- Land-based wind turbine blades are getting longer for the same power rating, to access low-wind resource sites and for higher energy capture





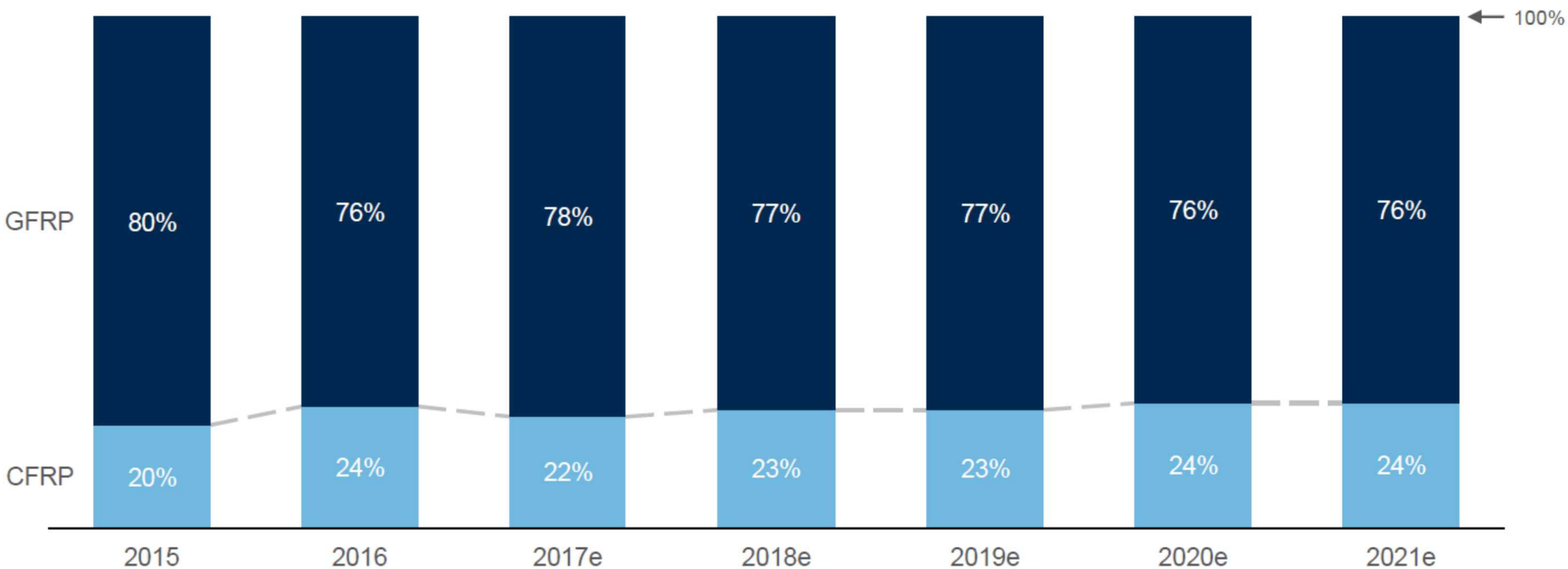
Source: MAKE
CAGR = Compound annual growth rate

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Wind Turbine Blade Material Trends

- Despite industry growth in blade length, carbon fiber usage in wind turbine spar caps is not predicted to grow over the next 5 years
- Stated reasons by turbine OEMs include price concerns, manufacturing sensitivities, and supply chain limitations/concerns
- High-modulus glass fiber has been pursued as an alternative

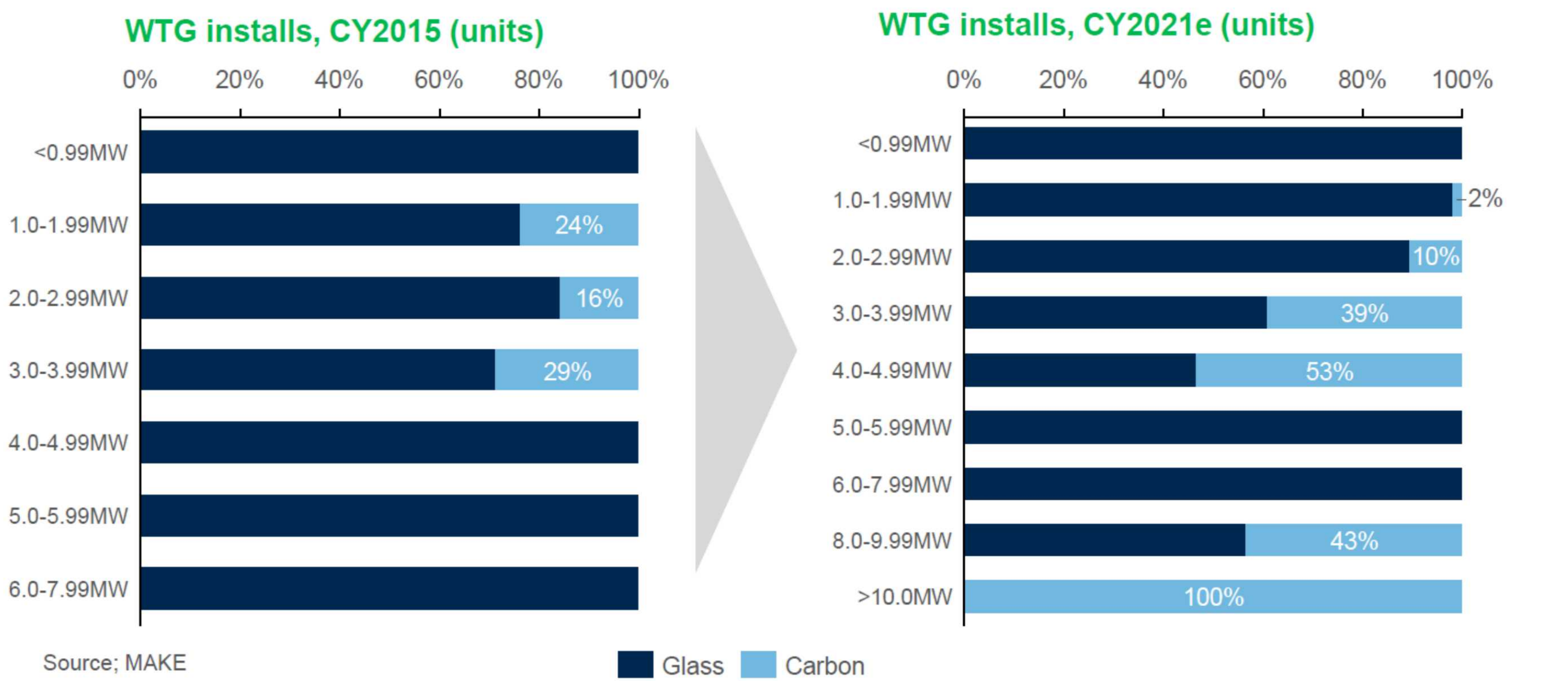
Global wind turbine installations, 2015-2021e (GW)



Source: MAKE

Wind Turbine Blade Material Trends

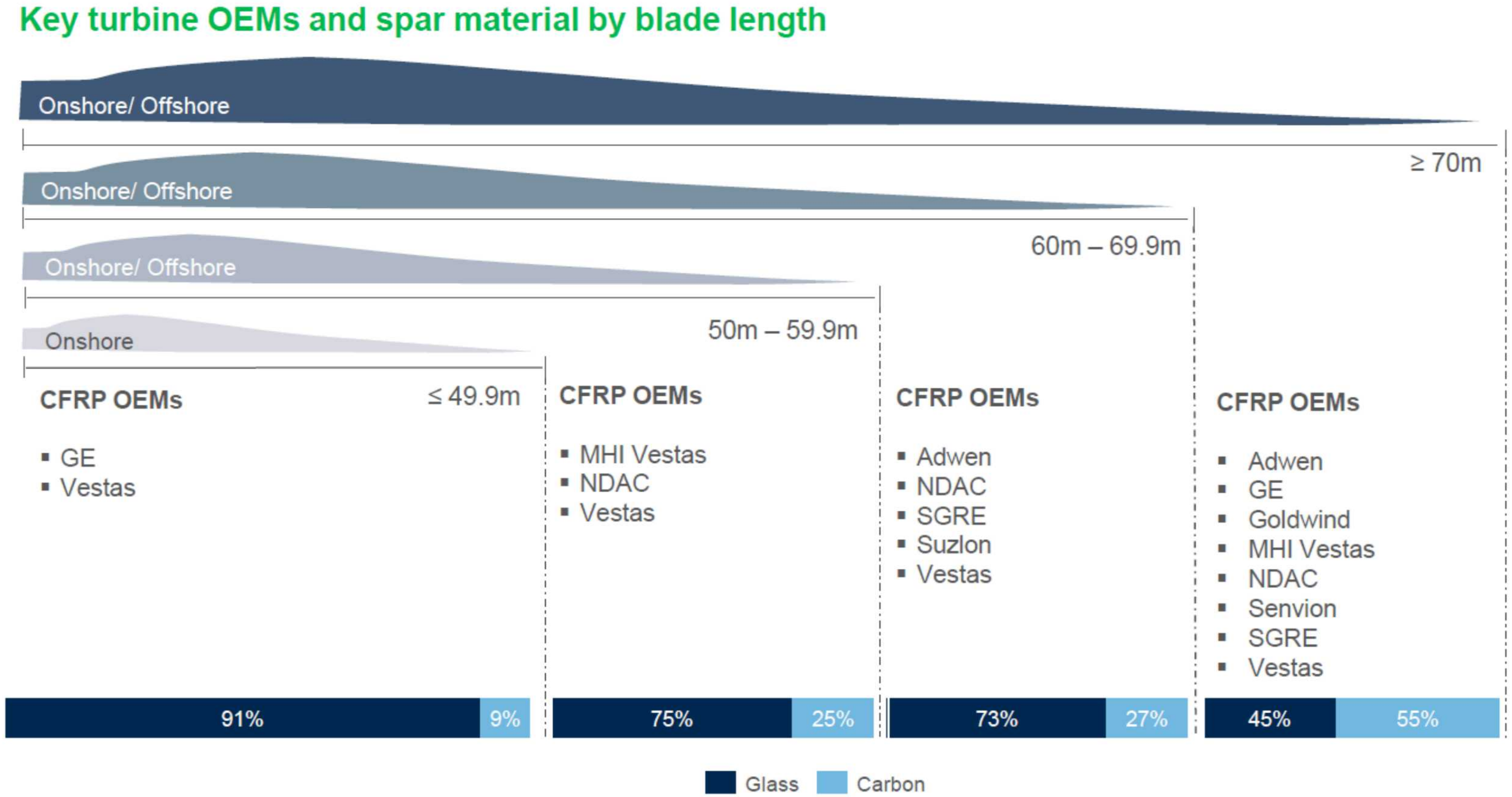
- In 2015, none of the installed 4-8 MW wind turbines utilized carbon fiber
- The usage of carbon fiber in blade designs is expected to increase for large, land-based machines and offshore wind turbines



Source; MAKE

Wind Turbine Blade Material Trends

- Carbon fiber blade designs produce a system value by reducing the blade and tower-top weight, however, OEMs have identified ways to design blades at all available lengths using only glass fiber



Note: % use of spar material on "current" and "prototype" turbine platforms in the market
Source: MAKE

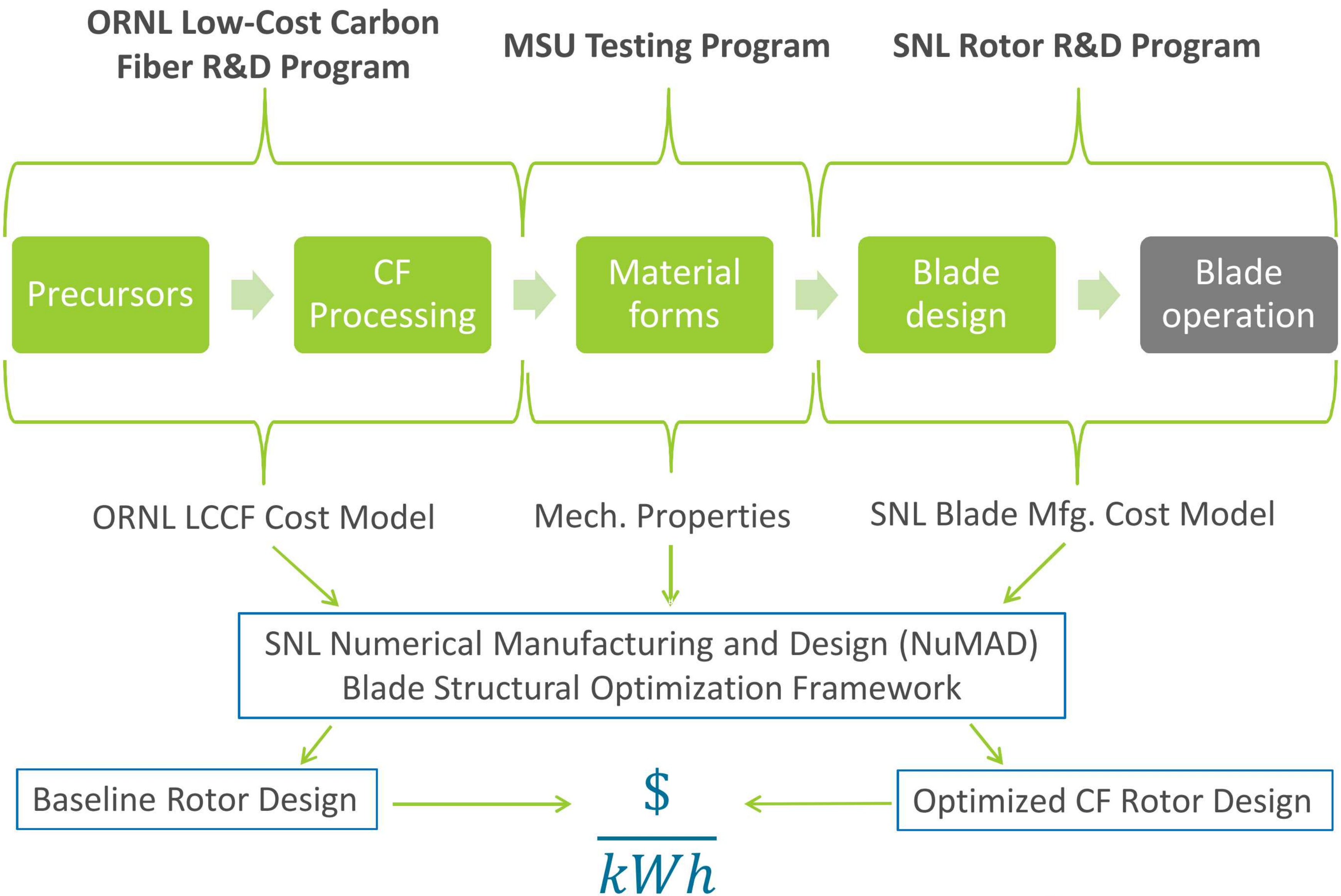
Optimized Carbon Fiber for Wind Energy Project

Sandia National Laboratories | Oak Ridge National Laboratory | Montana State University

The objective of this project is to assess the commercial viability of cost-competitive, tailored carbon fiber composites for use in wind turbine blades.

- Wind turbine blades have unique loading criterion, including nearly equivalent compressive and tensile loads
- The driving design loads for wind turbines vary for high and low wind speed sites, and based on blade length and weight – producing distinct material demands
- Composites for wind turbines are selected based on a cost-driven design, compared to the performance-driven aerospace industry

Project Overview



Material Testing

Material testing performed using industry baseline carbon fiber material and ORNL low-cost carbon fiber materials:

- **Industry baseline** (50k tow)
- **ORNL Low-cost carbon fiber**:
  - Precursor #1: Kaltex 457k tow
  - Precursor #2: Taekwang 363k tow
- Consistent properties can be achieved from the CFTF manufacturing processes, in addition to the process steps and precursor material being tailorable to generate desired material properties

Materials are tested in **(1) aligned strand infused** and **(2) pultruded** composite forms

- Ultimate tensile and compressive strength, fatigue testing

OAK RIDGE National Laboratory — CARBON FIBER TECHNOLOGY FACILITY

Lot Analysis for K20-HTU

Lot Number: TE4571150808

	Average	Standard Deviation
Tensile Strength (Ksi):	385.4	20.4
Tensile Modulus (Msi):	37.5	0.7
Elongation (%):	1.03	0.05
Linear Density (g/m):	14.71	2.18
Size (%)	1.18	0.38
Density (g/cc)	1.788	0.004
Date of Manufacture:	August 2015	

ORNL Material Properties for Kaltex Precursor (above) and Taekwang precursor (below)

OAK RIDGE National Laboratory — CARBON FIBER TECHNOLOGY FACILITY

Lot Analysis for T20-C

Lot Number: TE3631170205

	Average	Standard Deviation
Tensile Strength (Ksi):	389.5	9.3
Tensile Modulus (Msi):	36.8	0.3
Elongation (%):	1.08	0.03
Linear Density (g/m):	11.46	0.49
Size (%)	1.36	0.32
Density (g/cc)	1.720	0.003
Date of Manufacture:	February 2017	

Material Testing

1. Pultruded composite samples

Material	Composite Form	Layup	V_F [%]	E [GPa] 0.1-0.3%	UTS [MPa]	%, max	UCS [MPa]	%, min
ORNL T20 (Taekwang)	Pultrusion (third-party)	(0), 112017-5	51	123	846	0.69	-784	-0.64
Zoltek PX35	Pultrusion (third-party)	(0), 112017-6	53	114	1564	1.33	-897	-0.79
	Pultrusion (Zoltek)	(0)	62	142	2215	1.47	-	-
				138	-	-	-1516	-1.20

2. Aligned strand, infused composite samples

Material	Composite Form	Layup	V_F [%]	E [GPa] 0.1-0.3%	UTS [MPa]	%, max	UCS [MPa]	%, min
ORNL T20 (Taekwang)	Aligned strand	$(0)_5$ and $(0)_{10}$	50	126 (4)	968 (54)	0.75 (0.05)	-869 (46)	-0.69 (0.04)
ORNL K20 (Kaltex)	Aligned strand	$(0)_5$ and $(0)_{10}$	47	112 (6)	990 (49)	0.84 (0.06)	-872 (108)	-0.77 (0.44)
Zoltek PX35	Aligned strand	5.1 tows/cm	51	119	1760	1.48	-	-

Material Testing

1. Pultruded composite samples

Material	Composite Form	Layup	V_F [%]	E [GPa] 0.1-0.3%	UTS [MPa]	%, max	UCS [MPa]	%, min
ORNL T20 (Taekwang)	Pultrusion (third-party)	(0), 112017-5	51	123	846	0.69	-784	-0.64
Zoltek PX35	Pultrusion (third-party)	(0), 112017-6	53	114	1564	1.33	-897	-0.79
	Pultrusion (Zoltek)	(0)	62	142	2215	1.47	-	-
				138	-	-	-1516	-1.20

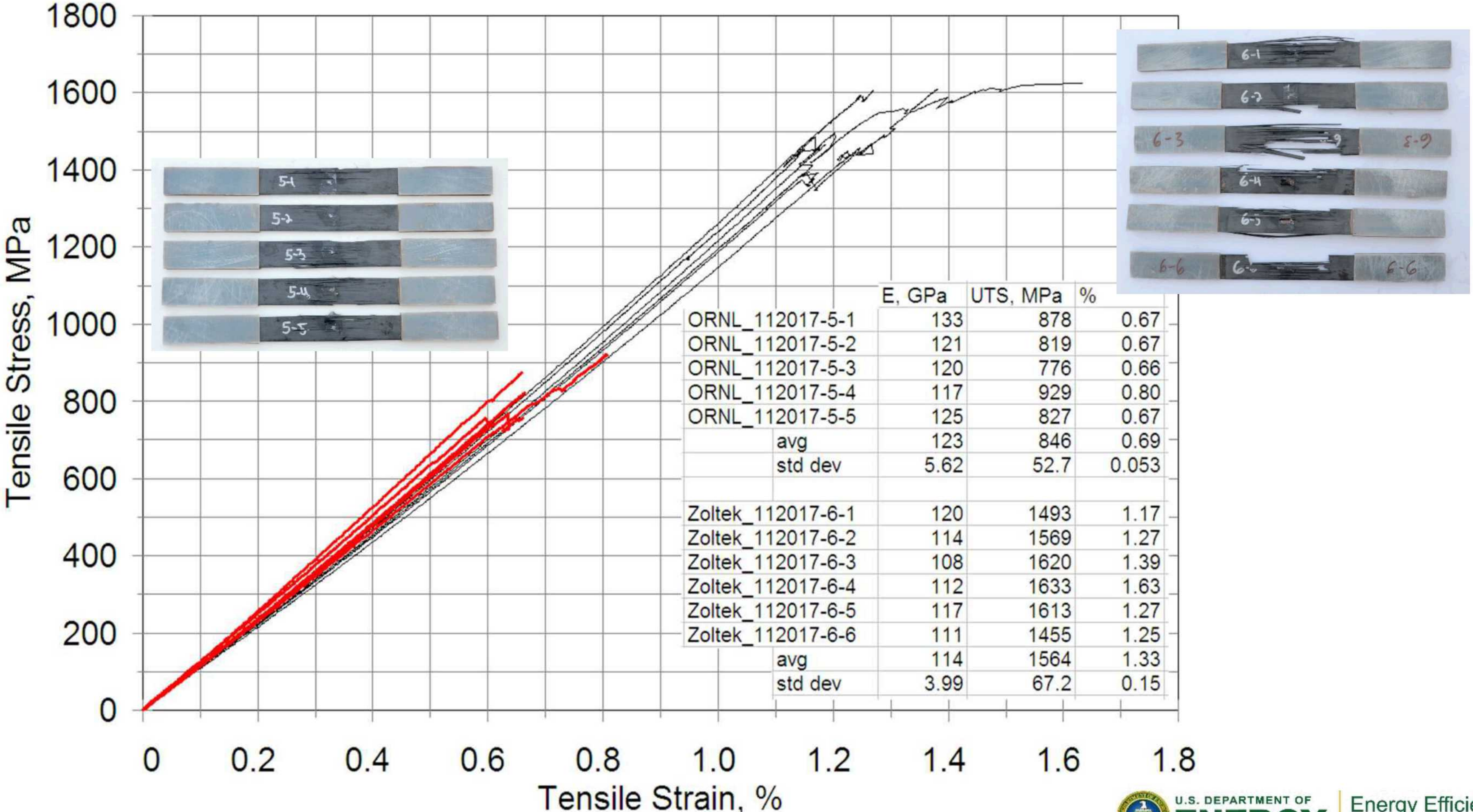
2. Aligned strand, infused composite samples

Material	Composite Form	Layup	V_F [%]	E [GPa] 0.1-0.3%	UTS [MPa]	%, max	UCS [MPa]	%, min
ORNL T20 (Taekwang)	Aligned strand	$(0)_5$ and $(0)_{10}$	50	126 (4)	968 (54)	0.75 (0.05)	-869 (46)	-0.69 (0.04)
ORNL K20 (Kaltex)	Aligned strand	$(0)_5$ and $(0)_{10}$	47	112 (6)	990 (49)	0.84 (0.06)	-872 (108)	-0.77 (0.44)
Zoltek PX35	Aligned strand	5.1 tows/cm	51	119	1760	1.48	-	-

Material Testing

Tensile tests on 112017-5 (ORNL T20) and 112017-6 (PX35) materials

- Ultimate tensile strength is substantially degraded in the heavy-tow fibers, however, compressive strength is more limiting for strength-driven blade designs



	E, GPa	UTS, MPa	%
ORNL_112017-5-1	133	878	0.67
ORNL_112017-5-2	121	819	0.67
ORNL_112017-5-3	120	776	0.66
ORNL_112017-5-4	117	929	0.80
ORNL_112017-5-5	125	827	0.67
avg	123	846	0.69
std dev	5.62	52.7	0.053
Zoltek_112017-6-1	120	1493	1.17
Zoltek_112017-6-2	114	1569	1.27
Zoltek_112017-6-3	108	1620	1.39
Zoltek_112017-6-4	112	1633	1.63
Zoltek_112017-6-5	117	1613	1.27
Zoltek_112017-6-6	111	1455	1.25
avg	114	1564	1.33
std dev	3.99	67.2	0.15

Material Testing

1. Pultruded composite samples

Material	Composite Form	Layup	V_F [%]	E [GPa] 0.1-0.3%	UTS [MPa]	%, max	UCS [MPa]	%, min
ORNL T20 (Taekwang)	Pultrusion (third-party)	(0), 112017-5	51	123	846	0.69	-784	-0.64
Zoltek PX35	Pultrusion (third-party)	(0), 112017-6	53	114	1564	1.33	-897	-0.79
	Pultrusion (Zoltek)	(0)	62	142	2215	1.47	-	-
				138	-	-	-1516	-1.20

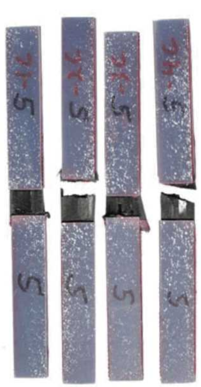
2. Aligned strand, infused composite samples

Material	Composite Form	Layup	V_F [%]	E [GPa] 0.1-0.3%	UTS [MPa]	%, max	UCS [MPa]	%, min
ORNL T20 (Taekwang)	Aligned strand	$(0)_5$ and $(0)_{10}$	50	126 (4)	968 (54)	0.75 (0.05)	-869 (46)	-0.69 (0.04)
ORNL K20 (Kaltex)	Aligned strand	$(0)_5$ and $(0)_{10}$	47	112 (6)	990 (49)	0.84 (0.06)	-872 (108)	-0.77 (0.44)
Zoltek PX35	Aligned strand	5.1 tows/cm	51	119	1760	1.48	-	-

Material Testing

Summary of compression tests: (with bonded on G10 tabs)

- UCS value for the heavy-tow ORNL fiber is similar to the commercial baseline material, which has 2% higher fiber volume fraction
- ORNL material has an effective 10% reduction in UCS
- (values are for third-party pultrusions, validation is being performed with aligned strand infusion samples)



-5-1C -5-2C -5-3C -5-4C

-6-1C -6-2C -6-3C -6-4C -6-5C -6-6C

ORNL T20 (third-party pultrusion)

Coupon	UCS [Mpa]	% Strain (calculated from 123 GPa)
112017-5C1	-713	-0.58
112017-5C2	-782	-0.64
112017-5C3	-699	-0.57
112017-5C4	-883	-0.72
Average	**-784**	**-0.60**
Std. Dev.	**36.3**	**0.031**

Zoltek PX35 (third-party pultrusion)

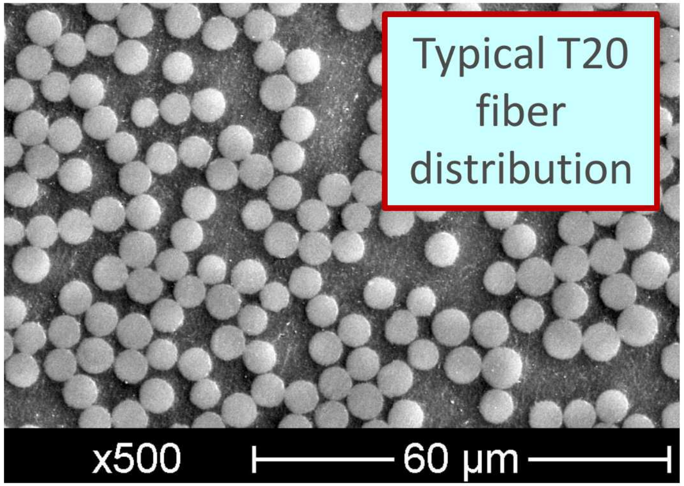
Coupon	UCS [MPa]	% Strain (calculated from 114 GPa)
112017-6C1	-874	-0.77
112017-6C2	-1041	-0.91
112017-6C3	-835	-0.73
112017-6C4	-894	-0.78
112017-6C5	-853	-0.75
112017-6C6	-887	-0.78
Average	**-897**	**-0.79**
Std. Dev.	**67.3**	**0.059**

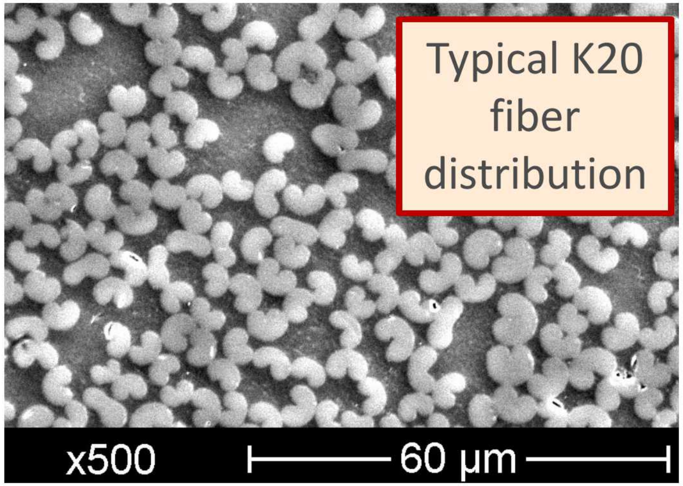
Material Testing

Aligned strand, infused composite samples

Material	Composite Form	Layup	V_F [%]	E [GPa] 0.1-0.3%	UTS [MPa]	%, max	UCS [MPa]	%, min
ORNL T20 (Taekwang)	Aligned strand	$(0)_5$ and $(0)_{10}$	50	126 (4)	968 (54)	0.75 (0.05)	-869 (46)	-0.69 (0.04)
ORNL K20 (Kaltex)	Aligned strand	$(0)_5$ and $(0)_{10}$	47	112 (6)	990 (49)	0.84 (0.06)	-872 (108)	-0.77 (0.44)

- ORNL Kaltex precursor has smaller fibers, heavier-tow, and kidney shaped fibers
- The non-round K20 material has approximately 6% higher UCS, but with greater variability (in early tests)

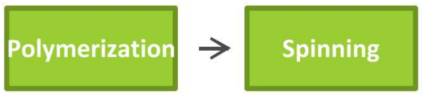




Carbon Fiber Cost Modeling

Precursor model (Baseline -- 7500 t/year line capacity)

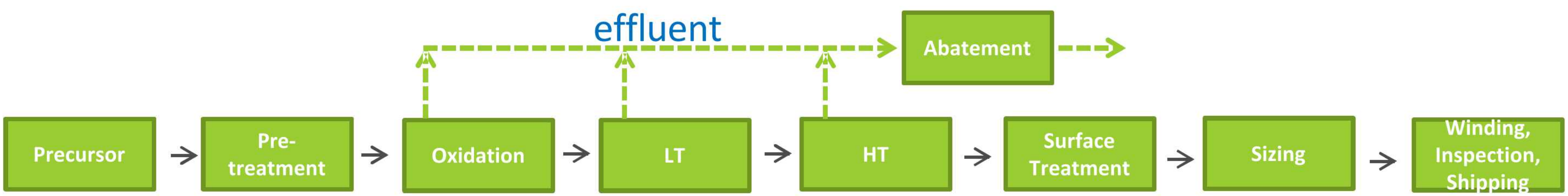
Evaluate precursor manufacturing at the level of two major process steps:



- User may examine any production volume from 1 - 45,000 t/y (7,500 t/y and 45,000 t/y used as low and high production volume)
- Test sensitivity of key parameters such as spin speed, process yield, raw material costs and ratios, energy vector costs, etc.

Carbon Fiber model (Baseline -- 1500 t/year line capacity)

Evaluate carbon fiber manufacturing at the level of nine major process steps:

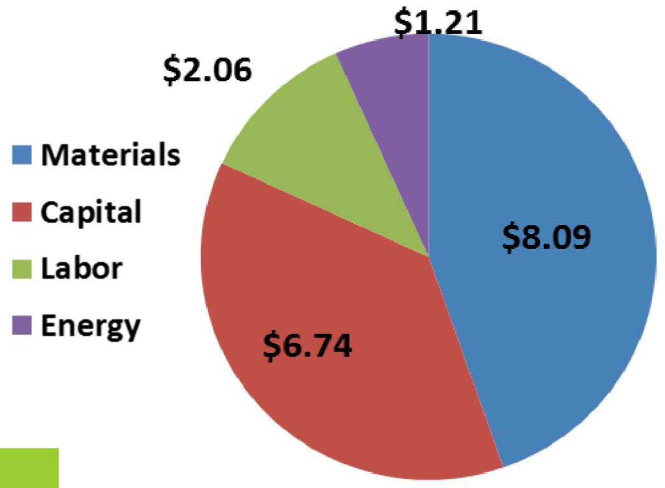


- User may examine any production volume from 1 - 18,000 t/y (economies of scale for a fully utilized carbon fiber lines between low and high production volume)
- Test sensitivity of key parameters such as line speed, residence times and temperatures of oxidation, LT, and HT, precursor cost, etc.

Carbon Fiber Cost Modeling

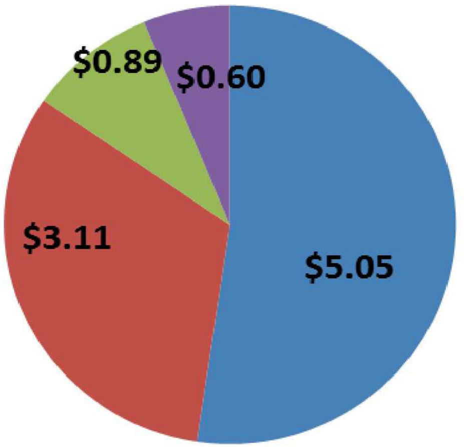
- Heavy-tow ORNL carbon fiber material is estimated to cost ~47% less than the baseline commercial material
- **$/UTS/kg** for the heavy-tow fiber is approximately **16% higher** than the baseline
- **$/UCS/kg** for the heavy-tow fiber is approximately **28% lower** than the baseline

Baseline Commercial CF: $18.11/kg



PARAMETER	BASELINE	HEAVY TEXTILE TOW
Precursor Cost	$1.65/lb	$1.02/lb
Tow Size	50K	457K
Tow Yield (g/m)	3.4	20
Tow Spacing	24 mm	50 mm
Strands/Line	120	58
Line Speed	211 kg/hr	461 kg/hr
Annual Prodn. Volume	1500 t/y	3290 t/y
Capital Investment	$58M	$58M

Heavy-Tow CF (K20): $9.65/kg



Carbon Fiber Cost Modeling

Parameter	Baseline $/kg (%)	Heavy Textile Tow $/kg (%)	Reduction $/kg (%)
Materials	$8.09 (44.7%)	$5.05 (52.3%)	$3.04 (38%)
Capital	$6.74 (37.2%)	$3.11 (32.3%)	$3.63 (54%)
Labor	$2.06 (11.4%)	$0.89 (9.2%)	$1.17 (57%)
Energy	$1.21 (6.7%)	$0.60 (6.2%)	$0.61 (50%)
TOTAL	**$18.11 (100%)**	**$9.65 (100%)**	**$8.46 (47%)**

- ✓ Lower precursor cost -- High output textile grade acrylic fiber used for clothing application today vs. specialty acrylic fiber
- ✓ Lower capital cost – Higher production capacity (heavy tow and higher conversion speed) for a significantly lower cost and simpler similar sized capital equipment available today (largest share of total cost reduction)
- ✓ Lower energy and labor cost – Economies of scale from an increased throughput
- ✓ Estimated heavy textile tow carbon fiber cost reduction potential is *conservative* as >3X increased throughput has been demonstrated at CFTF

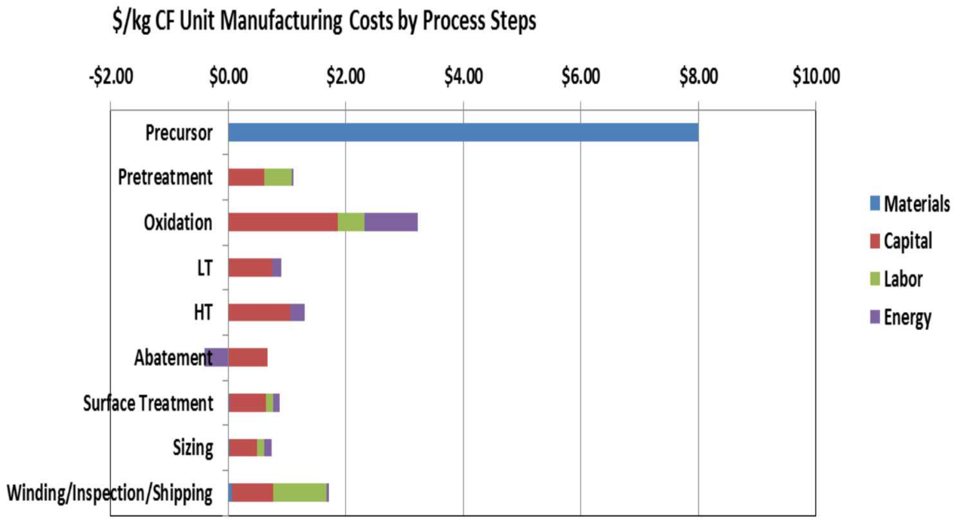
Carbon Fiber Cost Modeling

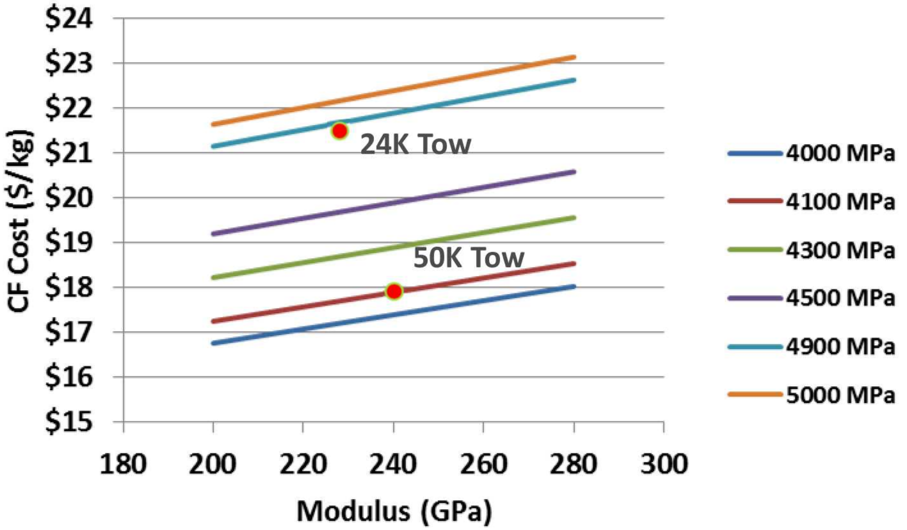
A cost model has been developed to estimate the carbon fiber cost sensitivity to mechanical properties:

- Fiber strength and modulus sensitivity calibrated to commercial 24K tow and 50K tow fiber costs
  - Used to correlate strength sensitivity to fiber cost
  - Fiber modulus correlated to; Low Temp. Furnace [1.14 MSI/100°C Increase], High Temp. Furnace [0.85 MSI/10 sec. Residence Time Increase] [0.24 MSI/1% Stretch Increase]
  - Linear fiber cost sensitivity to properties
  - Assumes no interdependency between fiber strength and modulus

➢ Fiber cost is more strongly correlated to material strength than modulus

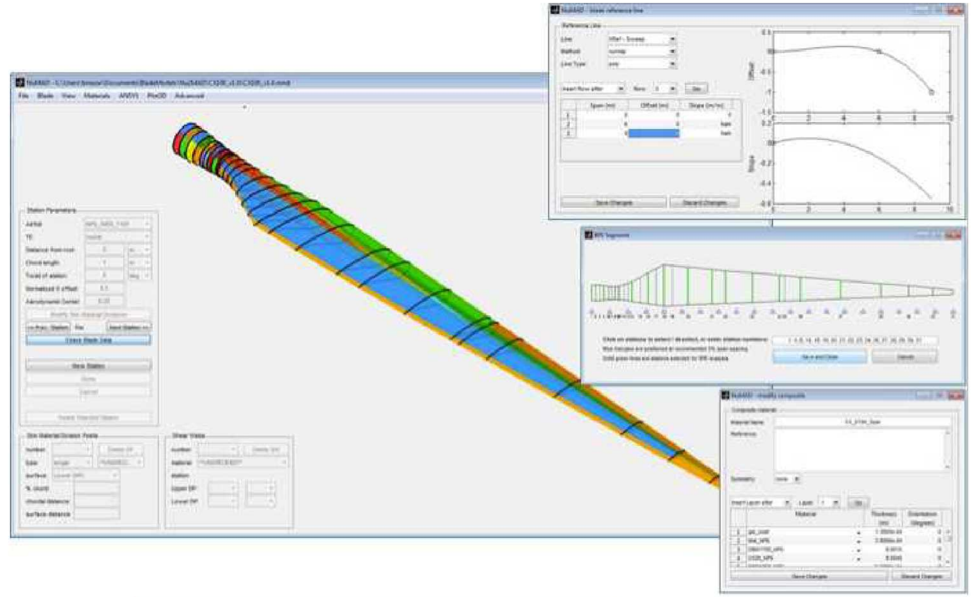
50K Tow Carbon Fiber Cost Distribution ($18.11/kg)

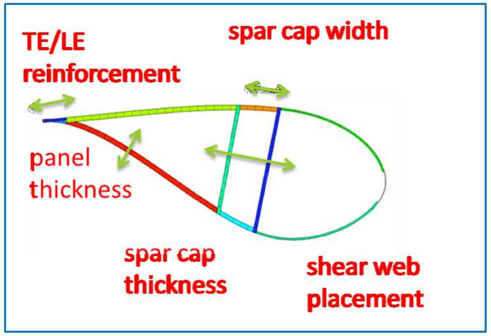




Wind Turbine Blade Optimization

- **Blade structural optimization** will be performed with <u>blade cost minimization</u> as the objective, including material and manufacturing cost contributions
- The **impact of material choices** will be assessed using cost estimates and tested mechanical properties
- Derived trends of material properties vs. cost will be used to more broadly address the question of **which properties matter most** for particular blade designs





Wind Turbine Blade Optimization

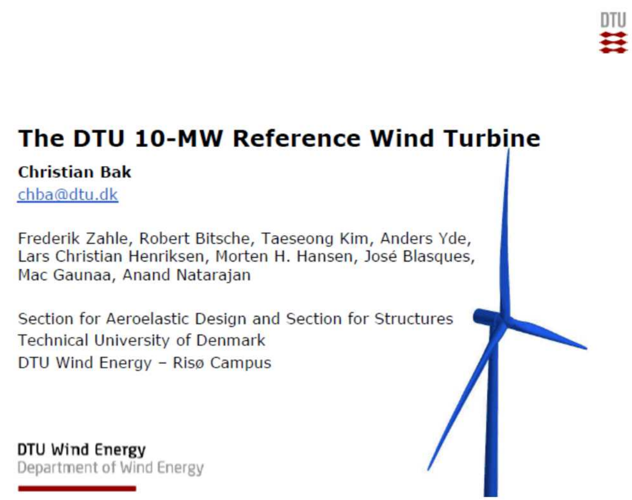
Structural and material optimization will be performed using **two reference blade models** that are representative of industry trends:

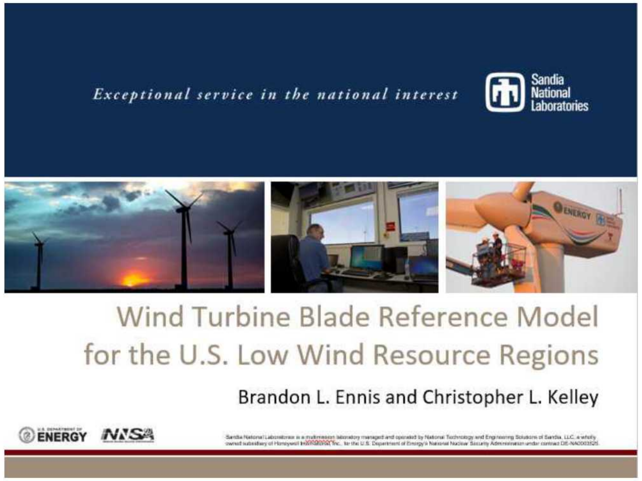
1. High wind resource (IEC class I-B), large wind turbine representative of future offshore wind turbines; **DTU 10 MW** aerodynamic design
2. Low wind resource (IEC class III-A), high energy capture wind turbine typical of development for the low wind speed sites across the U.S.; **SNL3.0-148** aerodynamic design

Blade structural optimization performed using NuMAD to produce **blade structural designs**:

- (**s1**) All-fiberglass reference design
- (**s2**) Cost-optimized design using carbon fiber cost and material property models

Ensures that the results cover the differences from driving load conditions and machine type





SNL3.0-148 Reference Blade Model

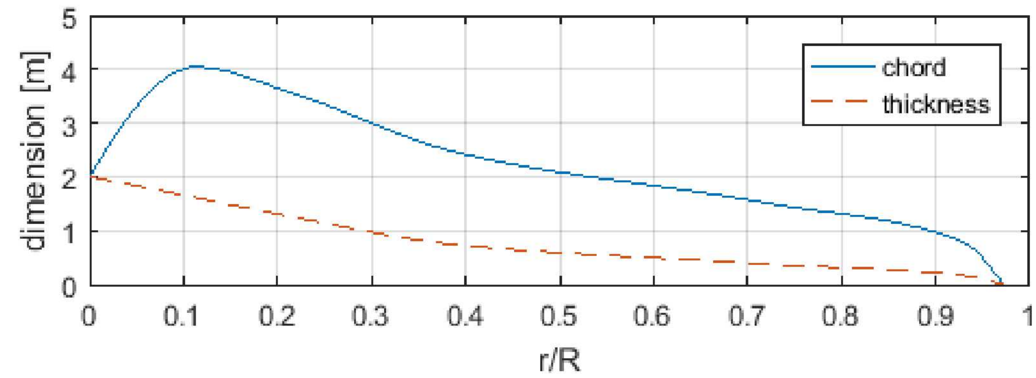
Publicly available reference model that is representative of the industry shift towards low specific power wind turbines for land-based sites. Can be used to identify and address the unique challenges faced for these machines, such as materials, controls, and aeroelastic coupling and tailoring.

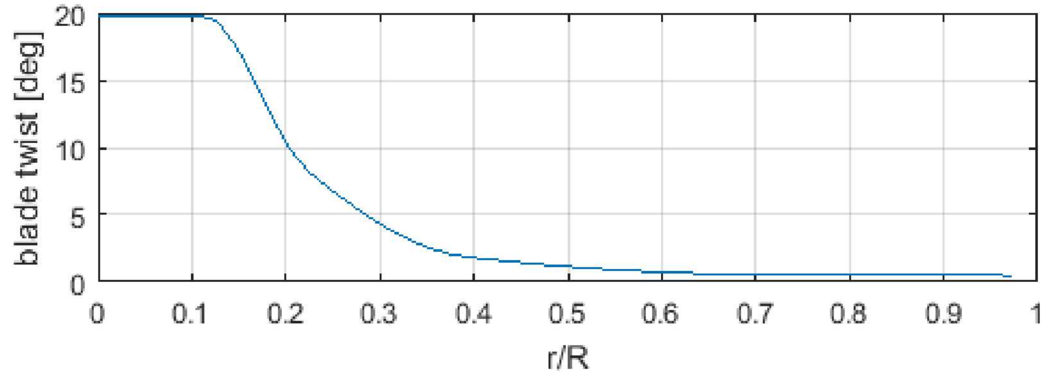
- 3 MW power rating
- 148m turbine diameter
- 72m blade length
- 175 W/m^2 specific power
- Three blade, upwind
- TSR = 9

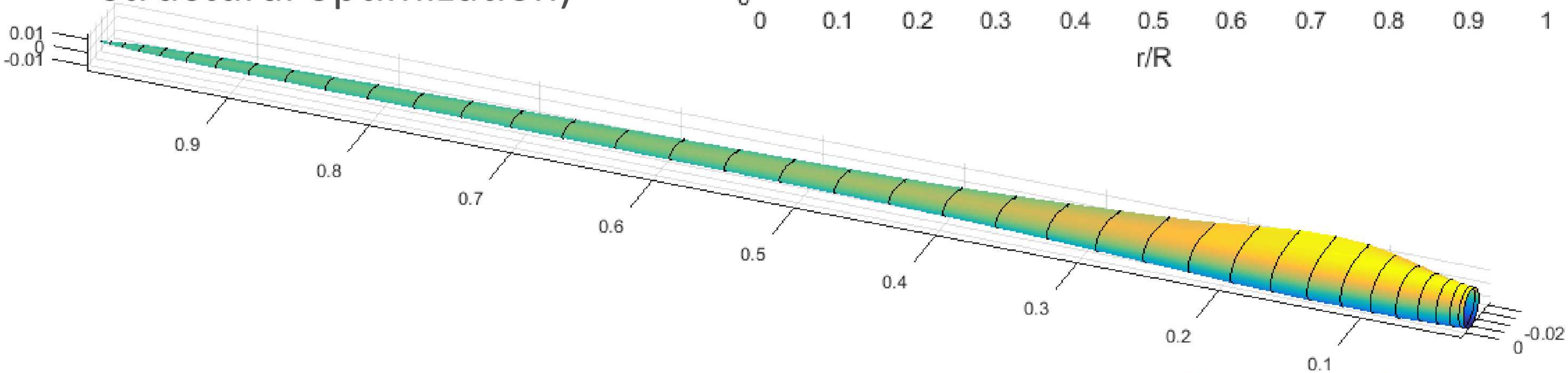
- Lightly loaded tip
  - Matches the root bending moment of the “optimal” induction design (a=1/3) while increasing energy capture through a longer blade
- Tower and turbine reference models from IEA Task 37 will be used with the blade model

SNL3.0-148 - 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% (will likely increase with structural optimization)

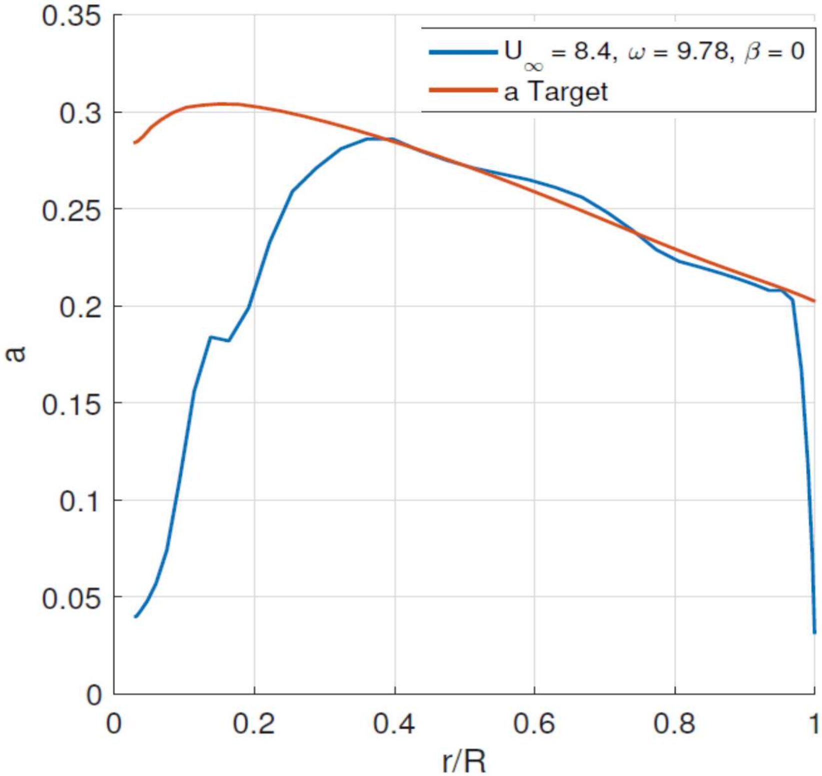


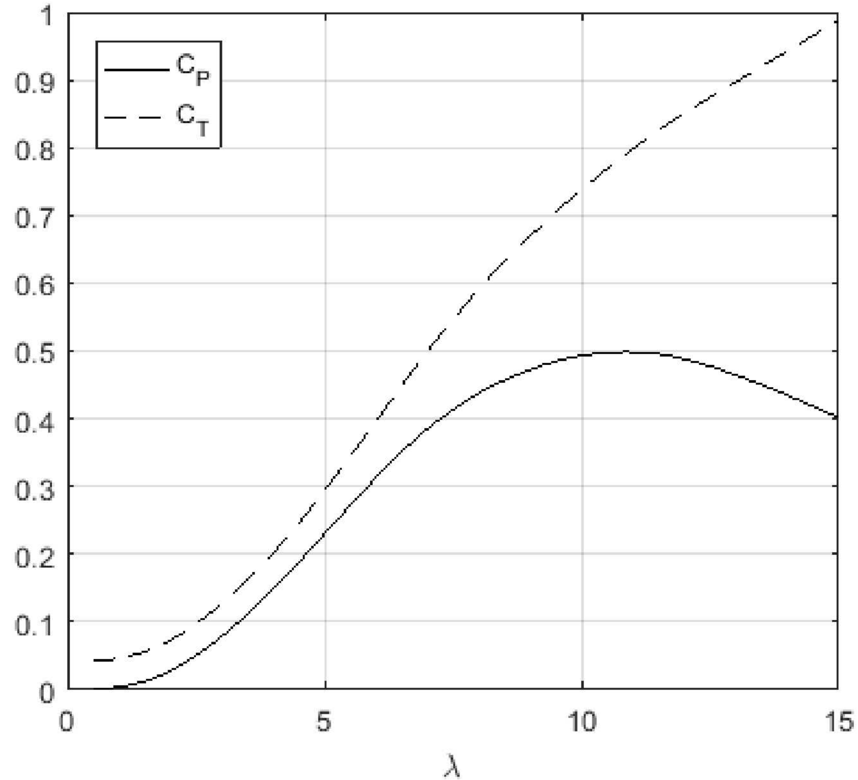




U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

SNL3.0-148 - 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

Summary

- Without further innovation, carbon fiber will continue to be utilized in certain wind turbine designs and represent a share of the industry
- OEMs continue to meet the load requirements of even the largest blades using all glass designs, motivated by the high cost of CFRP
- An innovative carbon fiber material purposefully optimized for the unique demands of a wind turbine may offer a more ideal solution than commercial, large-production carbon fiber or glass fiber alone
- This project seeks to address that perceivable material gap through an assessment of the effect of a range of material specification on blade cost