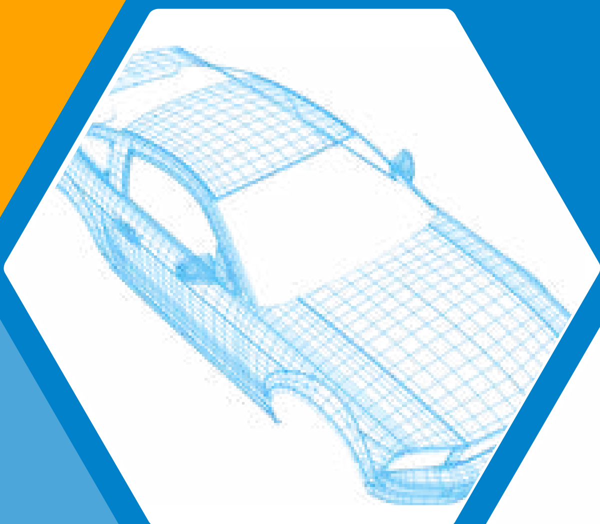
Institute for Advanced Composites Manufacturing Innovation
Technology Roadmap
PHASE 4



January 2019

Prepared by NEXIGHT GROUP

About this Roadmap

For half a century, fiber-reinforced polymer composites have enabled superior structural efficiency, environmental resistance, and design flexibility for a range of commercial and industrial applications. Reductions in cost, improvements in performance, and rising availability have stimulated the growth of composites and expanded their role beyond the aerospace industry. Today, composites are on the precipice of substantial commercial growth, and are regarded as a foundational technology needed to transition the United States into a clean energy economy.

The Institute for Advanced Composites Manufacturing Innovation (IACMI) led the development of this roadmap to guide the advancement and commercialization of low-cost, energy efficient composites for vehicles, wind turbines, and compressed gas storage applications. Supported by the U.S. Department of Energy's Advanced Manufacturing Office, IACMI developed this roadmap with engagement from stakeholders from these respective industries to identify promising research, development, and demonstration efforts needed to reduce technology implementation risk and develop a robust supply chain to support a growing advanced composites industry in the United States. The roadmap outlines the technology pathways to achieving its 5-year technical goals: 25% reduction in carbon fiber-reinforced polymer (CFRP) cost, 50% reduction in CFRP embodied energy, and 80% recyclability or reuse into useful products. It is also important to note that this roadmap calls for research and development activities that are beyond IACMI's current scope, capabilities, and funded activities. These recommendations are intended to inform the entire composites industry and its supply chain by placing IACMI's activities into a broader, industry-wide context.

This roadmap was developed under the guidance of Uday Vaidya, Chief Technology Officer, IACMI, and members of the IACMI Technical Advisory Board. The composites manufacturing industry experts who made crucial contributions through phone interviews, workshop attendance, and roadmap reviews, are also identified in Appendix A of this report. Nexight Group supported the overall roadmapping process and prepared this roadmap.

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Executive Summary

Transitioning the United States into a clean energy economy will require the widespread adoption of transformative technologies that save energy and reduce emissions. To accelerate progress toward this ultimate vision, the United States must invest in high-value, innovative research and development that bridges the gap between applied research and widespread commercialization.

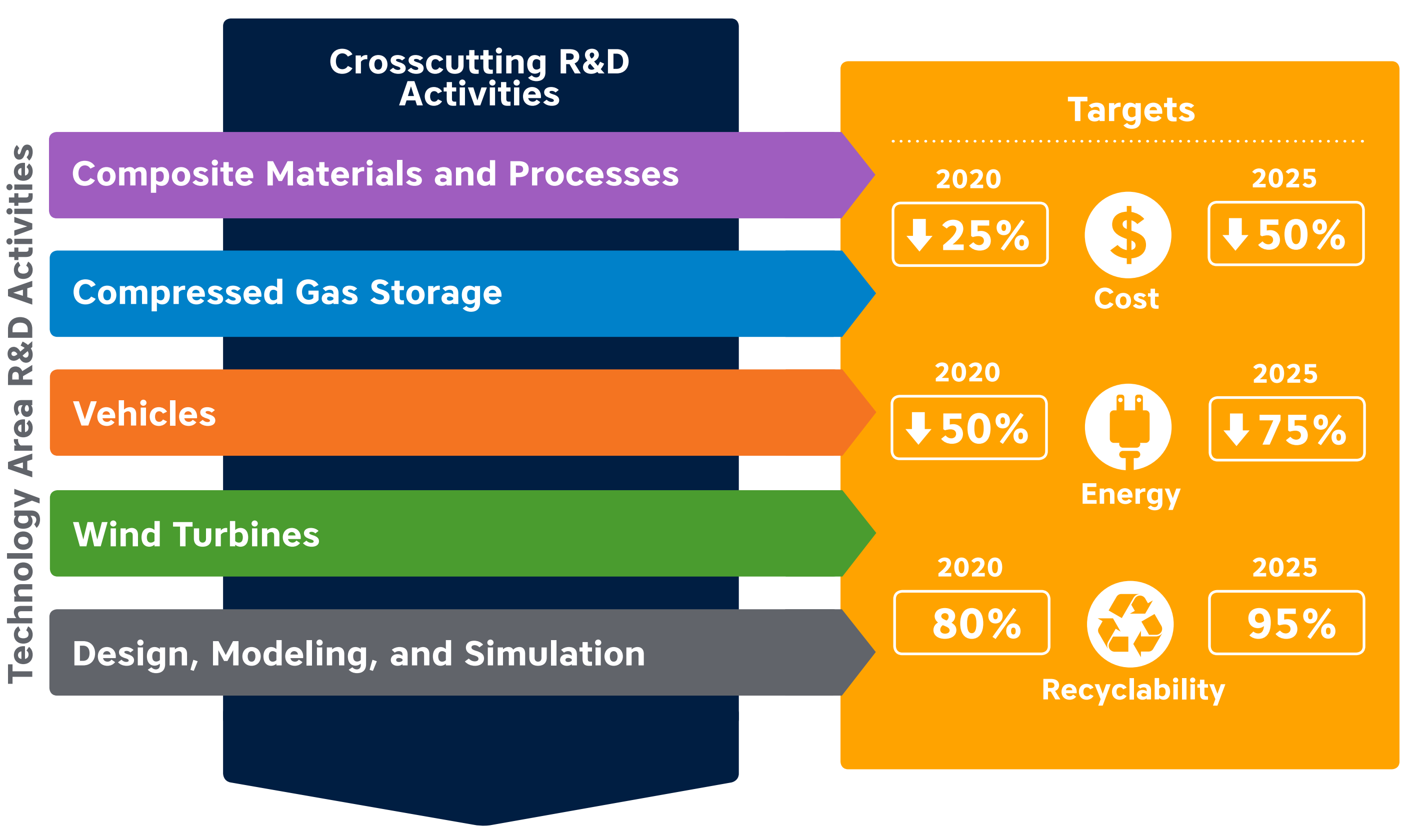
The need for innovation is urgent, particularly given trends toward electric technology in both the consumer automotive and mass transit sectors, as well as Federal initiatives to increase renewable electricity generation by 2020 and other future fuel economy standards for automobiles. Fiber-reinforced polymer composites (FRPCs) can be a key enabler of energy efficiency gains and emissions reductions. The cost-competitive, high-volume production of these materials can enable high-performance wind turbine blades in the power generation sector, automotive lightweighting, and improved compressed gas storage (CGS) tanks for alternative fuel vehicles in the transportation sector.

The Institute for Advanced Composites Manufacturing Innovation (IACMI) answers this call by providing the research-to-manufacturing infrastructure necessary to accelerate the transition of advanced composites manufacturing technologies into the marketplace and facilitate the integration of innovative methodologies and practices across supply chains.

To guide its efforts to enhance the energy efficiency and cost-effectiveness of fiber-reinforced polymer composites to encourage their cost-competitive, high-volume production and widespread use, IACMI has developed three specific technical targets to achieve by 2020:

- 25% reduction in carbon fiber-reinforced polymer (CFRP) cost
- 50% reduction in CFRP embodied energy
- 80% recyclability or reuse into useful products

Figure 1. Roadmapping Strategy



Roadmapping Strategy

The strategy offered in this roadmap, illustrated in Figure 1, calls for coordinated research and development efforts to achieve IACMI's overarching goal of widespread adoption of fiber-reinforced polymer composites by 2020 and beyond. **To effectively carry out the roadmap strategy, IACMI has created a framework of focus areas and activities to guide the work that it supports or funds.**

Technology Areas

To better target its efforts and investments, IACMI has identified three applications and two additional areas in which advanced composites manufacturing can impact national energy and economic security:

Composite Materials and Processes

Focuses on reclaimed carbon fiber composite designs, nondestructive evaluation (NDE)-based process controls, materials characterization approaches, novel additive manufacturing methods, and more efficient precursors and conversion processes.

Compressed Gas Storage

Focuses on factory automation techniques, predictive integrated computational materials engineering (ICME) approaches, conformal tank designs, toughened and recyclable thermoplastic tank designs, and methods that enable reductions in safety factors to reduce the amount of carbon fiber required in tank designs.

Vehicles

Focuses on reducing composite manufacturing costs and improving recyclability through innovative design concepts, scalable fabrication processes, robust modeling and simulation tools, effective joining technologies, and reliable defect detection methods.

Wind Turbines

Focuses on demonstrating recyclable thermoplastic resins, exploring segmented wind turbine designs, employing automation to reduce cost and labor content, and designing joinable pultruded wind turbine components.

Design, Modeling, and Simulation

Focuses on educating and training the next-generation workforce to embrace composite design tools and methodologies, and successfully incorporating the multiphysics phenomena of manufacturing polymer composite materials and structures into simulation tools.

Efficient, cost-competitive composite materials can be instrumental in enabling high-performance wind turbine blades in the power generation sector, automotive lightweighting, and improved CGS tanks for alternative fuel vehicles in the transportation sector.

Crosscutting Subtopics

While the research activities proposed in this roadmap encompass a wide range of enabling technologies, IACMI has chosen to elevate eight key subtopics that cut across the five Technology Areas:

- **Additive technologies**
- **Crash worthiness and repair**
- **Design, prototyping, and validation**
- **Fiber-reinforced polymer (FRP) constituents**
- **Multimaterial joining**
- **Non-destructive evaluation**
- **Recycling**
- **Standardization and qualification**

These technical topics were selected because of their applicability across multiple Technology Areas and their potential to maximize progress against the 5- and 10-year IACMI technical targets. As IACMI makes decisions about which projects to pursue each programmatic year, these subtopics will help to ensure the integration of technical activities across the five Technology Areas.

Priority Research and Development (R&D) Activities

At the core of this strategic framework for achieving IACMI's goals are applied research and development activities that can be pursued through industry-led projects. IACMI stakeholders from the vehicles, compressed gas storage, and wind energy value chains first identified collaborative, pre-competitive activities within each Technology Area and then prioritized a core group of those as priority R&D activities—those activities with the greatest potential to accelerate the development and adoption of clean energy manufacturing technologies to help achieve its technical targets as well as increase domestic production capacity, stimulate job growth, and encourage economic development.

The roadmap activities represent the collective input of members, partner organizations, and other stakeholders of the composites manufacturing industry. They serve primarily as a catalyst for IACMI and its members to:

1. Propose and launch technology demonstration projects that advance the nation's energy and economic security and address IACMI's technical targets
2. Identify shared existing resources (e.g., composites manufacturing equipment, facilities, and expertise) that can help accelerate R&D innovation
3. Forge strategic partnerships across the composites manufacturing supply chain to align efforts with industry objectives, reduce technical risks, and achieve rapid commercialization

Roadmap Update: Progress and Achievements

Because the original roadmap was forward-looking, IACMI is treating it as a living document, periodically reviewing it to re-evaluate the proposed activities and priorities to accommodate any changes in stakeholder priorities as well as the current state of the composites manufacturing landscape.

This first roadmap update highlights the progress and pacing of technical activities that IACMI and its partners have undertaken in pursuit of the initial Technical Targets since the publication of the initial roadmap in 2016.

These efforts are highlighted in several ways throughout this update:

Funded projects and case studies

IACMI has undertaken more than 50 individual projects with close to 100 unique partners. Roadmap activities that have generated funded projects—whether completed or in progress—are identified in the priority activity table in each Technology Area chapter.

Additionally, each Technology Area chapter includes an example IACMI project showcase.

Focused expansion of crosscutting subtopic areas

This report includes a new chapter—Crosscutting Technologies—which summarizes not only the original eight subtopics but also the roadmap addenda that IACMI has recently completed within four topic areas that look across the Technology Areas: embodied energy reduction, recyclability of FRPCs, multimaterial joining, and noise, vibration, and harshness (NVH).

Each topic area features a graphical table of additional priority roadmapping activities as identified by IACMI's membership.

Evaluation of potential new technology areas

Since the launch of the initial five key Technology Areas outlined in the roadmap, IACMI members have also recognized several additional significant areas of interest in which composites may have significant potential to help key manufacturing sectors: aerospace, infrastructure, and mass transit. The Path Forward chapter provides, for each area, an overview, opportunities for partnerships and commercial potential, and current and planned IACMI project work that may be beneficial to these manufacturing sectors. IACMI will continue to evaluate these areas as part of the ongoing roadmapping strategy.

Path Forward

The low-cost, energy efficient production of advanced fiber-reinforced polymer composites for vehicles, wind turbines, and CGS applications is expected to revitalize U.S. manufacturing and innovation and yield substantial economic and environmental benefits. The research and development activities identified in this roadmap will advance the state of composites manufacturing technologies, boost U.S. manufacturing competitiveness and job growth, and promote the widespread adoption of high-performance composites. IACMI is enabling this vision through high-value research, development, and demonstration programs that reduce technical risk for manufacturers while training the next- generation composites workforce. Continuing to pursue the activities identified in this roadmap will ultimately enable the insertion of advanced composites in the power generation and transportation sectors and help to transition the United States into a clean energy economy.

Workforce Development Achievements

In addition to its support of manufacturing technologies, IACMI is committed to activities and initiatives that build the skills and workforce critical to the growth of composite industry companies of all sizes:

- Through IACMI's partnerships, over 1,200 professionals have been trained in hands-on workshops and seminars since IACMI's launch
- Online training program through partnership with Tooling-U SME: Trained 120 current industry technicians and workers
- Through joint partnerships, hold Closed Mold Alliance Training Workshops four times a year to train technicians who work or are transitioning to work in the composites industry. In 2017 alone, more than 500 total attendees were hosted at training workshops
- Hosted more than 75 student interns since 2016

1 Composite Materials and Processes

The widespread integration of high-performance composite materials in vehicles, wind turbines, and CGS applications can significantly reduce lifecycle energy consumption and emissions. High strength-to-weight ratio, exceptional durability, and directional properties are some of the key benefits that make composite materials a valued choice for high-performance products across multiple markets and industries.

Yet high-volume, large-scale production will only be economically viable with lower-cost carbon fibers and advancements to pervasive technologies including fast-curing resin systems, innovative recycling technologies, effective characterization methods, and process design and control solutions.

IACMI's Composite Materials and Processes Technology Area will support the industrialization of advanced composites by developing cutting edge manufacturing technologies for vehicles, wind turbines, and CGS application areas. **As part of an integrated approach to facilitate the transition of innovative composite manufacturing technologies to U.S. industry, IACMI is pursuing pursue activities with its partners that accomplish the following objectives:**

Advanced carbon fiber technologies via alternative precursors, efficiency processes, and interface engineering

Researchers are examining alternative precursors and processing approaches to engineer carbon fiber materials that yield superior final part properties at reduced production energy levels. Low energy conversion processes, such as microwave- and plasma-based conversion technologies, are of particular interest to the composites manufacturing community.

To reduce the cost and energy requirements of carbon fiber materials, IACMI will pursue efforts that include establishing lab-scale test methods to match efficient composite manufacturing processes, determining process-specific final part properties of composites, and evaluating bio-fiber blending as a low-cost fiber option.

Demonstrate production of high-value intermediates and composites from reclaimed carbon fiber

Products made from recovered discontinuous carbon fibers demand a fraction of the energy needed to produce virgin material with only minor reductions in mechanical properties. The development of carbon recycling technologies and recovery methods to reuse carbon fiber scrap represents an enormous opportunity for energy, waste, and cost reduction.

Although the end-of-life recycling infrastructure for composite materials remains underdeveloped, IACMI will pursue several activities to advance the state of recycling technologies and recovery methods which include conducting injection overmolding projects that use recycle long-fiber thermoplastics, developing accurate cost models for different recycling techniques, demonstrating prototypical production of components that use recyclate materials, evaluating thermal value propositions of recycling waste streams, and characterizing molded parts made with recycled carbon fiber.

Apply NDE data to process design and control

NDE methods and technologies provide critical manufacturing data through in-line diagnostics, structural health monitoring, and traditional end-of-line product inspection. When coupled with advanced data analytics, manufacturers can close the loop around NDE information and process decision making to effectively reduce waste, processing variability, manufacturing costs, and processing time. NDE can also play a major role in the collection, sorting, classification, reclamation, and reuse of scrap or spent materials.

IACMI will support efforts across the other Technology Areas by creating effective NDE training programs across the supply chain, conducting critical pilot demonstrations of various NDE technologies, designing multiscale and multiphysics data analytics for process monitoring and material state diagnostics, and establishing inspection techniques and criteria for cost-effective joint evaluation.

Apply materials characterization capabilities to technology advancement and benchmarking

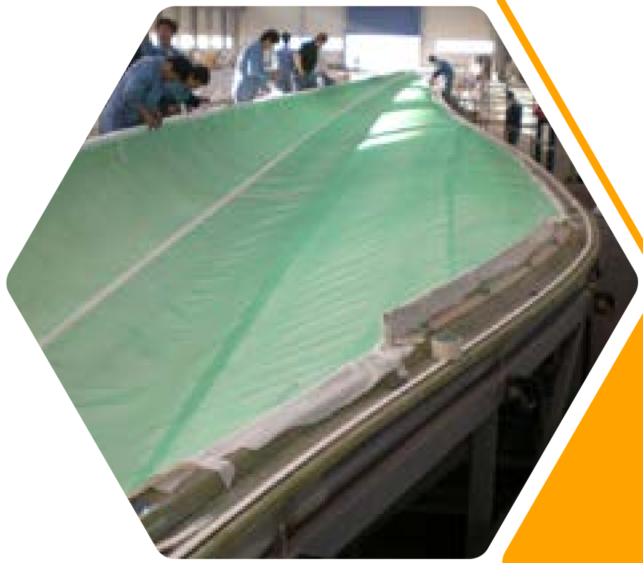
Characterization tools—such as microscopy, spectroscopy, X-ray and neutron radiography—are broadly used for measuring composite structural characteristics and behavior. These tools include critical enabling technologies throughout the product development process (i.e., model validation, NDE, crashworthiness evaluation, and qualification testing).

Using world-class characterization capabilities to advance the state of composite manufacturing technologies, IACMI will work with industry partners to develop new characterization approaches for setting data standards, support crash model development and crashworthiness demonstration efforts, conduct independent materials testing and data sharing, and develop characterization protocols for constructing high-fidelity models for materials structure and behavior.

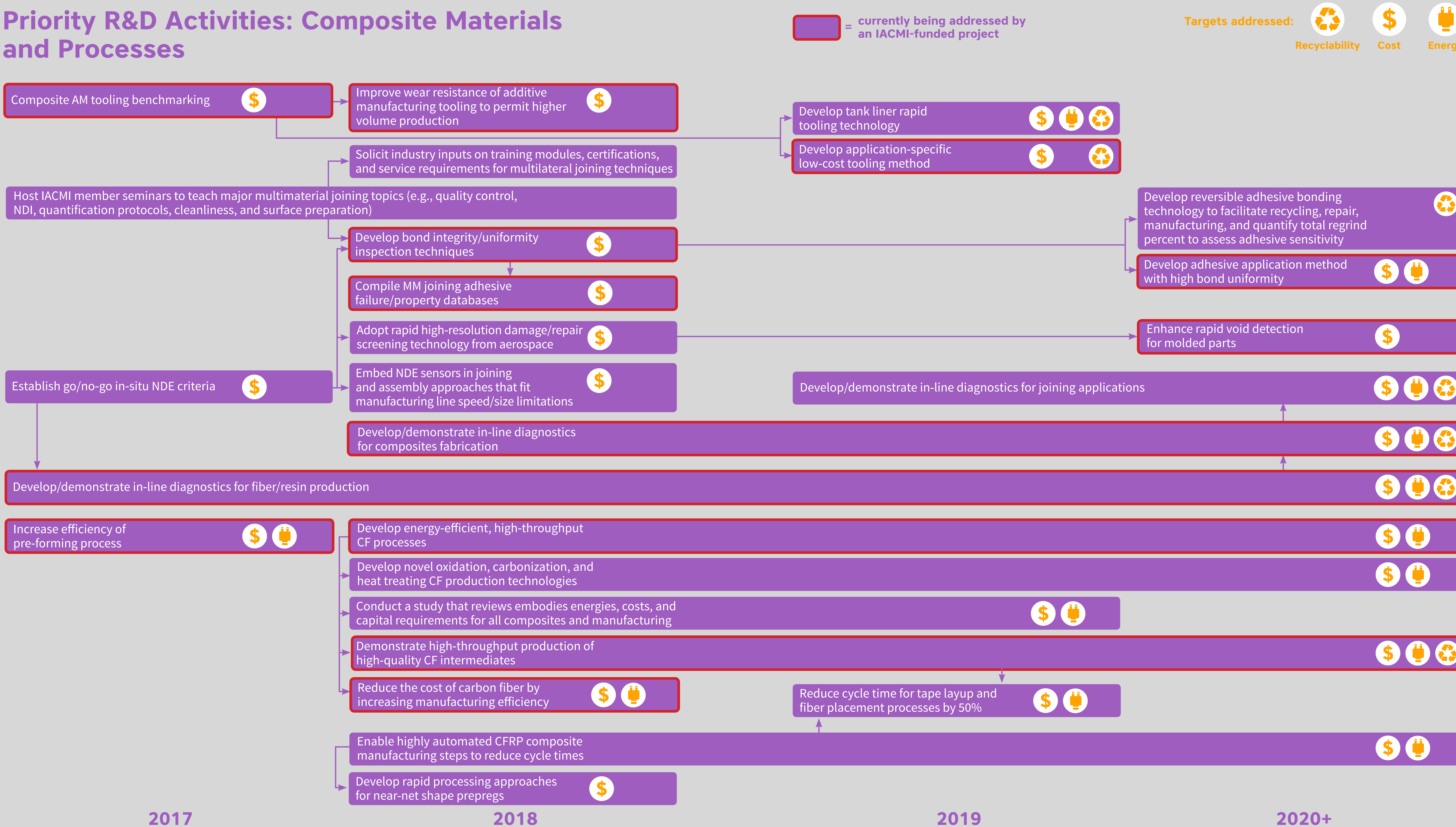
Apply additive manufacturing to reclaimed structural fiber composites fabrication and rapid prototyping

The use of additive technologies in composites manufacturing offers a high-rate, low-cost alternative to traditional toolmaking approaches, and shows promise as an effective processing method for printing composite structures from reclaimed structural fibers. Additive approaches have the potential to significantly reduce composite toolmaking lead times and increase the recovery and reuse of structural carbon fibers.

IACMI and its industry partners will advance the state of additive technologies for composites manufacturing by considering projects that include benchmarking existing additive processes and improving the wear resistance of composite additive tooling.



Priority R&D Activities: Composite Materials and Processes



Priority R&D Activities: Composite Materials and Processes (cont.)

= currently being addressed by an IACMI-funded project

Targets addressed: Recyclability, Cost, Energy

- Identify manufacturing processes to validate predictive tools for part crashworthiness design
- Create a system design platform for materials and processes optimized for energy
- Create "building block" offal design method
- Develop scalable composite fabrication processes (e.g., co-molding, SMC, injection molding) and models for predicting random/continuous fiber orientation
- Demonstrate innovative CF product and packaging forms
- Standardize sizes, properties, data, and test methods for new continuous fiber thermoplastics
- Develop fast-curing resins and adhesives
- Develop >50cP viscosity in-situ polymerized TPCs
- Use CF surface engineering to enhance interfacial properties, functionalities, and resin compatibilities
- Conduct study of fiber-matrix surface chemistry and interactions for recycled carbon fibers for various recycling processes
- Execute a long-term effect to re-insert recycled composites into the overall supply chain (i.e., lessons learned from aluminum and wood waste industries)
- Launch "Design for Sustainability" initiatives to foster environmental stewardship for FRPC-based products (i.e., consideration for end-of-life recyclability)
- Define value proposition of recycling waste streams for achieving two-year payback
- Demonstrate energy-efficient chemical/mechanical technologies to separate/reclaim CF from manufacturing waste and end-of-life components, and into individual reclamation streams
- Demonstrate method for recovering continuous fibers in a user-friendly format
- Foster processes that convert reclaimed CF/CFRP into downcycle material applications (e.g., converted tire rubber for road surfacing)
- Develop a technology that "unzips" composites to base raw material streams
- Develop markets for recovered CF applications
- Demonstrate a recycled CF (rCF) form to fabricate sheet molding compound (SMC)
- Coordinate with OEM to demonstrate prototypical production of automotive components using recyclate materials
- Develop production methods for aligned, discontinuous fiber intermediates using reclaimed fibers
- Develop robust composite fabrication processes/equipment for reclaimed materials

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Priority R&D Activities: Composite Materials and Processes (cont.)

= currently being addressed by an IACMI-funded project

Targets addressed: Recyclability, Cost, Energy

- Characterize molded parts of recycled CFRPs
- Integrate curated composite recyclate property dataset(s) into predictive model(s) to fabricate recycled carbon fiber (rCF) parts
- Demonstrate new and alternative CF precursors (e.g., polyethylene [PE], textile-PAN, nanocellulose, lignin)
- Reduce byproduct/scrap rates of CF intermediates, pre-forms, and composites production processes without sacrificing design performance
- Increase offal reuse rates in part designs
- Incorporate end-of-life (recovered) CF and GF into high-profile applications with $5/lb cost target
- Establish standards for characterizing NVH of FRPC as a function of constituent materials; identify NVH simulation "master curves"
- Characterize NVH properties of existing FRPCs (e.g., fatigue properties from cyclic loading/dampening tests)
- Conduct early-stage prototype test-beds for composites/metals to establish baseline for controlling NVH behavior
- Reconcile characterization of NVH properties with modeling inputs
- Benchmark capabilities of existing simulation tools (e.g., force-displacement/stability analysis)
- Develop approaches/protocols for evaluating 3rd party data (e.g., adhesives), and create incentives so that adhesive OEMs are more willing to share their experimental data (e.g., open-access databases or access-controlled)
- Demonstrate low-NVH FRPC component via coupled FEA & acoustic simulation models
- Create a user friendly materials selection design tool based on mass-vibration trade-offs and application requirements
- Integrate CAE-based simulation tools for buzz, squeak, and rattle (BSR) into cvfHUB
- Build a tool with integrated design constraints for fastening, joining, and decoupling approaches
- Examine NVH sensitivity to aging and fatigue; use as simulation input
- Study buzz, squeak, and rattle (BSR) and other common sources of NVH; integrate into modeling tools as design criteria
- Study NVH-reducing characteristics of additives, fillers, and other reinforcing agents (e.g., microspheres)
- Benchmark key NVH reduction technologies (e.g., constrained layer dampers, elastomeric bushings, liquid applied dampers, viscoelastic tapes)

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PROJECT SHOWCASE: Optimized Resins and Sizings for Vinyl Ester/Carbon Fiber Composites

Status: ☑ COMPLETED

Objectives

- Design resins and sizings for vinyl ester/carbon fiber composites
- Develop technology suitable for high speed production of automotive parts via prepregging
- Demonstrate advantages relative to incumbent epoxy-based systems

Although there are many composite fabrication processes, this project focused exclusively on developing technology suitable for production of prepregs that could be compression molded to produce a fabricated composite part. Additionally, this technology was targeted at the automotive industry, where short cycle times are needed to produce vehicle volumes in excess of 100,000 parts per year.

Partners

- Ashland Performance Materials LLC (lead)
- Michelman, Inc.
- Michigan State University
- University of Dayton Research Institute
- Zoltek Corporation

Technical Targets Addressed

Accomplishments and Benefits

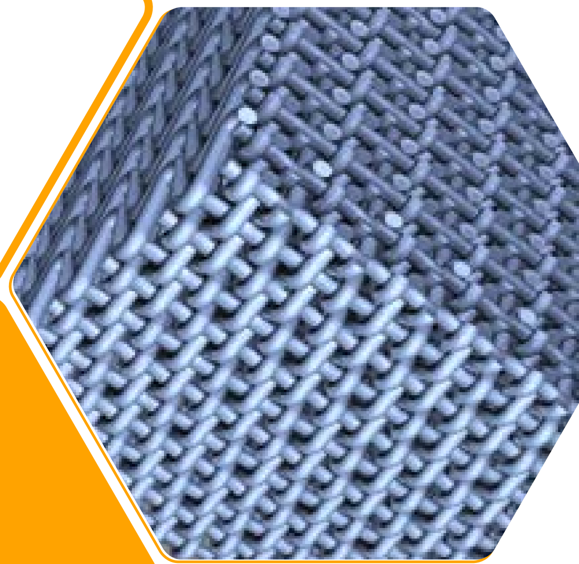
The project team demonstrated an optimized vinyl ester/carbon fiber prepreg system with the following attributes and benefits:

- No reactive diluent styrene (an additional environmental benefit)
- Long shelf life (> 23 months)
- No need for refrigeration (can be stored at room temperature)
- Fast cure (≤ 3 minutes, compared with 10 minutes for previous epoxy-carbon benchmark system)
- Improved resin-fiber interface

The work performed in this project moved the Technology Readiness Level for vinyl ester/carbon fiber composites from 3 to 4.

Additionally, this project offers opportunities for reductions in scrap waste, energy, and costs:

- IACMI has calculated a **22% reduction in the cost** to produce a compression-molded automotive hood inner using vinyl ester prepregs. While the calculation does not account for savings associated with recycling of scrap and avoidances of landfill costs, additional cost reduction is possible if re-use options for prepreg scrap are taken into consideration.
- One of the shortcomings of epoxy-based prepregs is the high amount of scrap, which often ends up in a landfill. With carbon fiber as the reinforcement, this scrap contains a considerable amount of embodied energy that is wasted. This project demonstrated that with vinyl esters, recovery of carbon fibers from prepreg scrap is much easier than with epoxies, creating opportunities for **significant reductions in embodied energy**. Additionally, the project demonstrated the possibility of co-molding vinyl ester prepreg scrap with Sheet Molding Compound (SMC).
- The drive to shorter cycle times critical to the automotive industry from a parts-per-year standpoint also has energy implications. This project demonstrated that significantly shorter molding times are possible with vinyl esters relative to epoxies; since compression molding is an energy-intensive process, these shorter molding times can also lead to **energy savings**.



2 Compressed Gas Storage

Composite materials can help meet the growing demand for compressed natural gas (CNG) vessels—and eventually hydrogen storage tanks—as a low-emissions alternative to gasoline and diesel. The widespread adoption of composites in Type IV storage tanks will require significant cost reductions through improved materials and manufacturing methods.

Carbon fiber composites represent the greatest percentage of Type IV tank costs, but low-cost carbon fibers suitable for CGS tanks have not yet been developed. To achieve DOE targets of 50% cost reduction by 2024 at a 500,000 unit per year production volume, IACMI will pursue factory automation techniques as well as design and manufacturing methods that enable tougher, more robust resin systems and tank designs that reduce the amount of carbon fiber required in CGS tank designs by enabling a reduction in safety factor from 2.25 to 1.5. **IACMI and its industry partners will achieve cost, energy, and waste reductions by focusing on the following objectives:**

Focus on factory automation and lean manufacturing techniques

Automation strategies are crucial to permitting high-volume production of composite CGS tanks. They increase productivity, reduce variability, eliminate waste, and are vital to reducing the cost of Type IV storage tanks.

Several different activities can improve the composite CGS tank automation infrastructure such as standardizing materials characterization tests for effective qualification at increasing automation scales, developing techno-economic models to quantify the cost benefits of automation, and innovative NDE techniques for end-to-end data collection to optimize automation steps and product quality.

Demonstrate tough, recyclable thermoplastic tank designs using high-speed tow placement

Compared with epoxy matrix resins, thermoplastic resins offer greater damage tolerance in CGS tank applications. When used in towpregs, thermoplastics could facilitate higher winding rates and more consistent material quality. By improving manufacturing and assembly methods and advancing automation technologies, thermoplastic composites could significantly reduce scrap rates compared with other composite fabrication approaches.

Facilitating the development of thermoplastic composite CGS tanks requires efforts that include developing crashworthiness and repair acceptability standards along with associated cost models, characterization methods to qualify novel composite CGS tanks, relate coupon-level test data to CGS tank performance to rapidly screen new resins and intermediate forms, and validation protocols for accelerated aging tests to increase confidence in performance predictions.

Enable high-volume manufacture of conformal composite CGS tanks

Composite-wrapped conformable tanks can solve the dimensional fuel storage issues associated with cylindrical CGS tanks on alternative fuel vehicles. Improving design and manufacturing approaches for low-cost, non-cylindrical composite CGS tanks could significantly impact the transportation sector.

Some of the approaches needed to realize conformal composite CGS tank production at large scales will require rapid additive tooling solutions to fabricate tank liners and support structures, new characterization methods and testing standards to validate models and qualify novel composite tank architectures, and techno-economic cost models to quantify and reduce tank manufacturing and assembly costs.

Employ predictive ICME approaches for tank design, manufacture, and certification

Through simulation of fiber placement, cure kinetics, and other aspects of composite manufacturing processes, advanced computational models help accelerate product development for key CGS applications by predicting product performance. As confidence increases in performance predictions, manufacturers can effectively reduce prototyping and qualification testing efforts, resulting in lower embodied energies and costs of CFRP storage tanks.

Efforts to improve the accuracy of predictive design approaches include demonstrating composite manufacturing processes to validate predictive analysis tools, generating and sharing key materials properties to inform process models, and assessing variability in end-to-end process simulations.

PROJECT SHOWCASE: Thermoplastic Composite Compressed Gas Storage (CGS) Tanks

Status: ☐ IN PROGRESS

Objectives

This project aims to develop a disruptive manufacturing route for higher performing, lower cost compressed gas storage (CGS) tanks using thermoplastic as a replacement for conventional thermoset resins. The team is formulating a new polyamide resin and developing a novel laser-assisted automated fiber placement (AFP) method to produce CGS tanks with superior toughness, increased damage resistance, and improved degree of safety compared with current epoxy-based systems.

The project team—which includes world-class expertise in CGS design, AFP fabrication methods, and materials evaluation and mechanical testing—will formulate a polyamide thermoplastic resin, as well as test and demonstrate a unidirectional (UD) composite tape over-wrapped pressure vessel (COPV) to achieve:

- Reduced processing time
- Increased safety performance
- Improved durability and damage tolerance
- Reduced weight
- Enhanced recyclability

Partners

- DuPont Performance Materials (lead)
- Composites Prototyping Center
- Steelhead Composites
- University of Dayton Research Institute

Technical Targets Addressed

Project Approach

The project pathway includes the following steps to test and demonstrate creating CGS vessels using a thermoplastic-based rather than a thermoset-based process:

- Formulate polyamide resin and combine with carbon fiber to create a thermoplastic UD tape
- Use a novel laser-assisted AFP process to place and consolidate UD tape on aluminum vessel liner to meet requirements of compressed gas storage vessels
- Characterize the performance characteristics of the vessel liner and the thermoplastic UD composite tape

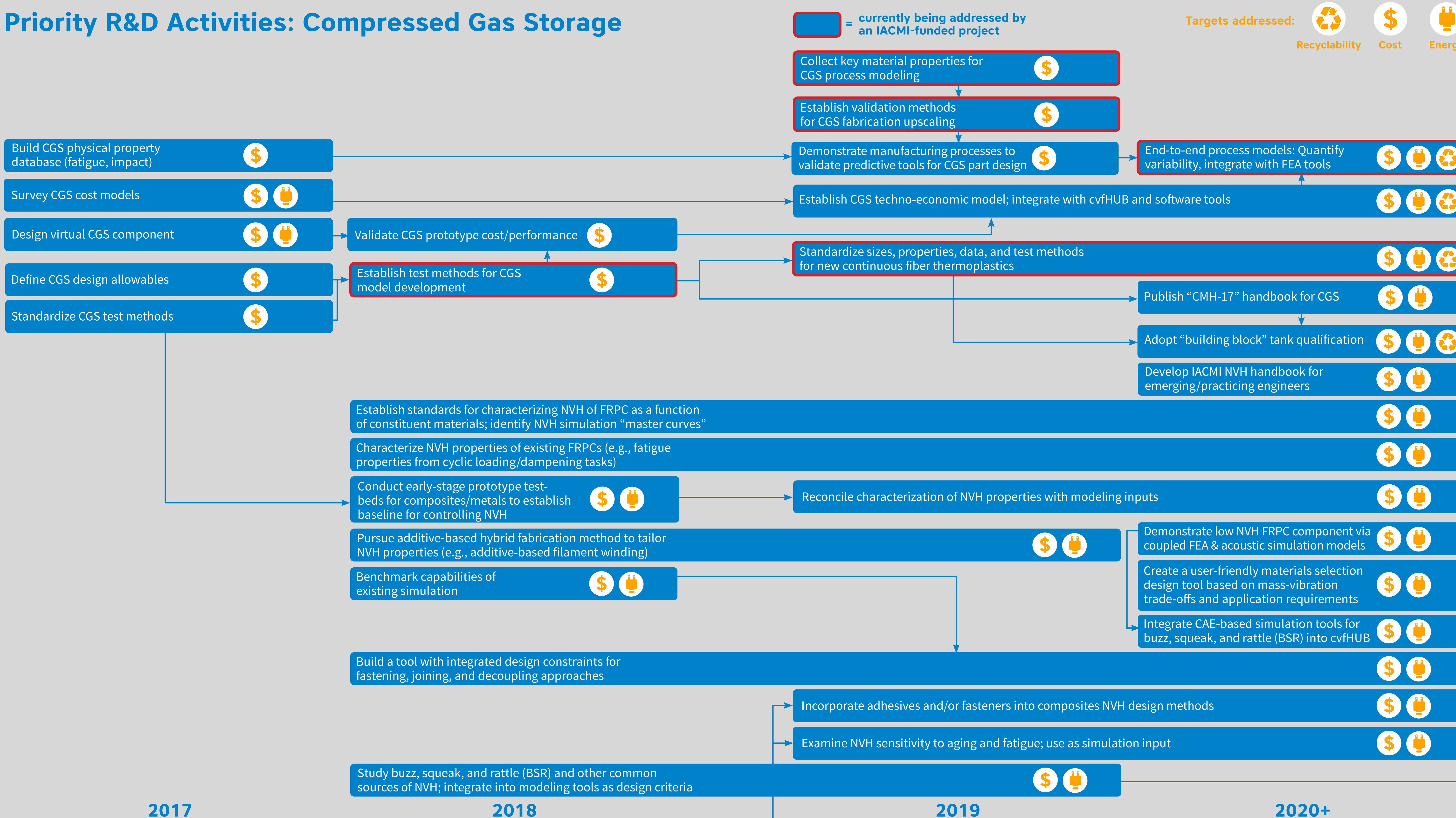
Progress to Date

- Formulated low viscosity polyamide resin with high toughness
- Fabricated high quality thermoplastic UD tape
- Semi-optimized AFP processing conditions
- Designed and fabricated thermoplastic COPV
- Conducted successful burst test of lightly-wrapped COPV

In the remaining period of study, the project team will:

- Optimize the design for wrapping helical plies to improve fiber efficiency
- Optimize AFP processing conditions
- Refine the techno-economic model of the thermoplastic COPV to reflect current assumptions associated with capital cost utilization and wrap pattern design optimization

Priority R&D Activities: Compressed Gas Storage



Priority R&D Activities: Compressed Gas Storage (cont.)

(Red outline) = currently being addressed by an IACMI-funded project

Targets addressed: Recyclability, Cost, Energy

- Develop multifunctional design solutions for NVH (structural-acoustic, thermal-acoustic, impact acoustic, etc.) — Cost, Energy
- Pursue noise-cancelling technologies (e.g., active tuning, shape-memory polymers, piezoelectric devices) to reduce — Cost, Energy
- Study NVH-reducing characteristics of additives, fillers, and other reinforcing agents (e.g., microspheres) — Cost, Energy
- Benchmark key NVH reduction technologies (e.g., constrained layer dampers, elastomeric bushings, liquid applied) — Cost, Energy
- Demonstrate new and alternative CF precursors (e.g., polyethylene [PE], textile-PAN, nanocellulose, lignin) — Cost, Energy (currently being addressed by an IACMI-funded project)
- Conduct a study that reviews embodied energies, costs, and capital requirements for all composites and mfg. processes — Cost, Energy
- Enable highly automated CFRP composite manufacturing steps to reduce cycle times — Cost, Energy
- Demonstrate recyclable TP structural CGS composites — Cost, Recyclability (currently being addressed by an IACMI-funded project)
- Demonstrate manufacture of thermoplastic composite CGS tanks — Cost, Recyclability (currently being addressed by an IACMI-funded project)
- Develop accelerated aging tests for composite joint durability — Cost
- Develop tank liner rapid tooling technology — Cost, Energy, Recyclability
- Develop surface treatment techniques for liners and mandrels in composite tank fabrication — Cost, Energy
- Host IACMI member seminars to teach major multimaterial joining topics (e.g., quality control, NDI, qualification protocols, cleanliness, and surface preparation)
- Compile MM joining adhesive failure/property databases — Cost (currently being addressed by an IACMI-funded project)
- Develop adhesive application method with high bond uniformity — Cost, Energy, Recyclability
- Develop case studies on successful multimaterial joining efforts
- High-speed NDE benchmarking for CGS — Cost, Recyclability
- Develop scalable in-situ NDE tools and analytics — Cost (currently being addressed by an IACMI-funded project)
- Develop a technology that "unzips" composites to base raw material streams — Energy, Recyclability
- Demonstrate NDE techniques for collecting "re-lifing" lifecycle data on CGS tanks or wind turbines — Cost, Recyclability (currently being addressed by an IACMI-funded project)
- Develop markets for recovered CF applications — Recyclability
- Establish a "Design for "Repurpose" approach and demonstrate on low-value CGS tank applications — Energy, Recyclability
- Execute a long-term effort to re-insert recycled composites into the overall supply chain (i.e., lessons learned from aluminum and wood waste industries) — Energy, Recyclability
- Increase offal reuse rates in part designs — Cost, Energy, Recyclability
- Reduce byproduct/scrap rates of CF intermediates, pre-forms, and composites production processes w/o sacrificing design performance — Energy, Recyclability
- Demonstrate method for recovering continuous fibers in a user-friendly format — Recyclability
- Launch "Design for Sustainability" initiatives to foster environmental stewardship for FRPC-based products (i.e., consideration for end-of-life recyclability) — Recyclability
- Foster processes that convert reclaimed CF/CFRP into downcycle material application (e.g., converted tire rubber for road surfacing) — Energy, Recyclability

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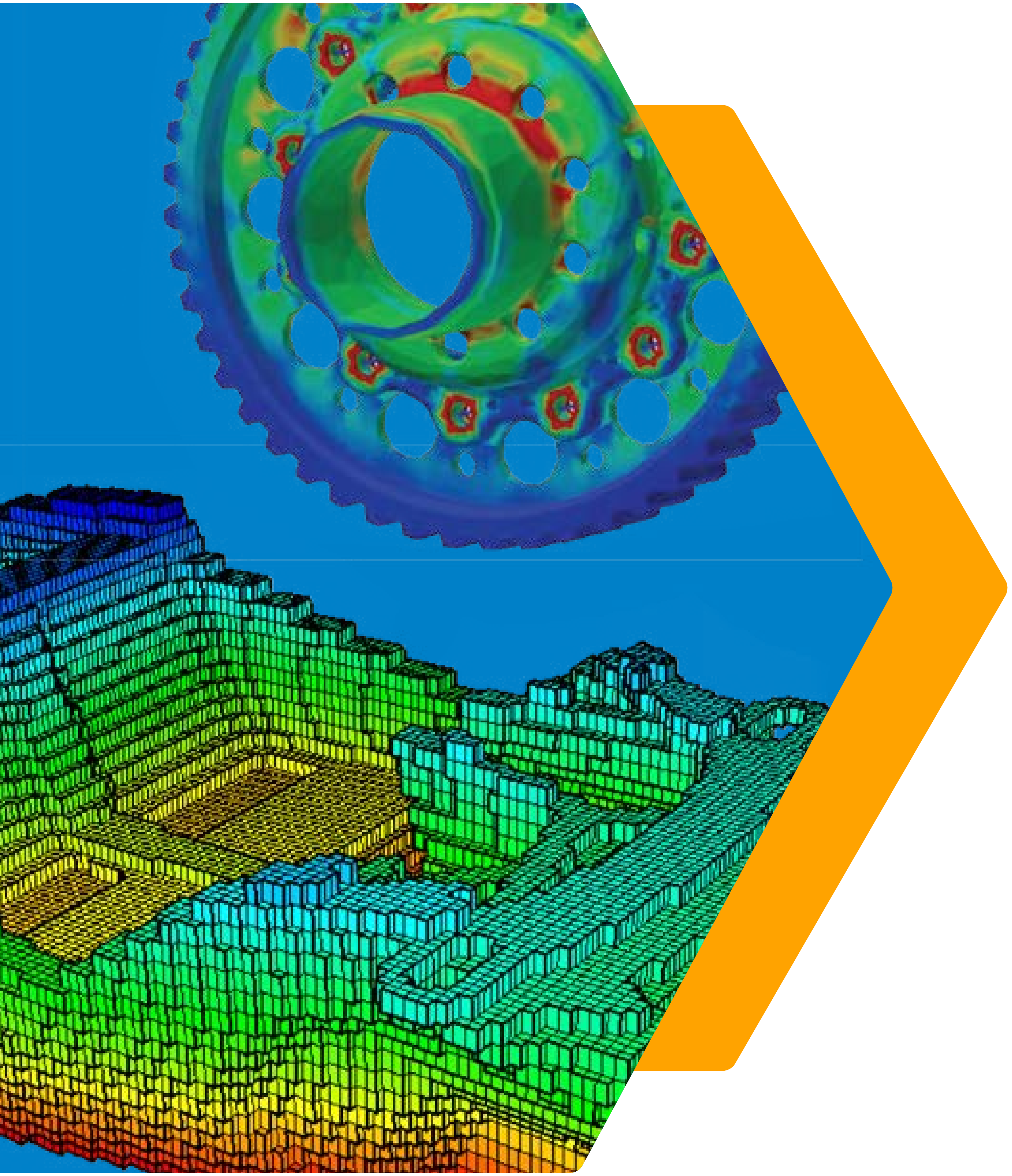


3 Design, Modeling, and Simulation

Maintaining a digital product definition using modeling and simulation tools is a foundational methodology for designing, manufacturing, and sustaining composite products across all application areas. Modeling and simulation tools help designers predict structural behavior, reduce production steps, optimize design, and manage product testing and prototype development for composite products.

Lifecycle prediction is essential for reducing the cost of composites manufacturing, and accelerating innovation throughout the entire supply chain.

Advancing the state of composites manufacturing simulation relies on two major aspects: educating and training the next-generation workforce to embrace composite design tools and methodologies and successfully incorporating the multiphysics phenomena of manufacturing polymer composite materials and structures into simulation tools.

IACMI's Design, Modeling, and Simulation Technology Area (DMS TA)—which offers modeling and simulation tools to help the composite manufacturing industry shorten the development cycle for composite products—is providing educational opportunities to graduate students by exposing them to commercial crash simulation tools. **To attain cost reductions, energy efficiency improvements, and greenhouse gas reductions for the composites manufacturing community, IACMI's DMS TA will consider key R&D activities each programmatic year around the following research objectives:**

Provide access to advanced composites simulation tools across the supply chain

Platforms that host and integrate commercial software tools are crucial for members of the supply chain that have little to no access to comprehensive simulation tools. Users can significantly reduce costs and shorten product development lifecycles by using such platforms to conduct end-to-end process simulations, carry out highly complex simulations on off-site supercomputers, and correlate predicted and real-world data across length scales.

Hosted by IACMI, the Composites Virtual Factory HUB (cvfHUB) is a secure, web-based platform that accelerates product development by providing members with access to commercial simulation tools for solving design, manufacturing, and performance issues of composite materials. Activities that support the objectives of cvfHUB and ultimately increase knowledge transfer across the supply chain include convening training workshops on composite design and assembly methodologies, establishing test methods to generate model validation data for increased prediction confidence, integrating cost models into shared platforms, and hosting databases and platforms that successfully link material properties to end-use performance.

Demonstrate crash simulation tools and methods

Simulating crashworthiness reduces the risk associated with integrating composites into product designs and helps manufacturers remain compliant with safety standards and crash performance requirements. Increasing confidence in crash performance predictions effectively reduces the number of costly, time-intensive qualification tests required to substantiate composite structural designs—especially for vehicle lightweighting.

Several activities to advance the state of crash simulation tools and methods for the composites manufacturing industry include teaching best practices of designing and optimizing composites for crashworthiness, identifying representative composite components to demonstrate and improve crash models, and standardizing test methods to support model validation and increased crash prediction accuracy.

Deploy phenomena-based composite simulation tools

Optimizing product design requires that simulation tools account for the multiphysics phenomena involved in composites manufacturing, including curing, flow, melting, solidification, heat transfer, fiber orientation, and several others. Multiple composite manufacturing phenomena, which collectively dictate performance characteristics, can be captured by integrating several commercial simulation tools into comprehensive suites to maximize the impact on cost, energy, and waste reduction targets.

Phenomena-based integrated tool suites will continue to provide significant advantages for the composites manufacturing community by addressing a range of activities such as validating existing modeling and simulation tools for various processes and production scales, assessing variability of end-to-end process simulations, increasing user-friendliness of tools, and developing additive manufacturing process models.

PROJECT SHOWCASE: Thermoplastic Composites Parts Manufacturing Enabling High Volumes, Low Cost, Reduced Weight with Design Flexibility – Phase 2

Status: ☑ COMPLETED

Objectives

- Reduce the cost of manufacture (COM) of continuous carbon fiber reinforced polymer (CFRP) composites by using a near net shape process (NNS)—automated fiber placement (AFP)—on a relatively inexpensive carbon fiber/polymer tow-preg.

Partners

- DuPont (lead)
- Fibrtec Inc.
- Purdue University

Technical Targets Addressed

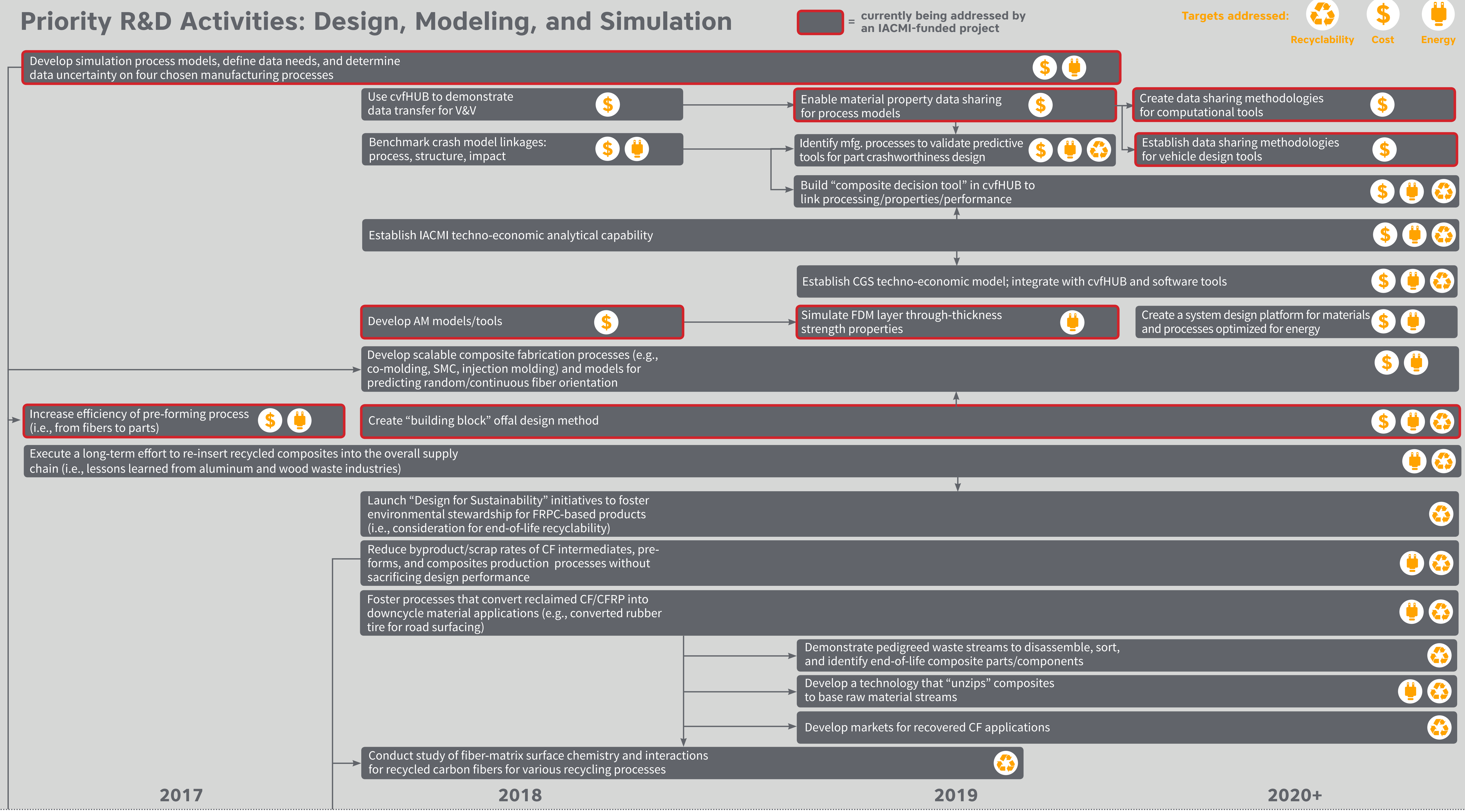
Accomplishments and Benefits

This project demonstrated a new carbon fiber composite manufacturing process that has exhibited favorable fabric formability characteristics compared to traditional woven materials. This new material combines Fibrtec's flexible coated tow, FibrFlex®, with DuPont's Rapid Fabric Formation (RFF) technology and a proprietary DuPont polyamide resin, all supported by Purdue University's extensive modeling and characterization capabilities. The coated tow material is a partially impregnated carbon fiber/polyamide composite tow in which the carbon fiber is not fully wetted with the polyamide, yielding a more flexible tow material than one that is fully impregnated. The RFF process is an ultrafast way of manufacturing fabrics with tows in varying orientations without the need to lift the tow during processing.

Experiments, modeling, and simulations have all shown that this process/materials combination is a potential method for producing lower-cost, continuous CFRP materials that conform well during molding with outstanding physical properties, while also reducing carbon fiber waste by up to 30 percent.

In addition, this project determined that embodied energy was reduced by over 40 percent using this processing scheme. The combination of these materials and process schemes will therefore lead to a decrease in cost for carbon fiber composite structures, making them more amenable for adoption in the automotive and other industries, reduce embodied energy, and directly lead to a creation of jobs in the industry.

Priority R&D Activities: Design, Modeling, and Simulation



Priority R&D Activities: Design, Modeling, and Simulation (cont.)

[box outlined in red] = currently being addressed by an IACMI-funded project

Targets addressed: Recyclability, Cost, Energy

- Incorporate end-of-life (recovered) CF and GF into high-profile applications with $5/lb cost target
- Develop production methods for aligned, discontinuous fiber intermediates using reclaimed fibers
- Develop robust composite fabrication processes/equipment for reclaimed materials
- Integrate curated composite recyclate property dataset(s) into predictive model(s) to fabricate recycled carbon fiber (rCF)
- Increase offal reuse rates in part design
- Demonstrate new and alternative CF precursors (e.g., polyethylene [PE], textile-PAN, nanocellulose, lignin)
- Establish standards for characterizing NVH of FRPC as a function of constituent materials; identify NVH simulation "master curves"
- Characterize NVH properties of existing FRPCs (e.g., fatigue properties from cyclic loading/dampening tests)
- Conduct early-stage prototype test-beds for composites/metals to establish baseline for controlling NVH behavior
- Reconcile characterization of NVH properties with modeling inputs
- Develop approaches/protocols for evaluating 3rd party data (e.g., adhesives) and create incentives so that adhesive OEMs are more willing to share their experimental data (e.g., open access or access- controlled databases)
- Demonstrate low-NVH FRPC component via coupled FEA & acoustic simulation models
- Create a user-friendly materials selection design tool based on mass-vibration trade-offs and application requirements
- Integrate CAE-based simulation tools for buzz, squeak, and rattle (BSR) into cvfHUB
- Benchmark capabilities of existing simulation tools (e.g., force-displacement/ stability analysis)
- Build a tool with integrated design constraints for fastening, joining, and decoupling approaches
- Examine NVH sensitivity to aging and fatigue; use as simulation input
- Study buzz, squeak, and rattle (BSR) and other common sources of NVH; integrate into modeling tools as design
- Benchmark key NVH reduction technologies (e.g., constrained layer dampers, elastomeric bushings, liquid applied dampers, viscoelastic tapes)
- Study NVH-reducing characteristics of additives, fillers, and other reinforcing agents (e.g., microspheres)

2017 | 2018 | 2019 | 2020+

4 Vehicles

Trends in electric technologies and rising fuel economy standards—which aim to reduce emissions, improve energy security, and boost the economy—are compelling automakers to maximize vehicle mass reduction opportunities through the integration of fiber-reinforced composites. However, their implementation is constrained by high costs, long production times, unreliable joinability, low recyclability, and an underdeveloped supply chain.

Traditional composites manufacturing technologies for vehicles offer either high volume manufacturing or significant weight savings, but not both. **Using a multi-faceted approach to achieve reductions in cost, embodied energy, and recyclability, the IACMI Vehicles Technology Area will work with industry on projects that accomplish the following overarching objectives:**

Explore innovative design concepts for automotive composites

The shape, properties, and functionalities of composites can be fully customized for designing vehicles, but automakers must ensure that composites enable mass reduction without sacrificing safety, performance, and quality.

IACMI's Vehicles Technology Area will produce innovative vehicle design concepts by addressing activities such as facilitating round-robin studies that compare composites joint and interface designs for various assembly methods, establishing design optimization approaches for manufacturability and recyclability, validating composite crash simulation models, and creating techno-economic analyses of automotive composite parts to provide manufacturers with design, prototyping, and validation examples.

Demonstrate high-rate, robust, and scalable fabrication processes

The widespread commercialization of low-cost, energy-efficient composites will require the development of fabrication techniques that are reliable and scalable to high-volume production rates in the automotive sector.

To enable robust and scalable manufacturing approaches for automotive composites, IACMI will focus on activities such as collaborating with OEMs on cycle time and weight savings targets, and demonstrating high-volume fabrication processes including prepreg compression molding, high-pressure resin transfer molding, and hybrid molding.

Develop robust modeling and simulation tools for reliable cost and performance predictions

Process modeling and crash simulations are essential for vehicle lightweighting as they can considerably reduce the cost and product development time of fiber-reinforced composite structures. Boosting the adoption rate of high-performance automotive composites strongly relies on making these tools more accurate and reliable for predicting manufacturing costs and decreasing the risk of technology implementation.

Improving the accuracy and reliability of modeling and simulation tools for automotive applications requires a range of activities including assessing variability in end-to-end simulated manufacturing processes, conducting accelerated tests and validating models with experimental data, incorporating composite joint designs in crashworthiness models, and sharing key materials properties to inform simulation efforts.

Foster development of effective multimaterial joining technologies

Multimaterial joining technologies help automakers gradually introduce composite components into vehicles to reduce risk when lightweighting. This requires joining technologies that reliably permit composites implementation without comprising the structural integrity of the vehicle.

To enable the development of effective composite joining technologies, IACMI will consider activities that include designing tools for predicting service life of dissimilarly bonded materials, advancing interfacial inspection and quantification methods for evaluating bond integrity and uniformity, and developing case studies on successful multimaterial joining efforts.

Enable rapid and reliable detection of composite defects

As automotive composites reach higher-volume production rates, there will be a critical need for NDE procedures and technologies—for both in situ and post-build inspections—that can rapidly and reliably detect structural flaws. These key enabling technologies are indispensable for reducing manufacturing costs, ensuring quality, and encouraging the broad acceptance of composites within the automotive industry.

Ensuring that NDE technologies keep up with the pace of composite manufacturing innovation will require activities including generating end-to-end inspection data to confirm long-term reliability of structural composites, establishing go/no-go criteria for conducting in situ inspections, providing training opportunities on NDE techniques, and developing techno-economic models for assessing various composite NDE approaches.

FRPCs and the Future of Automotive Mobility

As the landscape in each technology area evolves, IACMI stays abreast of current trends or future technologies that could represent a potential new or expanded market for composite materials. In the Vehicles area, there is currently a convergence of the three major technology-driven trends influencing future of automotive mobility.

Autonomous Vehicles

- **Trend:** It is estimated that by 2030, up to 50 percent of passenger vehicles sold could be highly autonomous, with up to 15 percent fully autonomous. Self-driving vehicles could help reduce traffic congestion, enable mobility for those unable to drive due to physical limitations, and significantly reduce or eliminate human-caused vehicle crashes (human error is a contributing factor in the majority of all crashes).[i]
- **Impact:** Advanced driver-assist systems, sensors, cabling, and other automated driving features could increase average vehicle weights by 200-300 pounds. The lighter weight characteristic of FRPCs could help offset that addition by reducing component weight by more than 60 percent.[ii]

Electrification

- **Trend:** By 2030, battery-electric vehicles and alternative propulsion systems may comprise 8 percent of the global automotive market,[iii] and electrified propulsion could potentially approach or surpass internal combustion engines in global market share.[iv]
- **Impact:** Advanced lightweight composites can help extend vehicle range, reduce recharging downtime, and offset the added weight of battery systems, electric motors, thermal management systems, and other advanced electric propulsion technologies.

Shared Mobility

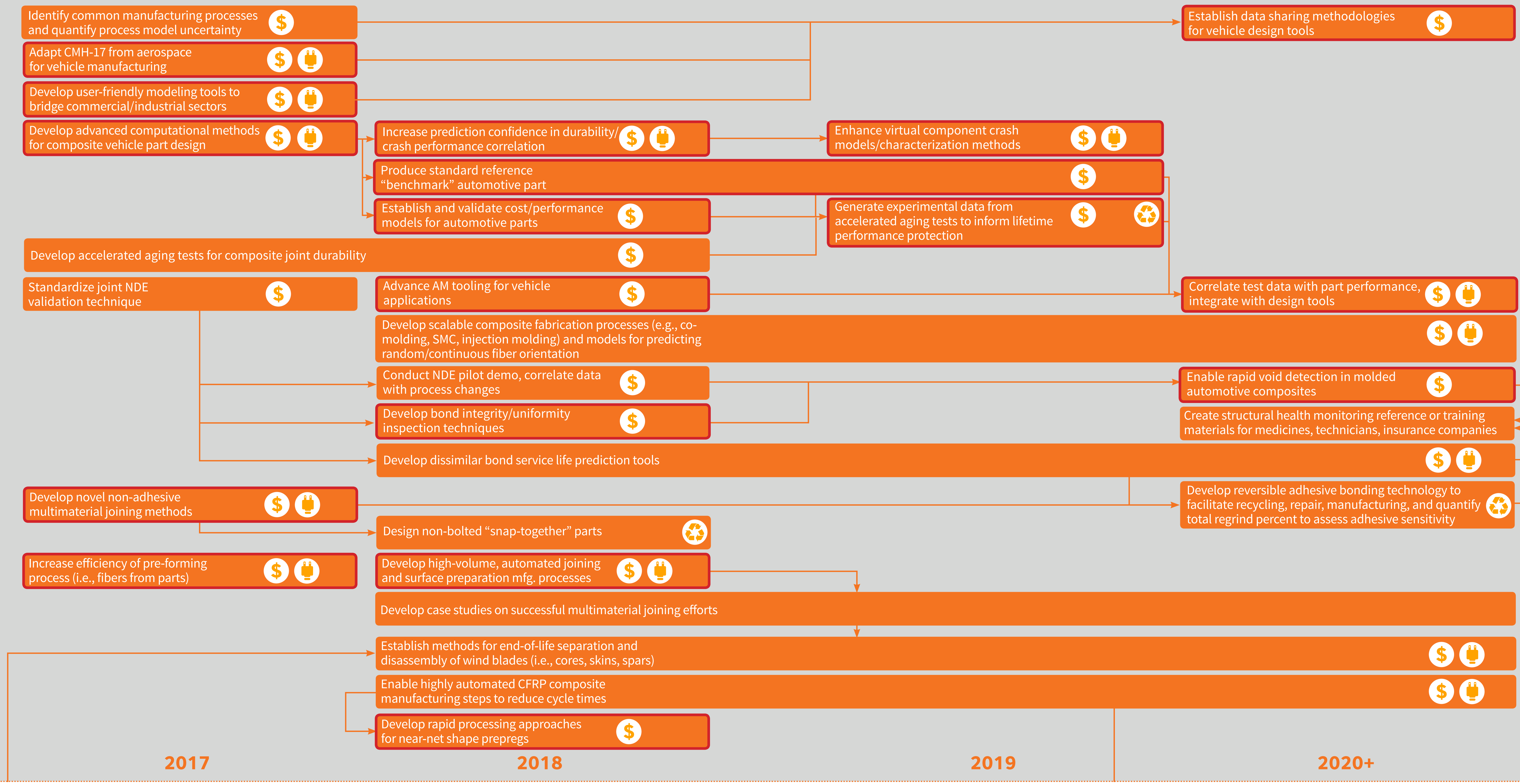
- **Trend:** Ride-sharing and car-sharing mobility services coupled with changing consumer preferences are causing some drivers to abandon conventional individual vehicle ownership models. Some estimates are that 1 out of 10 cars sold by 2030 will potentially be shared vehicles.[v]
- **Impact:** High durability vehicle interiors and corrosion resistant structural materials, such as FRPCs, will help increase the lifespan of shared and fit-for-purpose vehicles. Additionally, because shared vehicles may travel at least 5 times as many annual miles as individual vehicles, automakers are likely to integrate high durability lightweight materials that can last 10 to 15 years.[vi] And the anticipated shorter lifecycles of shared and autonomous vehicles will drive the need for materials with better recyclability characteristics,[vii] such as thermoplastic composites.

[i] Gao, Paul et al., *Automotive revolution – perspective toward 2030: How the convergence of disruptive technology-driven trends could transform the auto industry*, McKinsey & Company, 2016.
[ii] Smith, Brett et al., *Technology Roadmaps: Intelligent Mobility Technology, Materials and Manufacturing Processes, and Light Duty Vehicle Propulsion*, Center for Automotive Research, Ann Arbor, MI, June 2017, https://www.cargroup.org/wp-content/uploads/2018/01/Technology_Roadmap_Combined_23JAN18.pdf.
[iii] Martinez, Michael, *Electrification, autonomy won't gain widespread adoption for decades, CAR study says*, Automotive News, February 2018, http://www.autonews.com/article/20180221/MOBILITY/180229955/autonomous-electric-vehicles-not-accepted-widely-for-decades.
[iv] Mosquet, Xavier et al., *The Electric Car Tipping Point: The Future of Powertrains for Owned and Shared Mobility*, The Boston Consulting Group, January 2018.
[v] Gao, Paul et al., *Automotive revolution – perspective toward 2030: How the convergence of disruptive technology-driven trends could transform the auto industry,* McKinsey & Company, 2016.
[vi] Center for Automotive Research, *The Impact of ACES on Design, Materials, and Manufacturing*, June 2018, https://www.cargroup.org/the-impact-of-aces-on-design-materials-and-manufacturing/.
[vii] Modi, S.; Spulber, A. and Jin, J, *Impact of Automated, Connected, Electric, and Shared (ACES) Vehicles*, Center for Automotive Research, Ann Arbor, MI, 2018.

Priority R&D Activities: Vehicles

= currently being addressed by an IACMI-funded project

Targets addressed: Recyclability Cost Energy



Priority R&D Activities: Vehicles (cont.)

[orange box outlined in red] = currently being addressed by an IACMI-funded project

Targets addressed: Recyclability, Cost, Energy

- Develop TS/TP composite manufacturing methods with cycle times under three minutes
- Reduce cycle time for tape layup and fiber placement processes by 50%
- Execute a long-term effort to re-insert recycled composites into the overall supply chain (i.e., lessons learned from aluminum and wood waste industries)
- Launch "Design for Sustainability" initiatives to foster environmental stewardship for FRPC-based products (i.e., consideration for end-of-life recyclability)
- Investigate reuse tech. and secondary uses for CFRP offal
- Optimize CF re-sizing steps with minimum property loss from recovery, and increase reuse of recycled CF to reduce overall demand for virgin CF
- Demonstrate pedigreed waste streams to disassemble, sort, and identify end-of-life composite parts/components
- Foster processes that convert reclaimed CF/CFRP into downcycle material applications (e.g., converted tire rubber for road surfacing)
- Develop a technology that "unzips" composites to base raw material streams
- Develop markets for recovered CF applications
- Develop robust composite fabrication processes/equipment for reclaimed materials
- Demonstrate low-cost blended bio-fibers
- Demonstrate new and alternative CF precursors (e.g., polyethylene [PE], textile-PAN, nanocellulose, lignin)
- Coordinate with OEM to demonstrate prototypical production of automotive components using recyclate materials
- Reduce byproduct/scrap rates of CF intermediates, pre-forms, and composites production processes without sacrificing design performance
- Develop production methods for aligned, discontinuous fiber intermediates using reclaimed fibers
- Demonstrate a recycled CF (rCF) form to fabricate sheet molding compound (SMC)
- Increase offal reuse rates in part designs
- Incorporate end-of-life (recovered) CF and GF into high-profile applications with $5/lb cost target

2017 | 2018 | 2019 | 2020+

Priority R&D Activities: Vehicles (cont.)

= currently being addressed by an IACMI-funded project

Targets addressed: Recyclability, Cost, Energy

- Support workforce development programs in automotive composites manufacturing
- Host IACMI member seminars to teach major multimaterial joining topics (e.g., quality control, NDI, qualification protocols, cleanliness, and surface preparation)
- Develop IACMI NVH handbook for emerging/practicing engineers
- Benchmark capabilities of existing simulation tools (e.g., force-displacement/stability analysis)
- Build a tool with integrated design constraints for fastening, joining, and decoupling approaches
- Study buzz, squeak, and rattle (BSR) and other common sources of NVH; integrate into modeling tools as design
- Incorporate adhesives and/or fasteners into composites NVH design methods
- Examine NVH sensitivity to aging and fatigue; use as simulation input
- Integrate CAE-based simulation tools for buzz, squeak, and rattle (BSR) into cvfHUB
- Demonstrate low-NVH FRPC component via coupled FEA & acoustic simulation models
- Conduct early-stage prototype test-beds for composites/metals to establish baseline for controlling NVH behavior
- Reconcile characterization of NVH properties with modeling inputs
- Create a user-friendly materials selection design tool based on mass-vibration trade-offs and application requirements
- Characterize NVH properties of existing FRPCs (e.g., fatigue properties from cyclic loading/dampening tests)
- Establish standards for characterizing NVH of FRPC as a function of constituent materials; identify NVH simulation “master curves”
- Benchmark key NVH reduction technologies (e.g., constrained layer dampers, elastomeric bushings, liquid applied dampers, viscoelastic tapes)
- Study NVH-reducing characteristics of additives, fillers, and other reinforcing agents (e.g., microspheres)
- Pursue additive-based hybrid fabrication method to tailor NVH properties (e.g., additive-based filament winding)
- Pursue noise-cancelling technologies (e.g., active tuning, shape-memory polymers, piezoelectric devices) to reduce NVH/energy of damping materials
- Develop multifunctional design solutions for NVH (structural, acoustic, thermal-acoustic, impact-acoustic, etc.)

2017 | 2018 | 2019 | 2020+

PROJECT SHOWCASE: Optimized Carbon Fiber Production to Enable High Volume Manufacturing of Lightweight Automotive Components

Status: ☐ IN PROGRESS

Objectives

- Carbon fiber consistency and production rate
- Intermediate production and mechanical performance
- Molding cycle times
- Recyclability of in-plant scrap

Although there are many composite fabrication processes, this project focused exclusively on developing technology suitable for production of prepregs that could be compression molded to produce a fabricated composite part. Additionally, this technology was targeted at the automotive industry, where short cycle times are needed to produce vehicle volumes in excess of 100,000 parts per year.

Partners

- Ford Motor Company (lead)
- Dow
- DowAksa USA
- Continental Structural Plastics (CSP)
- Michigan State University
- Oak Ridge National Laboratory
- Purdue University
- University of Tennessee

Technical Targets Addressed

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Project Approach

This 3-year project is a multi-workstream, multi-stakeholder effort to jointly develop, integrate, and optimize carbon fibers, resin systems, composite intermediates, molding techniques, automation methods, modeling approaches, and waste reduction strategies across the automotive supply chain.

Progress to Date

- Invented a novel material—the VORAFUSE™ P6300 epoxy resin system—designed for high-volume manufacturing of aligned carbon fiber composite parts to replace metal in the primary body structure and chassis (B-pillar)
  - Completed a technology readiness project with Ford, yielding release of the epoxy material specification and launch on Ford GT as a technology demonstrator
  - Completed development of next generation lower-cost resin system formulation; Scale-up in progress
- Invented chopped carbon fiber sheet molding compound (SMC)—the VORAFUSE™ M6400—designed for automotive deck lids and lift gates
  - Demonstrated key critical-to-quality (CTQ) requirements: rapid forming & molding conducive to automation; mechanicals & heat per specification; shelf stability room temperature for 3 months; low tack and thermoformability to meet process needs; 100% trim scrap reclamation
  - Simulation of SMC production process for optimization and scale-up and SMC mechanical performance
  - Production scale-up, prototyping, and testing of compression molded liftgate and decklid assemblies
- Commissioned prepreg line at the IACMI-MSU Scale-up Research Facility (SURF) and validation of target throughput and mechanical performance
- Determined meso-scale morphology features (fiber orientation) of molded parts
- Developed internal mold release (IMR) compatible with subsequent paintability and adhesive bonding requirements
- Two patent grants and 22 cases filed

6 Wind Turbines

Fiber-reinforced polymer composites have been a major enabler of the growth of the wind energy industry, helping to reduce greenhouse gas emissions from power generation. Despite continued growth in U.S. wind energy capacity, composite production processes remain labor-intensive. Additionally, innovations are needed to lower the cost of wind energy, improve the reliability of existing thermoset-based composite wind turbine technologies, and enable the entry of thermoplastic-based composite wind turbine technologies.

Today's composite wind turbines—ordinarily made with thermosetting resins—are time-consuming to produce, economically challenging to recycle, and increasingly difficult to transport as blade lengths increase to capture more energy. **To reduce costs, improve quality, and increase the recyclability of composite wind turbine technologies, IACMI's Wind Turbines Technology Area will oversee activities that target the following objectives:**

Integrate advanced thermoplastic resins into current production processes

Due to their exceptional strength and fatigue properties, thermosetting resin matrices make up the vast majority of wind turbines. Although thermosetting resins are not out of scope for the development of innovative wind turbine technologies, thermoplastics have shorter cycle times and are more suitable for recycling.

Increasing the use of thermoplastics for wind turbine components requires a variety of activities, including developing novel in situ polymerization methods to improve thermoplastic fatigue performance; demonstrating large-scale jointed blade designs; standardizing sizes, properties, and test methods; and establishing design-for-recyclability methods that rely on lifecycle analysis in wind turbine blade design and manufacture.

Increase automation of fiber placement and inspection technologies

Automation can alleviate time-consuming NDE inspection techniques during pre-production as well as the costly labor required in wind turbine fabrication. In addition to reducing cost and production cycle time, automation can make wind turbines safer, more reliable, and more efficient.

IACMI will increase the use of automation in fiber placement and NDE technologies through projects that include conducting techno-economic analyses of labor costs via automated tape laying (ATL) and automated fiber placement (AFP) methods, developing in-process NDE methods for high-throughput wind turbine fabrication, and establishing links between simulation efforts and manufacturing demonstrations of ATL and AFP technologies.

Design modular wind turbine components for affordable transport and installation

Lowering the cost of wind energy requires significant increases in the scale of wind turbine blades and towers, but these larger sizes make transportation logistically difficult. In addition to simplifying construction while reducing transportation costs, segmented wind turbine components can mimic palm trees through load alignment and effectively reduce cantilever forces at dangerous wind speeds to lower risk of catastrophic damage.

To enable segmented wind turbines, IACMI will consider activities such as investigating novel joint spar design concepts, generating experimental data to enhance life performance predictions for jointed composites, enhancing in-field blade manufacturing and assembly approaches, employing low-cost additive tooling methods to reduce blade manufacturing lead times, and developing prototypes to validate the cost and performance of modular wind turbine designs.

Demonstrate pultruded composite wind turbine components

The use of pultruded carbon fiber sheet materials for wind turbine elements like blade spar caps can enable larger, lighter rotors with higher capacities for capturing energy. Pultruded carbon fiber composites—ideal for modularized wind turbine design—can reduce the risk of wrinkle defects, increase blade quality, reduce labor content, and decrease overall cycle times.

IACMI will work with its industry partners to advanced readily joinable pultruded composites by investigating lightweight carbon fiber jointed spar design concepts that facilitate self-aligning, developing low-viscosity resins and preforms suitable for pultrusion processes, and conducting techno-economic analyses for the evaluation of pultruded composite prototypes.

PROJECT SHOWCASE: Thermoplastic Composite Development for Wind Turbine Blades

Status: ☐ IN PROGRESS

Objectives

Thermoset-based fiber-reinforced composites are the current material of choice for large-scale wind turbine components; however, challenges in manufacturing costs, performance, and recyclability are limiting. This project aims to develop thermoplastic materials and processing to lower production costs and improve recyclability of wind turbine blades with applicability to components demonstrated at large scale.

Partners

- TPI Composites Inc. (lead)
- Arkema Inc.
- Colorado School of Mines
- Johns Manville Inc.
- National Renewal Energy Laboratory (NREL)
- Purdue University
- University of Tennessee
- Vanderbilt University

Technical Targets Addressed

Project Approach

This project provided a manufacturing demonstration for a 9-meter-long thermoplastic composite wind turbine blade, constructed using a vacuum-assisted resin transfer molding (VARTM) process; partner materials used included fiberglass, thermoplastic resin, recycled polyethylene terephthalate foam, and low-cost carbon fiber pultruded spar caps.

Progress to Date

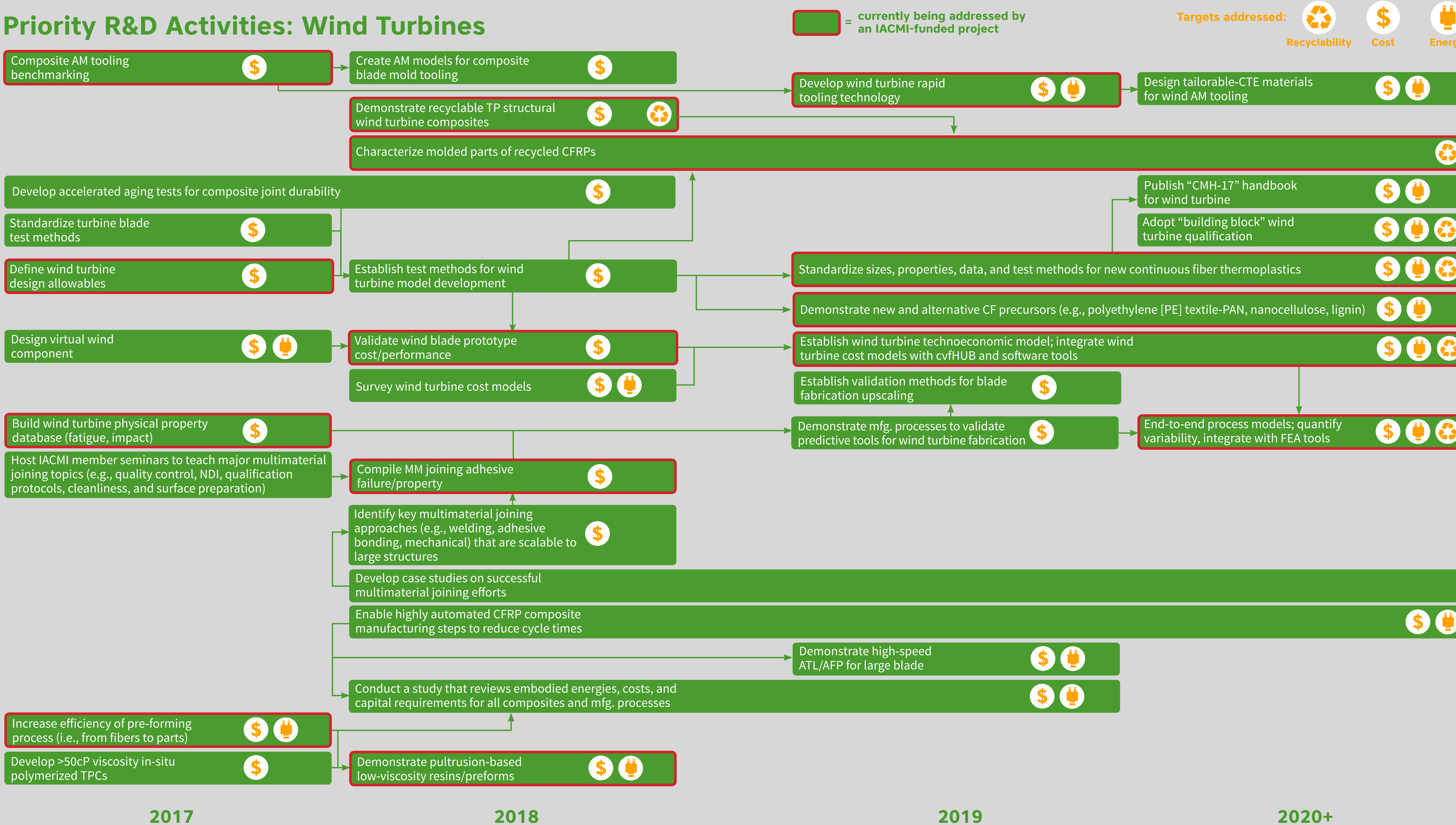
As part of the project, the team developed thermoplastic resin formulations, including an additive designed to control the peak exothermic temperatures, with demonstrated infusion and cure times of less than 3 hours.

To date, this is the first time in the United States that a wind turbine blade has been manufactured using a thermoplastic resin matrix material and VARTM process.

The project highlights the efficiency and energy savings associated with manufacturing thermoplastic composite blades, including:

- Significant reduction in energy consumption through a reduced heating process and faster cure times
- Increase in recyclability as thermoplastics can be recycled at the end of their life span by reheating and decomposing the materials

Priority R&D Activities: Wind Turbines



Priority R&D Activities: Wind Turbines (cont.)

= currently being addressed by an IACMI-funded project

Targets addressed: Recyclability, Cost, Energy

- High-speed NDE benchmarking for wind blades
- Develop multiscale/multiphysics in-situ NDE tools; apply to process controls to reduce scrap/waste
- Develop in-situ NDE methods for wind components
- Enable rapid void detection in molded wind components
- Develop an inspection technique (e.g., ultrasound) that tests frequencies of entire wind blades to identify defects
- Conduct a study and demonstration on wind blade life-extension
- Demonstrate NDE techniques for collecting "re-lifing" lifecycle data on CGS tanks or wind turbines
- Design blades with hybrid/multimaterial CFRPs and demonstrate a novel "Design for Disassembly" approach
- Establish methods for end-of-life separation and disassembly of wind blades (i.e., cores, skins, spars)
- Demonstrate CFRP jointed blade design (i.e., ease of disassembly) along with transportation solutions
- Demonstrate de-polymerizable resins for wind blades, build process-specific cost model
- Execute a long-term effort to re-insert recycled composites into the overall supply chain (i.e., lessons learned from aluminum and wood waste industries)
- Launch "Design for Sustainability" initiatives to foster environmental stewardship for FRPC-based products (i.e., consideration for end-of-life recyclability)
- Reduce byproduct/scrap rates of CF intermediates, pre-forms, and composites production processes without sacrificing design performance
- Define value proposition of recycling waste streams for achieving two-year payback
- Increase offal reuse rates in part designs
- Foster processes that convert reclaimed CF/CFRP into downcycle material applications (e.g., converted tire rubber format)
- Demonstrate pedigreed waste streams to disassemble, sort, and identify end-of-life composite parts/components
- Develop a technology that "unzips" composites to base raw material streams
- Develop markets for recovered CF applications

2017 | 2018 | 2019 | 2020+

7 Crosscutting Subtopics

In the initial roadmap strategy, IACMI and its stakeholders identified eight topic areas that look across all five of the Technology Areas. These subtopics aim to capture the full range of enabling technologies needed to maximize progress against the 5- and 10-year IACMI technical targets of cost, energy, and waste reduction for composites manufacturing technologies.

Additive Technologies

Additive technologies—which are finding greater use in composites manufacturing—can be used to produce parts with greater complexity with fewer assembly steps and less material waste. One of the growing trends for composites is the use of additive manufacturing (AM) techniques to produce mold tools for forming composite parts, including on-demand lay-up tools, master patterns, and water-soluble washout mandrels. Conventional processes for making metal-based mold tools tend to require many steps between design and final transport to a part producer, which can take several months. These long lead times can exceed the pace at which users develop next-generation composite part designs, necessitating a redesign of the mold tools. AM technologies are solving this problem by helping manufacturers rapidly produce polymer-based composite mold tools.

The composites manufacturing industry is also using additive approaches to fabricate fiber-reinforced composites. For example, Big Area Additive Manufacturing (BAAM)—which removes the limitations of printer working size—can be used to repurpose reclaimed chopped carbon fibers. Though this process has been used to demonstrate the feasibility of 3D-printed vehicles, composite-based AM techniques at commercial scales will require practical design-for-manufacturability tools, simulation suites, reduced processing times, and processing enhancements to enable z-direction property improvements.

Crashworthiness and Repair

When manufacturers develop safety-critical or high-value products, they must prove the crashworthiness and practical repairability of their assemblies. In this case, crashworthiness refers to a structure's ability to absorb the energy of a collision in a safe, controlled manner and repairability is the ability to accurately evaluate damage and to restore a damaged product or component to acceptable working condition. While manufacturers must first be concerned with the safety and well-being of product users, assessing a structure's crashworthiness and repairability can also minimize the number of costly, time-consuming physical tests needed before broad commercialization, and can extend the usable life of a product.

The ability to assess crashworthiness and repairability is complicated by the inherent complexity of composite materials structures. Composites have complex fracture and fatigue mechanisms due to the combination of brittle fibers with ductile matrices. As a result, external damage to composite structures may not always be visible. Current methods for manual repair of composites are expensive, time-consuming, and subject to human error. As composites gain increased acceptance among manufacturers—particularly for vehicle lightweighting—the composites manufacturing industry must develop novel materials testing and characterization standards to support model validation efforts and improve the accuracy of predictive simulation. Opportunities to improve the cost, speed, and safety of composite repair approaches include automated repair technologies; repair acceptability standards; and the deployment of rapid, low-cost NDE tools for industry technicians.

Design, Prototyping, and Validation

Design, prototyping, and validation are integral to turning conceptual designs into high-performance components (e.g., composite structures) and verifying that these components meet their intended product requirements. These product development steps rely on a robust understanding of material limits, processing capabilities, principles of mechanical design, and best manufacturing practices to optimize the safety, reliability, and performance of a system.

Due to the large number of composite design variables and the lack of performance-based standards, it is difficult for designers to accelerate materials selection and characterization testing efforts and take full advantage of the properties and performance characteristics of composites. Additionally, the anisotropy—or direction-dependent properties—of composites requires designers to subject prototypes to extensive testing to define a structure's propensity to failure propagation. To minimize costs, mitigate implementation risks, and reduce the overall duration of product development, the composites industry must develop standardized test methods and material properties for as-manufactured composite parts, conduct sensitivity analyses of representative components to quantify and control process variability, and identify application-specific composites design rules that enable iterative feedback loops between designers and engineers.

Multimaterial Joining

Manufacturers use multimaterial design approaches to selectively integrate new materials, such as high-performance fiber-reinforced composites, into components without imposing significant technology implementation risk. Whether the design objective is to reduce weight or add functionality, joining dissimilar materials is an increasingly critical issue faced by manufacturers across industries and application areas.

Multimaterial joining is an imperative design consideration for promoting the widespread adoption and integration of composites in critical applications. Each joining approach—including adhesive bonding, mechanical fastening, or a combination—offers unique challenges, requiring designers to carefully evaluate the impact of each on product safety, manufacturability, cost, repairability, recyclability, and performance. Though adhesive bonding of composites often enables weight reduction and lower part count, it is difficult to properly verify bonding integrity. While mechanical fastener designs are generally easier to repair and disassemble, the cutting, machining, and bolting of composite parts may induce stress concentrations and delamination risks. To advance composite joint design for the broad manufacturing community, the composites industry should develop robust inspection techniques, novel joining and assembly processes, reliable lifetime performance prediction methods, and experimentally validated design tools.

Nondestructive Evaluation

NDE is an essential inspection step that helps manufacturers improve processing cost and quality, reduce waste, and assess feasibility of new processing approaches. Newer materials and innovative designs for enhancing product performance—including those with advanced composites—are creating a constant demand for novel NDE inspection methods, state-of-the-art instrumentation, and skilled inspectors capable of synthesizing and interpreting measurement data. Boosting confidence in NDE inspection results across the supply chain is crucial to realizing cost and energy reductions in composites manufacturing environments.

The broad manufacturing community, however, currently lacks robust NDE data on known composite defect types and sizes, which are essential to assuring the integrity and long-term reliability of structural composites. Additionally, the absence of dependable NDE design acceptance criteria combined with inadequate sensitivity of composite inspection methods precludes the ability to rapidly detect defects and void levels—a critical need for high-volume production of composite materials. While NDE for composites will benefit from technological advancements, novel inspection strategies, and new characterization standards, one of the most promising opportunities identified by the composites manufacturing community is the integration of NDE with simulation models and in-line process controls. This integrated approach allows manufacturers to improve manufacturing efficiencies through real-time diagnosis of part variance and helps support product design improvements by feeding predictive simulation models.

Recycling

Manufacturers are designing next-generation technologies with novel and increasingly complex combinations and formulations of materials, such as fiber-reinforced composites, that can be difficult to recycle using current practices. Few manufacturers are economically or logistically equipped with the infrastructure to reuse in-plant composites scrap, especially cured or partially cured composites and dry, unused fiber reinforcements. Since recycled chopped carbon fiber costs 70% less to produce and up to 98% less energy to manufacture than virgin carbon fiber, recycling technologies could create new markets from the estimated 29 million pounds of composite scrap sent to the country's landfills annually.[1]

While thermoplastic polymer matrices of fiber-reinforced composites are re-meltable and can be reprocessed into discontinuous-fiber composite products, thermoset polymers are more challenging to recycle due to their non-reversible chemistries. Pyrolysis is used to remove the matrices of these materials, but the risk of thermal degradation to the fibers often compromises their mechanical properties. To prevent manufacturing scraps and end-of-life products from reaching landfills, the manufacturing community requires new design methodologies, waste stream logistics, and innovative separation and remanufacturing technologies that enable the recycle and reuse of products.

FRP Constituents

The materials that make up composites are generally categorized into four main constituents:

- **Reinforcements**—high-tensile strength fibers made of glass, carbon, aramid, etc.
- **Resins**—the array that binds reinforcements to create a composite material with properties that are superior to either constituent on its own
- **Intermediates**—reinforcements with more complex architectures, such as sandwich core materials, fabrics, braids, preforms, or prepregs
- **Additives**—used to alter a resin's characteristics, such as viscosity, flexibility, fatigue resistance, energy absorption, electrical or thermal conductivity, and curing rate

Advanced techniques for manufacturing reinforcements, resins, additives, and intermediates, as well as optimized combinations of these components, could reduce composites manufacturing costs and energy consumption and improve component performance and recyclability. While the extensive variety of constituent materials creates infinite design possibilities, it also makes it difficult to create a set of industry-accepted standard-grade materials. Although unproven, the concept of "virtual" allowables would be a game-changer for the composites manufacturing industry by allowing design engineers to virtually generate allowables data while replacing numerous physical tests.

Standardization and Qualification

Standards are consensus-developed specifications that describe how a material can be designed, fabricated, tested, and characterized, and qualification is the practice of verifying materials performance for a given application by generating a statistical basis for material acceptance and quality control. Despite the critical importance of standards and qualification practices in ensuring material quality and reliability, there is currently a lack of industry-accepted standards and qualification practices in the composites field.

To establish standards for composites, the composites manufacturing industry must produce robust materials performance data, which is currently challenging due to the complexity of composite types (e.g., fabric, prepreg, film), sensitivity of fiber alignment, and a lack of reliable tools to extrapolate material properties from coupon-level to full assembly. Without the right processes and tools in place, qualification testing can also be expensive and time-consuming for manufacturers to incorporate into their operations. Focused efforts to create performance-based specifications, develop decision tools for composites, and share knowledge across the value chain will streamline the development and procurement of new composite materials and lower the cost and risk of implementing them into new applications.

Additional Roadmap Addenda Topics

Since the roadmap's publication, IACMI has continued to pursue ways of addressing the manufacturing innovation and technology needs of its stakeholders, including developing roadmap addenda within four targeted areas—two from the original cross-cutting topics and two additional topics selected by the membership:

- **Embodied energy reduction**
- **Recyclability of fiber-reinforced polymer composites**
- **Multimaterial joining**
- **Noise, vibration, and harshness (NVH)**

Within each of these topic areas, IACMI and its members identified project topics and activities, suitable for funding by IACMI, that are critical to achieving its technical goals. Summaries of these four roadmap addenda are outlined below.

Embodied Energy Reduction

The adoption of advanced composites will enable energy savings and greenhouse gas emissions reductions through targeted applications in vehicles, wind turbines, and compressed gas storage. Lighter-weight vehicles reduce fuel consumption, wind turbines operate more efficiently at a lower installed cost while displacing non-renewable energy sources, and compressed gas tanks permit the economic use of lower environmental impact fuels including natural gas and ultimately hydrogen. Yet, the energy-intensive nature of advanced composites production offsets some of the life-cycle energy advantages.

To help reduce composite production costs and greenhouse gas emissions for its members' institutions and the broad composites manufacturing industry, IACMI will fund technical activities that effectively lower the energy embodied in the materials and manufacturing of advanced composites.

Project Topics

Benchmarking, LCA, and Modeling

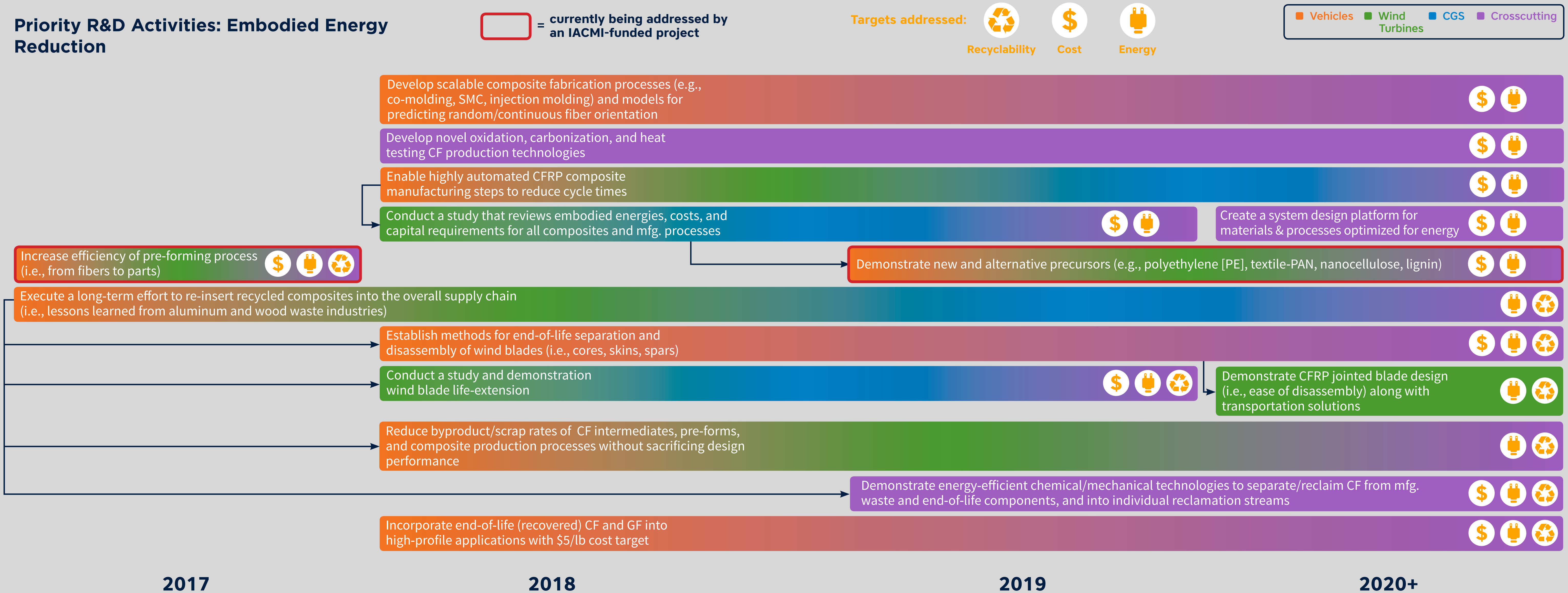
Technoeconomic models and analytical tools, such as ORNL's FRPC Energy Use Estimation Tool, help composite researchers and manufacturers estimate the embodied energy use of composite manufacturing processes to quantify energy savings pathways. Such insights offer substantial lifecycle energy advantages and encourage the integration of composites in high-value applications.

Fiber Processing Technologies

Fiber-reinforced polymer composites require a considerable amount of energy to produce; for CFRPs, the vast majority of embodied energy is attributed to the production of the fiber. Developing alternative precursors and optimizing fiber processing steps have the potential to significantly reduce the cost and embodied energy of CFRPs.

[1] Carberry, William. "Airplane Recycling Efforts Benefit Boeing Operators," Aero, Quarter 4 2008, https://www.boeing.com/commercial/aeromagazine/articles/qtr_4_08/article_02_1.html

Priority R&D Activities: Embodied Energy Reduction



Reclamation/Separation Technologies

Recovering carbon fiber from offal and end-of-life components uses as little as 10% of the energy required to produce virgin material. Novel technologies that efficiently remove the individual constituents of FRPCs could dramatically impact IACMI's energy and recyclability targets.

Secondary/Recycled Composite Applications

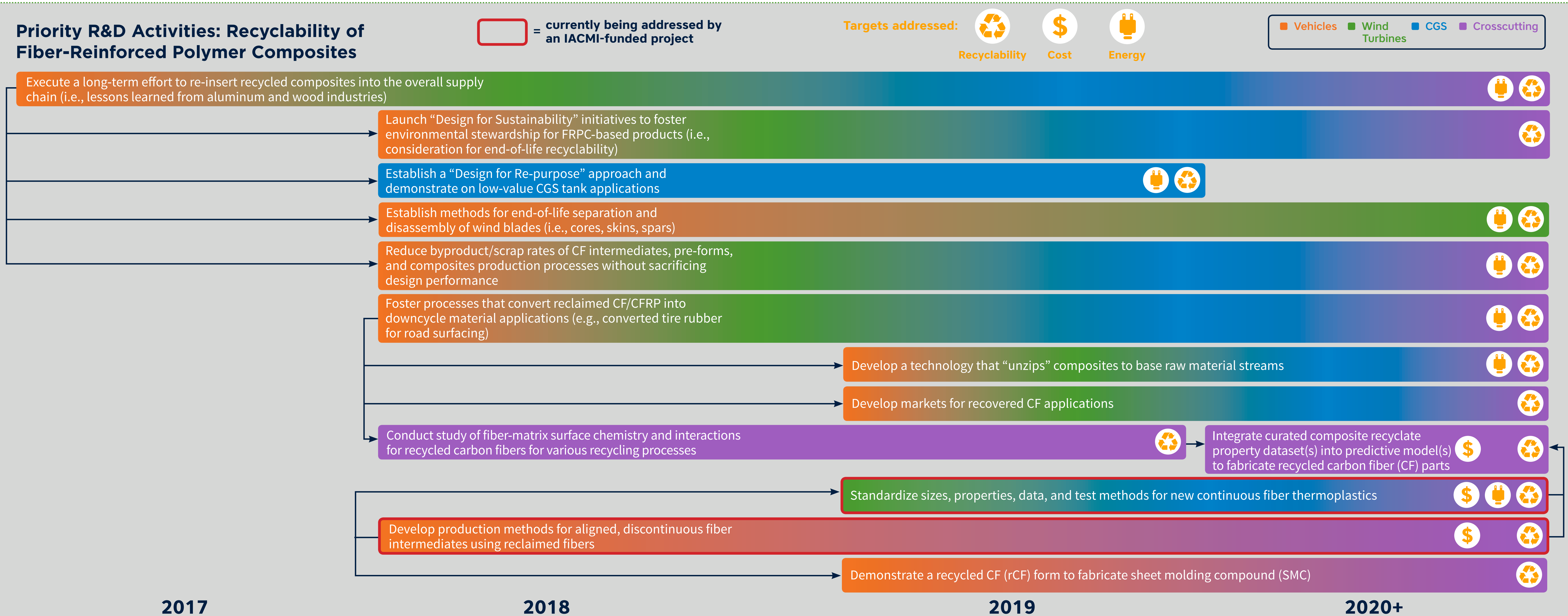
Recycled or recovered carbon fibers are far less energy-intensive to produce than their virgin material counterparts, yet major technical and economic barriers prevent their integration in key application areas. IACMI seeks to fund projects that lower the cost to recycle composites, preserve the quality of composite recyclates, and lead to new and innovative secondary-use applications and markets.

Part Production and Fabrication Methods

Fabricating and assembling FRPCs is a laborious, time-consuming, and energy-intensive process. In- line diagnostics, automation, and more efficient part production methods can decrease energy use through waste reduction and shorter cycle times.

Recyclability of Fiber-Reinforced Polymer Composites

For years, the composites industry has sought to achieve reliable processes for recycling both process scrap and end-of-life composites, leading in a perception of inferiority in terms of cradle-to-cradle sustainability. Further, the recovery of materials with high embodied energy, such as carbon fiber, presents a particularly compelling pathway to save energy and



benefit the environment because recycling avoids energy consumption associated with the production of new materials.

IACMI will fund technical activities that improve the sustainability of composite materials while reducing the amount of scrap and end-of-life composites sent to landfill.

Project Topics

Benchmarking, LCA, and Modeling

Composites recycling technologies are essential to satisfying IACMI's adjacent target goal: reducing the embodied energy content of FRPCs. Technoeconomic models and analytical tools, such as ORNL's FRPC Energy Use Estimation Tool, will help composite researchers and manufacturers to quantify cost and energy savings pathways for new FRPC recycling technologies. To commercialize innovative recycling methods and qualify new FRPC recyclate products, IACMI will consider projects involving high-throughput experiments, technology benchmarking, novel design methodologies, and predictive modeling approaches.

Part Production and Fabrication Methods

IACMI will fund technical projects for the development of new design approaches and fabrication methods to produce recycled carbon fiber (rCF) forms and structural composites with controlled fiber orientations.

Reclamation and Separation Technologies

Recovering carbon fiber from offal and end-of-life components uses as little as 10% of the energy required to produce virgin material. Novel technologies that efficiently remove individual FRPC constituents without integrity losses could dramatically impact IACMI's energy and recyclability targets.

Secondary/Recycled Composite Applications

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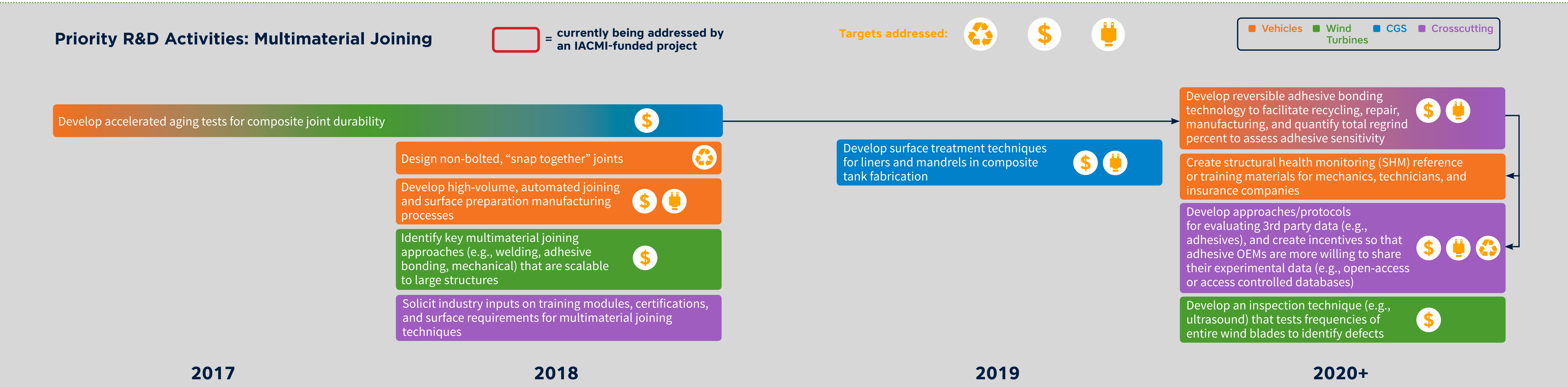

composites, preserve the quality of composite recyclates, and lead to new and innovative secondary-use applications and markets.

Multimaterial Joining

Instead of designing complex systems with single material solutions, manufacturers rely on multimaterial design approaches to selectively integrate advanced materials into components without imposing significant technology implementation risk. Multimaterial joining is therefore a crucial enabling technology for the integration of high-performance composites into wind turbine blades in the power generation sector, automotive lighting, and CGS tanks for alternative fuel vehicles in the transportation sector.

IACMI fully recognizes the unique challenges associated with multimaterial joining technologies, and possesses the expertise, capabilities, and equipment to help its members and partner organizations reduce technical risk and develop a robust supply chain.

Project Topics

Materials Selection and Design Tools

The broad composites manufacturing industry requires robust design tools, reliable test methods, and best practices to ensure that novel multimaterial joining techniques are sufficiently cost-effective and dependable to achieve design compliance, serviceability, and end-of-life requirements of key applications.

Novel Joining Techniques

The decreasing the cost of carbon fiber will continue to drive the development of economically practical and technically feasible multimaterial joining techniques. Facilitating the adoption and integration of composites will require a broad range of joining technologies and methods, including mechanical, adhesive, and welding-based approaches.

Monitoring, Inspection, and Repair

New materials and innovative designs for enhancing product performance—including those with advanced composites—are creating a constant demand for novel NDE inspection methods, state-of-the-art instrumentation, and skilled inspectors capable of synthesizing and interpreting measurement data. Robust sensing and inspection methods are essential to assessing the integrity, repairability, and producibility of multimaterial composite joints in key lightweighting applications.

Industry Needs and Partnership Opportunities

Increasing the technological maturity and acceptance of multimaterial joining techniques is essential to its widespread use across the composites manufacturing industry. The Institute seeks opportunities to foster collaborative partnerships, develop certification modules, and educate the composites manufacturing community to make multimaterial joining methods more accessible and adoptable across the entire supply chain.

Noise, Vibration, and Harshness (NVH)

Despite enabling significant energy savings and emissions reductions from lower fuel levels, component-wise automotive lightweighting can cause unfavorable levels of NVH in vehicle designs. Because noise and vibration energies take the path of least resistance within automotive structures, vehicle mass reduction can be a zero-sum game for automakers—especially when NVH issues are not proactively addressed in early stages of product and process design.

To avoid negative downstream impacts on weight, cost, and energy, IACMI will fund

Priority R&D Activities: Noise, Vibration, and Harshness

= currently being addressed by an IACMI-funded project

Targets addressed: Recyclability, Cost, Energy

Materials Specific Innovation | Modeling & Simulation Tools | NVH Design Methods

- Benchmark capabilities of existing simulation tools (e.g., force-displacement/ stability analysis)
- Develop IACMI NVH handbook for emerging/ practicing engineers
- Build a tool with integrated design constraints for fastening, joining, and decoupling approaches
- Study buzz, squeak, and rattle (BSR) and other common sources of NVH; Integrate into modeling tools as design criteria
- Incorporate adhesives and/or fasteners into composites NVH design methods
- Examine NVH sensitivity to aging and fatigue; Use as simulation input
- Conduct early-stage prototype test-beds for composites/metals to establish baseline for controlling NVH behavior
- Integrate CAE-based simulation tools for buzz, squeak, and rattle (BSR) into cvfHUB
- Demonstrate low-NVH FRPC component via coupled FEA and acoustic simulation models
- Reconcile characteristics of NVH properties with modeling inputs
- Create a user-friendly materials selection design tool based on mass-vibration trade-offs and application requirements
- Characterize NVH properties of existing FRPCs (e.g., fatigue properties from cyclic loading/dampening tests)
- Establish standards for characterizing NVH of FRPC as a function of constituent materials; Identify NVH simulation "master curves"
- Benchmark key NVH reduction technologies (e.g., constrained layer dampers, elastomeric bushings, liquid applied dampers, viscoelastic tapes)
- Study NVH-reducing characteristics of additives, fillers, and other reinforcing agents (e.g., microspheres)
- Pursue additive-based hybrid fabrication method to tailor NVH properties (e.g., additive-based filament winding)
- Pursue noise-cancelling technologies (e.g., active tuning, shape-memory polymers, piezoelectric devices) to reduce NVH/energy of damping materials
- Develop multifunctional design solutions for NVH (structural-acoustic, thermal-acoustic, impact-acoustic, etc.)

2018 | 2019 | 2020 | 2021+

technical activities that lead to reduced NVH levels in the design of advanced automotive composites.

Project Topics

Advanced Lay-up Techniques

Advanced lay-up techniques can enable highly tailored structures and fiber orientations that negate or reduce NVH quality issues in composites.

Characterization and Model Validation

Controlling NVH performance costs during early design stages necessitates an array of dynamic material and structural characterization methods to improve the accurately of predictive modeling tools.

Education and Workforce Development

IACMI will explore education and workforce development opportunities to ensure the composites manufacturing workforce is well-equipped with the knowledge and skills needed to address key NVH challenges.

Integrated Design and Process Modeling

Integrated design methods involve the coupling of computational models and experiments to permit the concurrent design of materials, components, structures, and their respective manufacturing processes. Such integrated design approaches can permit greater control of NVH performance costs during the early stages of product and process design.

Materials Selection and Design Tools

Comprehensive simulation tools and software suites are needed to address NVH challenges throughout each stage of the composites lifecycle—from initial manufacture, to end-of-life, to recycling and reuse.

Multimaterial Joints and Fasteners

Multimaterial design methods and technologies are imperative to promoting the widespread adoption and integration of composites in critical applications. Joints, fasteners, and other multimaterial solutions can simultaneously permit the selective integration of new high-performance composites while helping to solve core NVH issues.

Structural and Multifunctional Components

Unique fiber architectures, additively manufactured structural cores, and multifunctional or embedded sensor technologies can help solve NVH issues for both automotive and wind turbine applications.

8 Path Forward

Commercializing technologies for low-cost, energy efficient manufacturing of advanced fiber reinforced polymer composites for vehicles, wind turbines, and CGS applications could unleash significant economic and environmental benefits and help to revitalize U.S. manufacturing and innovation.

IACMI is committed to this future and is actively catalyzing industry efforts across its Technology Areas to develop a robust supply chain, reduce technical risk for manufacturers, and foster the next-generation composites workforce. Applied research and development efforts (focusing on Technology Readiness Levels [TRL] 4–7) are already underway to realize the initial 5-year targets of cost, energy, and recyclability, but success depends upon healthy participation of the composites manufacturing community and a continuous stream of projects to feed the pipeline of innovation. Even after the 5-year technical targets are met, efforts to commercialize cutting-edge composites manufacturing must persist as IACMI has already set its sights on aggressive 10-year targets.

Future Technology Areas

Since the identification of the five key Technology Areas outlined in the roadmap, IACMI members have also recognized several additional significant areas of interest in which composites may have significant potential to help manufacturing. IACMI will continue to evaluate these areas as part of the ongoing roadmapping strategy.

Aerospace

Aerospace applications have traditionally relied on thermoset composites. Recent advances in processing methods are making thermoplastic composites a more attractive option, including for primary structural components. Additionally, manufacturers are using composites for their lower weight and cost savings compared with conventional aluminum materials. For example, in the 1990s, only 10% of aircraft primary structures were composed of composite materials, compared with over 50% today.

Commercial Potential

Airbus and Boeing estimate aircraft fleets will double by 2035 compared with 2016. This represents a 20-year demand for 33,000+ new passenger and freight aircraft with a global market value of $5.2 trillion.

Advantages and Benefits of Composites for Aerospace Applications

Low weight
Each pound of total reduced aircraft weight equals about $10,000 in annual fuel costs

Superior performance
Offers high strength, structural rigidity, and fatigue resistance

Long lifespan
Resistance to corrosive and harsh environments extends usable life and reduces maintenance costs

Design flexibility
Thermoplastics can be re-melted, molded, and recycled at the end of their usable life

IACMI Project Work Relevant to Aerospace

IACMI is already funding or planning projects for existing Technology Areas that will benefit the aerospace industry by **reducing costs and embodied energy as well as increasing recyclability of scrap and waste:**

- Compared with incumbent epoxy/carbon prepreg systems for aerospace applications, **optimized vinyl ester/carbon systems** offer longer shelf lives, shorter compression molding times, and more recyclable prepreg scrap.
- **New injection overmolding processes** for making structural thermoplastic composite brackets deliver attractive cost and cycle time benefits over current processes for aerospace composites.
- **New near net shape manufacturing processes** for producing aerospace-grade continuous fiber-reinforced thermoplastic (CFRTP) composites can help reduce CF waste, reduce the cost to produce fabric preforms, and improve design flexibility compared to traditional woven materials.

Infrastructure

Composites are gaining more widespread use in infrastructure for both new construction (e.g., lightweight bridges and telecommunications towers) and infrastructure repair (e.g., repair and retrofitting of deteriorating bridges and columns). In fact, IACMI has already deployed successful composites applications in infrastructure, all supported with newly evolving building codes and specifications:

- Fiberglass reinforced rod in concrete structures
- Fully composite pedestrian bridges
- Cantilevered pedestrian walkways on conventional bridges
- Refined sewers and water systems

Commercial Potential

Nearly 10% of the nation's bridges are classified as structurally deficient and in need of repair or replacement. For 2016-2025, the American Society of Civil Engineers (ASCE) estimated current total outlays for U.S. infrastructure are $250 billion/year, with infrastructure needs estimated at as much as $460 billion/year.

While historically government purchasers of infrastructure have not supported use of new construction materials and techniques, Congressional leaders have expressed interest in renewing and repairing the domestic transportation and water infrastructure system, particularly through research into and use of innovative materials and associated techniques.

IACMI Project Work Relevant to Infrastructure

IACMI is already funding or planning projects for existing Technology Areas that will benefit the infrastructure industry:

- **Standardizing NDE/non-destructive testing (NDT) evaluation criteria** for the inspection of large-scale CFRP automotive structures can lower overall production costs and support long-term health and performance assessments for sustainable infrastructure applications.
- **Innovative joining techniques**, such as composite-based "snap-fit" systems, can enable the rapid fabrication of large-scale structures suitable for construction and infrastructure applications.
- **Accelerated test methods and examinations of key degradation behaviors**—including exposure to high temperatures, ultraviolet radiation, and other severe environmental conditions—can facilitate the acceptance and adoption of FRPCs for new construction applications.
- IACMI's workforce development efforts can provide crucial training and education programs for the **proper design and installation of FRPCs** for buildings and infrastructure.

Advantages and Benefits of Composites for Infrastructure Applications

Low weight
CFRPs can offer 70% less weight than conventional steel structures and GFRPs offer up to 60% weight savings compared to standard wooden planks

Superior performance
Offers high strength, seismic resilience, and damage tolerance

Long lifespan
High durability and corrosion resistance extends usable life and reduces maintenance costs

Design flexibility
Rapid fabrication and customization compared with conventional materials

Mass Transit

As highway congestion and concerns over vehicle emissions increase, trends toward vehicle automation, increased connectivity, and improved transportation efficiency are creating demand for more effective mobility solutions in mass transportation.

Advantages and Benefits of Composites for Mass Transit Applications

Low weight

Savings of up to 50% (structural) and 75% (non-structural)

Increased fuel efficiency, reduced power consumption, higher payload capacity, less track wear

Superior performance

Low thermal conductivity for reduced energy consumption (e.g., heating/cooling vehicle interiors); reduced NVH and higher damping

Long lifespan

High durability: resistance to scratching, wear and tear, and chemical corrosion

Design flexibility

Reduced component count; ease of assembly/disassembly reduces maintenance time and cost

Commercial Potential

Worldwide growth in transportation and increasing urbanization is putting strain on the transportation infrastructure; by 2030, there will be at least an additional 2 billion people in the middle-class sector globally. Bus transportation systems are already moving toward driverless autonomous buses, and there is increasing demand for lightweight materials for subways, street cars, and shuttles, as well as for rapid development of high-speed trains.

This demand—coupled with the 140,000 miles of railway track in the United States in need of repair—leads experts to predict that composite applications in the global rail industry will reach estimated $821 million by 2021.

IACMI Project Work Relevant to Mass Transit

IACMI is already funding or planning projects for existing Technology Areas that will benefit mass transit technologies:

- Large FRPC mass transportation components will benefit from **lightweight additively manufactured composite bond tools** that can be **cost-effectively** produced with **shorter lead times** compared with conventional metal-based mold tool.
- Projects that contribute to **greater automation of key FRPC manufacturing methods** like pultrusion, ATL, and AFP will help reduce the processing costs and variability of composite parts used for mass transit applications.
- **Robust, automated, and reproducible multimaterial joining techniques** will enable assembly, disassembly, maintenance, and repair of large, lightweight FRPC mass transportation components such as train car bodies, bus and streetcar paneling, and various interior structures.
- Additionally, mass transit is a natural extension of the existing **Vehicles Technology Area** as well as emerging special topics like **NVH** and **autonomous vehicles.**

Continuing the Progress

America's role as a global leader in advanced manufacturing and clean energy technologies is at stake. The composites industry, with IACMI's leadership, must continue to embrace the research and development activities in this roadmap to strengthen U.S. manufacturing competitiveness, prosperity, and security.

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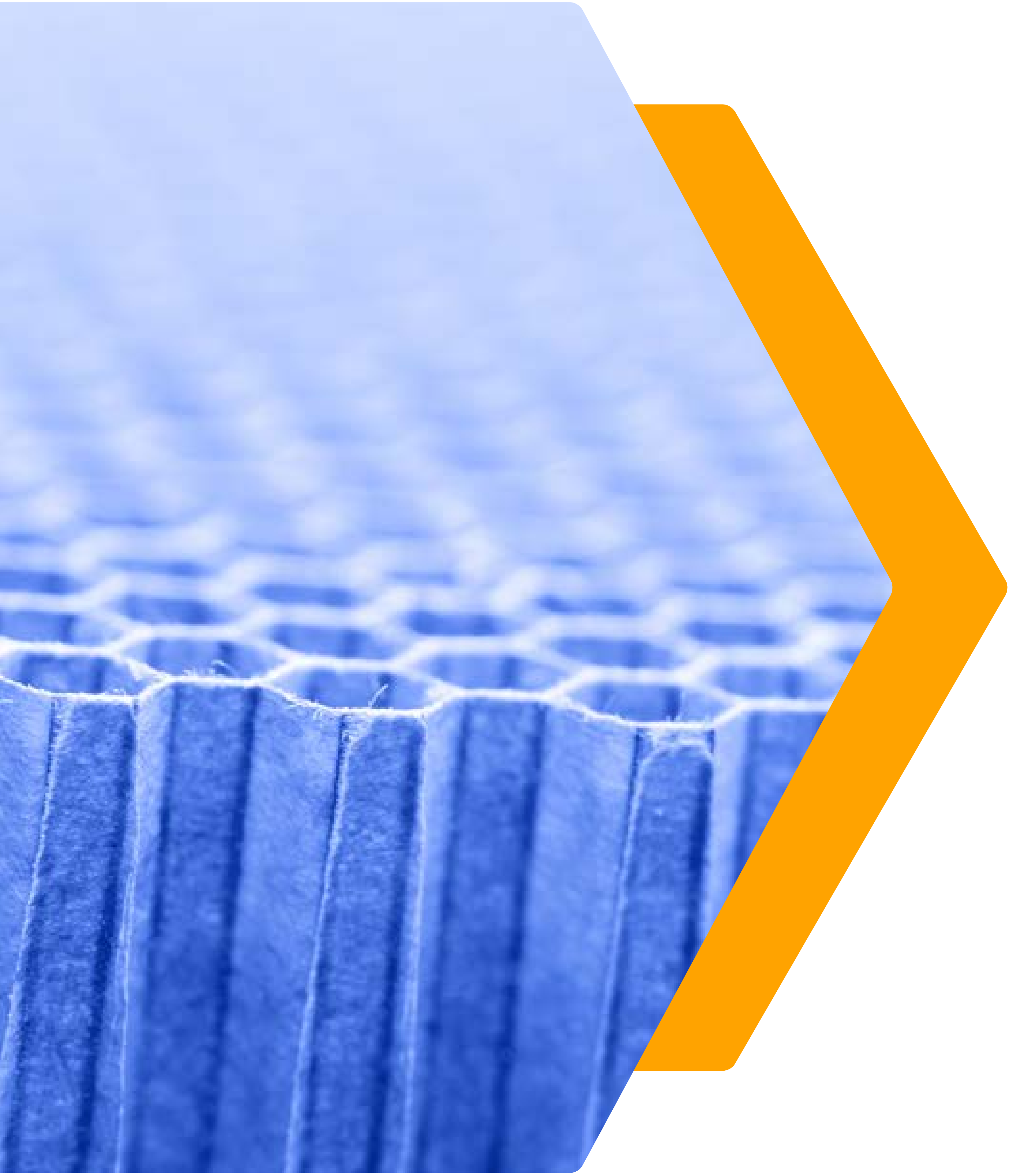

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B Appendix: Acronyms

AFP	automated fiber placement
AM	additive manufacturing
ASCE	American Society of Civil Engineers
ATL	automated tape laying
BAAM	big area additive manufacturing
BSR	buzz, squeak, and rattle
CAE	computer-aided engineering
CF	carbon fiber
CFRP	carbon fiber-reinforced polymer
CFRTP	continuous fiber-reinforced thermoplastic
CGS	compressed gas storage
CMH-17	Composite Materials Handbook-17
CNG	compressed natural gas
COM	cost of manufacture
COPV	composite overwrapped pressure vessel
cP	centipoise
CTE	coefficient of thermal expansion
CTQ	critical-to-quality
cvfHUB	Composites Virtual Factory HUB
DMS	design, modeling, and simulation
DOE	U.S. Department of Energy
FDM	fused deposition modeling
FEA	finite element analysis
FRP	fiber-reinforced polymer
FRPC	fiber-reinforced polymer composite
GF	glass fiber
HP-RTM	high-pressure resin transfer molding
IACMI	Institute for Advanced Composites Manufacturing Innovation
ICME	integrated computational materials engineering
IMR	internal mold release
lb	pound
LCA	lifecycle assessment
LIFT	Lightweight Innovations for Tomorrow
MM	multimaterial
MSU	Michigan State University
NDE	nondestructive evaluation
NDI	nondestructive inspection
NDT	nondestructive testing
NNS	near net shape
NREL	National Renewable Energy Laboratory
NVH	noise, vibration, and harshness
OEM	original equipment manufacturer
ORNL	Oak Ridge National Laboratory
PAN	polyacrylonitrile
PE	power electronics
R&D	research and development
rCF	recycled carbon fiber
RFF	Rapid Fabric Formation
SHM	structural health monitoring
SMC	sheet molding compound
SURF	Scale-up Research Facility
TA	Technology Area
TP	thermoplastic
TPC	thermoplastic composite
TRL	Technology Readiness Level
TS	thermoset
UD	unidirectional
V&V	verification and validation