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

Sandia National Laboratories

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Montana State University

Optimized Carbon Fiber Composites for Wind Turbine Blade Design

IACMI Member's Meeting

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Optimized Carbon Fiber for Wind Energy Project

Sandia National Laboratories

OAK RIDGE National Laboratory

MONTANA STATE UNIVERSITY

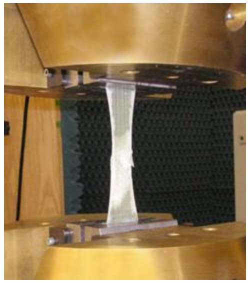
The objective of this project is to assess the commercial viability of cost-competitive, tailored carbon fiber composites for use in wind turbine blades.

- Wind turbine blades have unique loading criterion, including nearly equivalent compressive and tensile loads, and high fatigue cycles
- 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

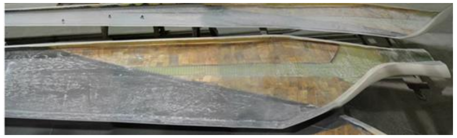
Project Overview

- Carbon fiber materials are characterized through cost modeling and mechanical testing
- These materials are compared through structural optimization and cost minimization for representative blade designs
- The impact of novel carbon fiber materials on blade spar caps is assessed through comparison to industry baseline carbon fiber and fiberglass materials

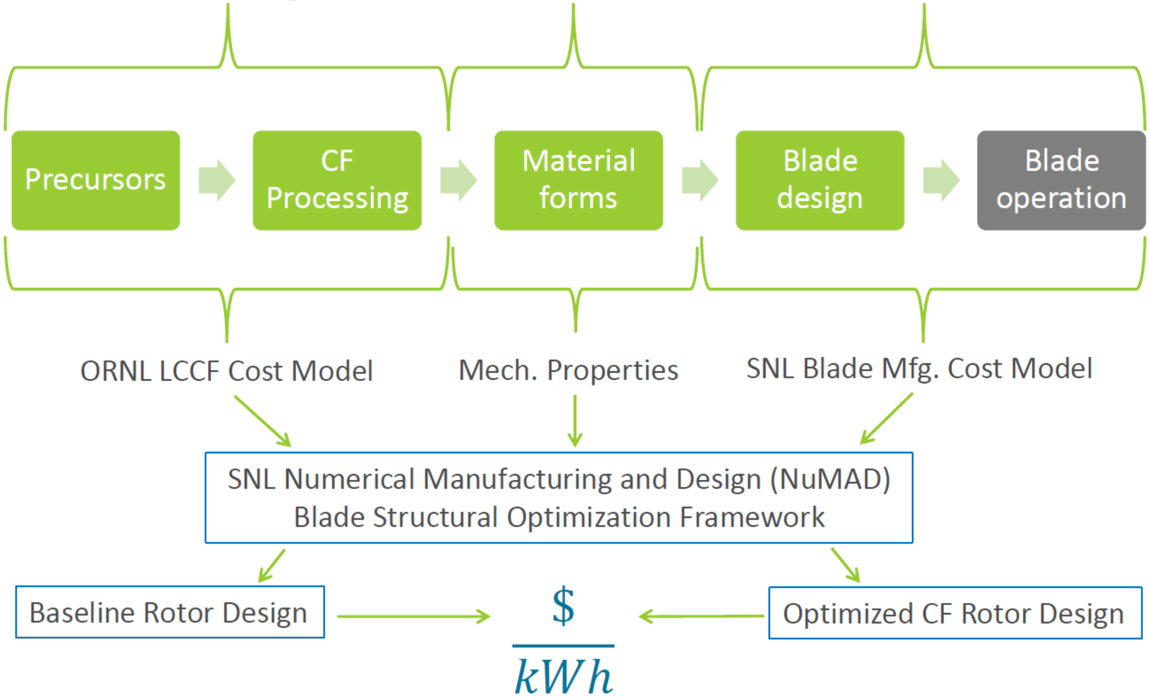
ORNL Low-Cost Carbon Fiber R&D Program



MSU Testing Program



SNL Rotor R&D Program



Precursors → CF Processing → Material forms → Blade design → Blade operation

ORNL LCCF Cost Model

Mech. Properties

SNL Blade Mfg. Cost Model

SNL Numerical Manufacturing and Design (NuMAD) Blade Structural Optimization Framework

Baseline Rotor Design

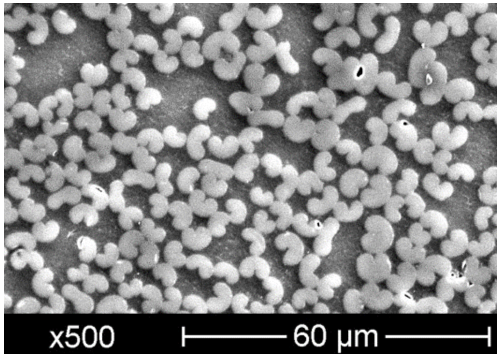
$\frac{\$}{kWh}$

Optimized CF Rotor Design

Evaluating Potential for Lower Cost Carbon Fiber

- **Textile Carbon Fiber (TCF)**
  - Acrylic fibers produced for textiles are similar chemically to those produced specifically as carbon fiber precursors, but significantly less expensive
    - Traditional carbon fiber precursor – 0.5K to 50K (500 to 50,000 filaments)
    - Textile fiber is typically 300K and above

- **ORNL has demonstrated various TCF routes to lower cost**
  - Kaltex (457K, micrograph image bottom right), Taekwang (363K), and other “precursors” show much potential as development continues
  - Opportunity to influence product characteristics such as form, fiber stiffness, and other factors



Carbon Fiber Cost Modeling

Parameter	Baseline $/kg (%)	Heavy Textile Tow (full-utilization) $/kg (%)	Reduction %
Materials	$8.09 (44.7%)	$5.05 (64.6%)	38%
Capital	$6.74 (37.2%)	$1.91 (24.4%)	72%
Labor	$2.06 (11.4%)	$0.47 (6.0%)	77%
Energy	$1.21 (6.7%)	$0.39 (4.9%)	68%
TOTAL	**$18.11 (100%)**	**$7.82 (100%)**	**57%**

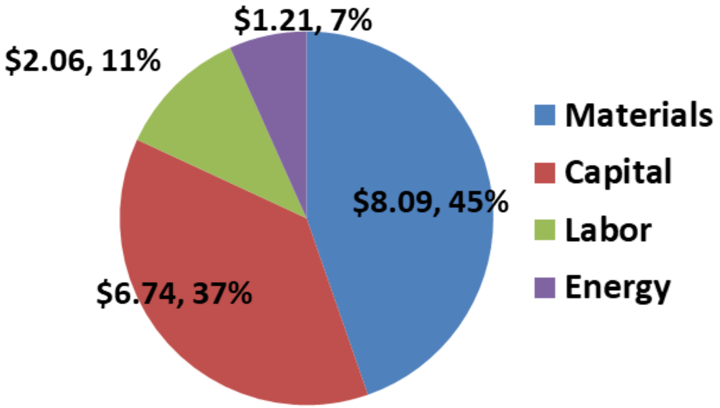
- ✓ Lower precursor cost -- High output textile grade acrylic fiber used for clothing application today vs. specialty acrylic fiber

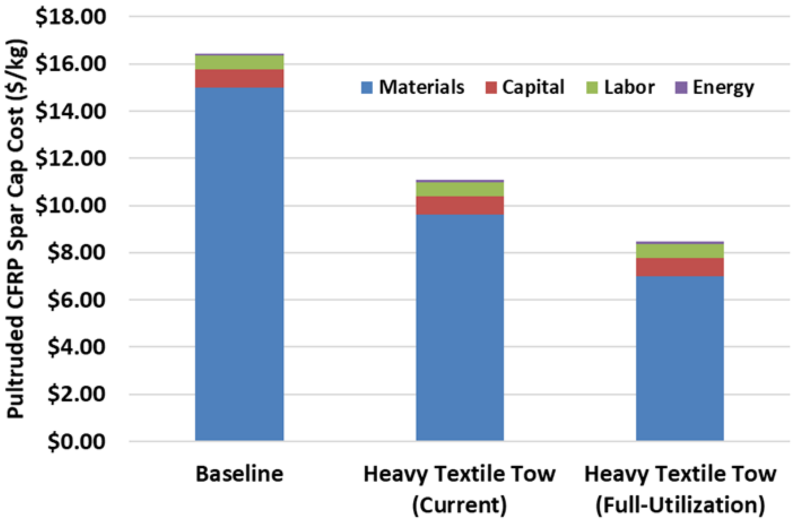
- ✓ Lower capital cost – Higher production capacity (similar conversion speed and tow spacing in addition to reduced oxidation time) using similar sized capital equipment (largest share of total cost reduction)

- ✓ Lower energy and labor cost – Economies of scale from an increased throughput

Optimized Carbon Fiber Composites Cost Modeling

- Material (45%) and capital (37%) cost shares dominate the baseline (50K tow) carbon fiber cost of $18.11/kg
- Lower precursor cost and economies of scale from a higher throughput lowers the heavy textile tow (457K tow) LCCF (current) cost of $11.19/kg
- With an increased throughput due to reduced tow spacing, and lower oxidation time from an utilization of exothermic heat, LCCF (Full-Utilization) cost is $7.82/kg
- A significant reduction of ~49% pultruded CFRP spar cap cost is projected using LCCF (Full-Utilization)





Mechanical Testing of Low-Cost Carbon Fiber

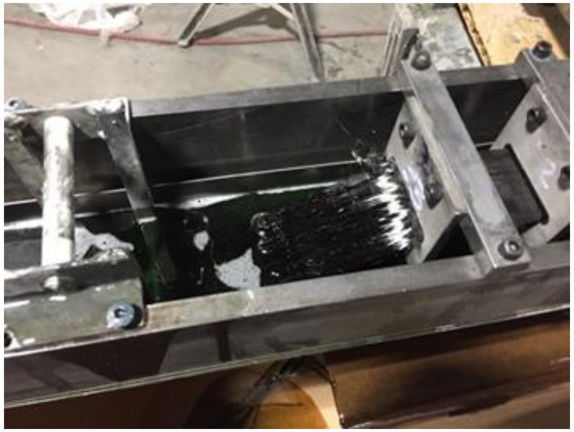
- Spar caps are the first logical application of carbon fiber in blades
- Tested unidirectional coupons; pultruded composite forms are the commercial use case in spars

1. Pultruded composite samples

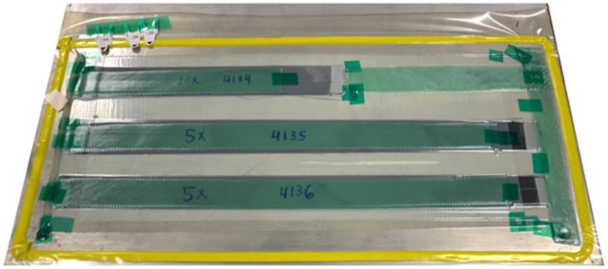
Material	Composite Form	Layup	V_F [%]	E [GPa] 0.1-0.3%	UTS [MPa]	%, max	UCS [MPa]	%, min
ORNL K20 (Kaltex)	Pultrusion (third-party)	(0), 112017-5	51	123	846	0.69	-769	-0.63
Zoltek PX35	Pultrusion (third-party)	(0), 112017-6	53	114	1564	1.33	-897	-0.79
	Pultrusion (Zoltek)	(0)	62	142	2215	1.47	-	-
				138	-	-	-1505	-1.16

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)	956 (63)	0.74 (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)	-863 (108)	-0.77 (0.44)
Zoltek PX35	Aligned strand	5.1 tows/cm	51	119 (4)	1726 (93)	1.4 (0.08)	-906 (44)	-0.74 (0.04)



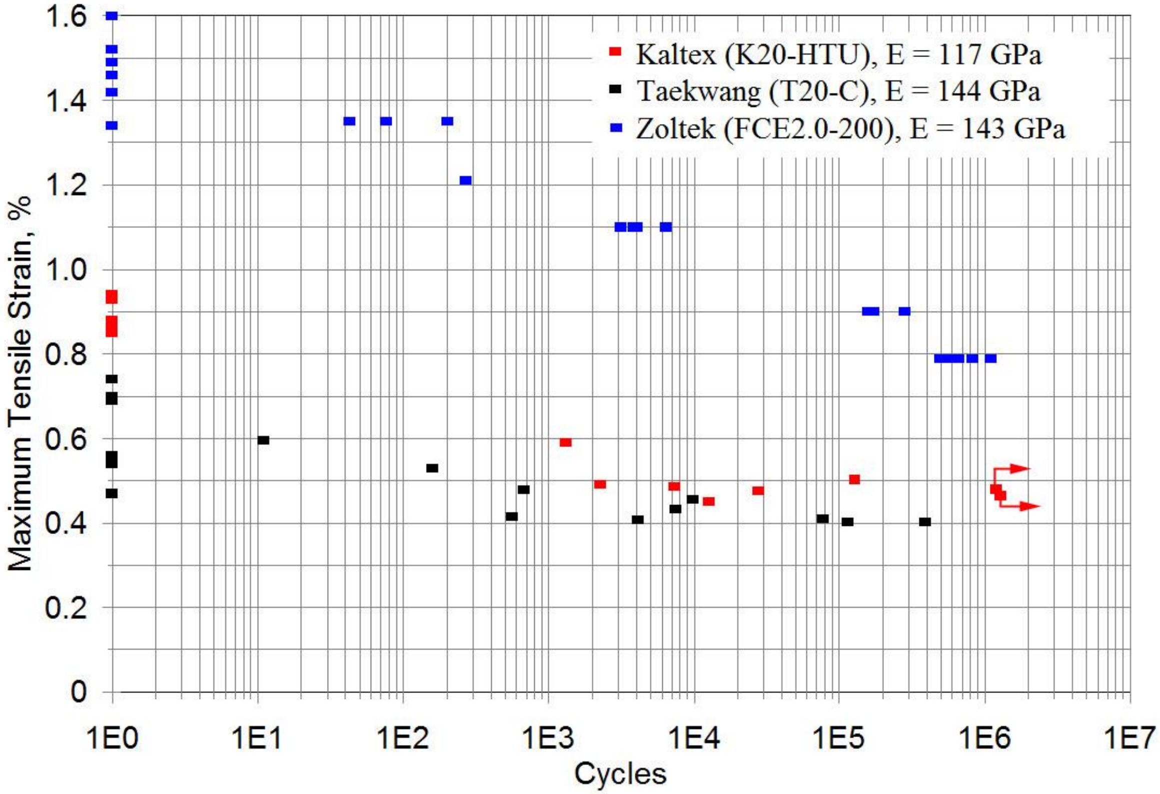
Pultrusions can produce spar caps very cost-effectively and with repeatable performance



MSU Aligned Strand infusions are useful for comparing fiber properties while minimizing manufacturing effects

Mechanical Testing of Low-Cost Carbon Fiber

- TCF materials show greater fatigue resistance than baseline carbon fiber
- Study materials were tested in fatigue (R=0.1) to understand performance of heavy-tow textile carbon fiber materials
- Baseline CF tested was in pultruded form (62% volume fraction) and TCF materials in aligned strand infusion (~50% volume fraction)



$$M = M_u \cdot N^{-1/m}$$

$$M_e = \frac{M_a}{1 - \frac{M_m}{M_u}}$$

$$D = \sum_{i=1}^{k} \frac{n_i}{N_i}\Big|_{M_{e,i}}$$

$$DEL = M_u \left(\frac{10^6}{D}\right)^{-1/m}$$

$$\frac{D_2}{D_1} = \left(\frac{DEL_2}{DEL_1}\right)^m$$

Blade Optimization – Pultruded Model Input CFRP

- Pultruded carbon fiber properties show advantage over fiberglass, but cost more

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	0.57	42.8	1180	-750	$2.06

- The heavy textile 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

Wind Turbine Blade Optimization

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

1. 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
2. High wind resource (IEC class I-B), large wind turbine representative of offshore wind turbines; **IEA 10 MW** aerodynamic design

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

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

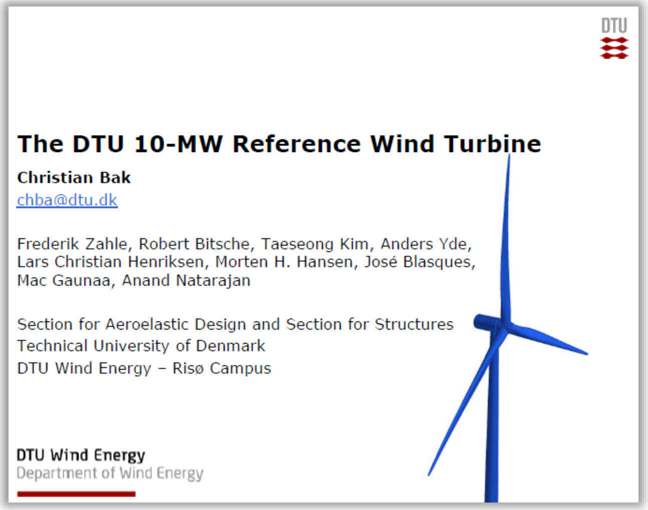
Ensures that the results cover the differences from driving load conditions and machine type

Exceptional service in the national interest

Sandia National Laboratories

Wind Turbine Blade Reference Model for the U.S. Low Wind Resource Regions

Brandon L. Ennis and Christopher L. Kelley



DTU

The DTU 10-MW Reference Wind Turbine

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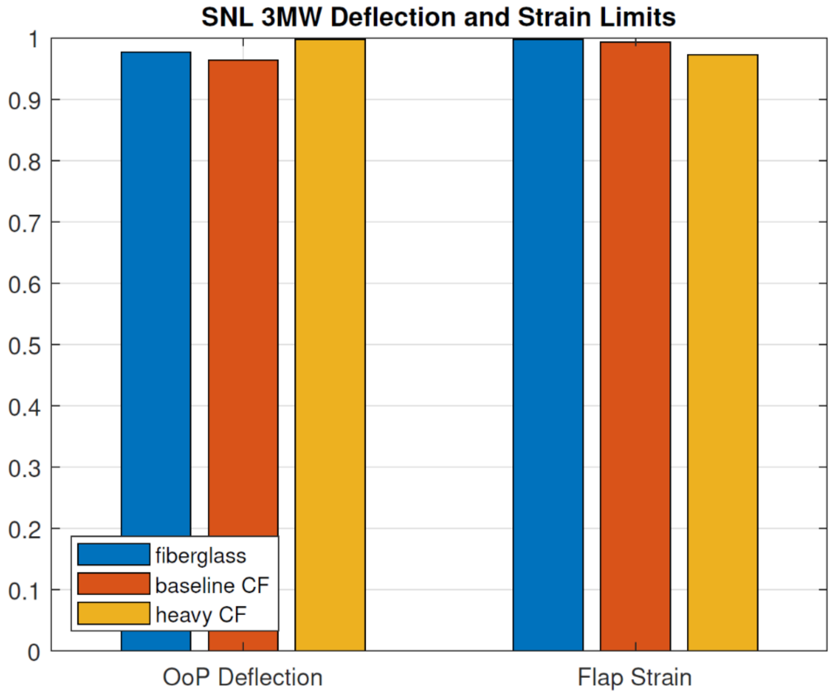
Initial Blade Optimization Results

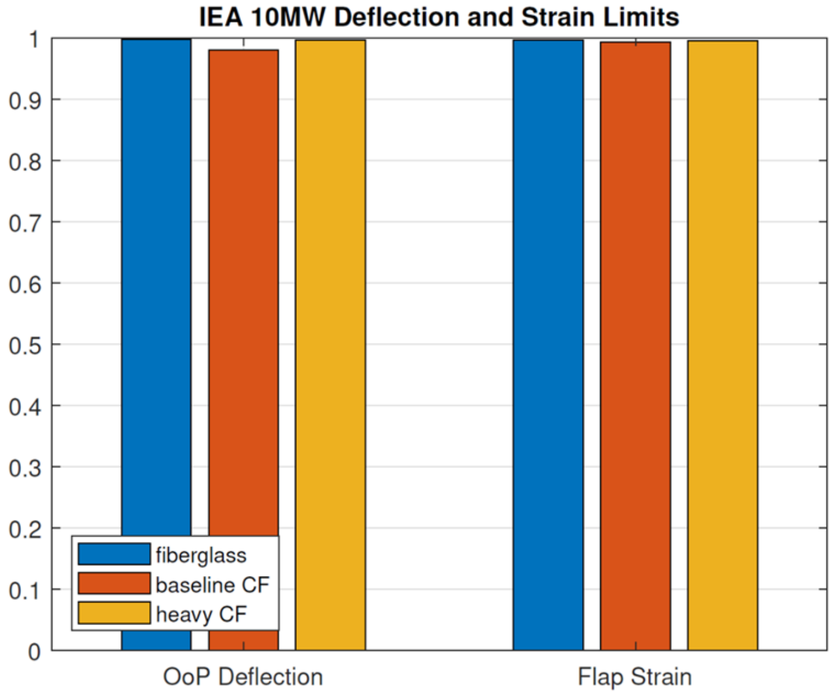
- Reduced load set in optimization:
  - IEC Design Load Case (DLC) 1.4: extreme coherent gust with wind direction change
  - IEC DLC 6.1: 50-year parked extreme wind model
- Solve for spar material layup
- Minimize mass subject to spar cap strain and a 15% deflection (characteristic)

- Results are preliminary, but are useful for showing the trends with the different materials. **<u>Next steps include</u>**:
  - Perform material fatigue analysis within the optimization
  - Detailed material sizing beyond the spar cap is the next step
    - TE/LE reinforcement through fatigue analysis
    - Panel layup through FEA buckling analysis
  - Checks utilizing the entire set of Design Load Cases

Initial Blade Optimization Results

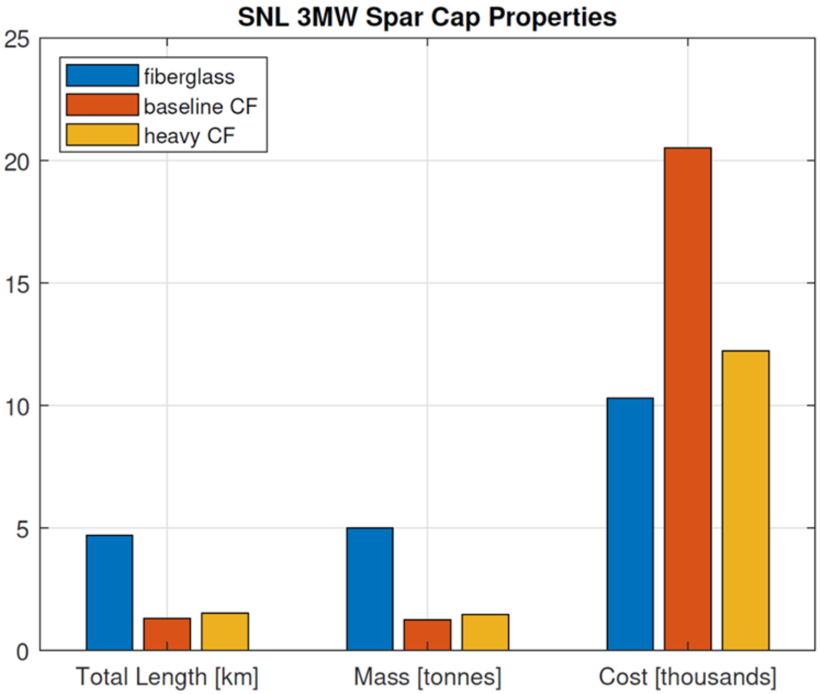
- The blade designs reach the tip deflection (15%) and material failure strain limits nearly simultaneously for the three study materials for both turbine designs
  - This is not the case for a 10% deflection limit, where the fiberglass blade has unused strength to achieve the lower deflection

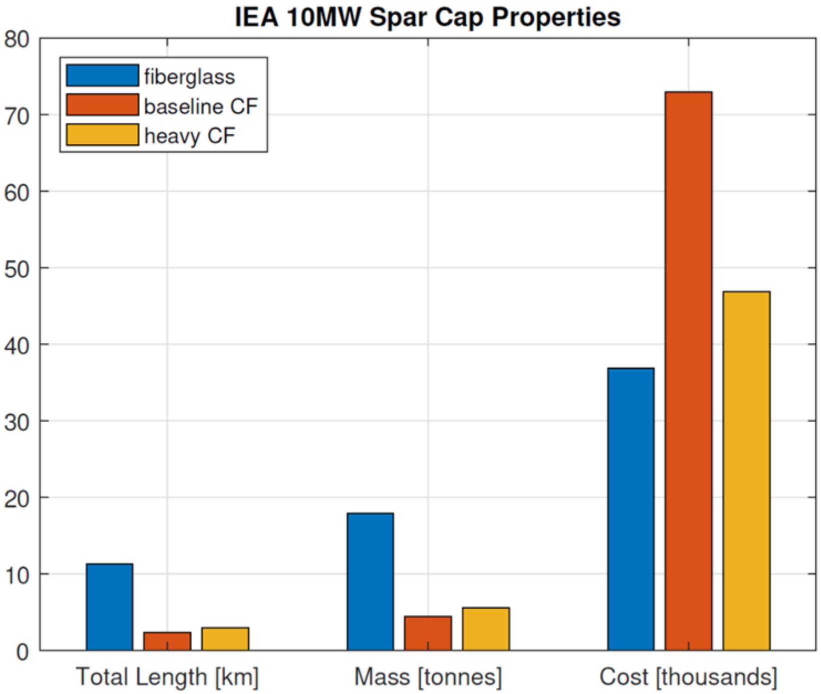

SNL 3MW Deflection and Strain Limits


IEA 10MW Deflection and Strain Limits

Initial Blade Optimization Results

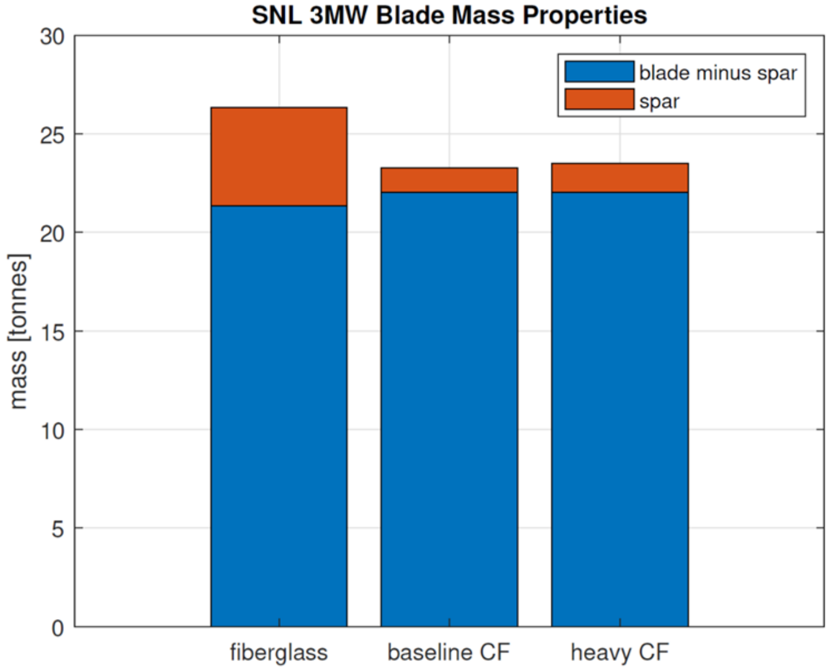
- The heavy-tow TCF is 36%-40% lower cost than the baseline carbon fiber material for the two turbine designs
- The heavy-tow TCF is more expensive than fiberglass, but lighter
  - Including fatigue would be expected to make the results more favorable to both carbon materials

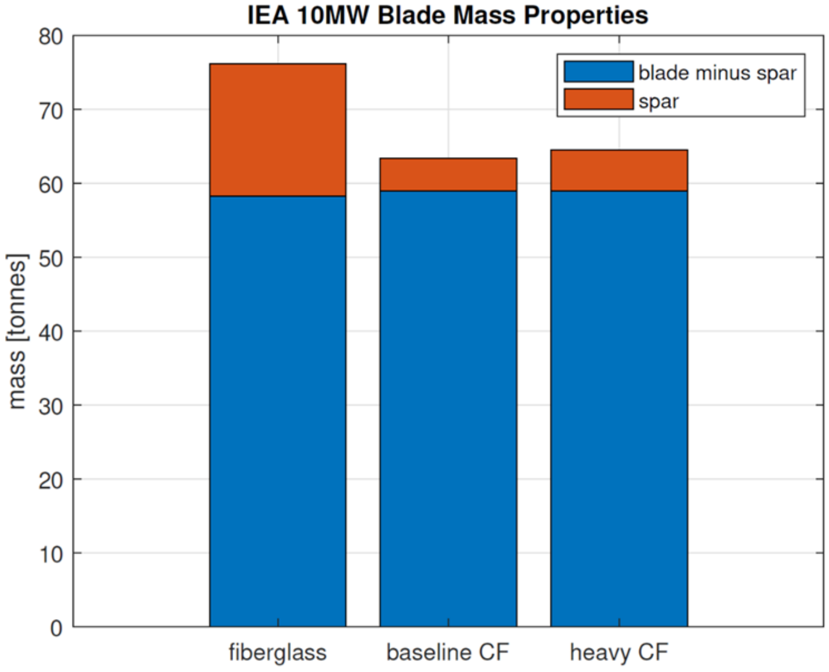

SNL 3MW Spar Cap Properties


IEA 10MW Spar Cap Properties

Initial Blade Optimization Results

- The specific stiffness and strength improvements of carbon results in weight reductions of 11% for 3 MW and 15% for 10 MW turbines
- Carbon enables slender designs to be more cost-effective which can substantially reduce blade mass due to reduced blade surface area and panel material


SNL 3MW Blade Mass Properties


IEA 10MW Blade Mass Properties

Summary of Heavy-Tow Textile Carbon Fiber Benefits

- The heavy-tow TCF has improved specific strength and stiffness per cost compared to baseline carbon fiber materials
    - Lower blade material costs compared to baseline carbon fiber
    - Fewer layers for carbon fiber could result in reduced manufacturing costs compared to glass fiber
- Carbon enables slender blade designs to be more cost effective
    - more aerodynamically efficient (AEP gains, reduced thrust loads) and utilize less shell material
- Carbon fiber blade designs have lower mass which produces system benefits on drivetrain and structural components/bearings
    - Weight reductions of 11% for 3 MW and 15% for 10 MW reference turbines
- Improved fatigue properties of carbon (specifically of TCF study material) will additionally favor the material for fatigue driven designs
- Carbon designs have higher modal frequencies compared to glass fiber designs
    - Provides a simple means to avoid dwelling at resonant conditions

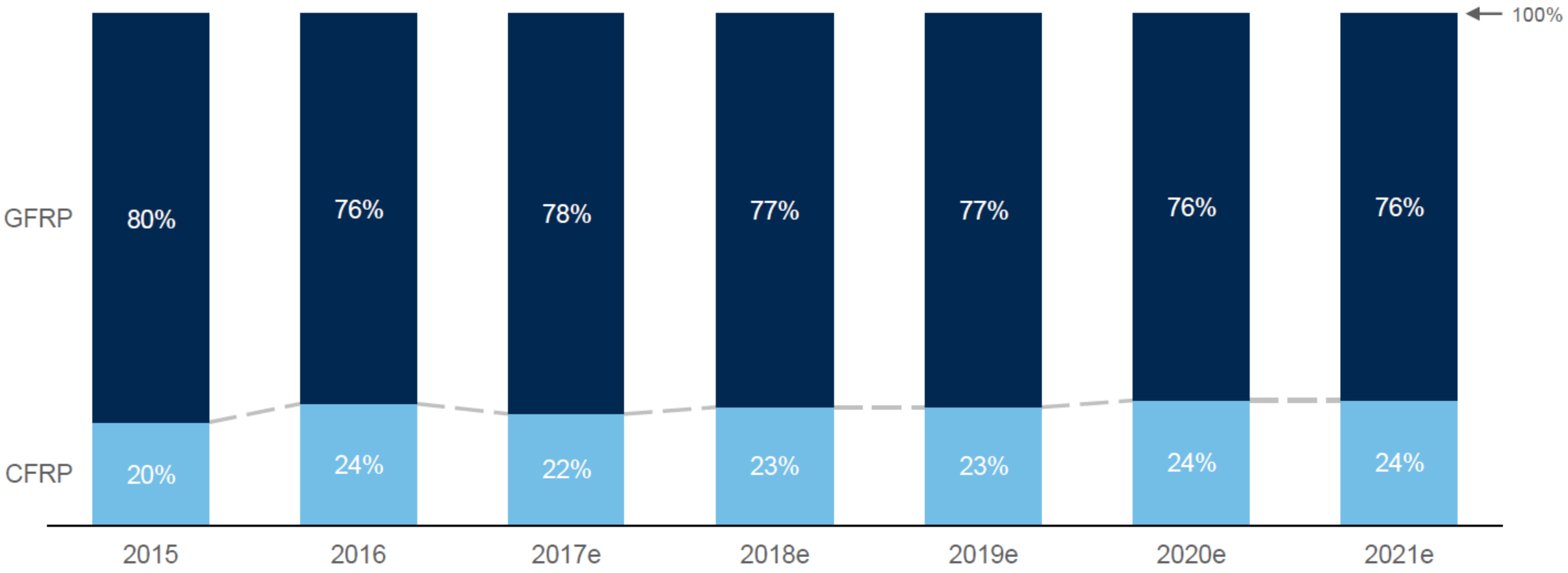
Optimized Carbon Fiber Composites for Wind Turbine Blade Design

Backup Slides

Wind Turbine Blade Material Trends

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

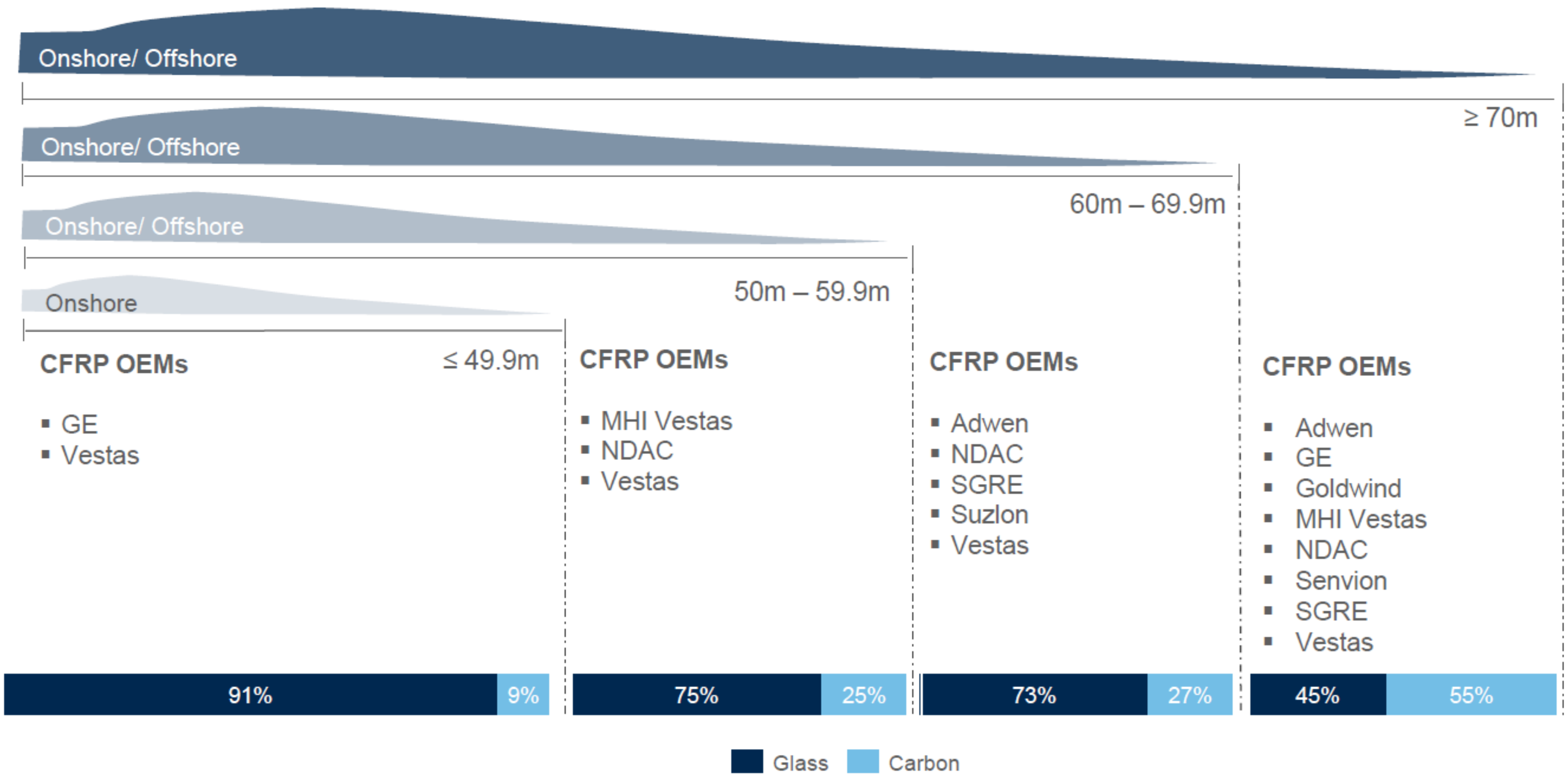


Source: MAKE

Wind Turbine Blade Material Trends

- 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

Key turbine OEMs and spar material by blade length



≤ 49.9m – CFRP OEMs

- GE
- Vestas

50m – 59.9m – CFRP OEMs

- MHI Vestas
- NDAC
- Vestas

60m – 69.9m – CFRP OEMs

- Adwen
- NDAC
- SGRE
- Suzlon
- Vestas

≥ 70m – CFRP OEMs

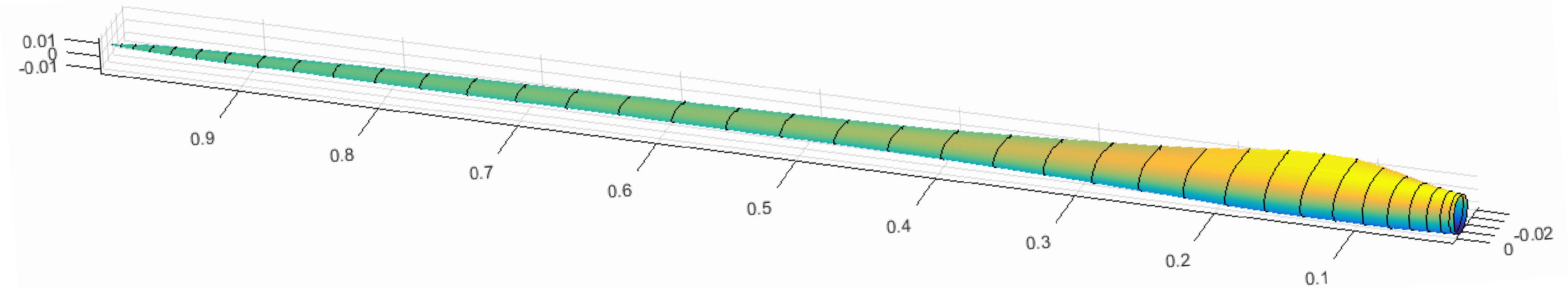
- Adwen
- GE
- Goldwind
- MHI Vestas
- NDAC
- Senvion
- SGRE
- Vestas

Note: % use of spar material on “current” and “prototype” turbine platforms in the market

Source: MAKE

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, developed within this project.

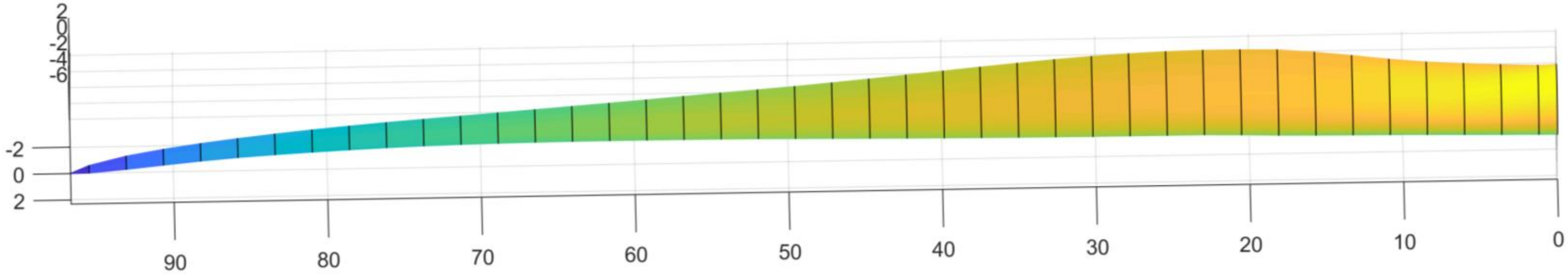


- 3 MW power rating
- 148 m turbine diameter
- 72 m blade length
- 175 W/m^2 specific power
- Class III-A site
- TSR = 9
- Blade solidity = 2.85%

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

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)
- Developed within IEA Task 37 by performing an aero-structural optimization from the DTU 10 MW while constraining blade root bending moment

Initial Blade Optimization Results

For a 10% deflection limit:

- This low wind-resource, Class III turbine is stiffness driven for the fiberglass design
  - Fiberglass (E glass) is not optimal for this design
- The two carbon fiber materials equally meet the deflection and strain limits