U.S. DEPARTMENT OF ENERGY | Energy Efficiency &

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Sandia National Laboratories

Oak Ridge National Laboratory

Montana State University

Optimized Carbon Fiber Composites for Wind Turbine Blades

Project Approach and Summary

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Optimized Carbon Fiber for Wind Energy Project

Sandia National Laboratories
OAK RIDGE National Laboratory
MONTANA STATE UNIVERSITY

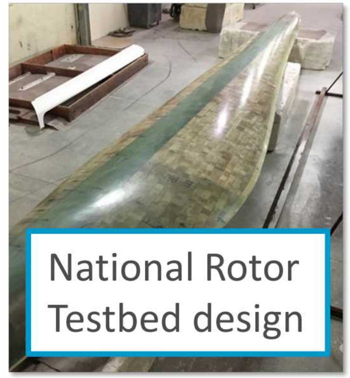
The objective of this project is to assess the commercial viability of cost-competitive, tailored carbon fiber composites for use in wind turbine blades.

- 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 – Team and Capabilities

Sandia National Laboratories

- DOE's designated rotor design group
- Experience in design, manufacturing, and testing of novel blade concepts



National Rotor Testbed design

Bend-twist coupled blade design

OAK RIDGE National Laboratory

- Composites development/applications and Leadership in DOE Low Cost Carbon Fiber Program
- Carbon Fiber Technology Facility for technology demonstration/licensing opportunities
- Cost-modeling utilized to guide focal activities

Carbon Fiber Technology Facility

MONTANA STATE UNIVERSITY

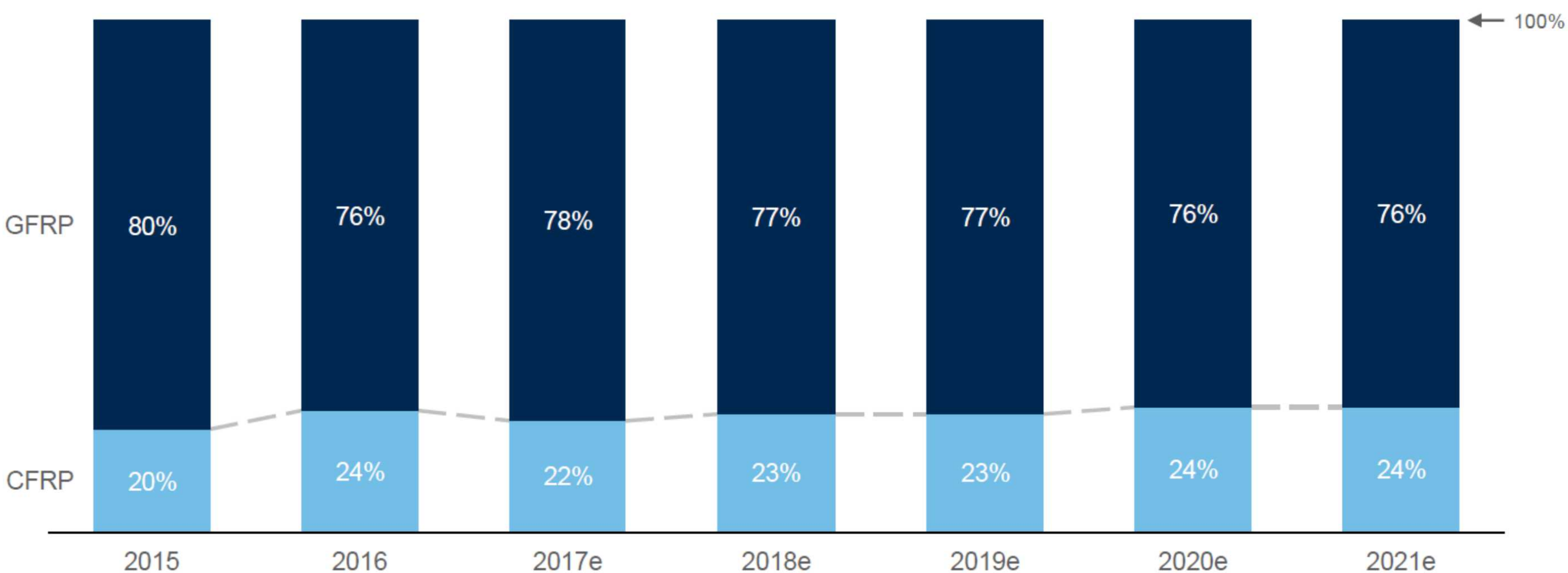
- Nearly 3 decades of experience and expertise in testing of composite materials for the SNL/MSU/DOE database
- Failure analysis methodologies utilized to characterize material failure progress during testing and post-mortem

Substructure test frame

Wind Turbine Blade Material Trends

- Despite industry growth in blade length, carbon fiber usage in wind turbine spar caps is not predicted to grow in the foreseeable future
- 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

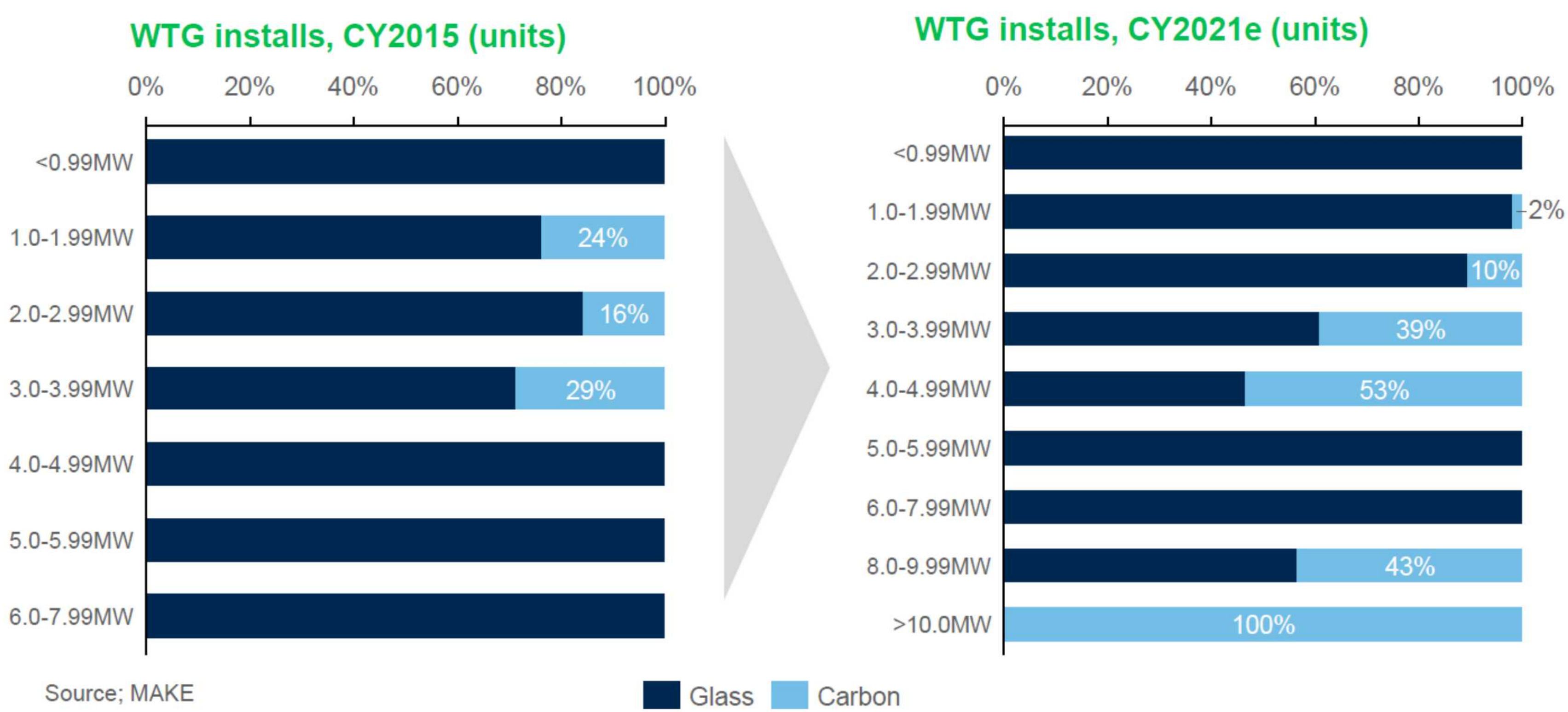
Global wind turbine installations, 2015-2021e (GW)



Source: MAKE

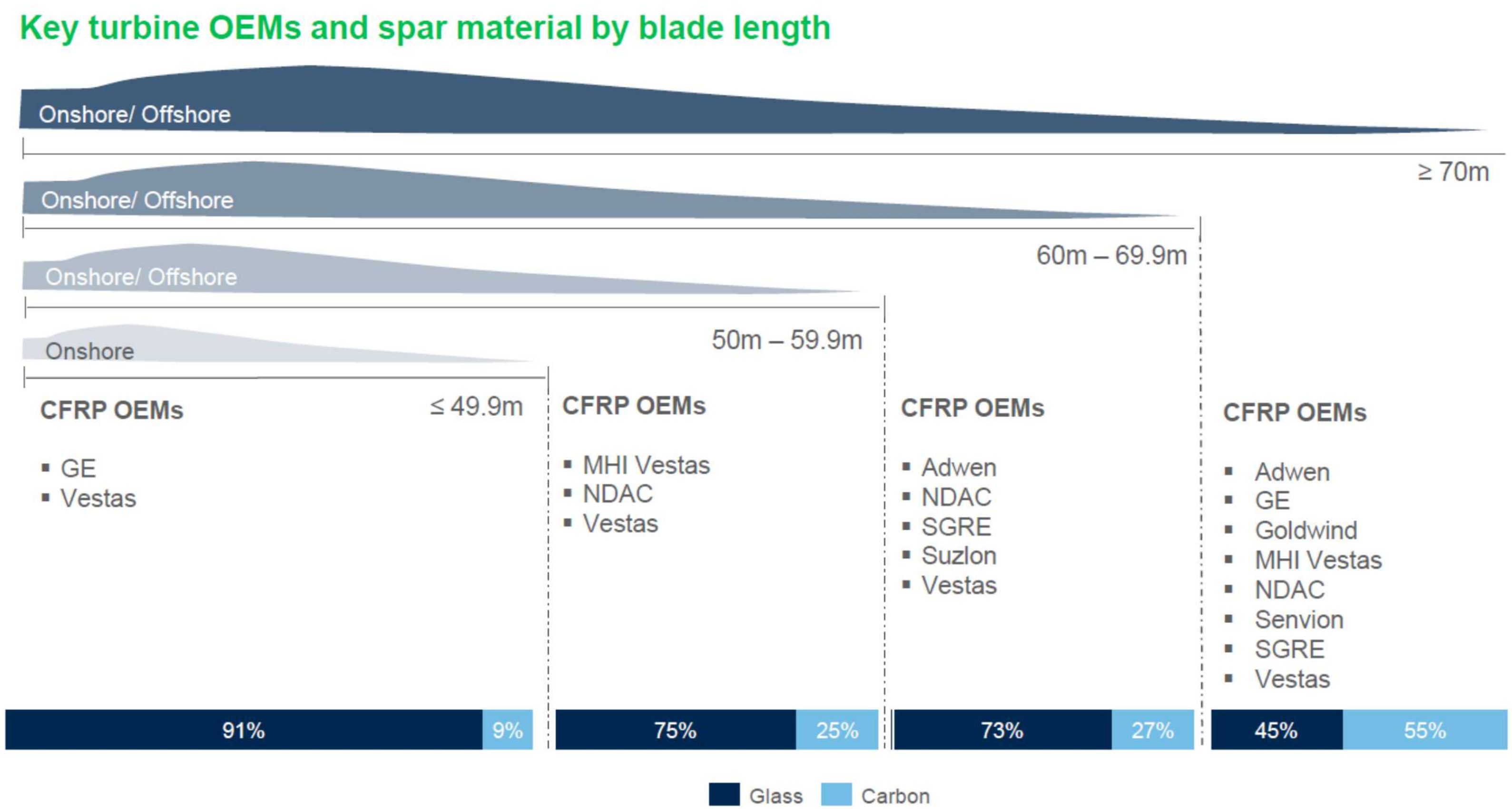
Wind Turbine Blade Material Trends

- 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



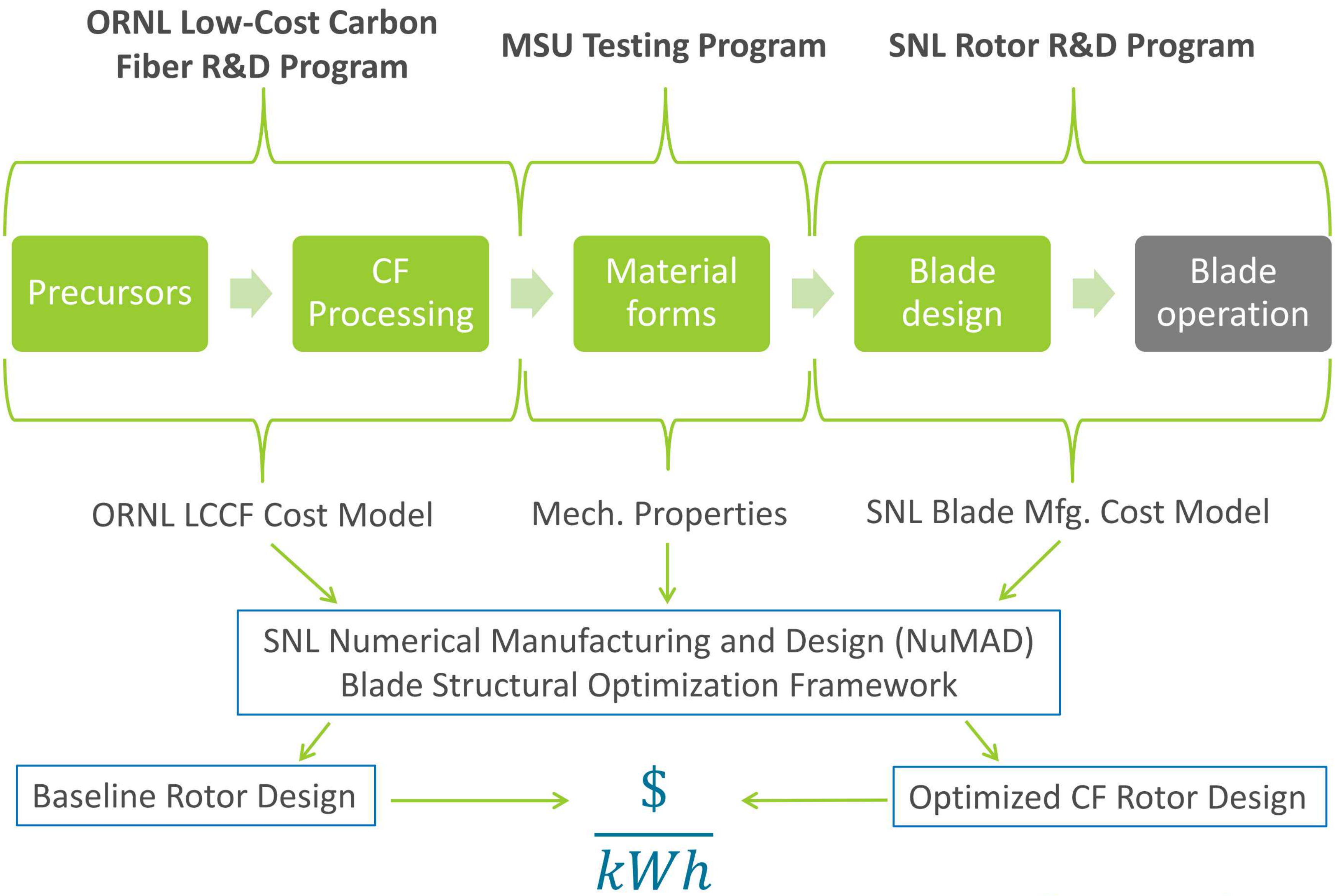
Wind Turbine Blade Material Trends

- 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



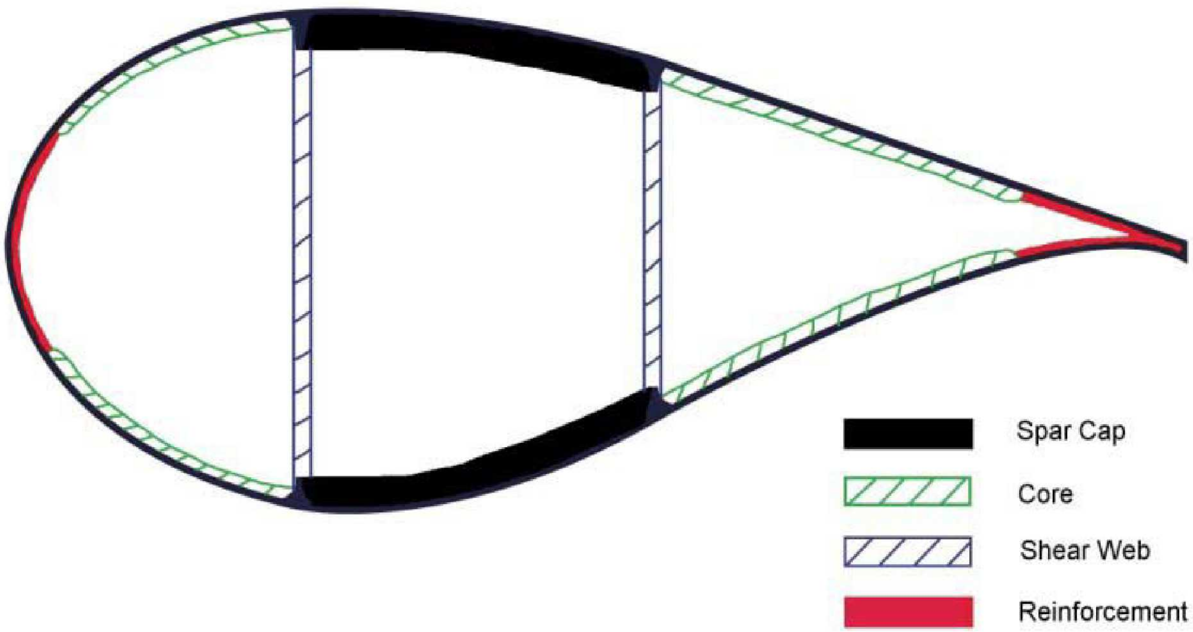
Note: % use of spar material on "current" and "prototype" turbine platforms in the market
Source: MAKE

Project Approach and Key Deliverables



Project Overview – Study Definition

- This project has studied the impact of novel and commercial carbon fiber materials on the main structural member of blades, the spar cap



Material Testing

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

- **Industry baseline** (50k tow)
- **ORNL Low-cost carbon fiber**:
  - Precursor #1: Kaltex 457k tow
  - Precursor #2: Taekwang 363k tow

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

- MSU aligned strand to minimize manufacturing bias and enable direct material comparison
- Pultrusion considered as the true form for carbon fiber in wind turbine blades

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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)

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Lot Analysis for T20-C

Lot Number: TE3631170205

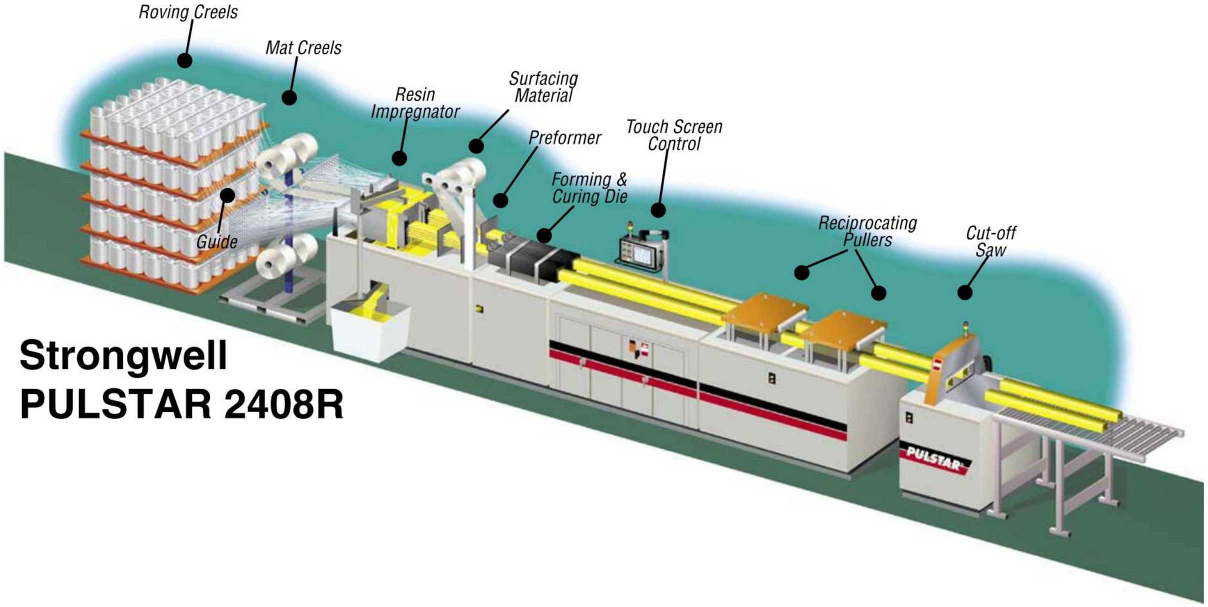
	Average	Standard Deviation
Tensile Strength (Ksi):	389.5	9.3
Tensile Modulus (Msi):	36.8	0.3
Elongation (%):	1.08	0.03
Linear Density (g/m):	11.46	0.49
Size (%)	1.36	0.32
Density (g/cc)	1.720	0.003
Date of Manufacture:	February 2017	

Material Testing

- The project team worked with a third-party pultruder to obtain pultruded samples of the CFTF heavy-tow materials
- No obvious differences from the Industry Baseline carbon fiber







Strongwell PULSTAR 2408R

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 K20 (Kaltex)	Pultrusion (third-party)	(0), 112017-5	51	123	846	0.69	-769	-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	-	-	-1505	-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 (0.10)
Zoltek PX35	Aligned strand	5.1 tows/cm	51	119 (4)	1726 (93)	1.48 (0.08)	-906 (44)	-0.74 (0.04)

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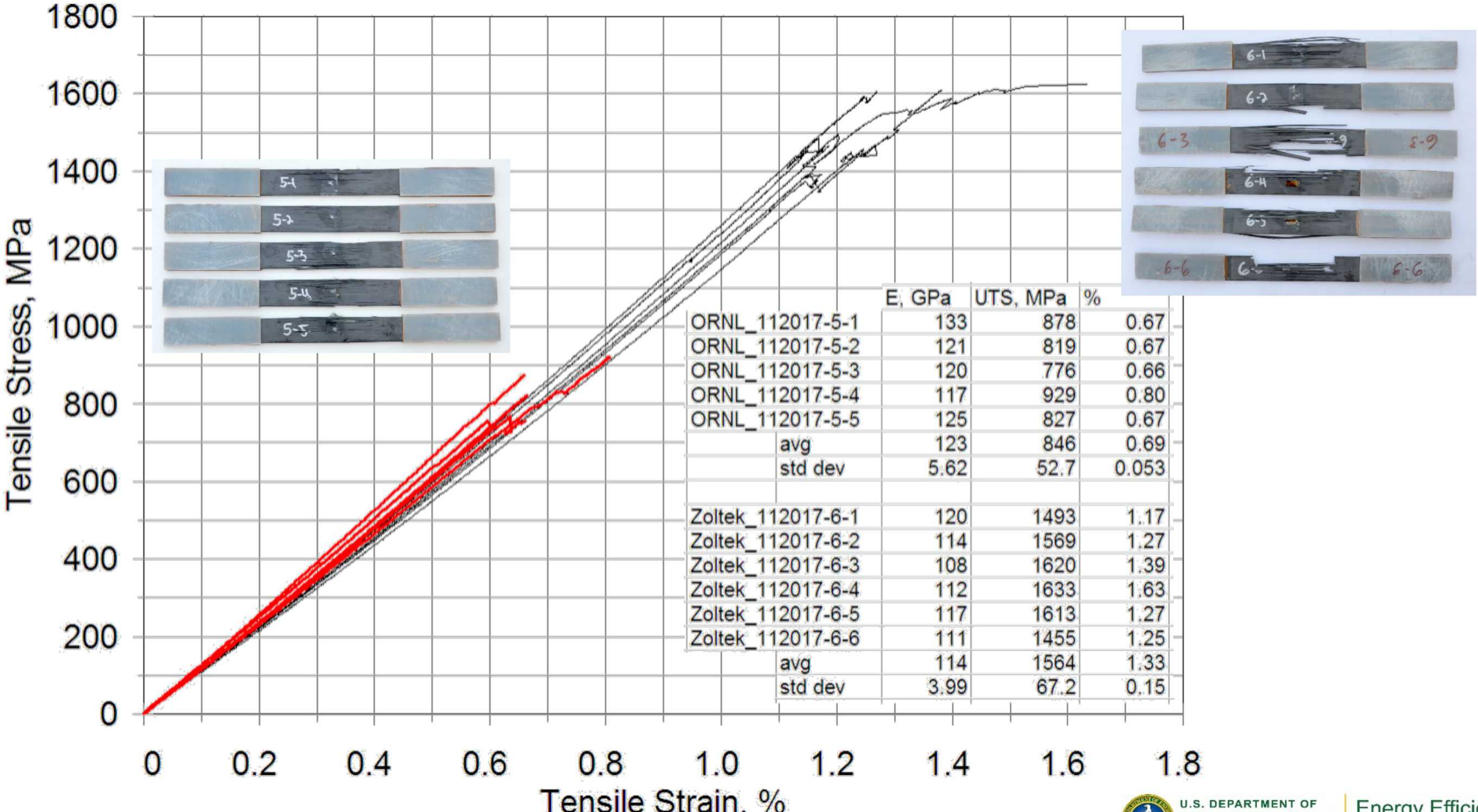
Material Testing

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 critical for wind turbine blade design



	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

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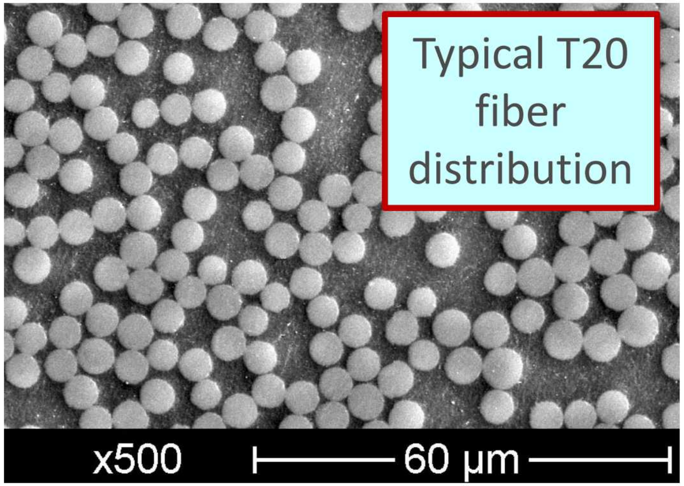
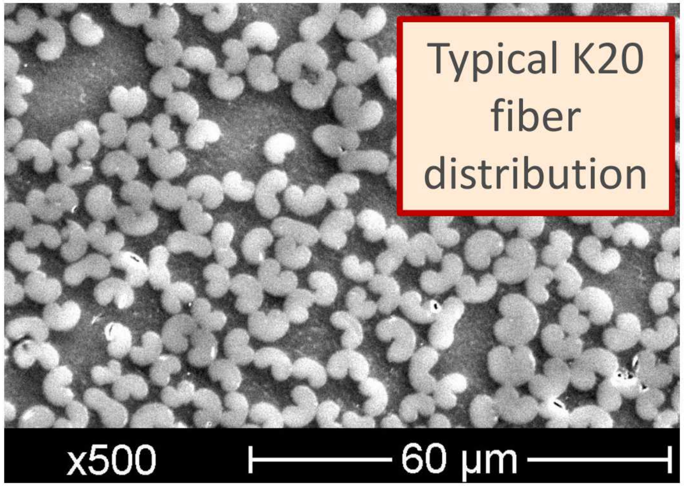
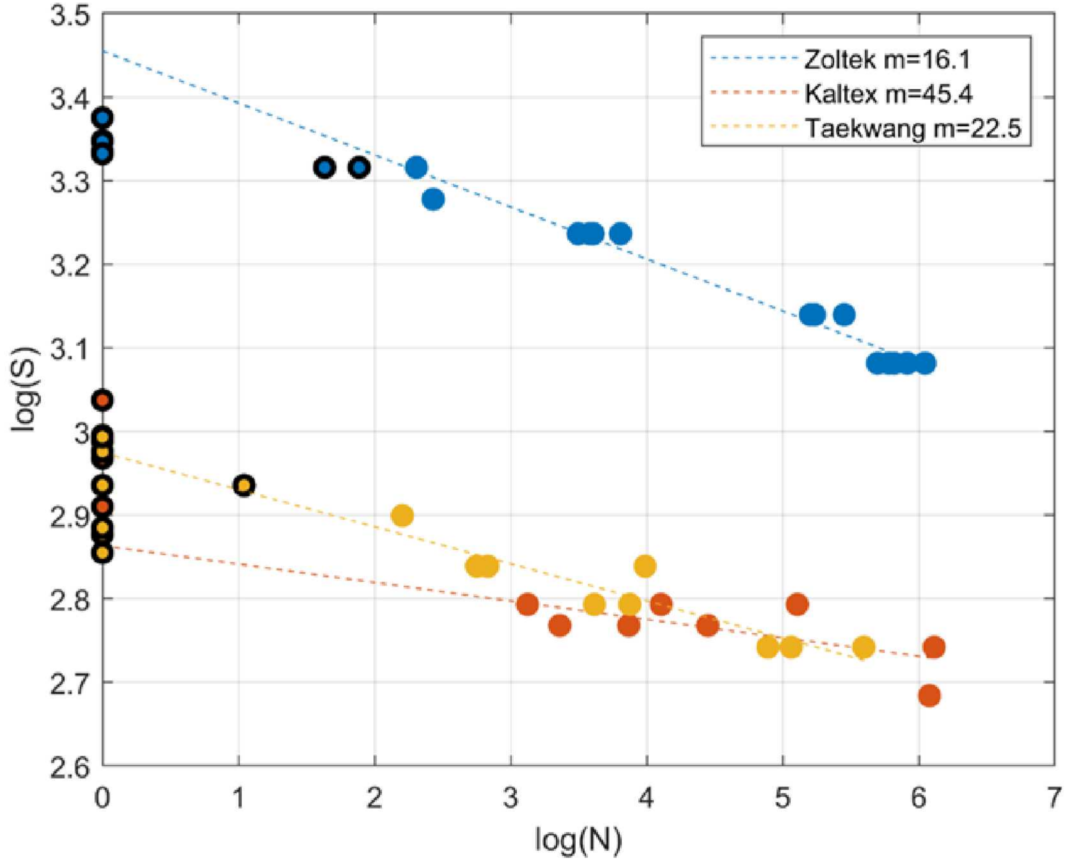
- ORNL Kaltex precursor has smaller fibers, heavier-tow, and kidney shaped fibers
- The non-round K20 material has approximately 6% higher UCS, but with greater variability (in early tests)





Material Testing

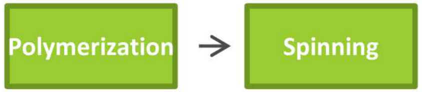
- Tension-tension fatigue tests at a single load cycle (R=0.1) were performed to compare the fatigue characteristics
  - **Zoltek 62% fiber volume fraction pultrusion** compared with the **textile carbon fiber materials in ~50% fiber volume fraction infusions**
- The textile carbon fiber materials were relatively fatigue insensitive



Carbon Fiber Cost Modeling

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

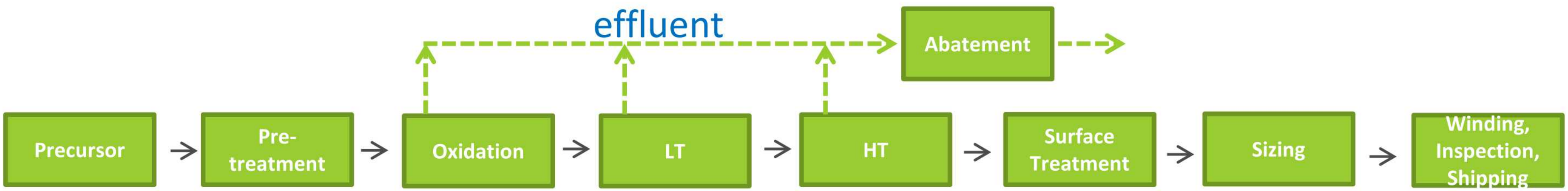
Evaluate precursor manufacturing at the level of two major process steps:



- 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

- The ORNL heavy-tow carbon fiber material is estimated to cost between 38-57% less than the industry baseline
- The (current) scenario represents the material processing as tested
- The (full-utilization) scenario is accounting for realistic commercial processing

PARAMETER	BASELINE	HEAVY TEXTILE TOW (current)	HEAVY TEXTILE TOW (full-utilization)
Precursor Cost	$3.63/kg	$2.24/kg	$2.24/kg
Tow Size	50K	457K	457K
Tow linear density (g/m)	3.7	15	15
Tow Spacing	24 mm	50 mm	24 mm
Strands/Line	120	58	120
Line Speed	9 m/min (211 kg/hr)	7 m/min (338 kg/hr)	8.45 m/min (843 kg/hr)
Annual Prodn. Volume	1500 tonnes/yr	2400 tonnes/yr	6000 tonnes/yr
Capital Investment	$58MM	$58MM	$58MM
Final Fiber Cost	$17.98/kg	$11.19/kg	$7.82/kg

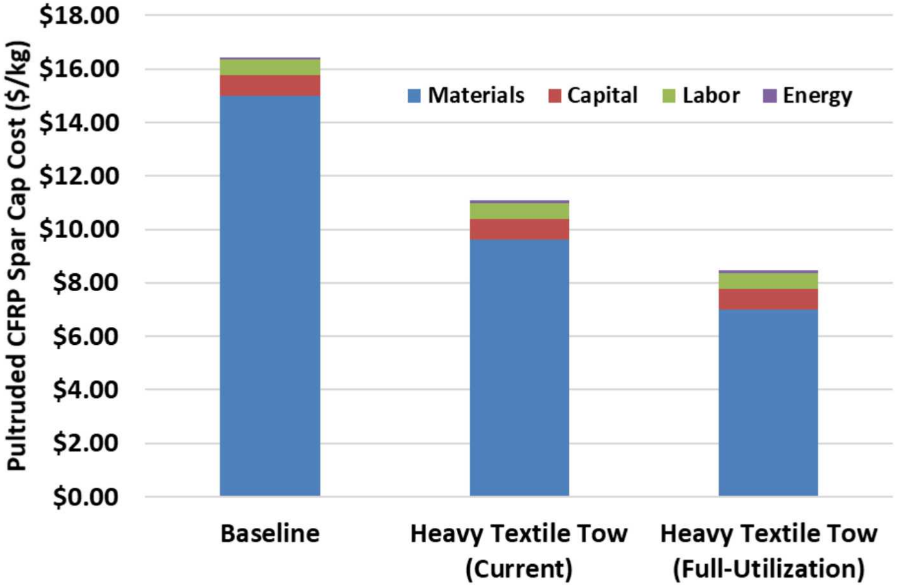
Carbon Fiber Cost Modeling

Parameter	Baseline $/kg (%)	Heavy Textile Tow (full-utilization) $/kg (%)	Reduction %
Materials	$8.09 (45.0%)	$5.05 (64.6%)	38%
Capital	$6.62 (36.8%)	$1.91 (24.4%)	71%
Labor	$2.06 (11.5%)	$0.47 (6.0%)	77%
Energy	$1.20 (6.7%)	$0.39 (4.9%)	68%
TOTAL	**$17.98 (100%)**	**$7.82 (100%)**	**57%**

- ✓ 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

Pultruded Composite Cost Model

- Pultrusion is arguably one of the most stable, repeatable and cost-competitive composite manufacturing processes of continuous fiber composites
- A pultrusion cost model was developed as part of the project to enablecost comparisons of the manufactured blade
- Pultruded form model input properties were estimated using the testing results and cost estimates and models from the project work



$$E = V_f E_f + (1 - V_f) E_m$$

$$S_{ut} \approx S_{ft} T_f \left[V_f + (1 - V_f) \, {}^{E_m}\!/_{E_f} \right]$$

$$S_{uc\,(vf2)} \approx \left({}^{S_{uc}}\!/_{S_{ut}} \right)_{vf1} S_{ut\,(vf2)}$$

Model Input Values for Spar Cap Materials

- Carbon fiber composites have significantly higher properties than fiberglass

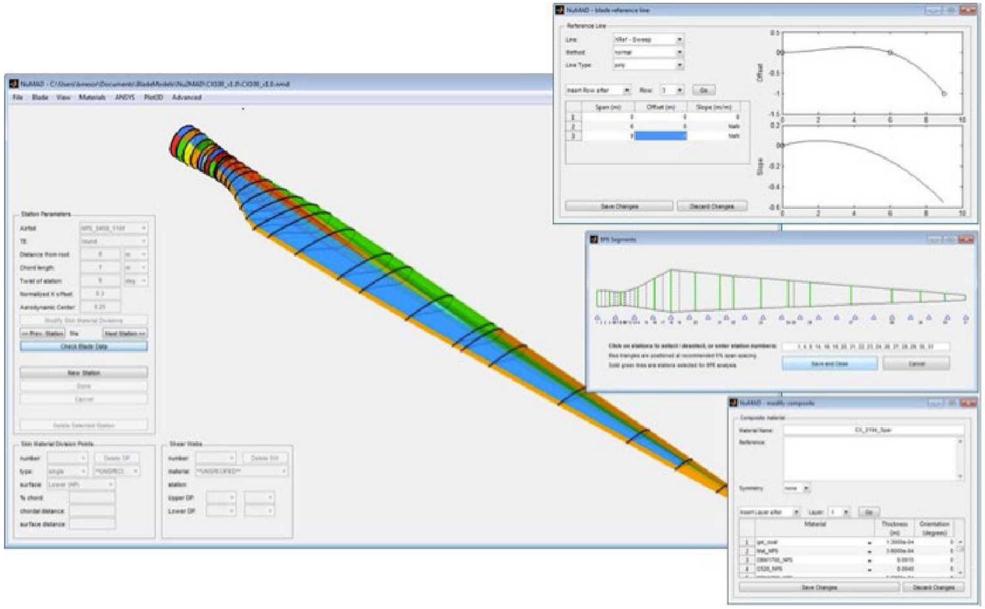
Material	Vf	E [GPa]	UTS [MPa]	UCS [MPa]	Cost [/kg]
Industry Baseline CFRP pultrusion	0.68	157.6	2427.3	-1649.2	$16.44
Heavy-Tow CFRP pultrusion	0.68	160.6	1508.5	-1315.0	$8.38 - $11.01
Fiberglass infusion	0.55	42.8	1169.7	-743.5	$2.06

- The heavy-tow carbon fiber shows cost-specific improvements in mechanical properties over the industry baseline carbon fiber over the cost estimate range

Material	UTS(MPa)/$/kg	%	UCS(MPa)/$/kg	%	E(GPa)/$/kg	%
Industry Baseline	147.6	**100**	-100.3	**100**	9.6	**100**
Heavy-Tow (full-utilization)	180.0	**122**	-156.9	**156**	19.2	**200**
Heavy-Tow (current)	137.0	**93**	-119.4	**119**	14.6	**152**
Fiberglass infusion	437.9	**297**	-311.7	**311**	20.8	**217**

Wind Turbine Blade Optimization

- **Blade structural optimizations** have been performed with blade material cost minimization as the objective
- The **impact of material choices** has been assessed using the developed cost estimates and 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

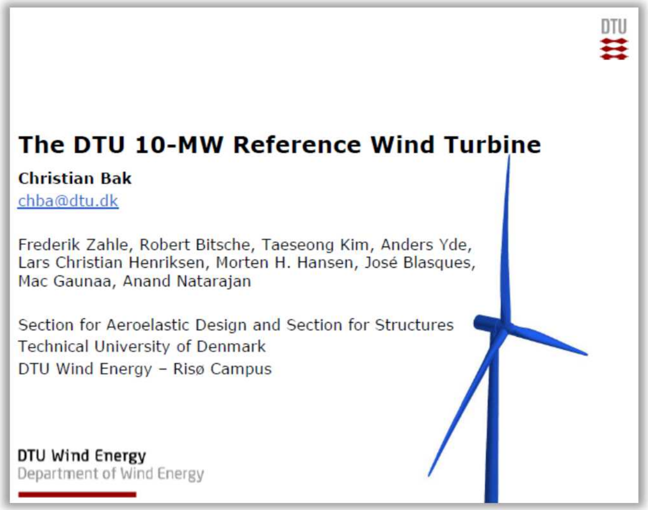
Structural and material optimizations have been performed using **two reference blade models**, representative of industry trends:

1. High wind resource (IEC class I-B), large wind turbine representative of future offshore wind turbines; **IEA 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

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

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

- (**s1**) All-fiberglass reference design
- (**s2**) Industry baseline reference design
- (**s3**) Heavy-tow textile carbon fiber reference


DTU

The DTU 10-MW Reference Wind Turbine

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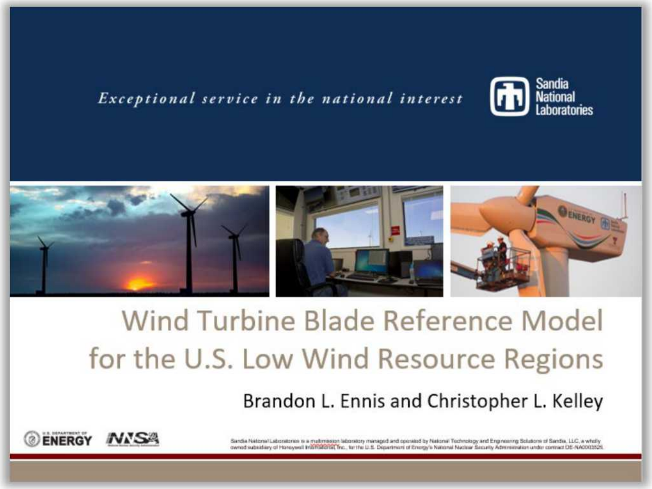
Frederik Zahle, Robert Bitsche, Taeseong Kim, Anders Yde, Lars Christian Henriksen, Morten H. Hansen, José Blasques, Mac Gaunaa, Anand Natarajan

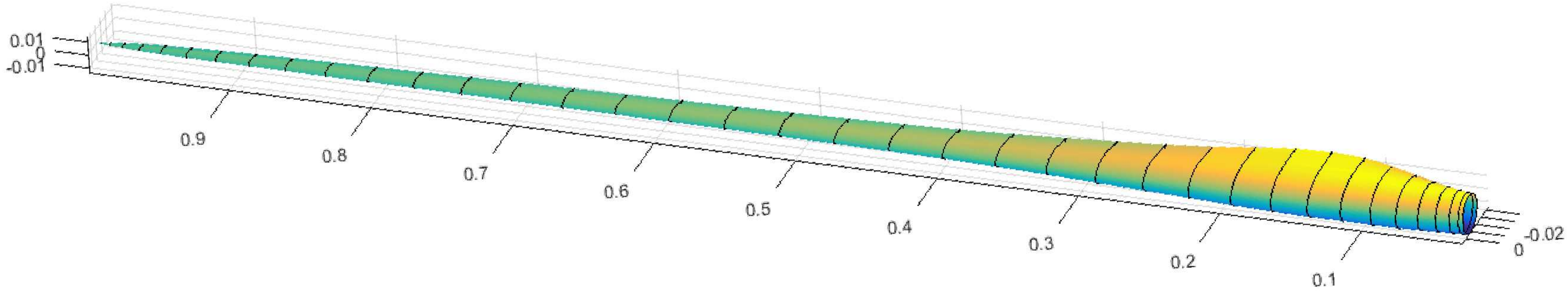
Section for Aeroelastic Design and Section for Structures
Technical University of Denmark
DTU Wind Energy – Risø Campus

DTU Wind Energy
Department of Wind Energy



SNL3.0-148 Reference Blade Model

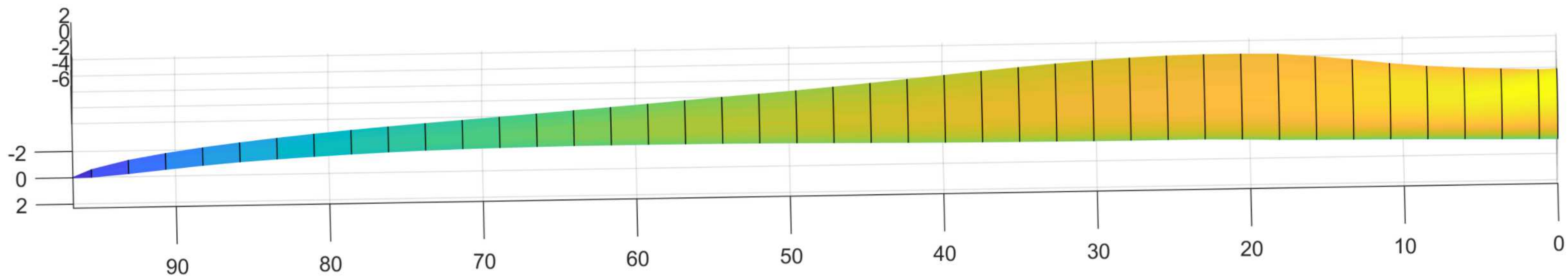
Publicly available reference model that is representative of the industry shift towards high energy capture wind turbines for land-based sites.



- 3 MW power rating
- 148 m turbine diameter
- 72 m blade length
- 175 W/m^2 specific power
- Class III-A site
- TSR = 9
- Blade solidity = 2.85%
- Lightly loaded tip
  - Matches the root bending moment of the "optimal" induction design (a=1/3) while increasing energy capture through a longer blade
- 30 year design life

IEA10.0-198 Reference Blade Model

Publicly available reference model that is representative of increasing machine rating and blade length typical for offshore sites.



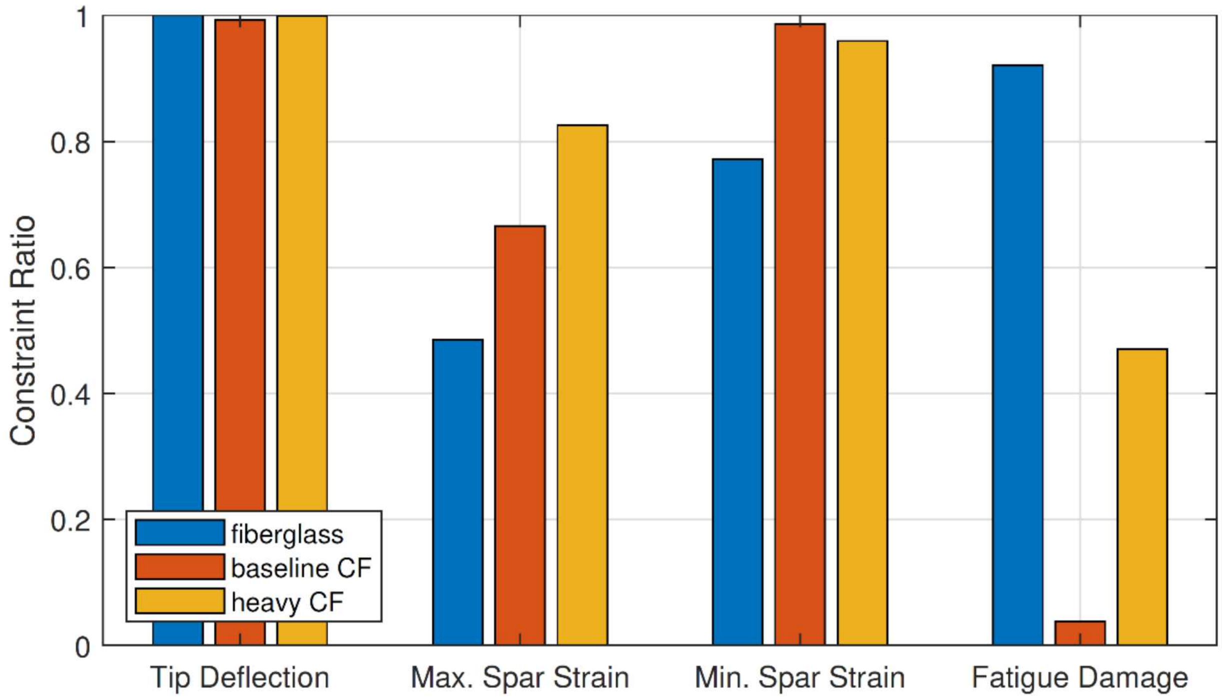
- 10 MW power rating
- 198 m turbine diameter
- 96.7 m blade length
- 325 W/m^2 specific power
- Class I-B site
- TSR = 9
- Blade solidity = 3.5%
- High-induction Region 2 design
  - Design operation has induction exceeding the aerodynamic "optimal" design (a=1/3)
- 25 year design life

Blade Optimization Results

- Reduced set of the most relevant design load cases were simulated within the optimization
  - IEC DLC 1.4: extreme coherent gust with wind direction change
  - IEC DLC 6.1: 50-year extreme wind model (turbine parked)
  - IEC DLC 1.2: normal turbulence model (fatigue analysis)
- Solve for spar cap material layup along the blade length
- Minimize spar cap material subject to constraints:
  - Design tip deflection of less than 20% of the blade length
  - Tensile and compressive failure strain limits
  - Spar cap fatigue damage not exceeding design life
- Blade shell material sized from global buckling checks performed offline (outside of the optimization)

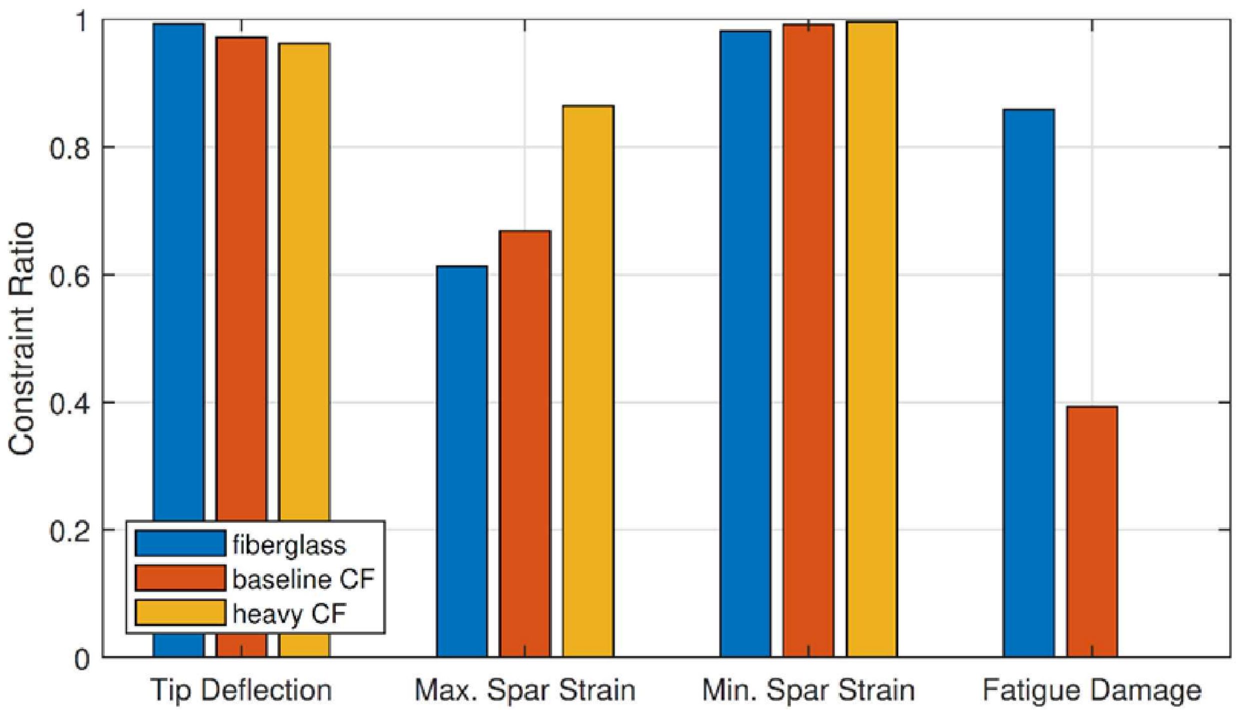
SNL 3MW Constraint Results

- This low wind-resource turbine is stiffness driven for the fiberglass spar
- The two carbon fiber materials nearly simultaneously meet the deflection and compressive strain limits
- The fiberglass design is fatigue-driven which drives the material demand up to meet the design life



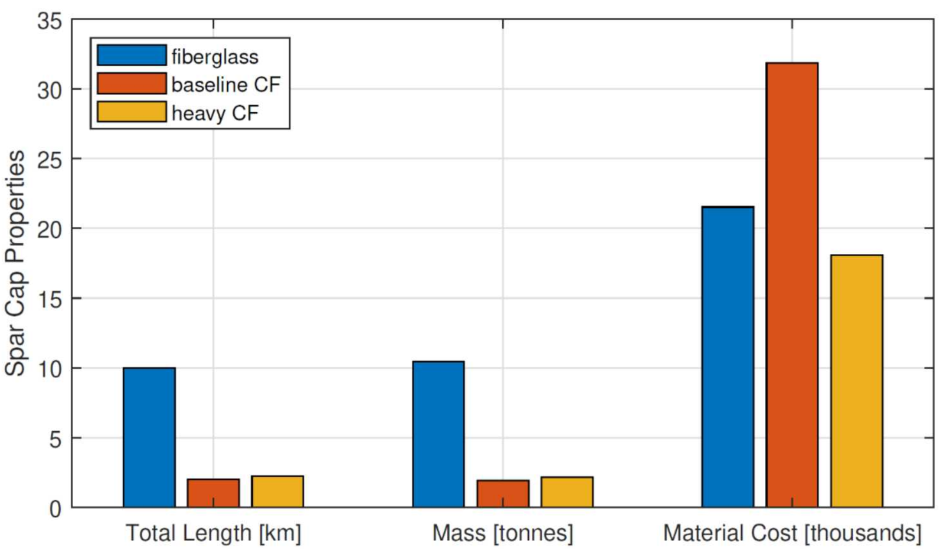
IEA 10MW Constraint Results

- The large offshore turbine is strength-driven for the fiberglass design
- Similar to the 3 MW design, the material compressive strength is what drives the design (not tensile strength) for the study materials
- The fatigue life of the two carbon fiber spar caps are over double the design life for both the 3 MW and 10 MW turbines

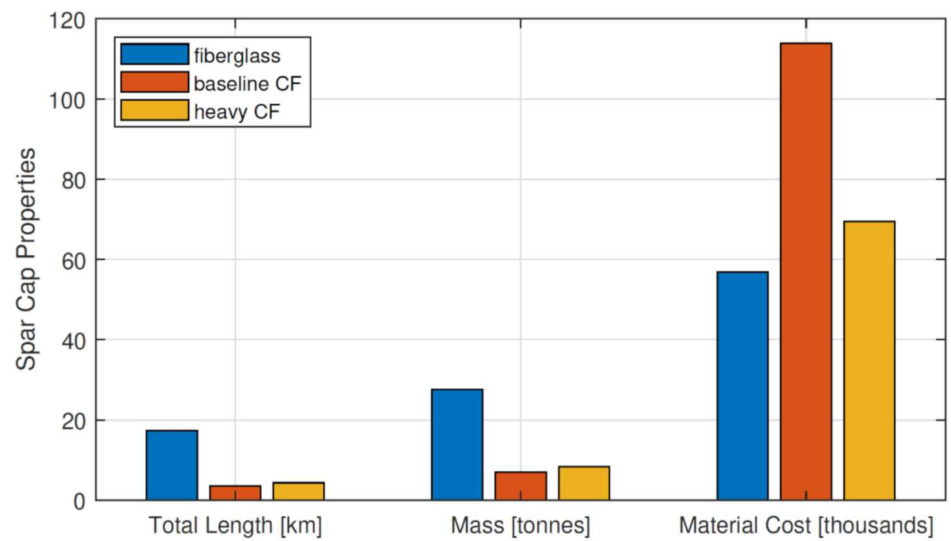


Spar Cap Comparison with Material and Turbine Type

- The optimized spar caps with the heavy tow textile carbon fiber have a 39-43% reduction in material cost compared to the industry baseline carbon fiber
- The heavy tow textile carbon fiber is found to be the optimal material for the 3 MW wind turbine over fiberglass for this fatigue driven design
- Carbon fiber pultrusions will likely have lower manufacturing costs due to the reduced number of layers required



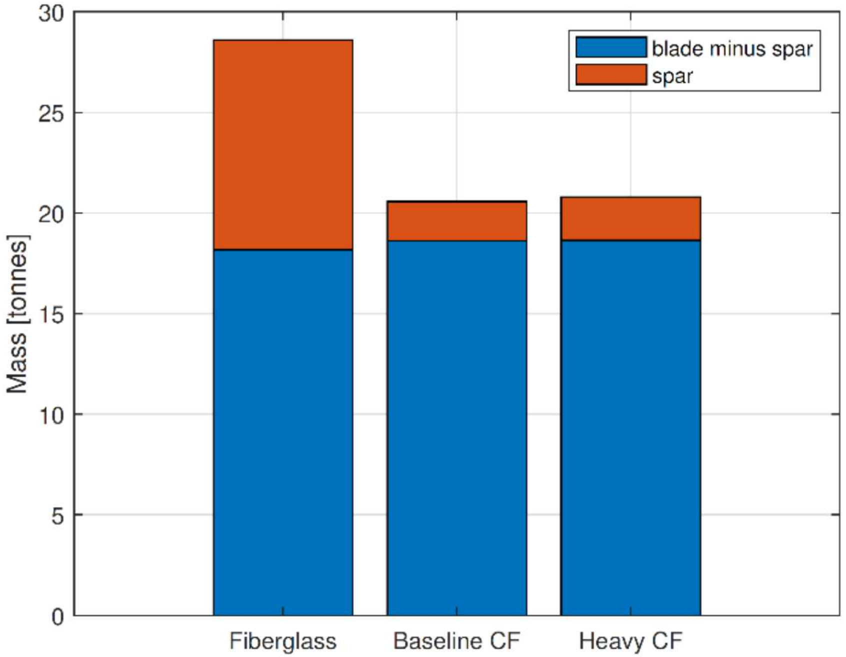
3 MW, Land-based Spar Cap Properties



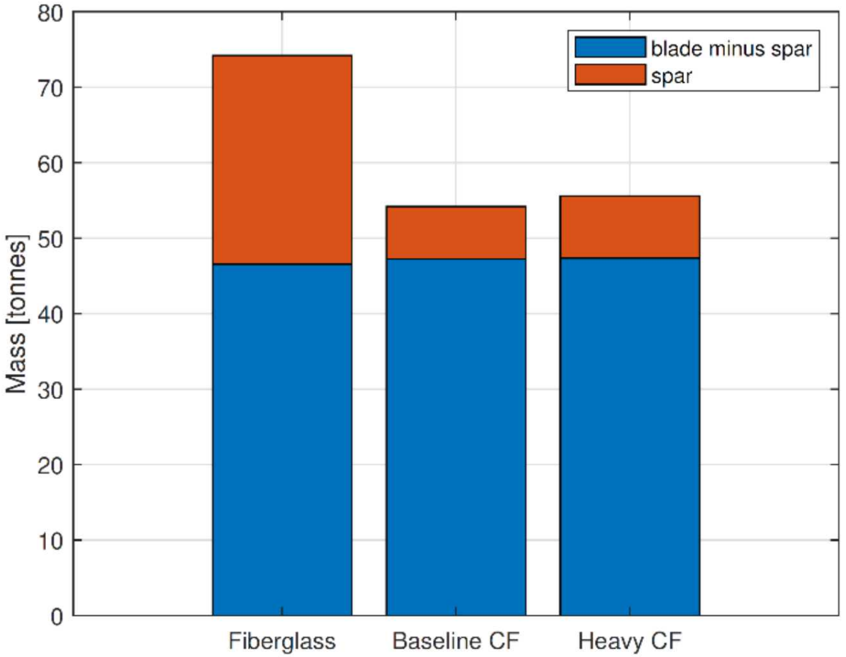
10 MW, Offshore Spar Cap Properties

Spar Cap Comparison with Material and Turbine Type

- The novel heavy tow textile carbon fiber blade is 25-27% lower mass than the fiberglass design for the two wind turbine models
- Carbon fiber spar caps produce a system benefit due to the lower blade mass which reduces the cost of the drivetrain and support members
  - This is not quantified in the spar cap material cost comparison, but is an added benefit over the fiberglass designs



3 MW, Land-based Blade Mass Comparison



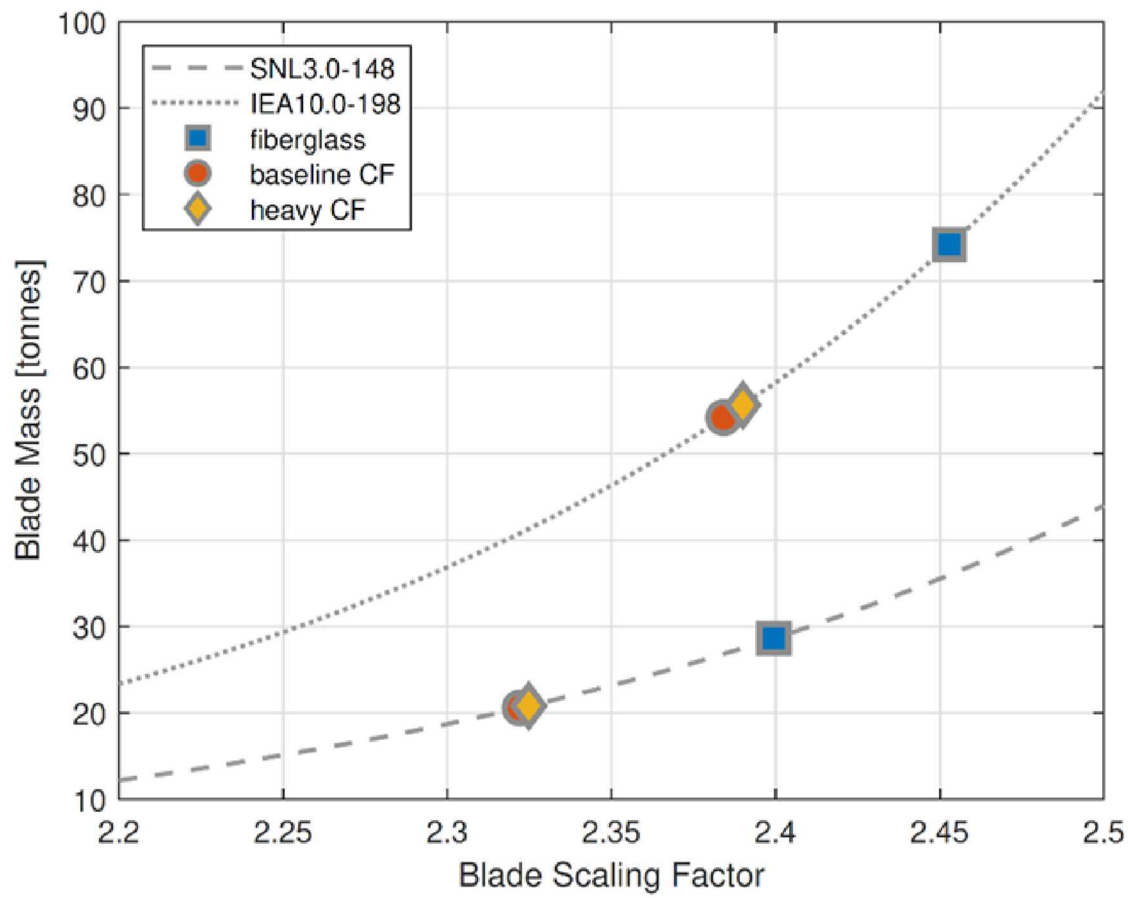
10 MW, Offshore Blade Mass Comparison

Blade Optimization Mass Results

- Blade mass scales with blade length to a power greater than 2

$$m_{blade} = L_{blade}{}^{x}$$

- Increasing blade length has been correlated with reductions in the levelized cost of wind energy
- Blade designs with carbon fiber spar caps enable longer blades by controlling mass



Blue square is fiberglass baseline
Red circle is industry baseline carbon fiber
Yellow diamond is heavy-tow textile carbon fiber

Summary

- The heavy-tow textile carbon fiber material has improved cost-specific strength and stiffness compared to the industry baseline carbon fiber
  - 56% increase in compressive strength-per-cost and 100% increase in modulus-per-cost
  - Results in 39-43% lower blade spar cap material costs compared to baseline carbon fiber in the two reference models
- Carbon fiber blade designs have lower mass which produces system benefits on the drivetrain and structural components and bearings
  - The novel textile carbon fiber has a 27% and 25% lower blade mass for the 3 MW and 10 MW reference turbines, respectively, compared to fiberglass spar cap designs
  - Enables longer rotors which capture more energy for low wind speed sites
- Improved fatigue properties of carbon (specifically of heavy tow study material) enables a longer fatigue life than fiberglass designs
  - The CFTF Kaltex material has a fatigue slope of m=45 for a (R=0.1) tension-tension test
  - The two carbon fiber spar caps retain a high end of life value due to their fatigue resistance which may be beneficial for recycling or extending turbine design life
- Carbon enables slender blade designs to be more cost effective
  - more aerodynamically efficient (energy gains, reduced thrust loads)
  - utilizes less shell material for slender, thin airfoil designs

Summary

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