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Optimized Carbon Fiber for Wind Energy; Project and Market Overview

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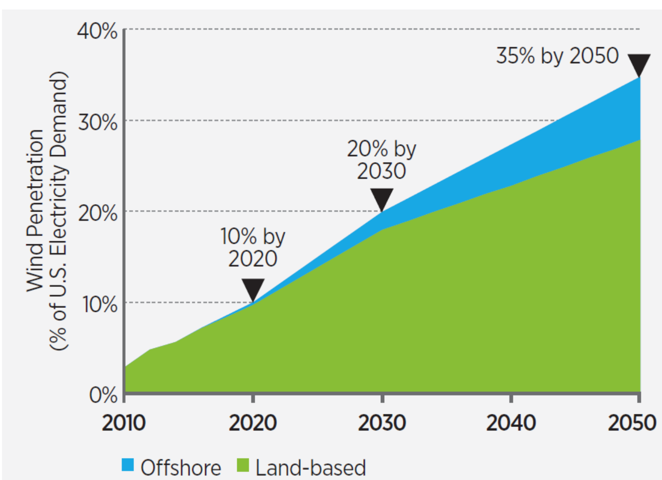
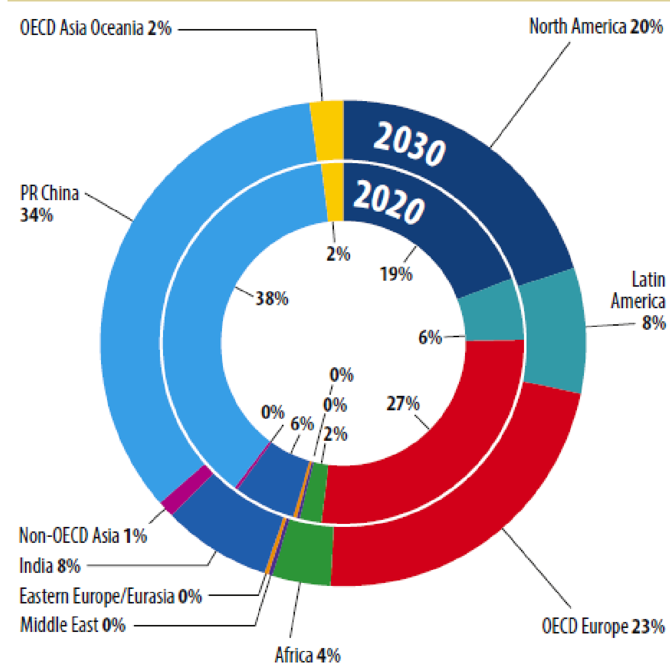
Wind Energy Industry Trends

- Global wind energy industry expected to double in capacity over the next decade
- The U.S. is on track to produce 35% of its electricity by wind energy in 2050
- China has the highest installed wind energy capacity, doubling that in the U.S.
- India and South America will likely see significant growth



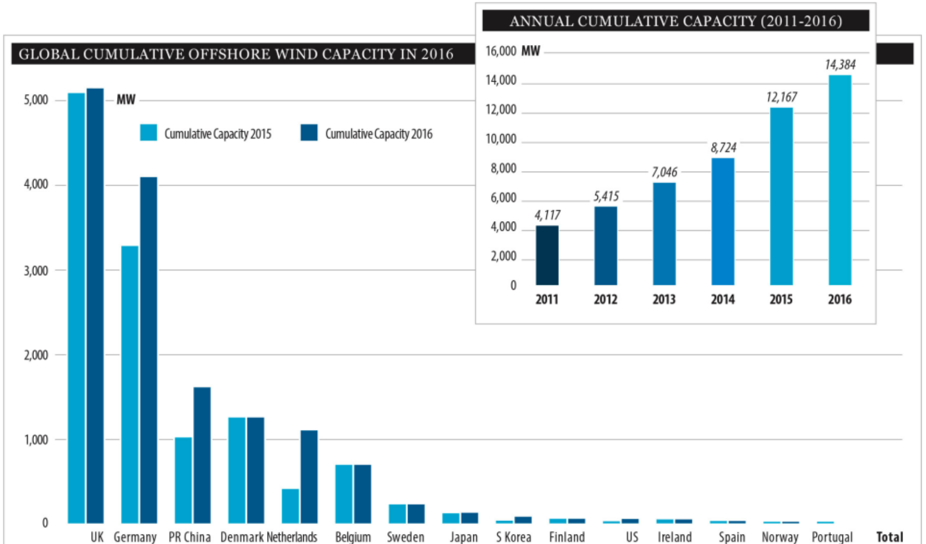


	2020	2030
North America	149,120	318,390
Latin America	42,997	129,491
OECD Europe	207,955	358,554
Africa	16,805	60,852
Middle East	777	4,995
Eastern Europe/Eurasia	644	1,895
India	44,734	116,257
Non-OECD Asia	2,344	14,842
PR China	291,439	541,577
OECD Asia Oceania	13,364	32,887
Global Total / MW	**797,028**	**1,675,624**

Source: GWEC, "Global Wind Energy Outlook 2016"

Wind Energy Industry Trends

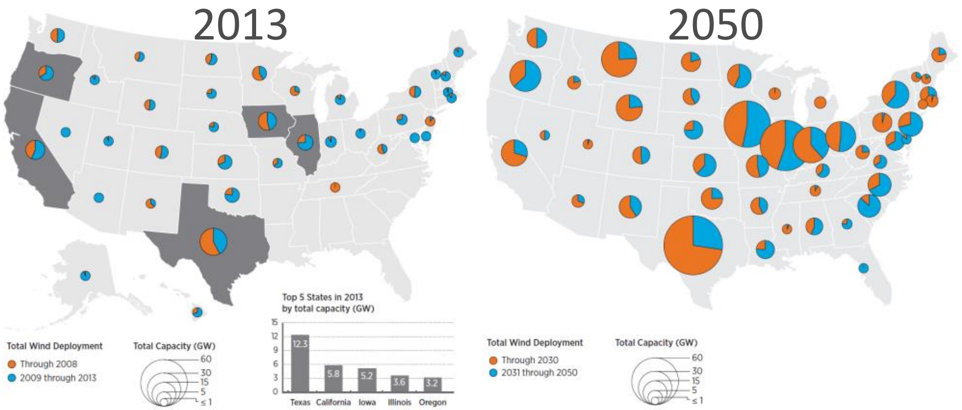
- New markets are opening as land and resource restrictions are faced across the world
- Offshore wind energy industry is growing globally
  - In 2016, the first offshore wind plant was installed in the U.S.
  - China has been installing offshore wind plants to access better wind resources
  - The first 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



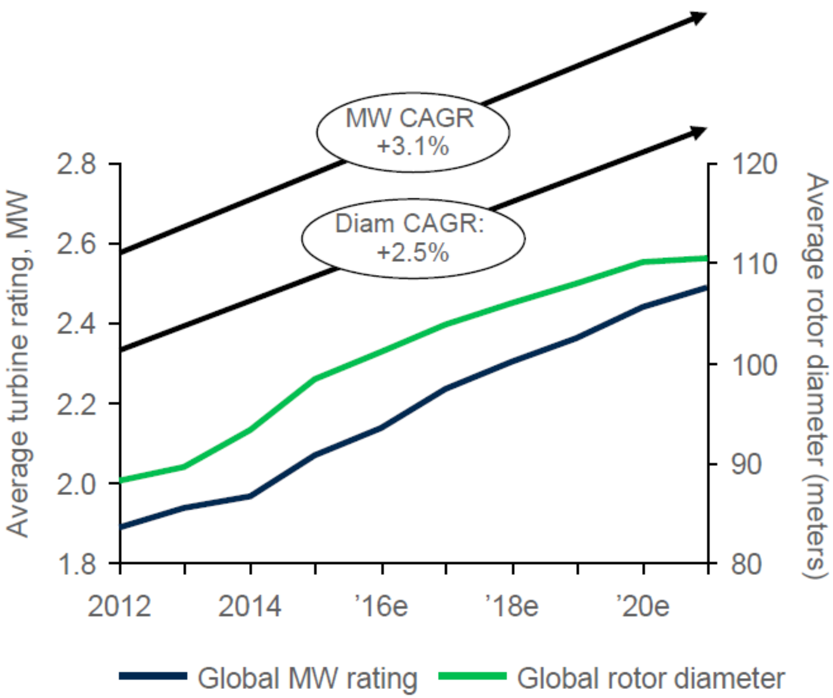
Scenario projections of U.S. wind energy installation through 2050
Source: DOE Wind Vision Report

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

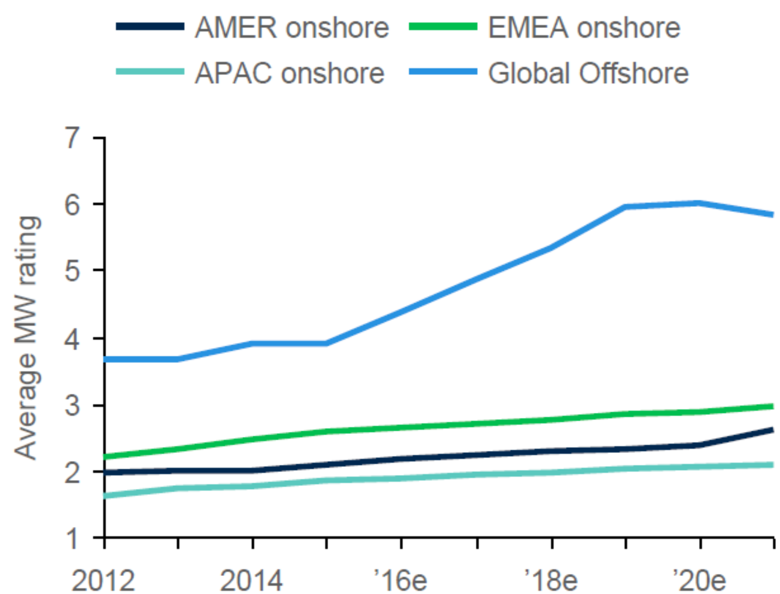
Wind Turbine Blade Trends

- 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

Global rotor diameter and MW rating growth



Regional MW rating average trends



Source: MAKE

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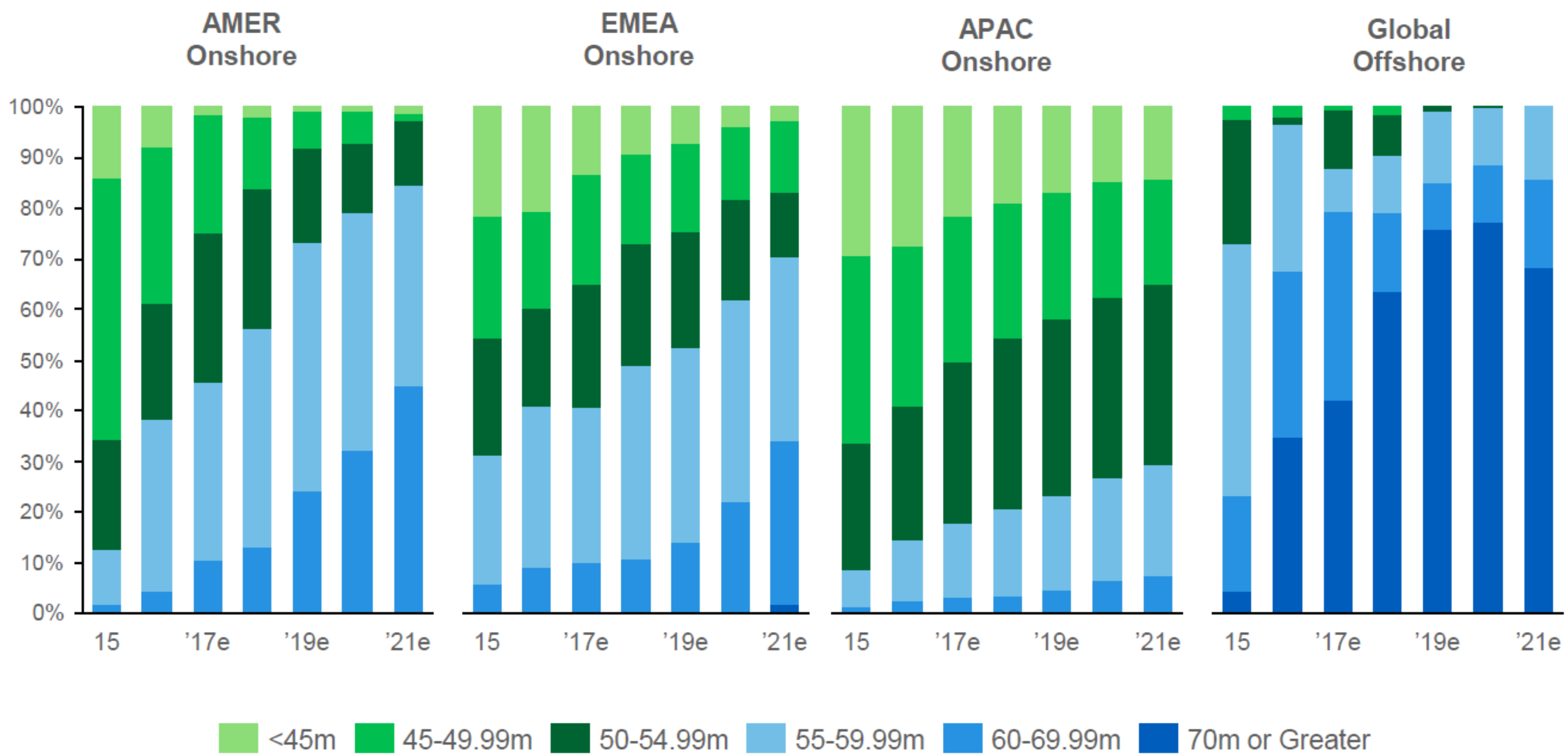
Wind Turbine Blade Trends

- Trends suggest that wind turbine designs will continue to utilize longer blades for land-based machines, particularly in the U.S. and Europe
- The offshore wind energy market will demand very large blades



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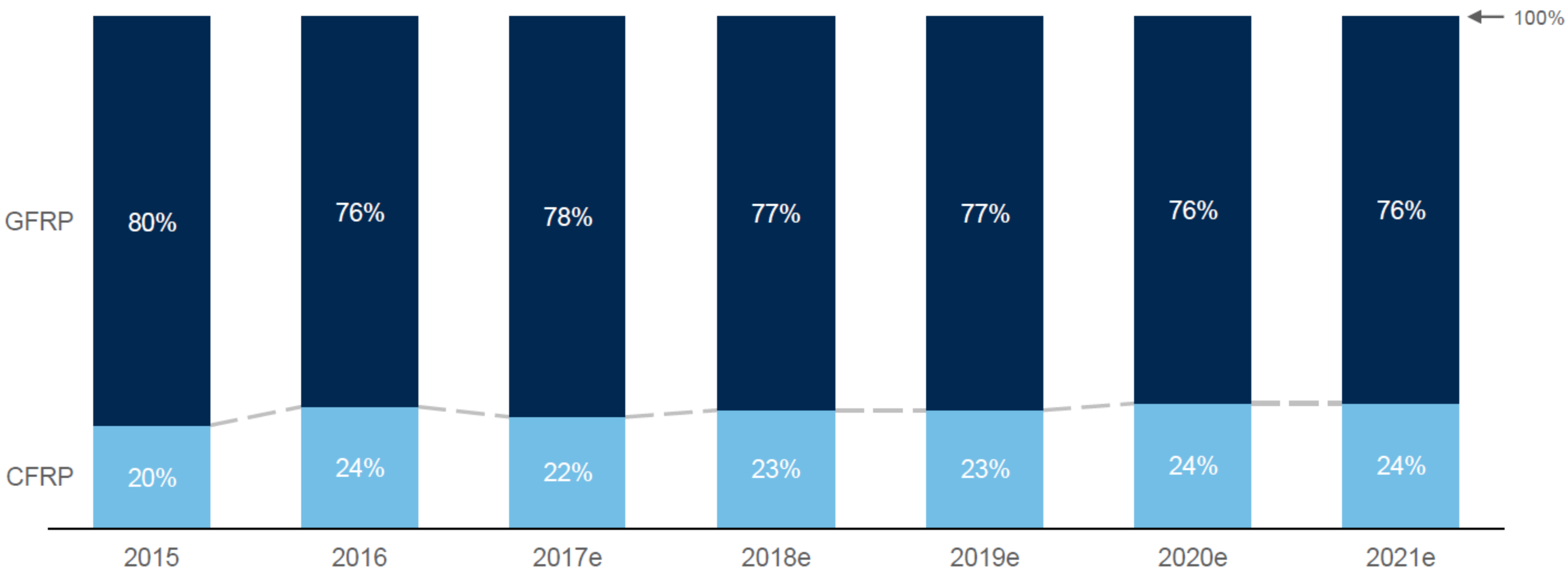
Wind Turbine Blade Material Trends

- 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

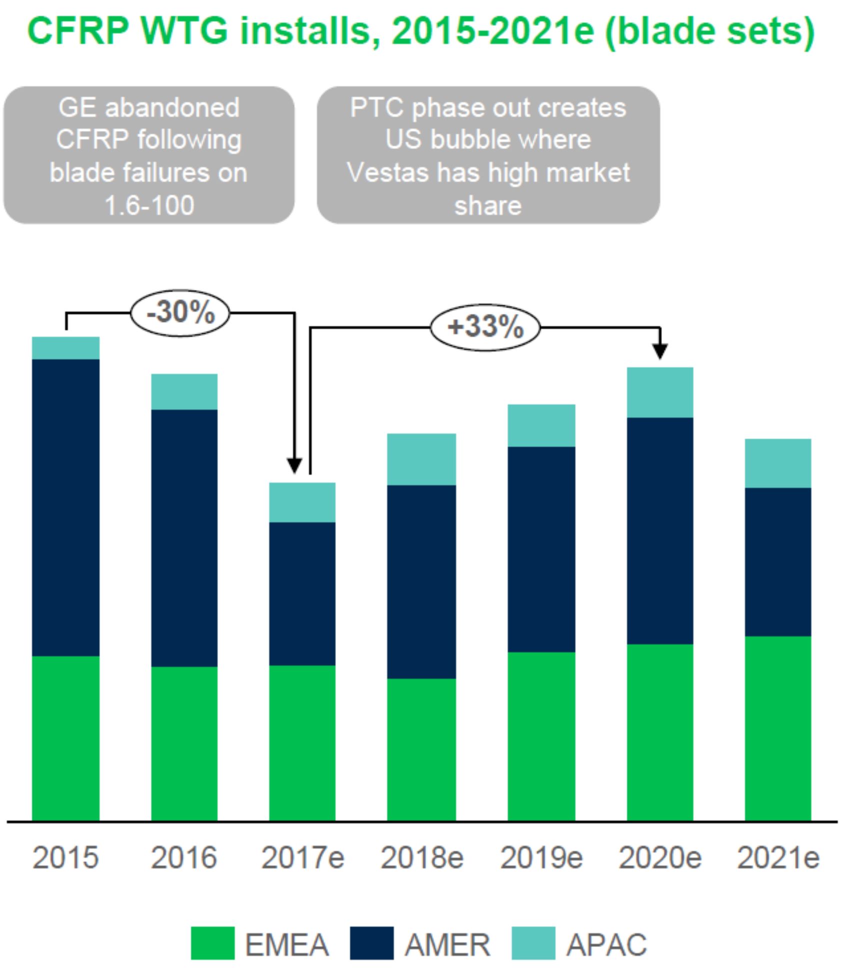
Global wind turbine installations, 2015-2021e (GW)



Source: MAKE

Wind Turbine Blade Material Trends

- In 2012, nearly 20% of global installations used carbon fiber blade designs (Source: MAKE)
- GE's transition away from carbon fiber blade designs reduced the market share of CFRP designs
  - GE may revisit the use of carbon fiber in their higher power capacity platforms
- The improved system performance of carbon fiber blade designs must result in a reduced cost of energy for OEMs to heavily utilize carbon fiber blade designs



Source: MAKE

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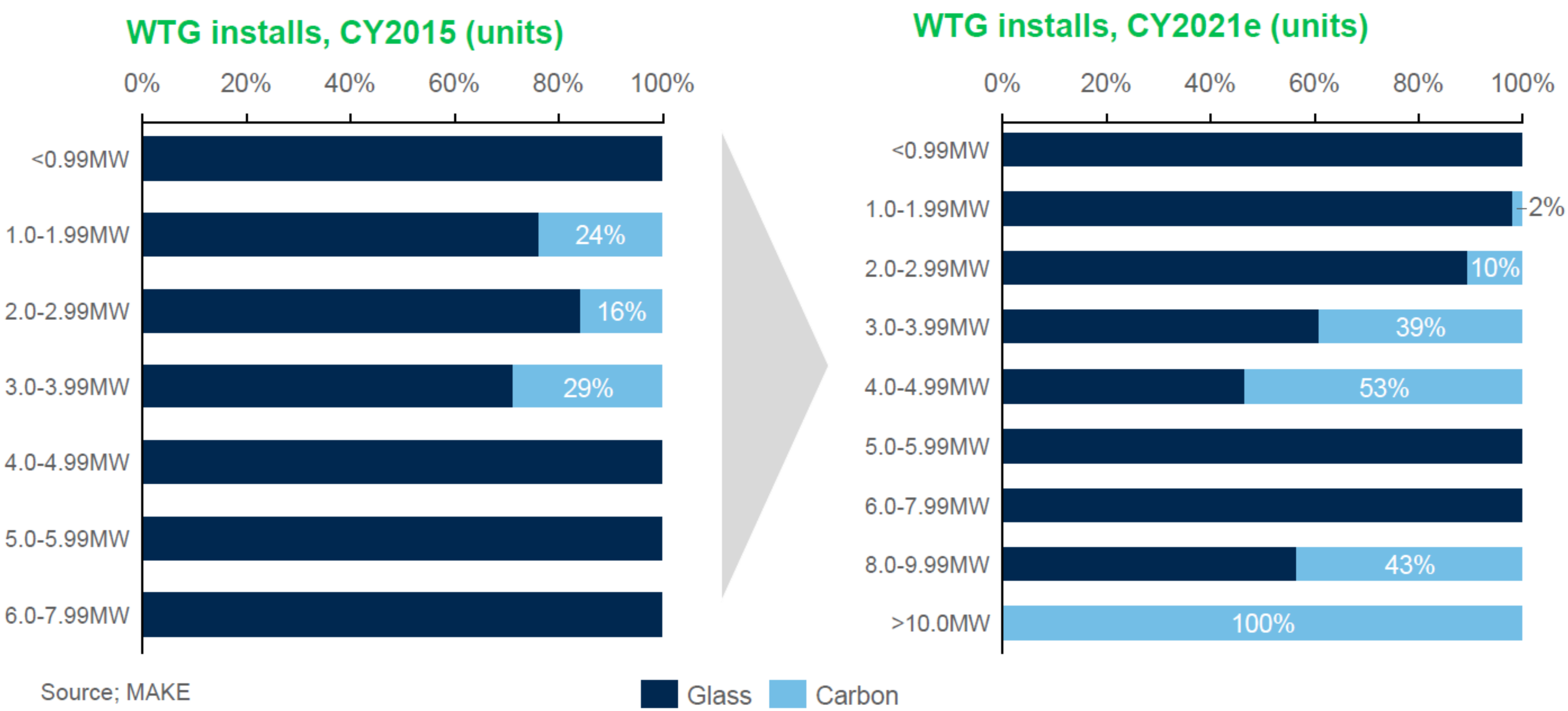
Wind Turbine Blade Material Trends

- 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

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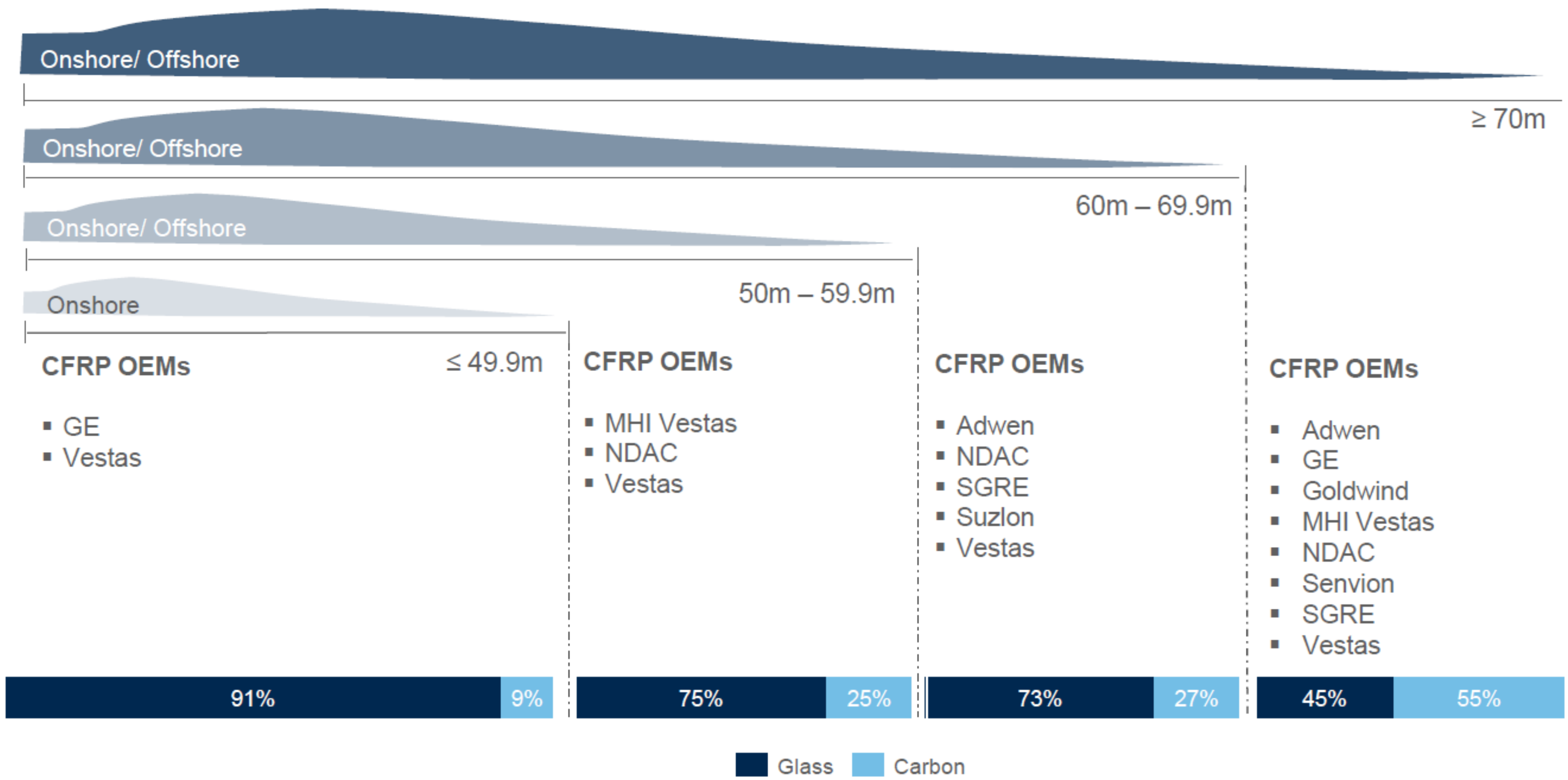
Wind Turbine Blade Material Trends

- 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



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

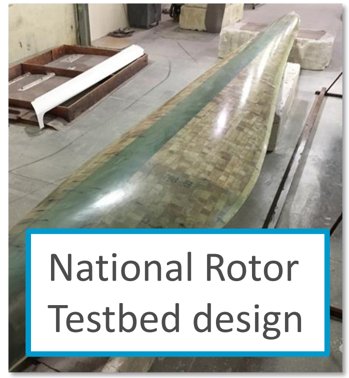
The objective of this project is to assess the commercial viability of cost-competitive, tailored carbon fiber composites for use in wind turbine blades.

- 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 – 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

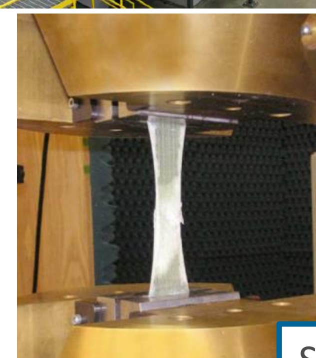
Oak Ridge National Laboratory

- 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

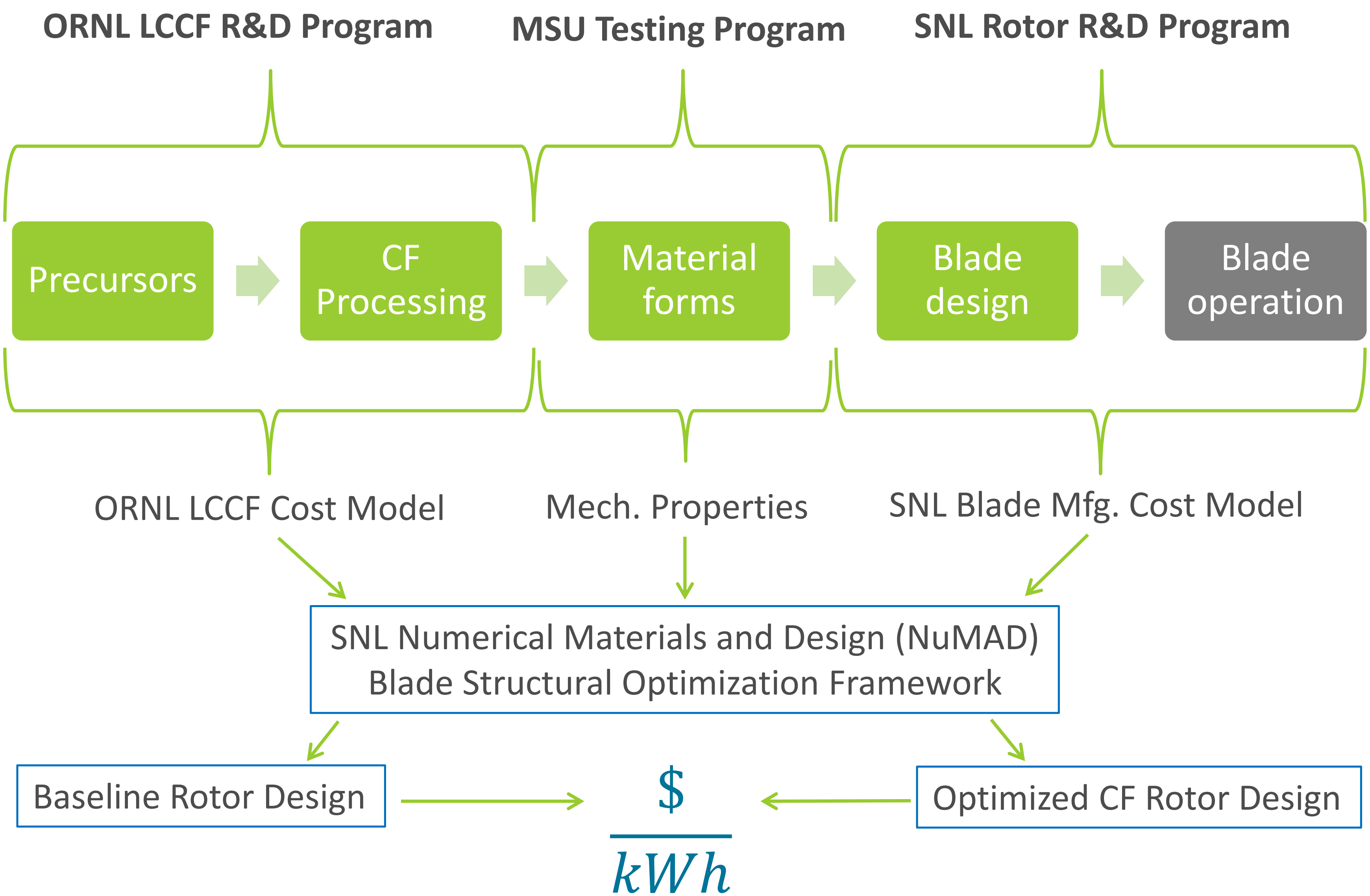
Montana State University

- 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

Project Overview



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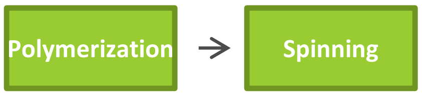
Carbon Fiber Cost Modeling

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

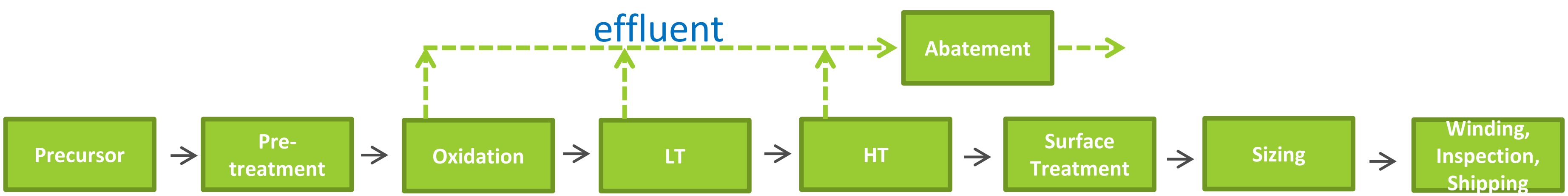
Evaluate precursor manufacturing at the level of two major process steps:



- 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

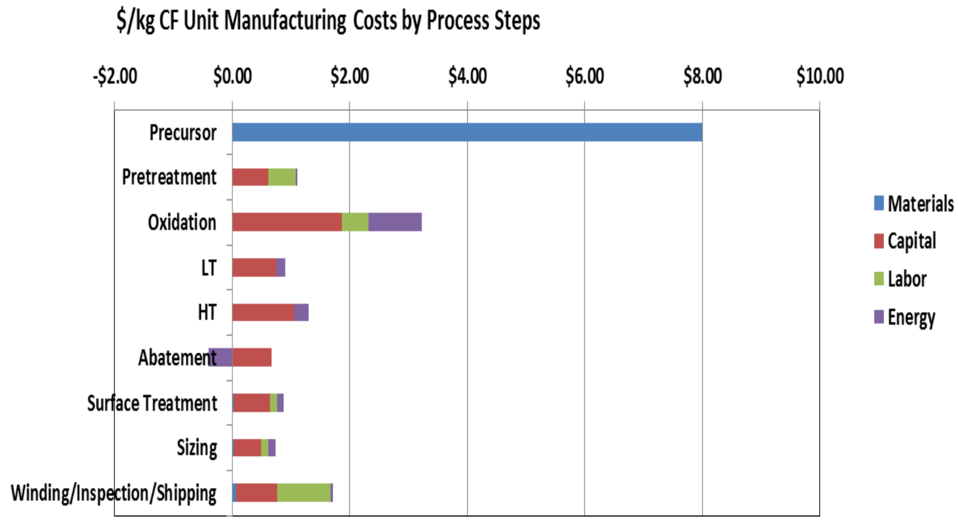
A cost model is being developed to estimate the carbon fiber cost variation to its mechanical properties:

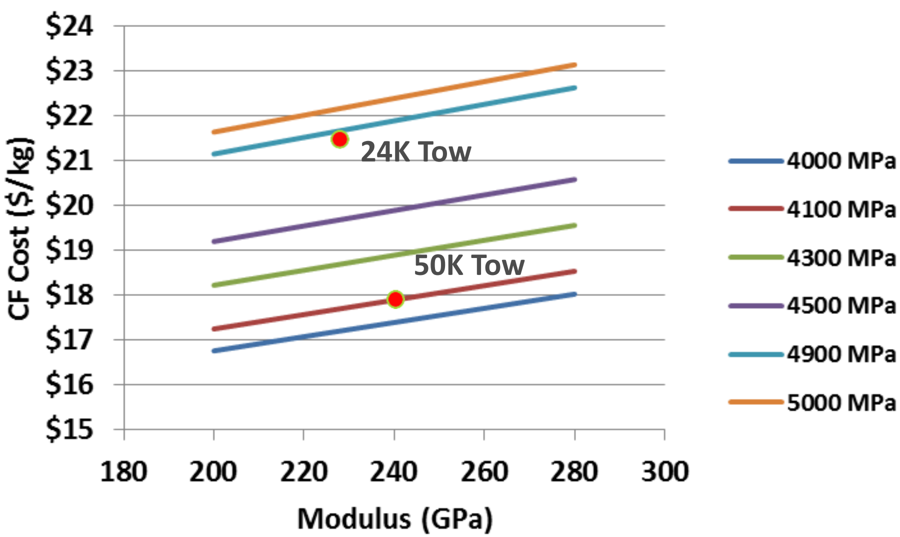
- Fiber strength and modulus sensitivity calibrated to commercial 24K tow and 50K tow fiber costs
  - Used to correlate strength sensitivity to fiber cost
  - Fiber modulus correlated to; Low Temp. Furnace [1.14 MSI/100°C Increase], High Temp. Furnace [0.85 MSI/10 sec. Residence Time Increase] [0.24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

➢ Fiber cost is more correlated to change in material strength than modulus

➢ Fiber properties will be correlated to final composite properties for blade cost impacts

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





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Material Testing

- Mechanical properties will be derived for baseline, commercial products and for CFTF low-cost carbon fiber materials
  - Industry baselines (2-3 will be selected)
  - CFTF Precursor #1: Kaltex 457k tow
- Materials will be tested in (1) aligned strand infused and (2) pultruded composite forms
- Failure analyses will be performed on the different samples to gain insight into why the materials fail, particularly insightful for the heavy-tow materials

OAK RIDGE National Laboratory

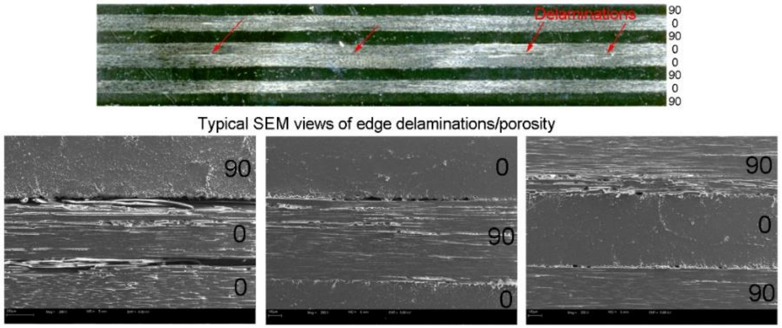
CARBON FIBER TECHNOLOGY FACILITY

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	

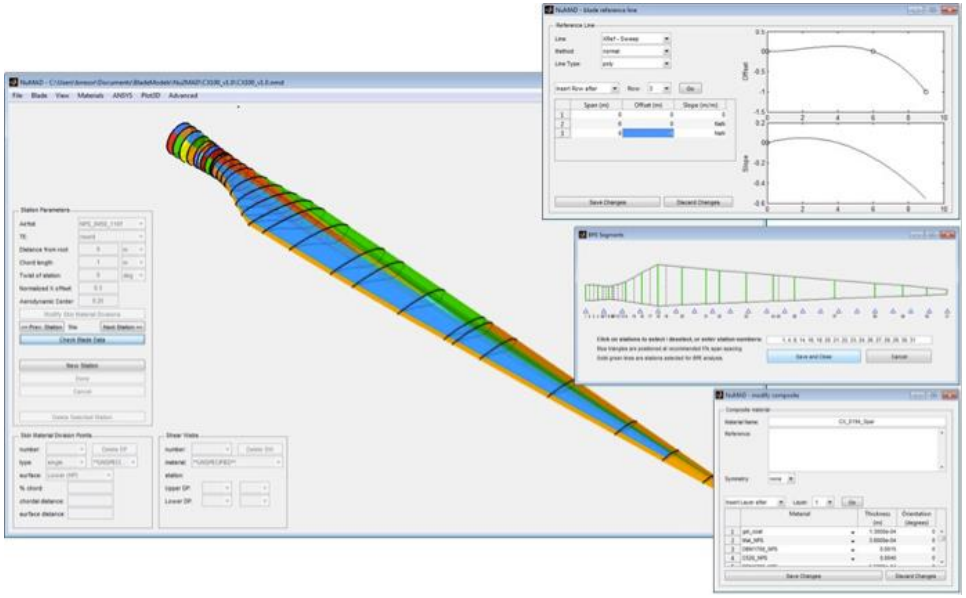
ORNL Material Properties for Kaltex Precursor

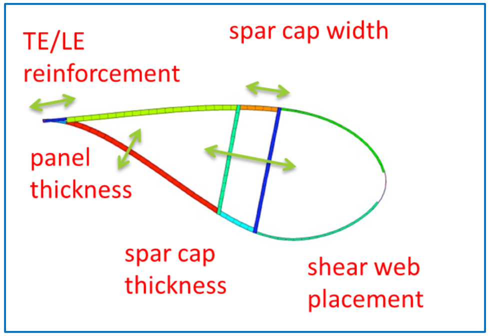


Typical SEM views of edge delaminations/porosity

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

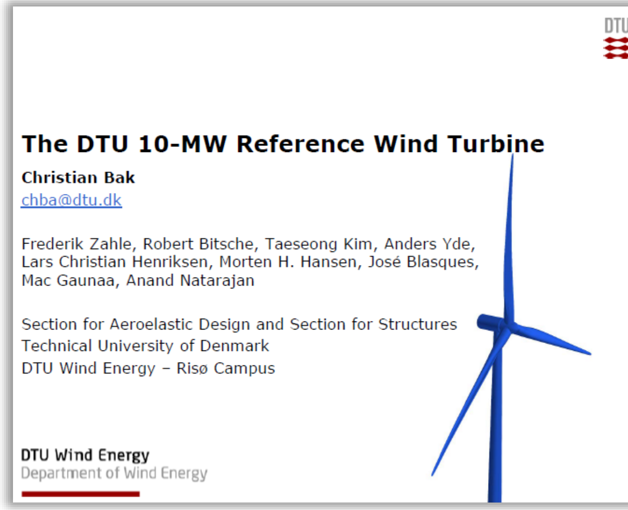
Structural and material optimization will be performed using **two reference blade models** that are representative of industry trends:

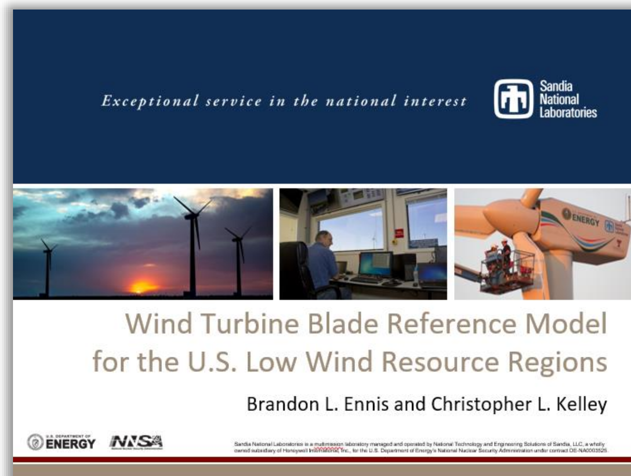
1. High wind resource (IEC class I-B), large wind turbine representative of future offshore wind turbines; **DTU 10 MW** aerodynamic design
2. Low wind resource (IEC class III-A), high energy capture wind turbine typical of development for the low wind speed sites across the U.S.; **SNL3.0-148** aerodynamic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





Summary

- Without further innovation, carbon fiber will continue to be utilized in certain wind turbine designs and represent a share of the industry
- Market trends towards longer blades and larger machines will drive demand for carbon fiber blade designs
- 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
  - What if there was an optimized carbon fiber material whose properties matched the system demands for wind turbines, and every OEM wanted to use it?
- This project seeks to address that perceivable material gap through a systems design approach that assesses the effect of a range of material specification on blade cost
- Interesting opportunities may exist for industry partnerships to find potential solutions:
  - Wind turbine design is influenced by material design, how else could material design be influenced by wind turbine design?