U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

Optimized Carbon Fiber Composites for Wind Turbine Blades

Project ID #T16

Brandon Ennis

Sandia National Laboratories

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NNSA

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FY17-FY18 Wind Office Project Organization

"Enabling Wind Energy Options Nationwide"

Technology Development	Market Acceleration & Deployment
Atmosphere to Electrons	Stakeholder Engagement, Workforce Development, and Human Use Considerations
Offshore Wind	Environmental Research
Distributed Wind	Grid Integration
Testing Infrastructure	Regulatory and Siting
Standards Support and International Engagement	
Advanced Components, Reliability, and Manufacturing	

Analysis and Modeling (cross-cutting)

Project Overview

T16: Optimized Carbon Fiber Composites for Wind Turbine Blades

Project Summary

- The objective of this project is to assess the commercial viability of cost-competitive, tailored carbon fiber composites for use in wind turbine blades. The project includes cost modeling and material testing of different low-cost and industry baseline carbon fiber materials. Material viability for wind turbine blade applications is assessed through structural blade design optimizations.

Project Objective & Impact

- Project results will be useful in guiding wind turbine blade designers and manufacturers on material selection through identification of more optimally suited carbon fiber materials for the wind energy application which don't exist commercially. Fiber manufacturers can use the results and make investments to target carbon fiber products for applicability to the wind energy industry.

Project Attributes

Project Principal Investigator(s)

Brandon Ennis – SNL

DOE Lead

Mike Derby, Lillie Ghobrial

Project Partners/Subs

Robert Norris –ORNL
Dave Miller – Montana State University

Project Duration

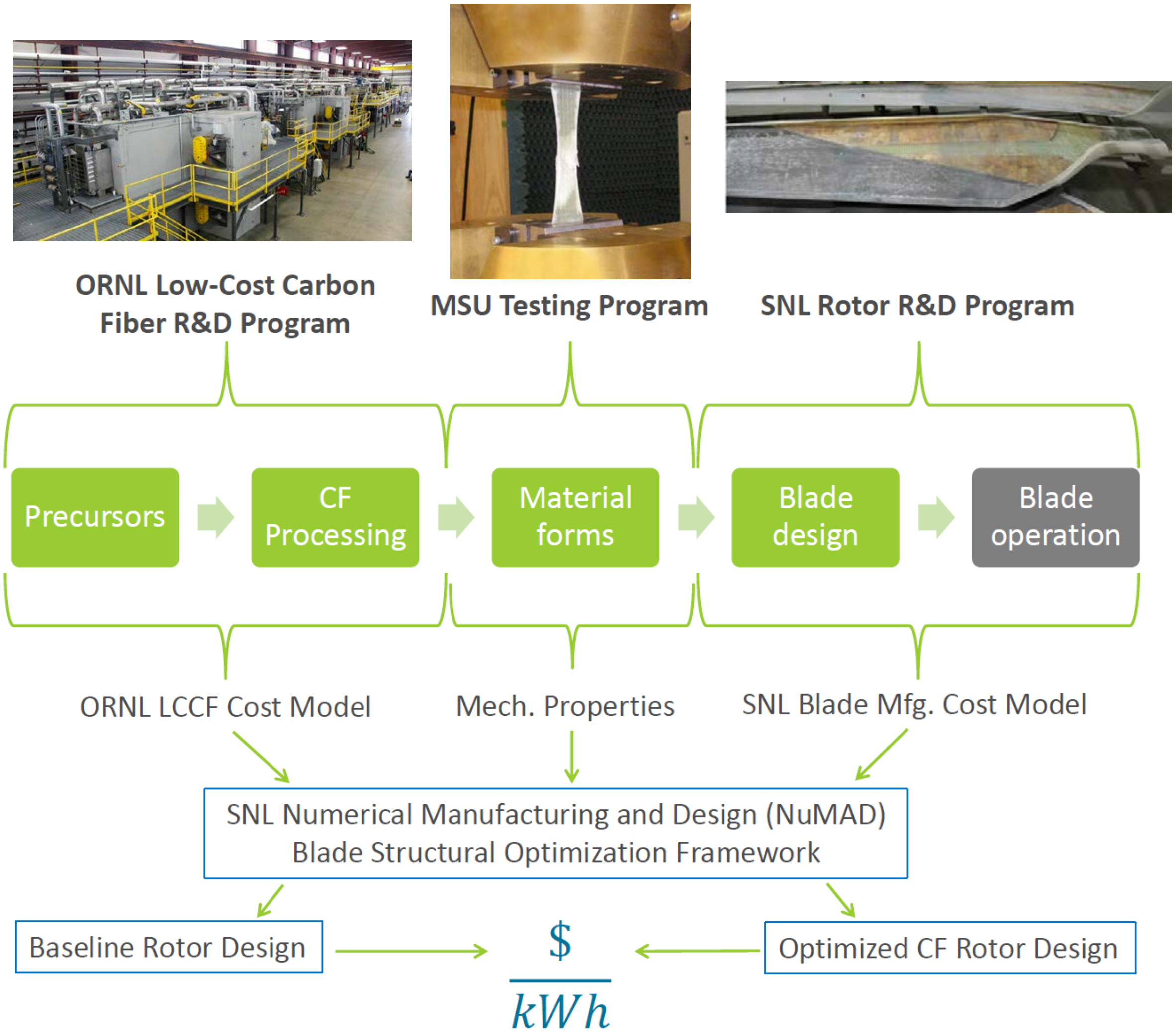
October 2016 – April 2019

Technical Merit and Relevance

- **Composites for wind turbines are selected based on a cost-driven design, compared to the performance-driven aerospace industry**
- **Wind turbine OEMs design blades based on commercially available materials, and fiber manufacturers produce materials based on industrial demand**
  - This isolated approach will not result in radical changes to commercial material design

Approach and Methodology

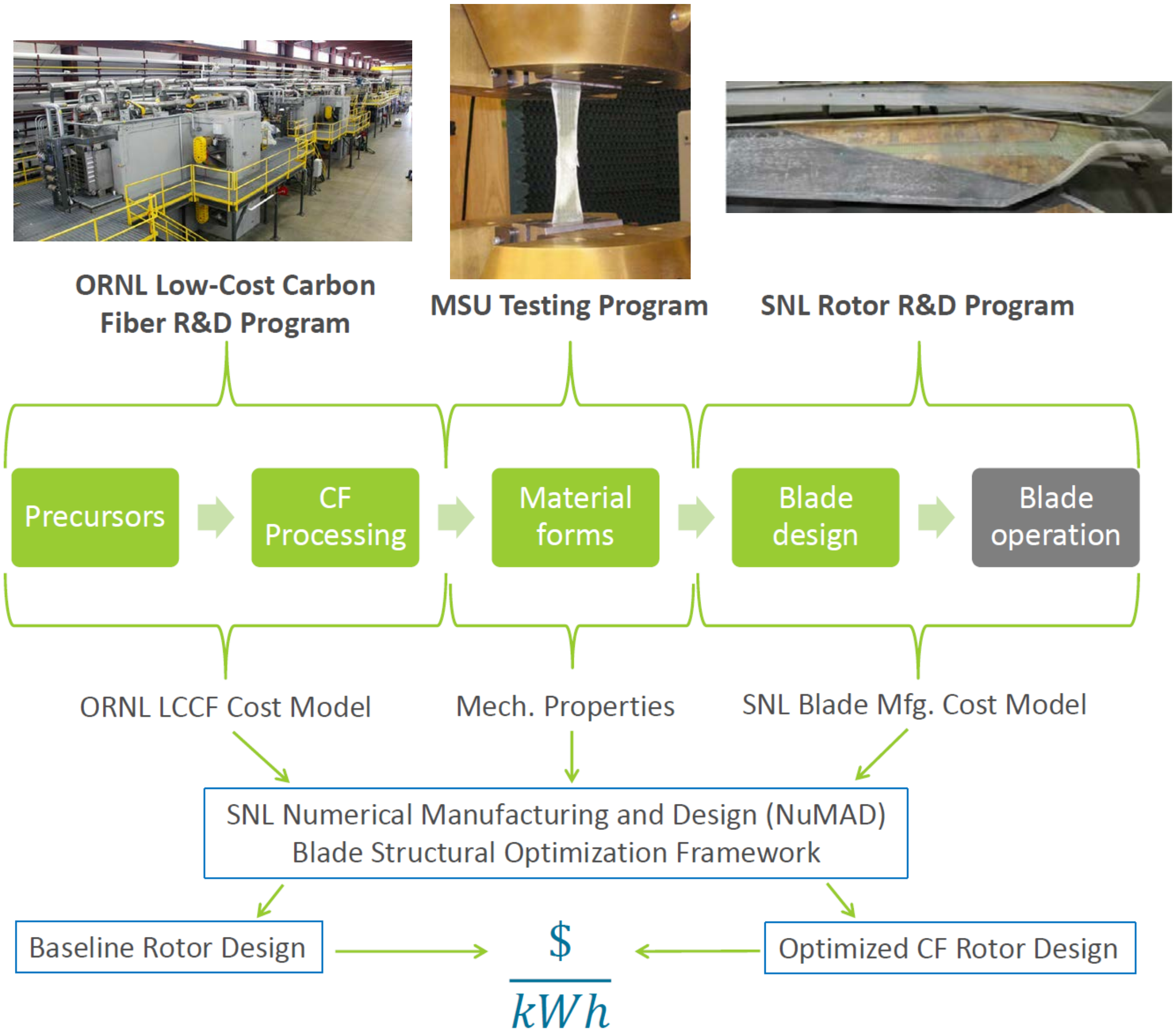
- Carbon fiber materials are compared in representative blade designs for the US through structural optimization and cost minimization
- The impact of novel carbon fiber materials on blade spar caps is assessed through comparison to industry baseline carbon fiber and fiberglass materials



Approach and Methodology

Approach requires:

- Development of cost models for novel carbon fiber materials in relevant composite forms, and mechanical test data of importance to the wind application
- Representative blade reference models which capture the different material demands to enable wind nationwide
- Collaboration with industry to ensure relevance and provide guidance on decisions

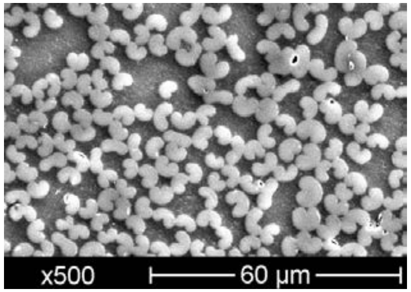


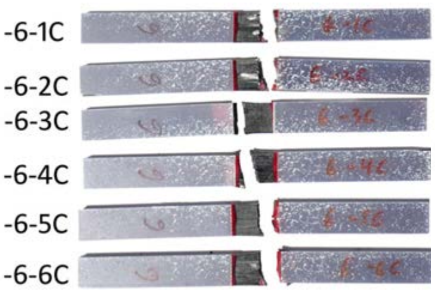
Accomplishments and Progress

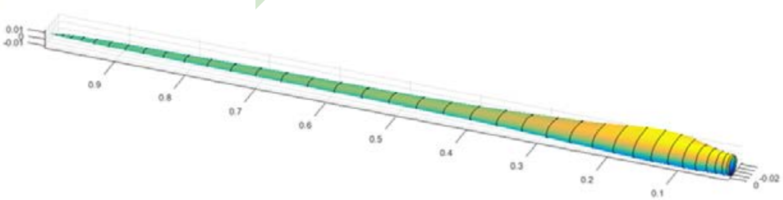
Fiscal Year 2017
- Project initiated
- Materials selected
- Advisory panel formed

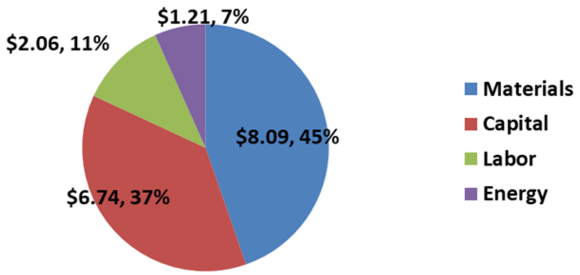
Fiscal Year 2018
- Final funding year
- Cost model developed
- Materials tested

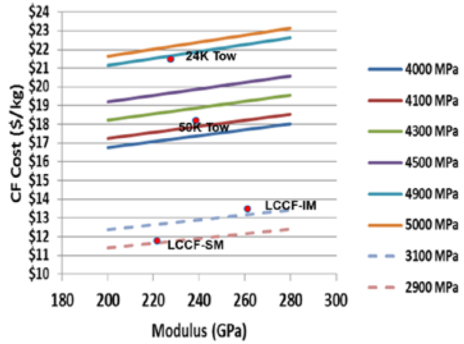
Fiscal Year 2019
- Optimizations studies
- Final report release
- Project concludes

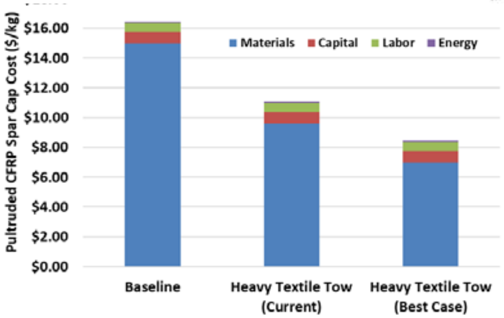






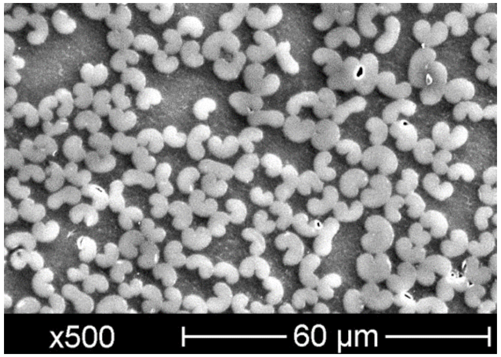






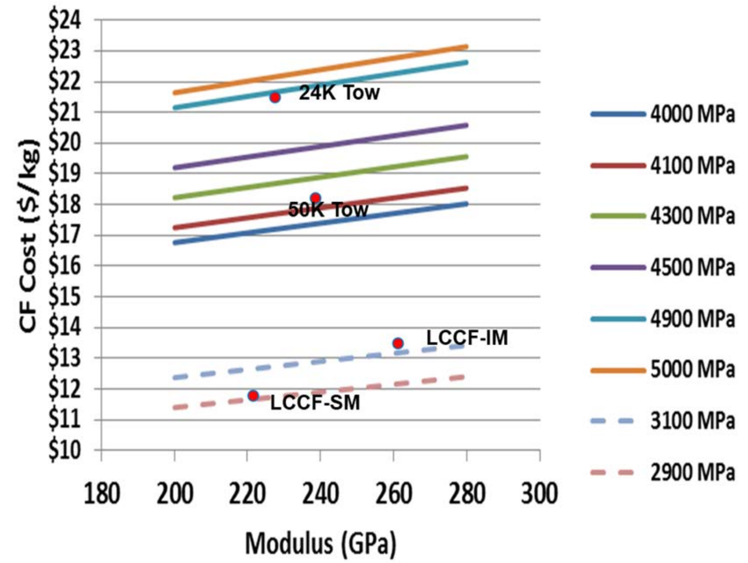
Evaluating Potential for Lower Cost Carbon Fiber

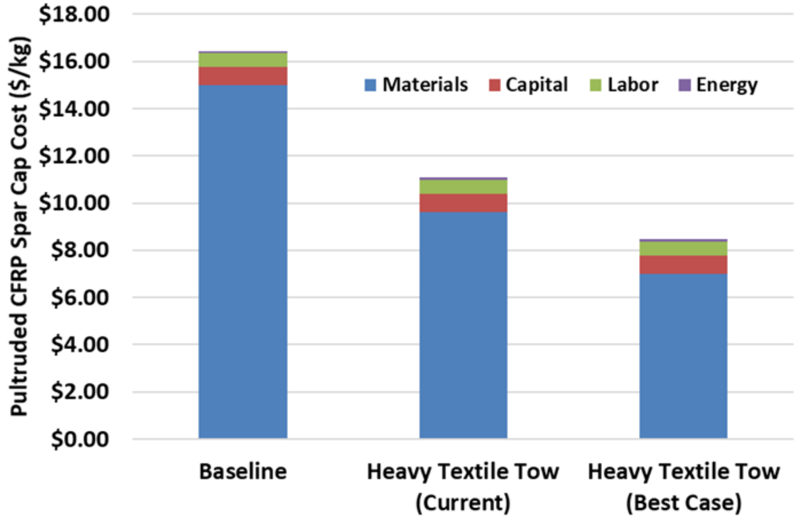
- **Textile Carbon Fiber (TCF)**
  - Acrylic fibers produced for textiles are similar chemically to those produced specifically as carbon fiber precursors, but significantly less expensive
  - Much of the cost difference is attributable to tow counts or number of filaments in each “bundle”
    - Traditional 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



Optimized Carbon Fiber Composites Cost Modeling

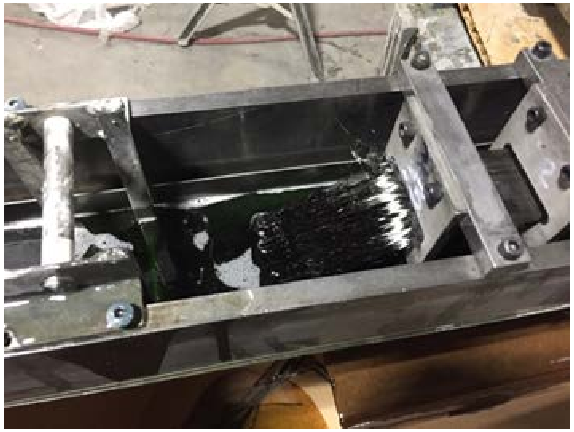
- Material (45%) and capital (37%) cost shares dominate the baseline (50K tow) carbon fiber cost of **$18.11/kg**
- Lower precursor cost and economies of scale from a higher throughput lowers the heavy textile tow (457K tow) LCCF (current) cost of **$11.19/kg**
- With an increased throughput due to reduced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





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 use case in spars



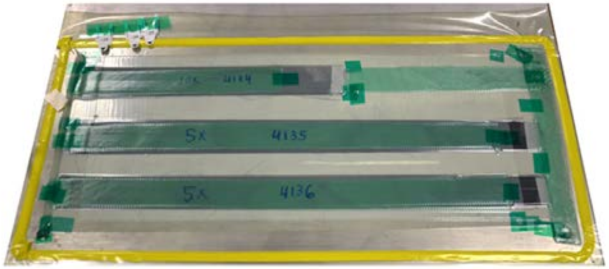
Pultrusions can produce spar caps very cost-effectively and with repeatable performance

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

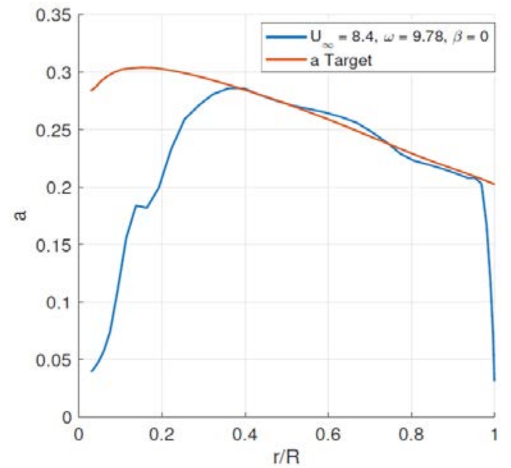
Material	Composite Form	Layup	V_F [%]	E [GPa] 0.1-0.3%	UTS [MPa]	%, max	UCS [MPa]	%, min
ORNL T20 (Taekwang)	Aligned strand	$(0)_5$ and $(0)_{10}$	50	126 (4)	956 (63)	0.74 (0.05)	-869 (46)	-0.69 (0.04)
ORNL K20 (Kaltex)	Aligned strand	$(0)_5$ and $(0)_{10}$	47	112 (6)	990 (49)	0.84 (0.06)	-863 (108)	-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)

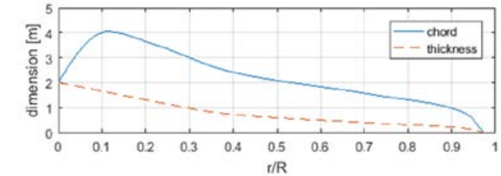


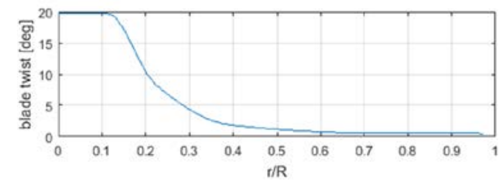
MSU Aligned Strand infusions are useful for comparing fiber properties while minimizing manufacturing effects

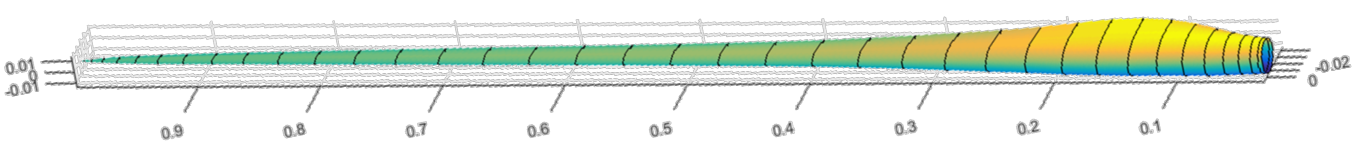
Rotor Design and Optimization

- 3 MW high energy capture reference model developed to study optimal carbon fiber materials for low wind resource sites
- 10 MW reference model selected to assess material performance and demands for high wind resource offshore sites
- Model spar cap material inputs defined from mechanical testing and cost modeling results









Material	Vf	E [GPa]	UTS [MPa]	UCS [MPa]	Cost [$/kg]
Industry baseline carbon fiber pultrusion	0.68	157.6	2424.1	-1645.4	$16.44
Heavy-tow carbon fiber pultrusion	0.68	160.6	1505.2	-1312.1	$8.38 - $11.01

Accomplishments and Progress

Material Selection and Cost Modeling:

- Heavy-tow, low-cost materials identified in production at ORNL
- Heavy-tow (457K) carbon fiber found to have 38-57% lower cost
- Pultrusion cost model developed, best-case 49% reduction in pultruded spar caps, resulting in a 56% improvement in UCS/$/kg

Mechanical Testing:

- Heavy-tow materials processed in pultruded forms
- Properties of importance to spar caps determined to assess material performance relative to baseline carbon fiber material
- Fatigue test results produced to understand material differences

Blade design and optimization:

- Representative 3 MW and 10 MW reference models defined to assess the varying material demands at different sites
- Optimization tools refined to perform the material selection

Accomplishments and Progress

Remaining Steps to Completion

Blade design and optimization:

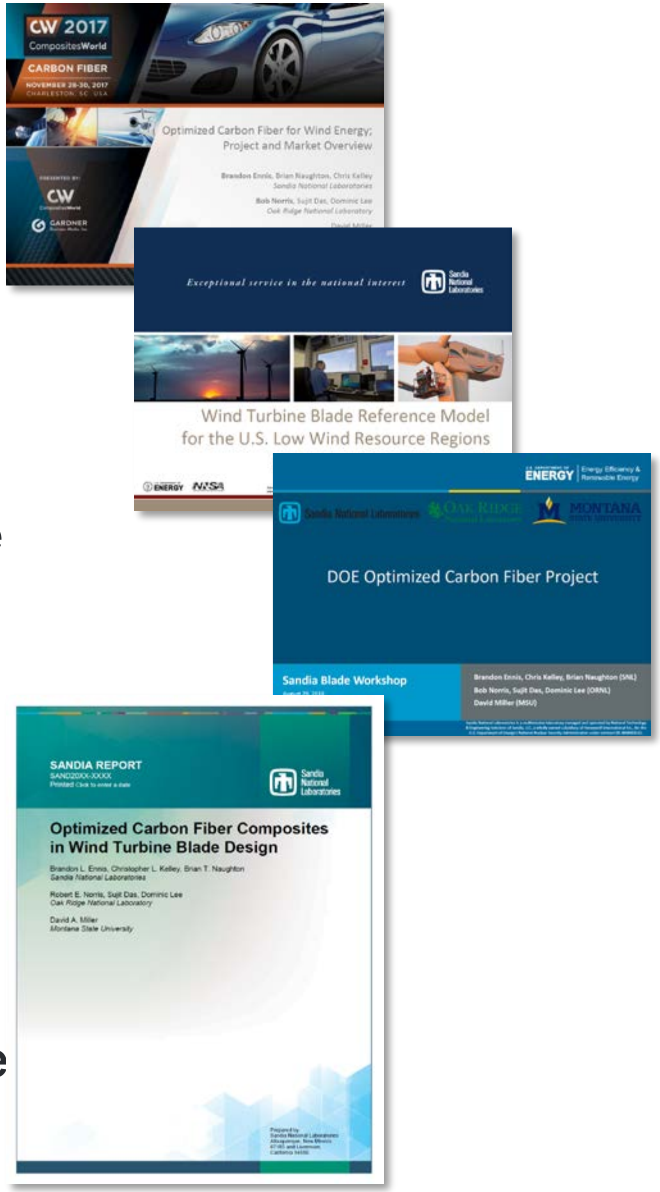
- Finalize optimization studies for land-based, low wind resource blade reference model
- Finalize optimization studies for offshore, high wind resource blade reference model
- Characterize optimal spar cap material properties for strength-driven and stiffness-driven applications

Record Keeping and Communication:

- Complete material testing report
- Complete project summary report
- Disseminate results to industry through industry meetings

Communication, Coordination, and Commercialization

- **Presentation of project and results at three conferences to communicate high-level project summary and detailed results** (Carbon Fiber 2017; North American Wind Energy Academy 2017; Sandia Blade Workshop 2018)
- **Industry advisory panel was established and convened annually to present project results and obtain feedback to ensure commercial relevance and project awareness** (including technical members from turbine OEMs, blade manufacturers, fiber manufacturers, and design consultants)
- **Final project report will be released at project conclusion including two additional conference presentations**
- **Plans for follow-on work and partnership with industry to refine material processing and reduce barriers to market**



Upcoming Project Activities

- **Finalize project summary report**
  – This project will provide feedback to industry on market needs and cost/performance tradeoffs
- **Big Adaptive Rotor (BAR) Project**
  – This project work will continue through the BAR project and will assess the impact of optimized carbon fiber material for aeroelastic tailoring and leading-edge/trailing-edge reinforcement
- **Carbon Fiber Material Design for Targeted Performance Enhancement**
  – Merit-reviewed proposal; logical next step to identify how materials can be further designed (from precursor) to produce the desired material properties