Institute for Advanced
Composites Manufacturing Innovation

Technology Roadmap
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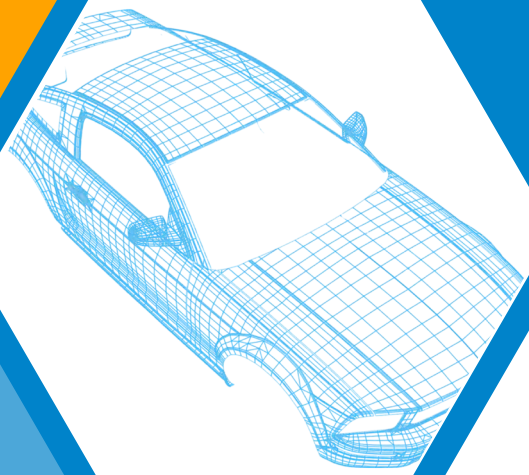

December 2016

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 US 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 five-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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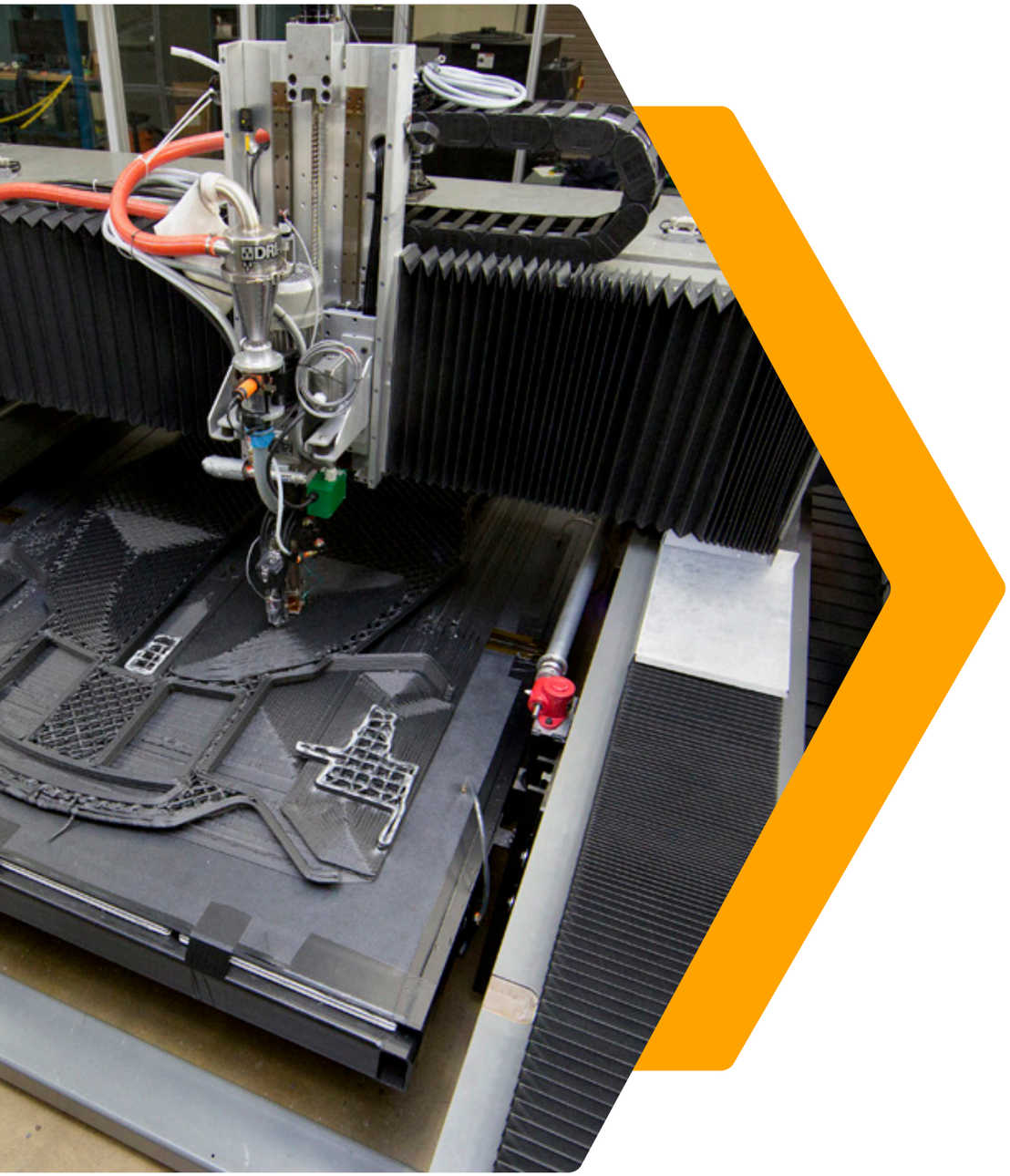


1 Executive Summary

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.

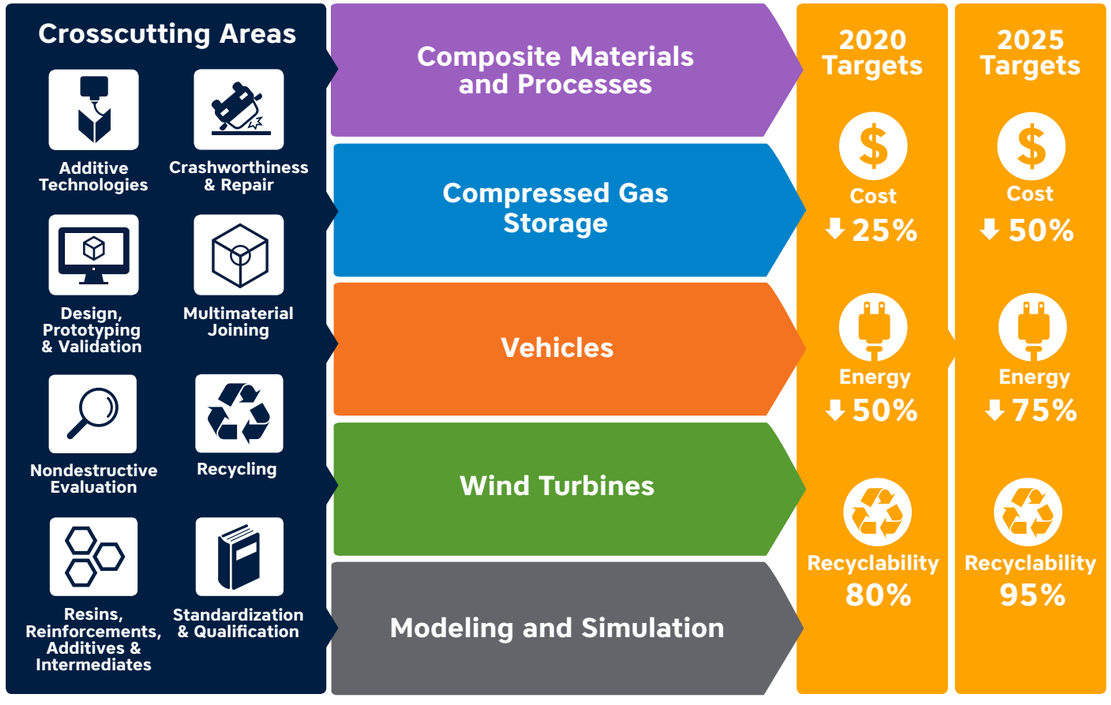
The need for innovation is urgent, particularly as the Federal government drives new clean energy initiatives, including the goal to double renewable electricity generation by 2020 and regulatory action to increase fuel economy standards for automobiles by 2025. Fiber-reinforced polymer composites can 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. IACMI is initially focused on three applications where advanced composites manufacturing can have significant national benefits: vehicles, compressed gas storage, and wind power. The Institute has set the following five/ten-year technical targets to demonstrate:

- 25%/50% lower carbon fiber-reinforced polymer (CFRP) manufactured cost
- 50%/75% reduction in CFRP embodied energy
- 80%/95% composite recyclability or reuse into useful products

This roadmap aggregates the collective views of IACMI stakeholders from the vehicles, compressed gas storage, and wind energy value chains, and identifies projects with the potential to accelerate the development and adoption of clean energy manufacturing technologies that enhance energy productivity, reduce lifecycle energy consumption, increase domestic production capacity, stimulate job growth, and encourage economic development.

Figure 1. Roadmapping Strategy



Roadmapping Strategy

The strategy offered in this roadmap calls for coordinated research and development efforts among the five IACMI Technology Areas to achieve widespread adoption of fiber-reinforced polymer composites by 2020 and beyond. Industry-led projects, which will draw upon the resources from one or more of IACMI's Technology Areas, are organized by eight subtopics that cut across the five Technology Areas to address the full range of enabling technologies needed to meet the 5- and 10-year technical targets.

Path Forward

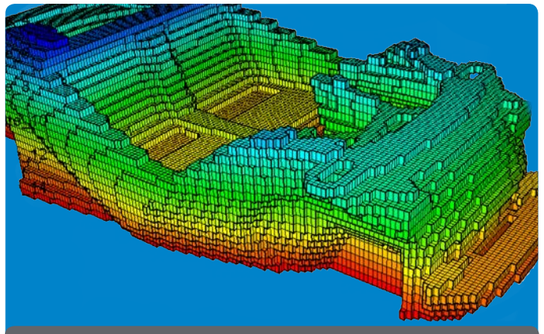
The low-cost, energy efficient production of advanced fiber-reinforced polymer composites in vehicles, wind turbines, and CGS applications is expected to revitalize U.S. manufacturing and innovation and yield substantial economic and environmental benefits. The research and development activities identified in this roadmap will advance the state of composites manufacturing technologies, boost U.S. 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. Pursuing 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.

Figure 2. IACMI Technology Areas and Key Technical Objectives

Composite Materials and Processes

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

- Advance carbon fiber technologies via alternative precursors, efficient processes, and interface engineering
- Demonstrate production of high value intermediates and composites from reclaimed carbon fiber
- Apply NDE data to process design and control
- Apply materials characterization capabilities to technology advancement and benchmarking
- Apply additive manufacturing to reclaimed structural fiber fabrication and rapid prototyping



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.

- Provide access to advanced composites simulation tools across the supply chain
- Demonstrate crash simulation tools and methods
- Deploy phenomena-based composite simulation tools

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.

- Focus on factory automation and lean manufacturing techniques
- Demonstrate tough, recyclable thermoplastic tank designs using high-speed tow placement
- Enable high-volume manufacture of conformal composite CGS tanks
- Employ predictive ICME approaches for tank design, manufacture, and certification

Vehicles

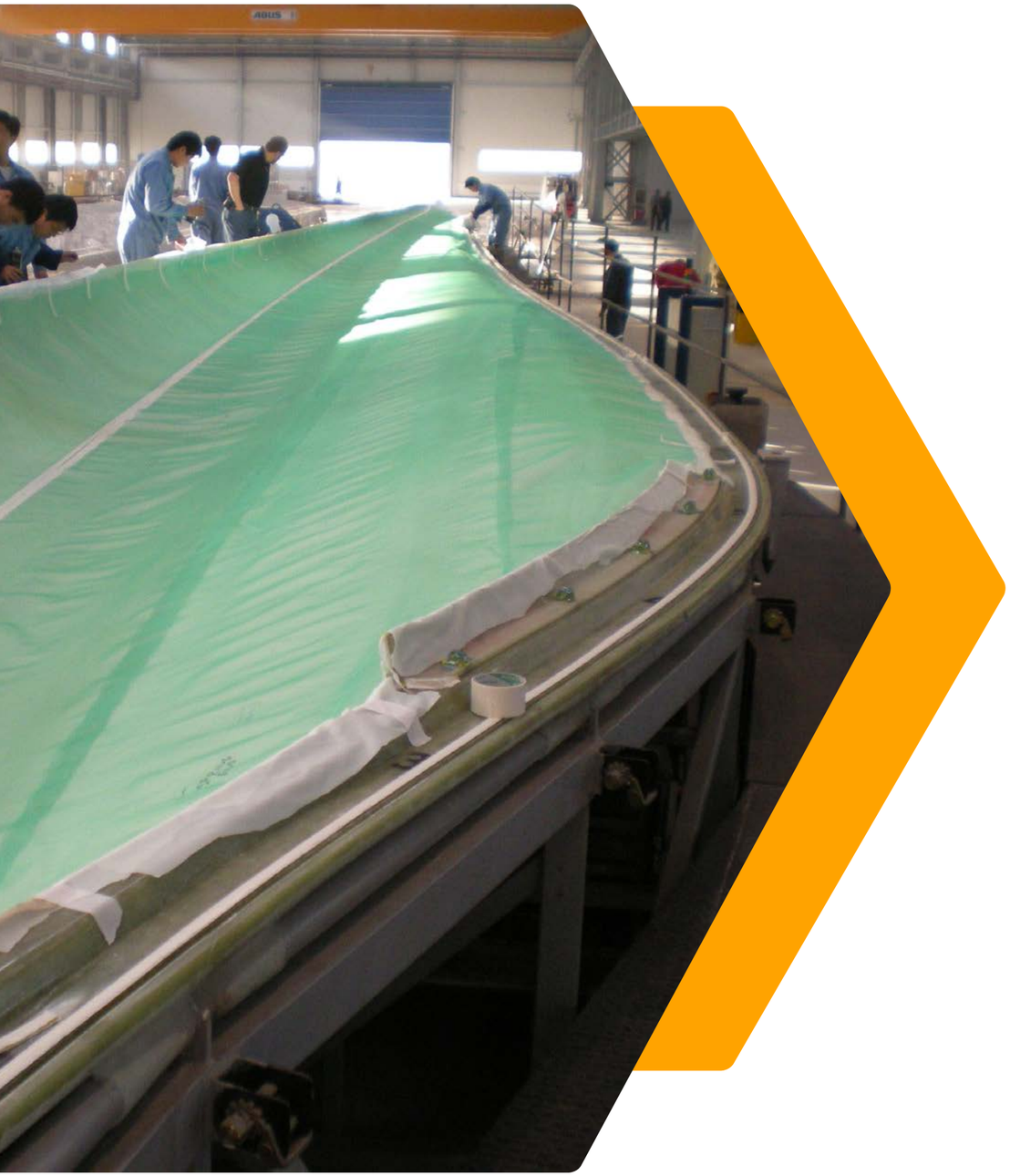
Focuses on reducing composite manufacturing costs and improving recyclability through innovative design concepts, scalable fabrication processes, robust modeling and simulation tools, effective joining technologies, and reliable defect detection methods.

- Explore innovative design concepts for automotive composites
- Demonstrate high-rate, robust, and scalable fabrication processes
- Develop robust modeling and simulation tools for reliable cost and performance predictions
- Foster development of effective multimaterial joining technologies
- Enable rapid and reliable detection of composite defects

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.

- Integrate advanced thermoplastic resins into current production processes
- Increase automation of fiber placement and inspection technologies
- Design modular wind turbine components for affordable transport and installation
- Demonstrate pultruded composite wind turbine components



2 Roadmapping Strategy

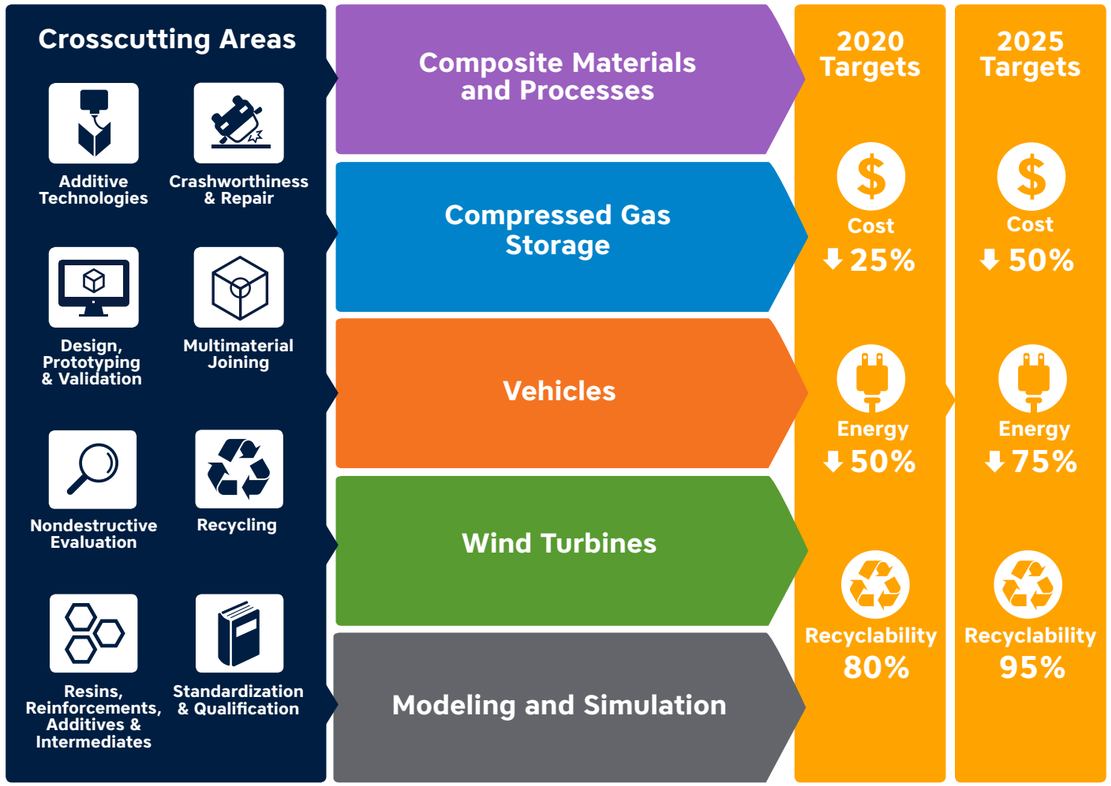
This roadmap presents an integrated strategy to achieving widespread adoption of fiber-reinforced polymer composites by 2020 and beyond.
The strategy highlights the need to coordinate research and development among the five IACMI Technology Areas toward the five- and ten-year technical targets of lower cost, reduced embodied energy, and increased recyclability of fiber-reinforced polymer composites.

Industry projects—led by OEMs or major suppliers—will draw upon the resources from one or more of IACMI's Technology Areas to commercialize composite manufacturing technologies and feed market growth. To address the full range of enabling technologies, these efforts are organized by eight key cross-cutting subtopics. IACMI will tap into its network of economic and workforce development resources in order to support private sector investments to demonstrate and implement these new technologies while providing valuable training opportunities that foster a skilled manufacturing workforce.

Composite Materials and Processes

The widespread integration of high-performance composite materials can significantly reduce lifecycle energy consumption and emissions, but high-volume, large-scale product manufacturing will only be economically viable via cost reductions in carbon fibers and advancements to pervasive technologies including fast-curing resin systems, innovative recycling technologies, effective characterization methods, and process design and control solutions.

Figure 3. Roadmapping Strategy



IACMI's Composite Materials and & Process Technology Area will focus on reclaimed carbon fiber composite designs, NDE-based process controls, materials characterization approaches, novel additive manufacturing methods, and more efficient precursors and conversion processes.

Modeling and Simulation

Maintaining a digital product definition through the use of modeling and simulation tools is a foundational methodology for designing, manufacturing, and sustaining composite products across all application areas.

IACMI's Design, Modeling, and Simulation Technology Area will focus 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.

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, but widespread adoption of composite Type IV CGS tanks will require significant cost reductions.

IACMI'S Compressed Gas Storage Technology Area will focus on factory automation techniques, predictive ICME approaches, conformal tank designs, tough and recyclable thermoplastic tank designs, and methods that enable reductions in safety factors to reduce the amount of carbon fiber required in tank designs.

Wind Turbines

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 grow in size to capture more energy.

IACMI'S Wind Turbines Technology Area will focus 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.

Vehicles

Rising fuel economy standards—which aim to reduce emissions and improve energy security—are compelling automakers to seek vehicle mass reduction opportunities through the integration of lightweight materials such as fiber-reinforced composites.

IACMI'S Vehicles Technology Area will seeks to reduce manufacturing costs and improve recyclability through innovative design concepts, scalable fabrication processes, robust modeling and simulation tools, effective joining technologies, and reliable defect detection methods.

Overview of Cross-Cutting Subtopics

In this roadmap, IACMI's technical activities are organized by eight key subtopics that cut across the five 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. 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.

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 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. In some cases, these long lead times exceed the pace at which users develop next-generation composite part designs, which then requires a redesign of the mold tools. Additive manufacturing 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 additive manufacturing 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 & 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, such as 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

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.

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.

Reinforcements, Resins, Additives, and Intermediates

The materials that make up composites are generally categorized into four main constituents: reinforcements, resins, intermediates, and additives. Resins are the array that binds reinforcements (i.e., fibers) to create a composite material with properties that are superior to either constituent on its own. Additives are used to alter a resin's characteristics, such as viscosity, flexibility, fatigue resistance, energy absorption, electrical or thermal conductivity, and curing rate; and intermediate forms are reinforcements with more complex architectures, such as sandwich core materials, fabrics, braids, preforms, or prepregs.

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 a number of physical tests.

Standardization & Qualification

Standards are consensus-developed specifications that describe how a material can be designed, fabricated, tested, and characterized; and qualification practices verify the performance of materials 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 (fabric, prepreg, film, etc.), 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.

Figure 4. Priority R&D Activities

Composite Materials and Processes

Targets addressed: Recyclability, Cost, Energy

- Establish go/no-go in-situ NDE criteria
- Adopt rapid high-resolution damage/repair screening technology from aerospace
- Develop bond integrity/uniformity inspection techniques
- Embed NDE sensors for joining approaches that fit manufacturing line speed/size limits
- Enhance rapid void detection for molded parts
- Develop adhesive application method with high bond uniformity
- Develop/demonstrate in-line diagnostics for fiber/resin production
- Increase offal reuse rates in part designs
- Define thermal value proposition for two-year payback on recycling waste streams
- Work with automotive OEM to demo recyclate-based component prototypes
- Develop/demonstrate in-line diagnostics for composites fabrication
- Reduce the cost of carbon fiber by increasing manufacturing efficiency
- Improve wear resistance of AM tooling to permit higher volume production
- Develop rapid processing approaches for near-net shape prepregs
- Develop/demonstrate in-line diagnostics for joining applications
- Develop rapid tooling technologies
- Develop application-specific low-cost tooling method
- Develop energy-efficient, high-throughput CF processes
- Develop fast-curing resins and adhesives
- Design alternative fiber precursors
- Use CF surface engineering to enhance interfacial properties, functionalities, and resin compatabilities
- Demonstrate innovative CF product and packaging forms
- Demonstrate high-throughput production of high-quality CF intermediates
- Demonstrate aligned fiber intermediates using reclaimed fibers
- Develop robust composite fabrication processes/ equipment for reclaimed materials

2017 2018 2019 2020

Figure 4. Priority R&D Activities (cont.)

Modeling and Simulation

Targets addressed: Recyclability, Cost, Energy

- Benchmark crash model linkages: process, structure, impact
- Use cvfHUB to demonstrate data transfer for V&V
- Enable material property data sharing for process models
- Create data sharing methodologies for computational tools
- Identify mfg. processes to validate predictive tools for part crashworthiness design
- Develop AM models/tools
- Simulate FDM layer through-thickness strength properties
- Build "composite decision tool" in cvfHUB to link processing/properties/performance
- Establish IACMI techno-economic analytical capability
- Create "building block" offal design method
- Develop simulation process models, define data needs, and determine data uncertainty on four chosen manufacturing processes

Compressed Gas Storage

- Build CGS physical property database (fatigue, impact)
- Compile MM joining adhesive failure/property databases
- Survey CGS cost models
- Design virtual CGS component
- High-speed NDE benchmarking for CGS
- Define CGS design allowables
- Standardize CGS test methods
- Demonstrate recyclable TP structural CGS composites
- Integrate CGS cost models with cvfHUB and software tools
- Validate CGS prototype cost/ performance
- Demonstrate NDE techniques for lifecycle data collection
- Establish test methods for CGS model development
- Demonstrate manufacture of thermoplastic composite CGS tank
- Collect key material properties for CGS process modeling
- Establish validation methods for CGS fabrication upscaling
- Demonstrate manufacturing processes to validate predictive tools for CGS part design
- Develop tank liner rapid tooling technology
- Establish CGS technoeconomic model
- Develop scalable in-situ NDE tools and analytics
- Develop adhesive application method with high bond uniformity
- End-to-end process models: Quantify variability, integrate with FEA tools
- Adopt "building block" tank qualification approach
- Develop scalable in-situ NDE tools and analytics

2017 2018 2019 2020

Figure 4. Priority R&D Activities (cont.)

Vehicles

Targets addressed: Recyclability, Cost, Energy

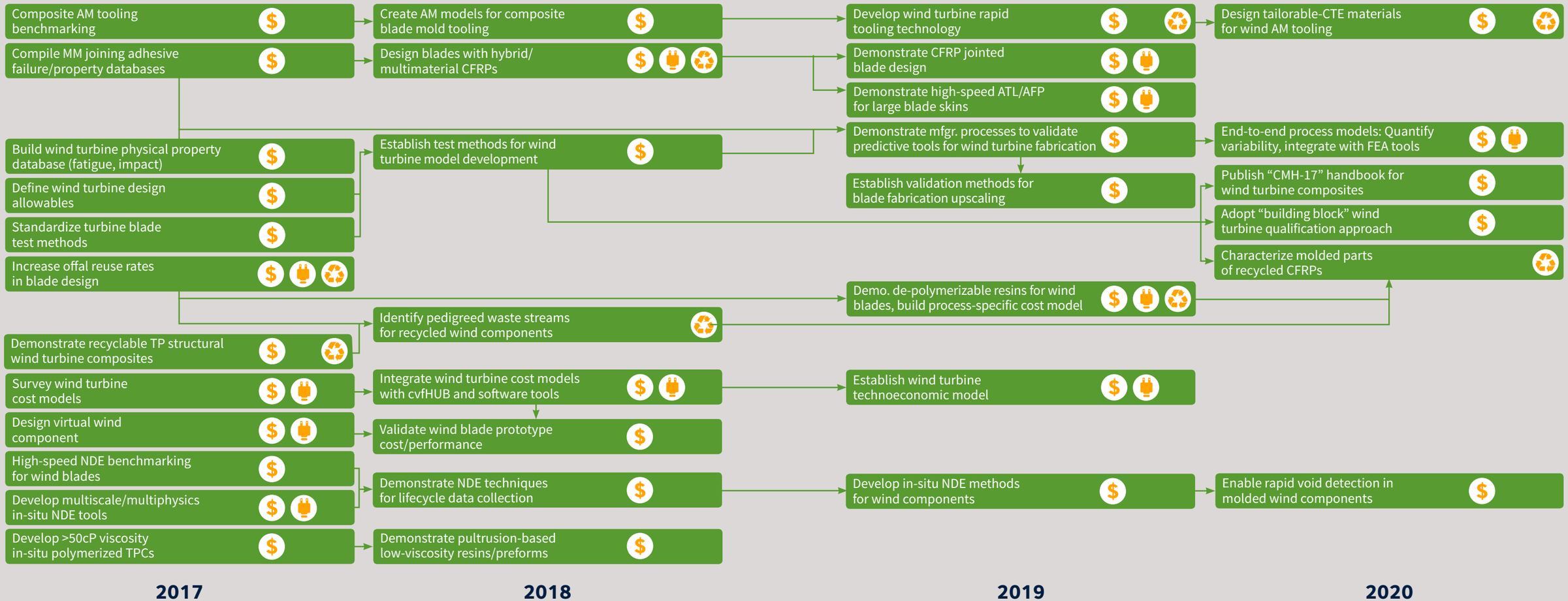
- Identify common manufacturing processes and quantify process model uncertainty
- Develop user-friendly modeling tools to bridge commercial/industrial sectors
- Host IACMI member seminars on multimaterial joining topics
- Develop advanced computational methods for composite vehicle part design
- Standardize joint NDE validation technique
- Advance AM tooling for vehicle applications
- Increase prediction confidence in durability/crash performance correlation
- Enhance virtual component crash models/characterization methods
- Produce standard reference "benchmark" automotive part
- Establish and validate cost/performance models for automotive parts
- Identify accelerated aging tests for composite joint durability
- Correlate test data with part performance, integrate with design tools
- Develop dissimilar bond service life prediction tools
- Conduct NDE pilot demo, correlate data with process changes
- Enable rapid void detection in molded automotive composites
- Develop bond integrity/uniformity inspection techniques
- Adapt CMH-17 from aerospace for vehicle manufacturing
- Establish data sharing methodologies for vehicle design tools
- Optimize sizing tech. to reduce property losses from fiber recovery
- Demonstrate low-cost blended bio-fibers
- Develop novel non-adhesive multimaterial joining methods
- Investigate reuse technology and secondary uses for CFRP offal
- Develop rapid processing approaches for near-net shape prepregs
- Develop TS/TP composite manufacturing methods with cycle times under three minutes
- Support workforce development programs in automotive composites manufacturing
- Reduce cycle time for tape layup and fiber placement processes by 50%

2017 2018 2019 2020

Figure 4. Priority R&D Activities (cont.)

Wind Turbines

Targets addressed: Recyclability, Cost, Energy



3 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.

Key Technical Objectives

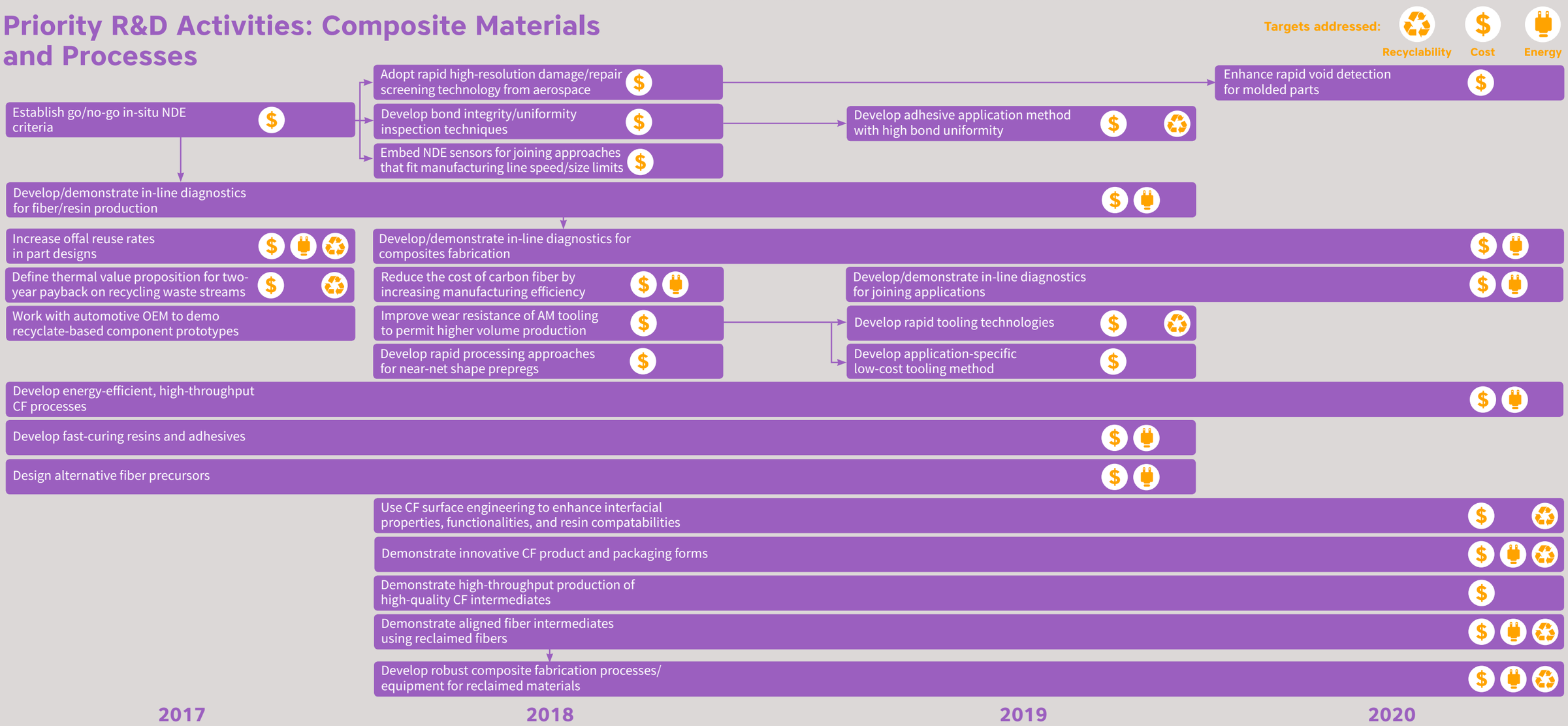
IACMI's Composite Materials and Processes Technology Area will support the industrialization of advanced composites by developing cutting edge manufacturing technologies for vehicles, wind turbines, and CGS application areas. As part of an integrated approach to facilitate the transition of innovative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

Advance carbon fiber technologies via alternative precursors, efficient 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

Priority R&D Activities: Composite Materials and Processes



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

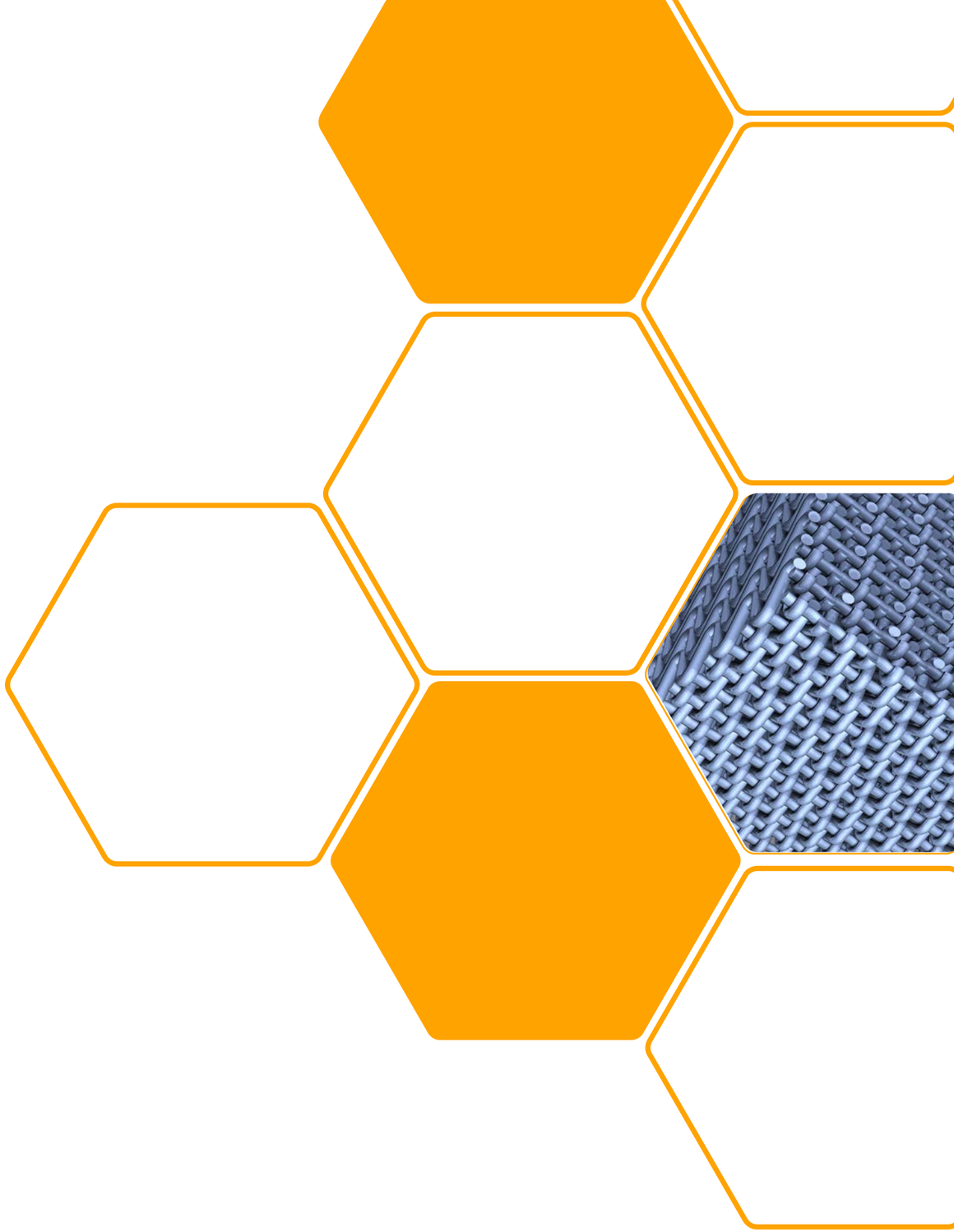
Characterization tools, such as microscopy, spectroscopy, X-ray and neutron radiography, are broadly used for measuring composite structural characteristics and behavior. These tools critical enabling technologies throughout the product development process including model validation, NDE, crashworthiness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

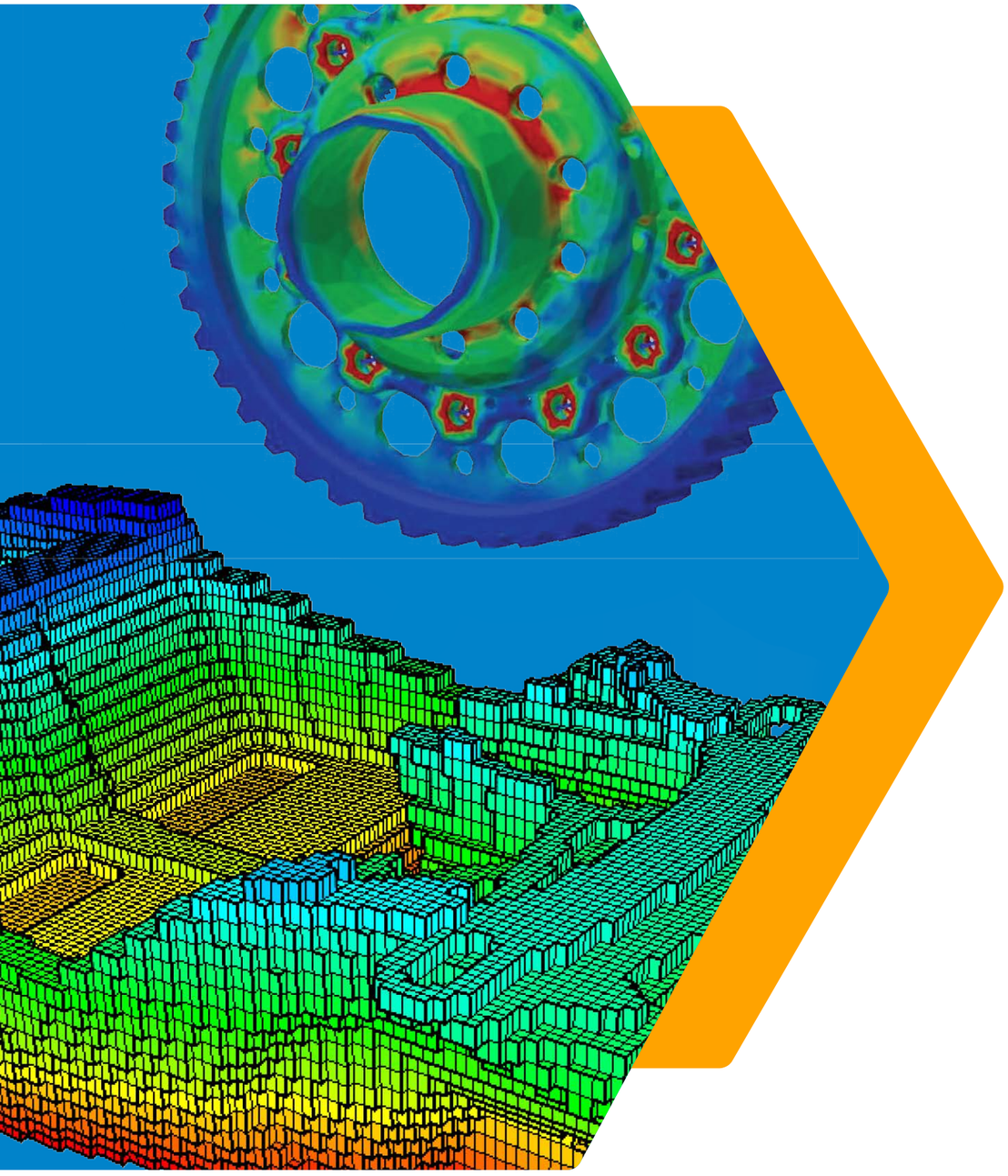
Using world-class characterization capabilities to advance the state of composite manufacturing technologies, IACMI will work with industry partners to develop new characterization approaches for setting data standards, support crash model development and crashworthiness demonstration efforts, conduct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

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.





4 Modeling and Simulation

Maintaining a digital product definition through the use of 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.

Key Technical Objectives

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 is a secure, browser-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 holding 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 database 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.

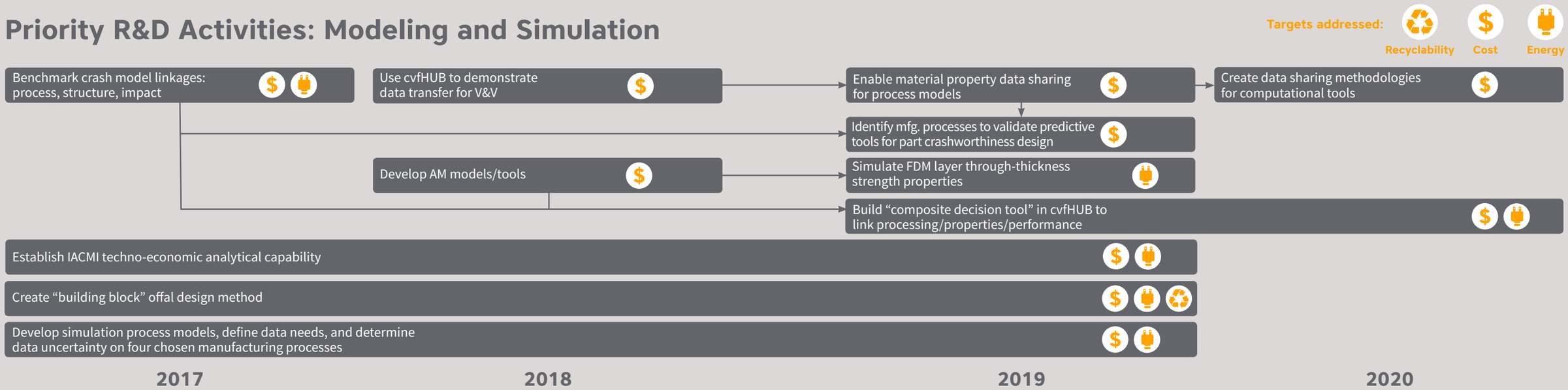
Several activities to advance the state of crash simulation tools and methods for the composites manufacturing industry include teaching best practices of designing and optimizing composites for crashworthiness, identifying representative composite components to demonstrate and improve crash models,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

Priority R&D Activities: Modeling and Simulation



5 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.

Key Technical Objectives

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 cost reduction goals of 30% by 2018 and 50% by 2020, 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.

A number of 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.

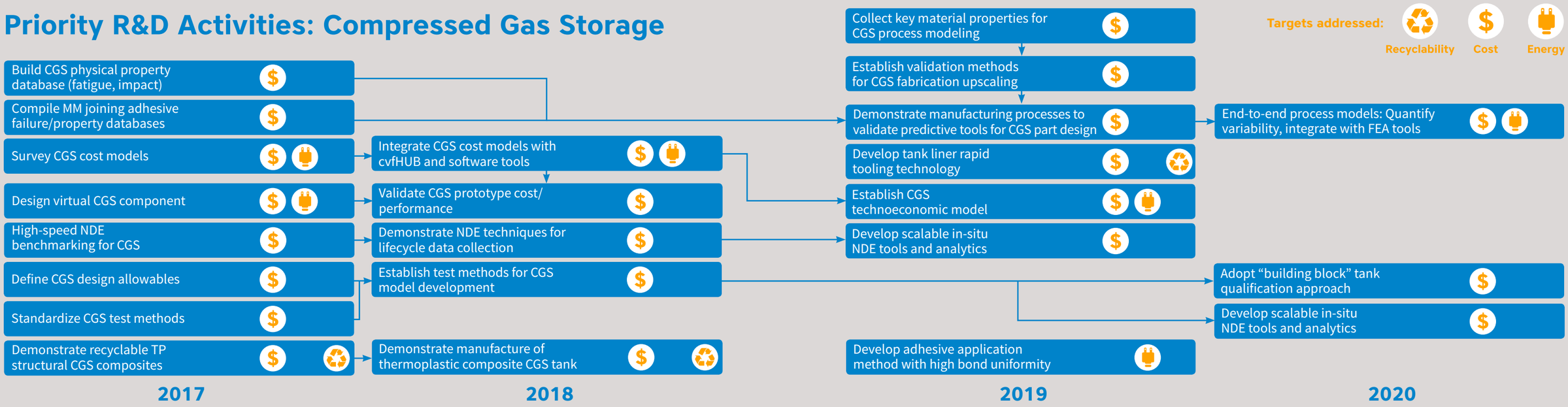
Some of the approaches needed to realize conformal composite CGS tank production at large scales will require rapid additive tooling solutions to fabricate tank liners and support structures, new characterization methods and testing standards to validate models and qualify novel composite tank architectures,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

Priority R&D Activities: Compressed Gas Storage



6 Vehicles

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.

Key Technical Objectives

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.

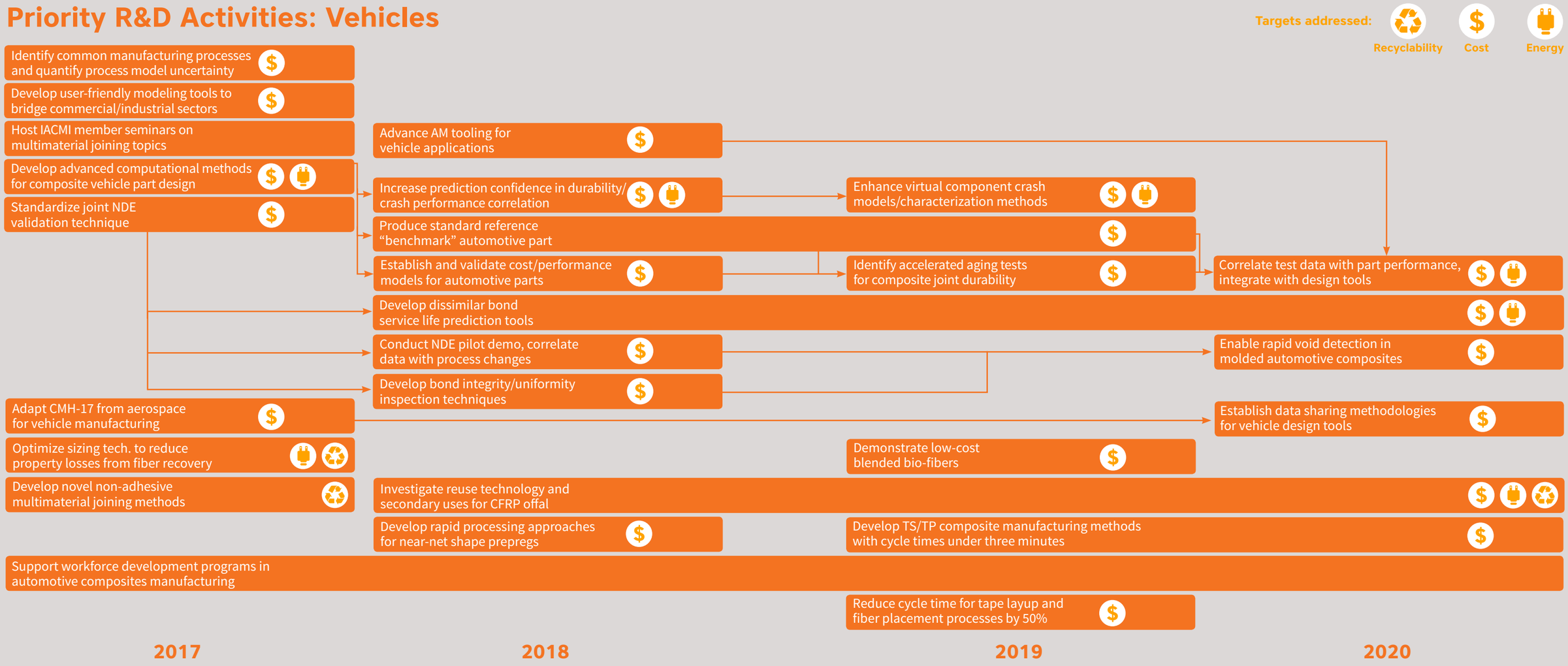
IACMI's Vehicles Technology Area will produce innovative vehicle design concepts by addressing activities such as facilitating round-robin studies that compare composites joint and interface designs for various assembly methods, establishing design optimization approaches for manufacturability and recyclability, 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

Priority R&D Activities: Vehicles



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 (HP-RTM), 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 as a way to reduce risk when lightweighting. This compels the need for 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.

7 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, and 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.

Key Technical Objectives

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 grow in size to capture more energy.

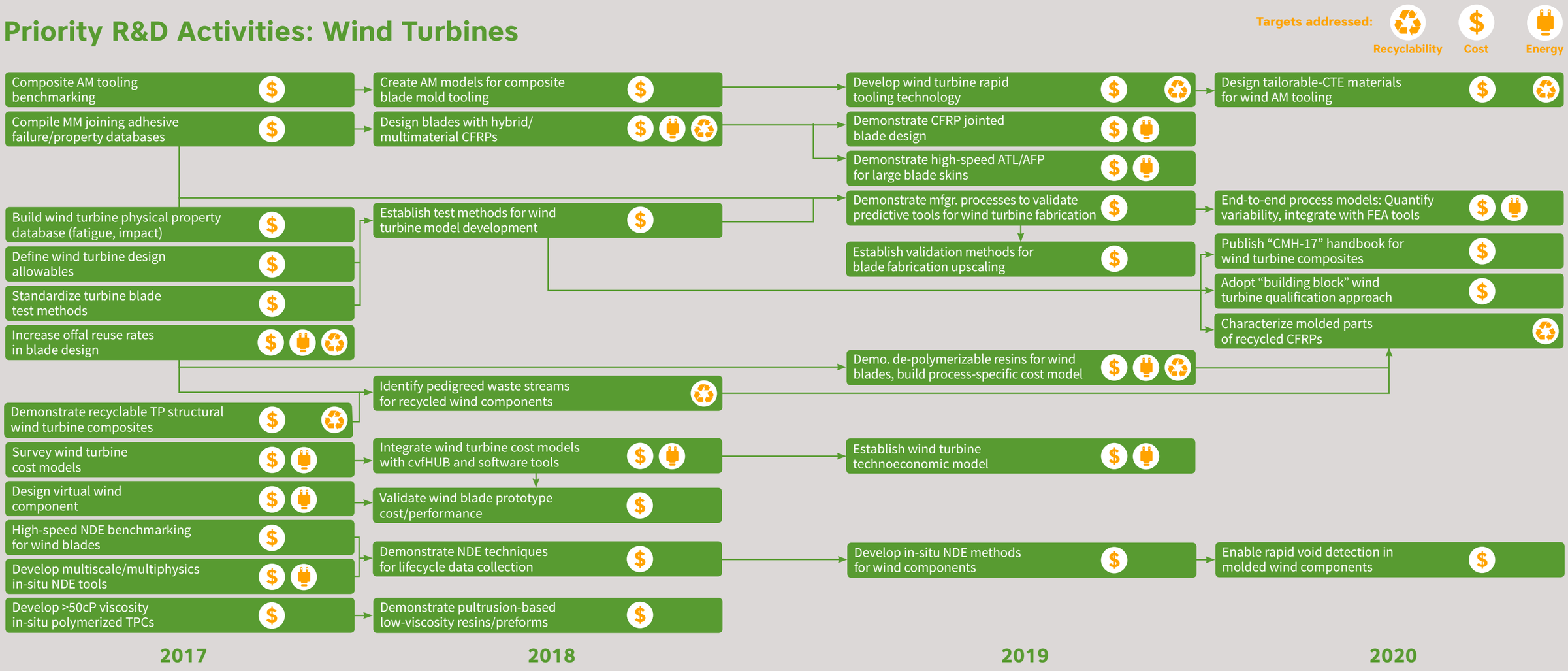
To reduce costs, improve quality, and increase the recyclability of composite wind turbine technologies, IACMI's Wind Turbines Technology Area will oversee activities that target the following objectives.

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 of 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

Priority R&D Activities: Wind Turbines



Automation can alleviate time-consuming NDE inspection techniques during pre-production as well as the costly labor content involved 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, which are ideal for modularized wind turbine design, can reduce the risk of wrinkle defects, increase blade quality, reduce labor content, and decrease overall cycle times.

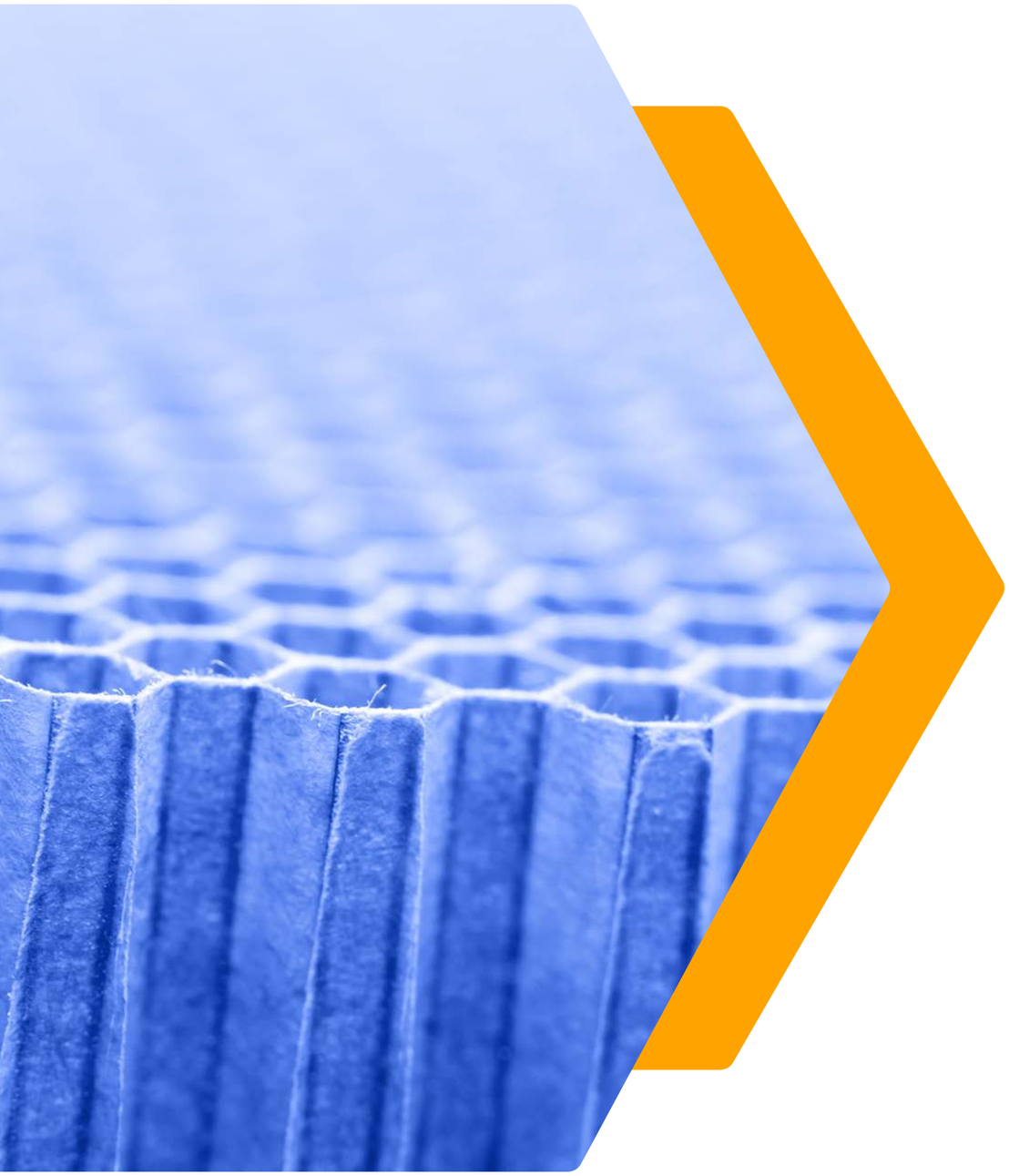
IACMI will work with its industry partners to advanced readily joinable pultruded composites by investigating lightweight carbon fiber jointed spar design concepts that facilitate self-aligning, developing low viscosity resins and preforms suitable for pultrusion processes, and conducting techno-economic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

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 five-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 five-year technical targets are met, efforts to commercialize cutting-edge composites manufacturing must persist as IACMI has already set its sights on aggressive ten-year targets.

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 embrace the research and development activities in this roadmap to strengthen U.S. manufacturing competitiveness, prosperity, and security.



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B Appendix: Acronyms

AFP	automated fiber placement
AM	additive manufacturing
ASTM	American Society for Testing and Materials
ATL	automated tape laying
BAAM	big area additive manufacturing
CAE	computer-aided engineering
CAFE	Corporate Average Fuel Economy
CF	carbon fiber
CFRP	carbon fiber reinforced polymer
CGS	compressed gas storage
CMH-17	Composite Materials Handbook-17
CNG	compress natural gas
CTE	coefficient of thermal expansion
cvfHUB	Composites Virtual Factory HUB
DFM	Design for Manufacturability
FDM	fused deposition modeling
HP-RTM	high-pressure resin transfer molding
IACMI	Institute for Advanced Composites Manufacturing Innovation
I-CAR	Inter-Industry Conference on Auto Collision Repair
ICME	integrated computational materials engineering
IIHS	Insurance Institute for Highway Safety
ISO	International Organization for Standardization
KBS	knowledge-based system
LIFT	Lightweight Innovations for Tomorrow
NDE	nondestructive evaluation
NDI	nondestructive inspection
NIAR	National Institute for Aviation Research
OEM	original equipment manufacturer
ORNL	Oak Ridge National Laboratory
R&D	research and development
SHM	structural health monitoring
SRS	software requirements specifications
TRL	Technology Readiness Level