U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

Additive Manufacturing in Wind Turbine Components and Tooling

Project ID #: T13

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Oak Ridge National Laboratory

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

T13: Additive Manufacturing in Wind Turbine Components and Tooling

Project Summary

- Cost must be competitive to enable wind energy nationwide.
- Additive Manufacturing (AM) is an efficient and rapid (design-to-product cycle) manufacturing technology that can produce complex parts with multiple integrated functionalities.
- However, applicability, value propositions, risks, etc. of different AM processes for wind are not known.
- This project will explore the applicability of AM as a manufacturing tool for wind turbine components and tooling.

Project Objective & Impact

Objectives:

- Leverage the successes of the 3D-printed blade mold to move beyond tooling to end use parts (indirect to direct manufacturing)
- Demonstrate the efficacy of AM in manufacturing of wind components/tooling;
- Understand appropriateness, value, advantages/disadvantages, etc. of different AM approaches.

Impacts:

- Ability to include appropriate AM processes in the manufacturing toolbox of wind turbine components and tooling will accelerate design innovation, reduce costs, decrease scraps, and reduce time-to-market, ultimately accelerating the deployment of wind and increasing the number of domestic renewable and manufacturing jobs.

Project Attributes

Project Attributes
Project Principal Investigator(s)
Brian K. Post (ORNL) Scott Carron (NREL)
DOE Lead
Michael Derby
Project Partners/Subs
TPI Composites Vestas
Project Duration
Sept. 1, 2015 – Sept. 30, 2019

Technical Merit and Relevance

AM is a rapidly developing technology that is efficient and can reduce manufacturing cost and time. It has proven itself in rapid prototyping and to a certain extent in tooling production.

Applying AM to wind turbine components and associated tooling has been, to date, impractical given the state of the art in AM systems which have neither the print volume, print speed, or economic viability to enable its use in wind applications.

New generations of AM technologies are being developed at ORNL's Manufacturing Demonstration Facility (MDF), that will enable technology innovation for large scale wind turbine components.

Potential benefits in applying AM to wind include:

- ✓ Increased design, materials and production location flexibilities
- ✓ Inform manufacturers on production process decisions
- ✓ Can impact all wind options - land-based, offshore, distributed
- ✓ Potential to innovate, reduce cost, first to market
- ✓ Potential to transform business models (e.g. digital inventory vs. warehousing)

Ultimately accelerate/increase deployment and jobs.

Approach and Methodology

This project is comprised of two sequential focus areas, each addressing one of the objectives.

<u>Focus One</u>: Efficacy of AM in manufacturing of Wind Components and Tooling (FY16-FY17).

Approach: - Leverage success of 3D printed blade mold project that produced a set of 13 meters-long research blade molds as a focused example for performance, value propositions, cost modeling, etc.
- Evaluate what major components/tooling may be addressable by *existing* and *forthcoming* AM processes.

Task 1: Survey of process and performance challenges in wind turbine manufacturing (ORNL and NREL).
Task 2: Cost/performance analysis of AM wind components/tools (*present* AM capability). (ORNL and NREL).
Task 3: Risk analysis and mitigation strategies (*present* AM capability). (ORNL and NREL).
Task 4: Cost/performance analysis, risk analysis and mitigation strategies of wind turbine components/tools (forthcoming AM capability). (ORNL and NREL).
Task 5: Industry collaboration to refine AM cost/performance analysis (ORNL, NREL and Vestas).

Approach and Methodology

<u>Focus Two</u>: Understand the appropriateness, costs, relative advantages and disadvantages of selected AM approaches in the manufacturing of a wind turbine component (FY18-FY19).

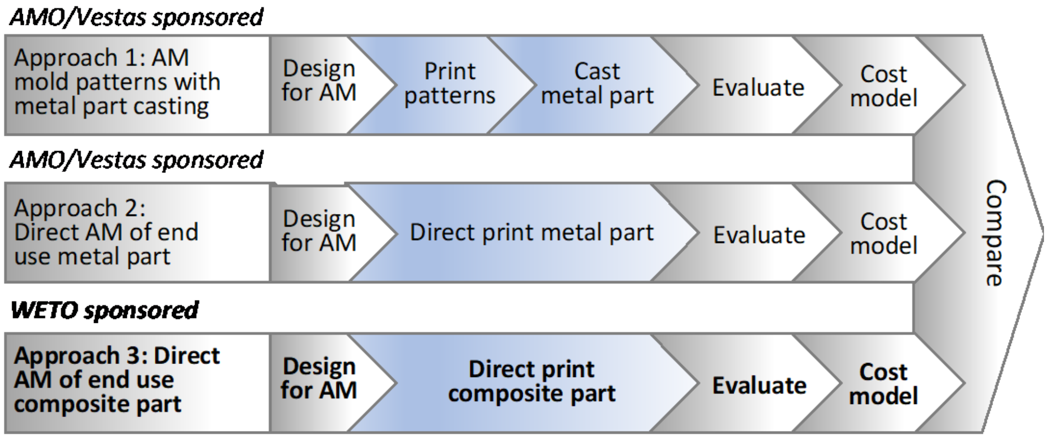
Approach: - Design a wind turbine part with industry partner (Vestas) based on selected AM approaches and performance rather than form.
- Manufacture the part using selected AM approaches, characterize for performance and develop cost models.

Task 6: Direct AM of carbon fiber reinforced thermoplastic composite wind turbine part.

Task 6.1 – Design of part for direct composite printing (ORNL and Vestas).

Task 6.2 – Print Composite part (ORNL).

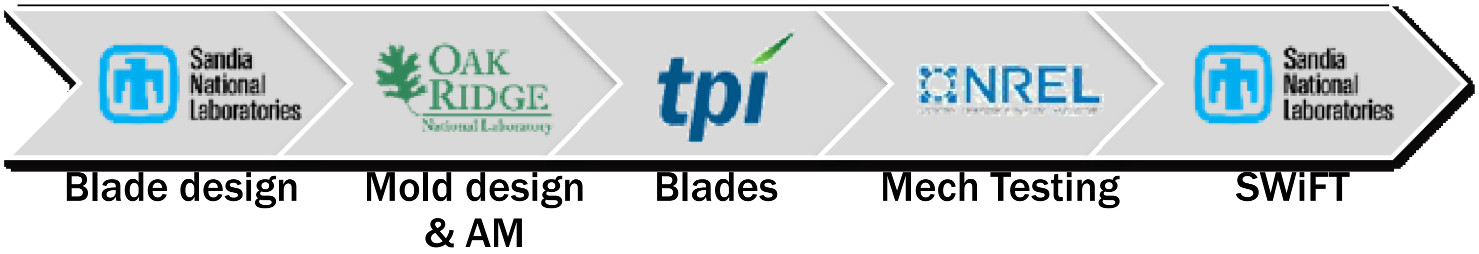
Task 6.3 – Characterize performance and cost modeling of composite part (ORNL, NREL and Vestas).



** Task 6 will be supplemented by parallel efforts using AM metal casting and direct AM metal printing approaches sponsored by EERE-Advanced Manufacturing Office and Vestas.*

Accomplishments and Progress

AM mold for 13-m research blades - Background

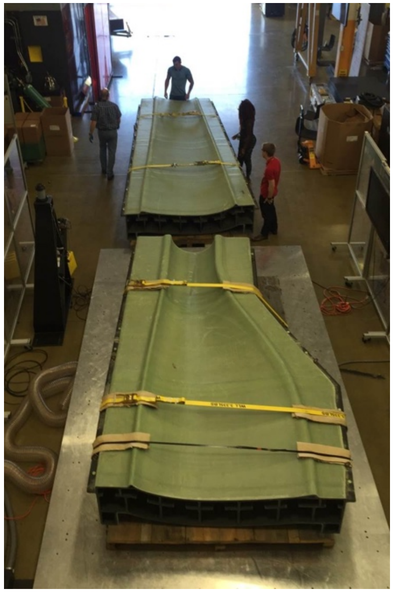


Traditional 50 m Mold	3D Printed 50 m Mold
Fabrication takes a total of <u>**27 weeks**</u> • 12 weeks: fabricate plug • 3 weeks: setup and inspect to confirm shape • 6 weeks: layup shell, attach frame, demold plug • 6 weeks: Electrical connections, cure, QA, shipping prep	Based on 13 m mold results, a 50 m mold can be designed, printed and finished in only <u>**20 weeks**</u> • 12 weeks: print mold sections • 4 weeks: glass and finish mold sections • 4 weeks: attach frame, install heaters, QA, shipping prep
1 pair of main plugs – reliable for 6 to 10 molds	<u>**No plugs are needed**</u>. Direct CAD to mold
Wires are embedded into the fiberglass surface by hand during mold fabrication to heat the surface	<u>**Air passages incorporated**</u> into design of the mold to accommodate heated air which is cycled throughout the mold

Accomplishments and Progress

AM mold for 13-m research blades – Technical

Parameter	Target (this period)	Stretch (low volume)	Production
Substrate bond interface & coatings	Short beam shear test with no failure of interface at ambient	Short beam shear test with no failure of interface at 40ºC	Short beam shear test with no failure of interface at 70ºC
Mold temp (+/-5ºC)	Ambient (need oven)	40ºC (resin flows)	70ºC (fast cure) with 100ºC peak
Mold distortion	Match HP to LP at ambient less than 1% of chord	Match HP to LP at 40ºC less than 1% of chord	Match HP to LP at 70ºC less than 1% of chord
Vacuum drop	30 mbar over 30 minutes	15 mbar over 60 minutes	15 mbar over 60 minutes
Assembly of mold pieces	Meet gap tolerance at room temp	Meet gap tolerance at 40ºC	Meet gap tolerance at 70ºC
Life	4 blades	12 blades	1,000 (production)



Accomplishments and Progress

AM mold for 13-m research blades – Manufacturing by Big Area Additive Manufacturing (BAAM)

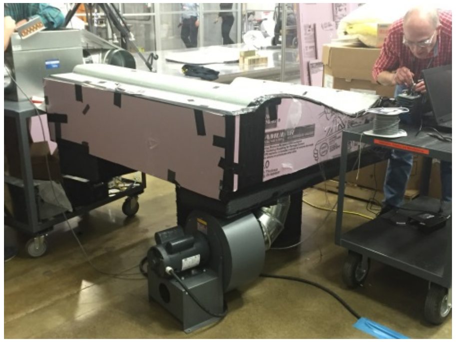
BAAM - 20 feet long, 8 feet wide and 6 feet tall at 100-lbs per hour
Mold printed in 8 subsections (1.6 - 1.8m long).
Subsections joined into 3 sections (3.6 - 5.2m long)

Wind turbine blade mold section manufactured on the BAAM-CI from 20% CF-ABS pellets

Accomplishments and Progress

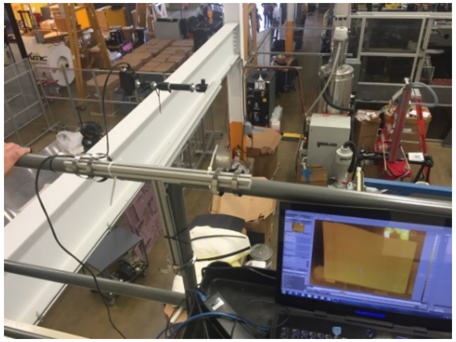
AM mold for 13-m research blades – Mold testing an qualification

- **Results from all tests met design requirements.**

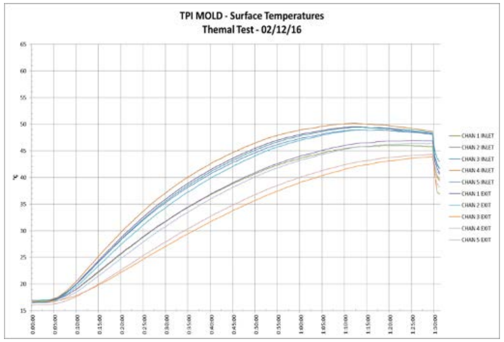


Experimental setup

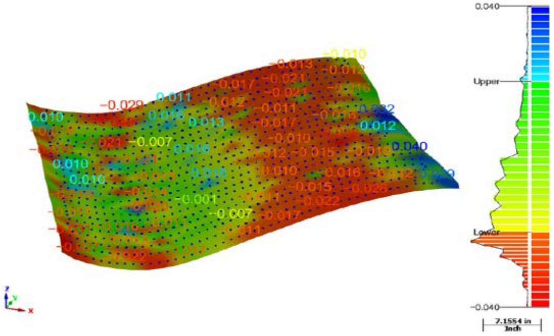
Laser tracker in foreground



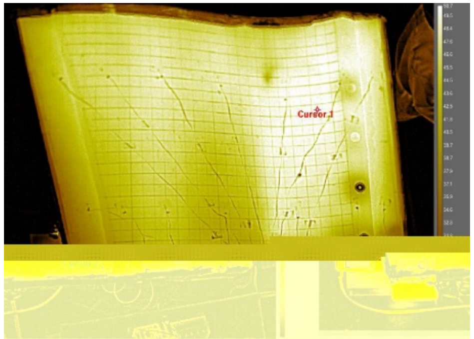
Thermal imaging on mold surface



Surface temp



Profile data



Accomplishments and Progress

AM mold for 13-m research blades – Mold prep and blade fabrication

Mold setup

Blade build

13-m blade

- TPI Manufactured 9+ Blades From Printed Molds for Sandia SWiFT Facility.
- TPI Confirms that expected tool life is 1000+ blades (same as conventional tool)
- Mold now resides in the NWTC at NREL and is being used for Manufacturing R&D (Institute for Advanced Composites Manufacturing Innovation (IACMI))

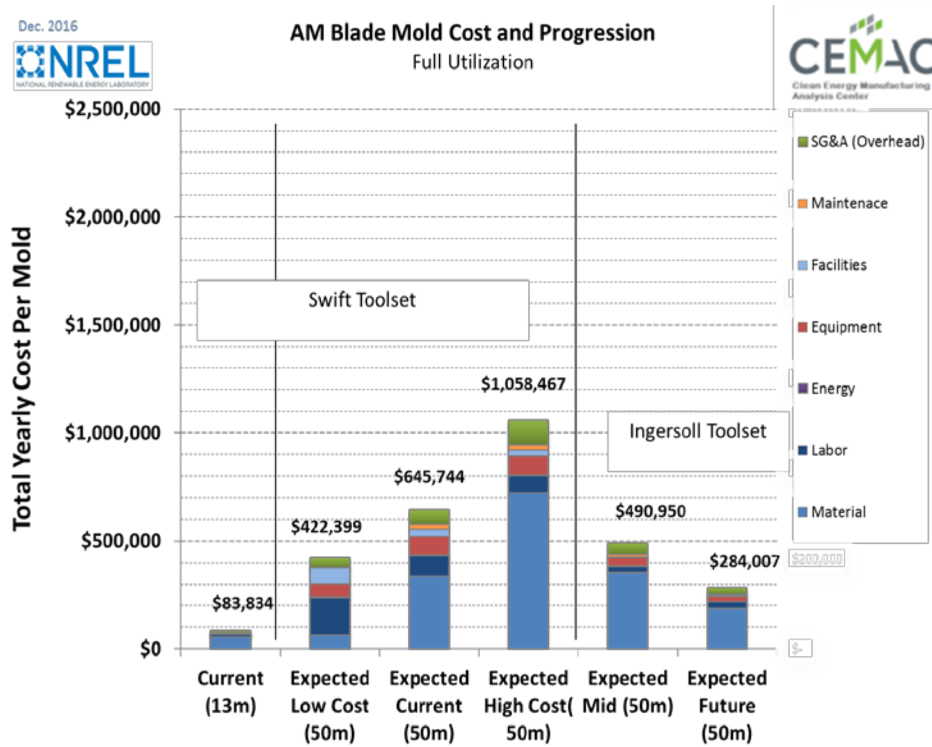
Accomplishments and Progress

AM mold for 13-m research blades – Cost Modeling

- Manufacturing cost model accounts for all steps: equipment, materials, pre-processing, processing & post processing.

- Presently, 50-m molds using BAAM is expected to cost ~\$646k under full machine utilization
  - Materials & labor are major cost components
  - High labor cost due to limited BAAM footprint

- Future hyper-scale machines ~284K – 491k /mold

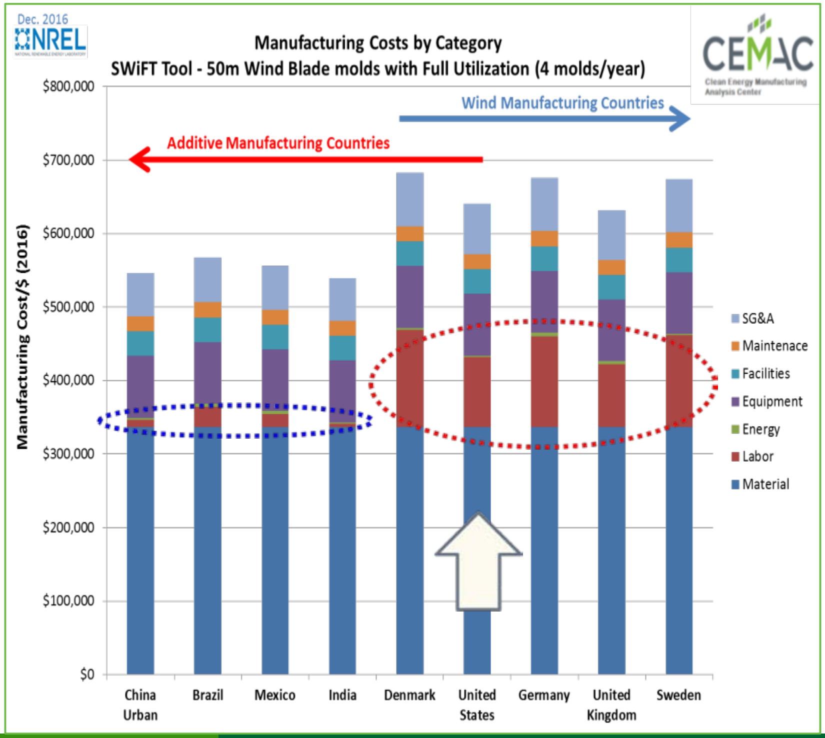


Accomplishments and Progress

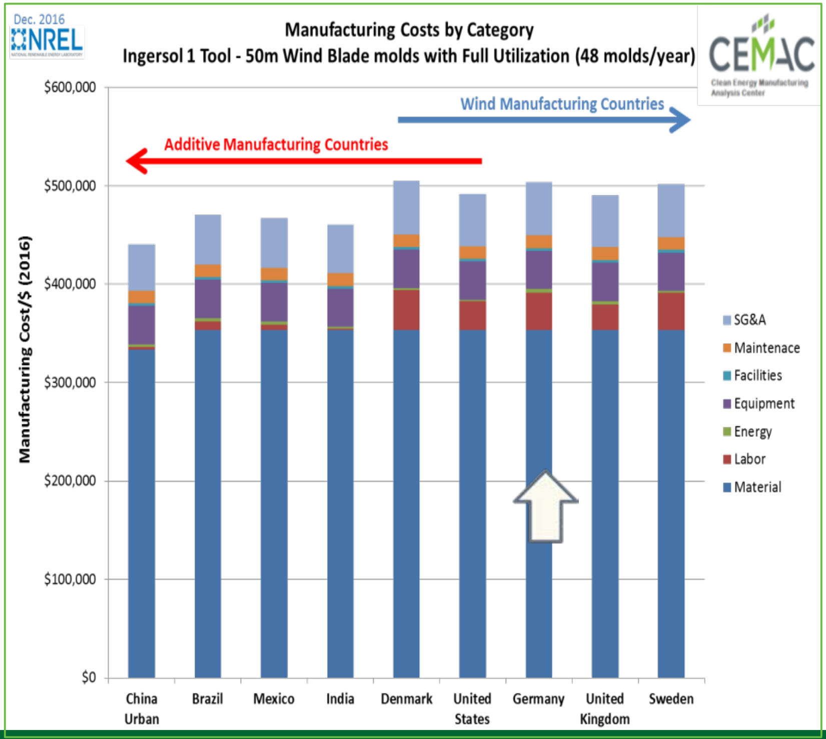
AM mold for 13-m research blades – Cost Modeling

- Higher labor cost associated with current smaller machines makes domestic manufacturing of large components (e.g. wind, aerospace, marine industries) less competitive with emerging market labor rates.
  - ❖ Availability of hyper-scale machines will increase competitiveness of domestic manufacturing.

BAAM



Hyper-scale



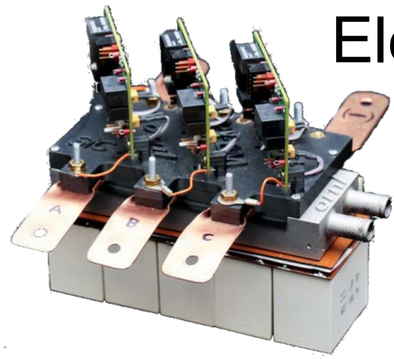
Accomplishments and Progress

Focus Area One – Summary of Accomplishments

- Brian Post selected as Additive Manufacturing Advisor to the Society of Manufacturing Engineers
- 2017 Federal Laboratory Consortium (FLC) Mid-Continent Region Outstanding Regional Partnership Award
- 2018 Federal Laboratory Consortium (FLC) National Technology Focus Award

	FY2017
Quarter One	Completed survey of wind turbine and tooling landscape with NREL that establishes the baseline for manufacturing.
Quarter Two	In collaboration with Vestas and NREL, completed initial update on the costs/performances and risks for wind turbine components and tooling that can be impacted by AM technologies.
Quarter Three	Established the feasibility of AM for selected high-valued wind turbine component(s) or tooling. Included onsite inspection of turbine components at NWTC
Quarter Four	In collaboration with Vestas and NREL, completed final update on the costs/performances and risks for wind turbine components and tooling that can be impacted by AM technologies.

Accomplishments and Progress Focus 1



Electronics packaging

Magnets

Heat Exchangers

Castings

Blades

Towers

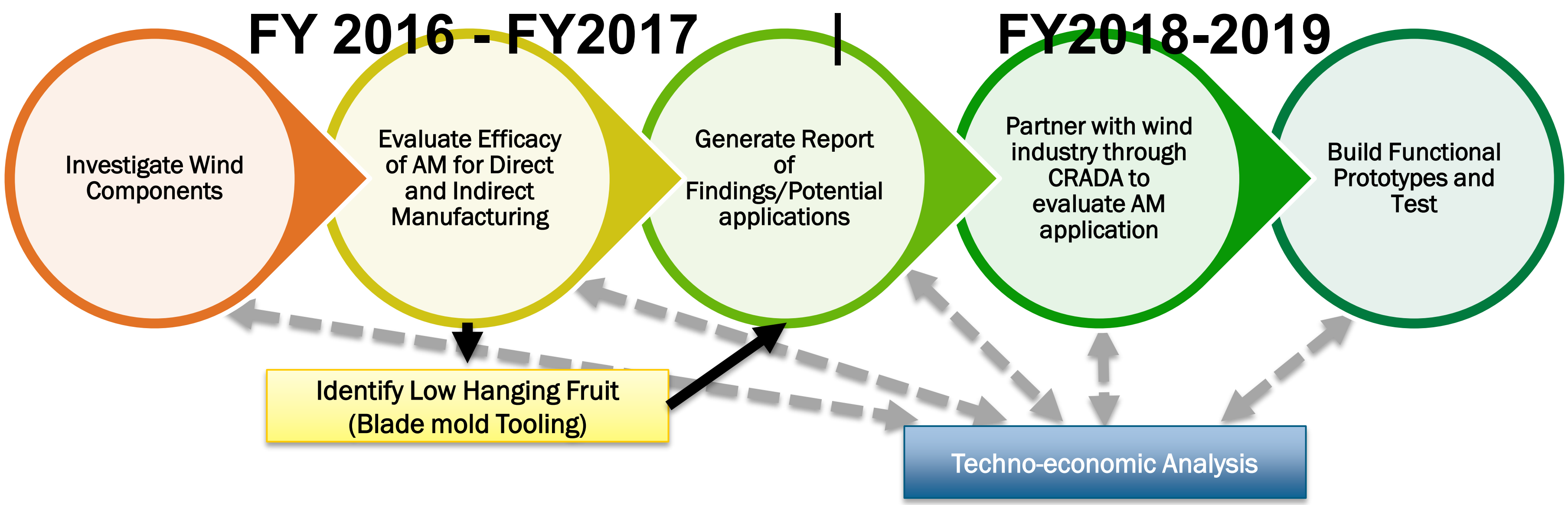
Accomplishments and Progress

Focus area Two – Summary of Accomplishment

- Mathias Jensen (Ph.D. student with vestas) visited ORNL's MDF for 2 week fellowship
- Working as a conduit between ORNL and Vestas Mathias was instrumental in selection of target application for comparative study
- On site meeting was held at ORNL to develop project approach and responsibilities

	FY2018
Quarter One	Develop mitigation strategies that can run parallel or in place of Vestas-related activities in the case of availability of additional funding or the Vestas CRADA being extensively delayed. ORNL to submit recommendations to DOE HQ Project Lead in report format, providing overview, potential impacts, potential collaborations, and estimated cost.
Quarter Two	Complete execution of Vestas CRADA: ORNL to work with sponsors and Vestas and provide required information to ensure the approval and execution of the Vestas CRADA.
Quarter Three	Complete initial project planning: ORNL to complete discussion with sponsors and Vestas on project paths forward, project plan and performance schedule.
Quarter Four	Complete project kickoff meeting: ORNL. NREL and Vestas personnel to meet with sponsors at a kickoff meeting to officially start the project and finalize project plan and schedule.

Accomplishments and Progress



Accomplishments and Progress for FY17/18

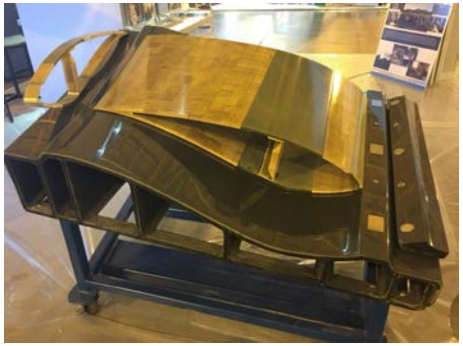
- Identified, with Vestas, a target structural nacelle component for direct AM production
- Identified 3 separate methodologies utilizing large scale AM to make the same component: reinforced composite print, foam print for lost foam casting, and direct metal print.
- Finalized CRADA with Vestas and ORNL
- Initialized multiparty unilateral NDA with ORNL, Vestas, and NREL for sharing technical and economic data to inform comparison study (granted Dec. 2018)
- Held successful project kickoff meeting at ORNL (Sept. 2018) to identify project plan/timeline and mitigation strategies and resolutions for technical concerns

Communication, Coordination, and Commercialization

- Results and findings are disseminated through open literatures, presentations, and direct communication with industry and stakeholders.
- Special effort to communicate to manufacturing community that is less familiar with opportunities for wind.
  - ➢ Manufacturing-centric conferences
  - ➢ Mold project included in standard AM slide deck
  - ➢ Mold segment as featured exhibit for ORNL Manufacturing Demonstration Facility (MDF) tour
  - ➢ Follow on work with multiple industries (aerospace, marine, and naval) using lessons learned from Blade mold success

Meetings:
- ➢ Solid Freeform Fabrication Conference Austin (Plenary)
- ➢ RAPID + TCT Conference
- ➢ JEC Knoxville Composites Conference
- ➢ SME Smart Manufacturing Seminar Series (2 events)

Exhibits:
- ➢ AWEA Windpower 2017
- ➢ ORNL MDF



Publications:
- ➢ ORNL Report


ORNL/TM-2017/479

The Current State of Additive Manufacturing in Wind Energy Systems

Date: December 2017

Oak Ridge National Laboratory

Upcoming Project Activities

Build Functional Prototypes and Test

- Design iteration with Vestas on structural component
- Manufacturing of components for testing
- Structural testing by Vestas to design loads
- Techno-economic analysis
- Report on findings /project debrief with key players and discussion of future opportunities

	FY2019
Quarter One	Complete design of part to be fabricated by composite additive manufacturing.
Quarter Two	Complete additive manufacturing of CF thermoplastic composite part.
Quarter Three	Evaluate performance of AM composite part and iterate design
Quarter Four	Complete characterization of composite part, cost modeling, and report on the comparison of the three parts produced by different AM approaches.