Quadrennial Technology Review 2015

Chapter 6: Innovating Clean Energy Technologies in Advanced Manufacturing

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U.S. DEPARTMENT OF
ENERGY

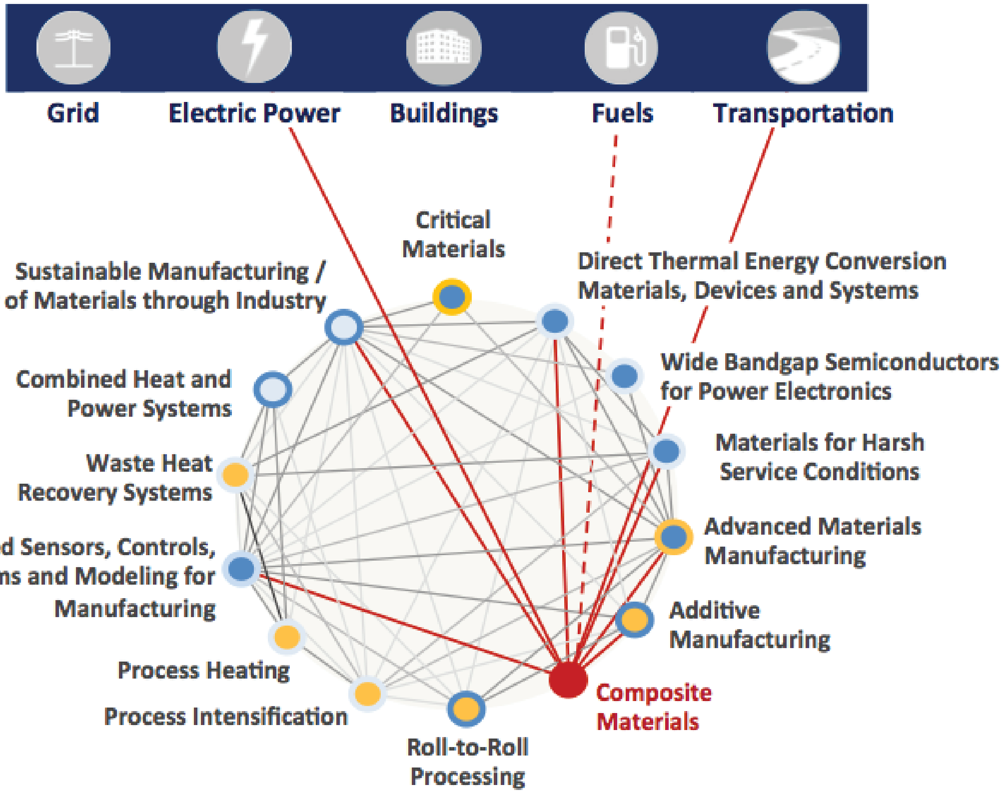
Quadrennial Technology Review 2015

Composite Materials

Chapter 6: Technology Assessments

This technology assessment is available as an appendix to the 2015 Quadrennial Technology Review (QTR). Composite Materials is one of fourteen manufacturing-focused technology assessments prepared in support of Chapter 6: Innovating Clean Energy Technologies in Advanced Manufacturing. For context within the 2015 QTR, key connections between this technology assessment, other QTR technology chapters, and other Chapter 6 technology assessments are illustrated below.

Connections to other QTR Chapters and Technology Assessments



Representative Intra-Chapter Connections

- **Additive Manufacturing:** 3-D printing of reinforced polymers and other composites
- **Materials for Harsh Service Conditions:** lightweight, durable structural components for automobiles; erosion-resistant composites for wind turbine blades and turbomachinery
- **Advanced Sensors, Controls, Platforms and Modeling for Manufacturing:** inspection techniques for quality control; automated tape laying and automated tape placement
- **Sustainable Manufacturing:** Lightweight materials manufacturing for life-cycle energy savings

Representative Extra-Chapter Connections

- **Fuels:** hydrogen fuel storage
- **Electric Power:** lightweight wind turbine blades
- **Transportation:** compressed gas storage for mobile applications; automotive lightweighting

Introduction to the Technology/System

Lightweight, high-strength, and high-stiffness composite materials have been identified as an important cross-cutting technology in U.S. clean energy manufacturing. These materials have the potential to substantially improve the efficiency of the transportation sector, enable efficient power generation, improve the storage and transport of reduced-carbon fuels, and increase renewable power production.[1] In order to reach this potential, advanced manufacturing techniques are required that will enable an expansion of cost-competitive production of advanced composite materials at commercial volumes. This Technology Assessment identifies manufacturing operations—from constituent materials production to final composite structure—that can benefit from technological advances through RDD&D. By reaching cost, energy, and performance targets at required production volumes, these advances could transform supply chains for clean energy and associated markets.

A composite can be defined as a combination of two or more materials that retain their macro-structure, resulting in a material that can be designed to have improved properties compared to the constituents alone.[2] Structural composite materials are often composed of a reinforcement material and a matrix material. The reinforcement material provides mechanical strength and transfers most of the loads in the composite, while the matrix material maintains alignment or spacing and protects the reinforcement from abrasion and the environment. The combination of a reinforcement material with an appropriate matrix material can enable products that are lighter-weight or have other unique properties relative to monolithic materials (like metals), while providing similar or better performance properties. There are many methods to manufacture composites owing to the diversity of composite materials and combinations. While composites encompass a wide range of matrix/reinforcement combinations, fiber-reinforced polymer (FRP) composites are targeted in this Technology Assessment due to their high performance characteristics and broad applicability to key clean energy applications. Other types of composites, such as metal-matrix composites, have application areas outside the scope of this Technology Assessment, and are addressed elsewhere;[3] these composites offer advantages specific to the application (such as conductivity, durability, hardness, radiation resistance, high strength at higher temperatures) and have different manufacturing challenges than FRP composites.[4]

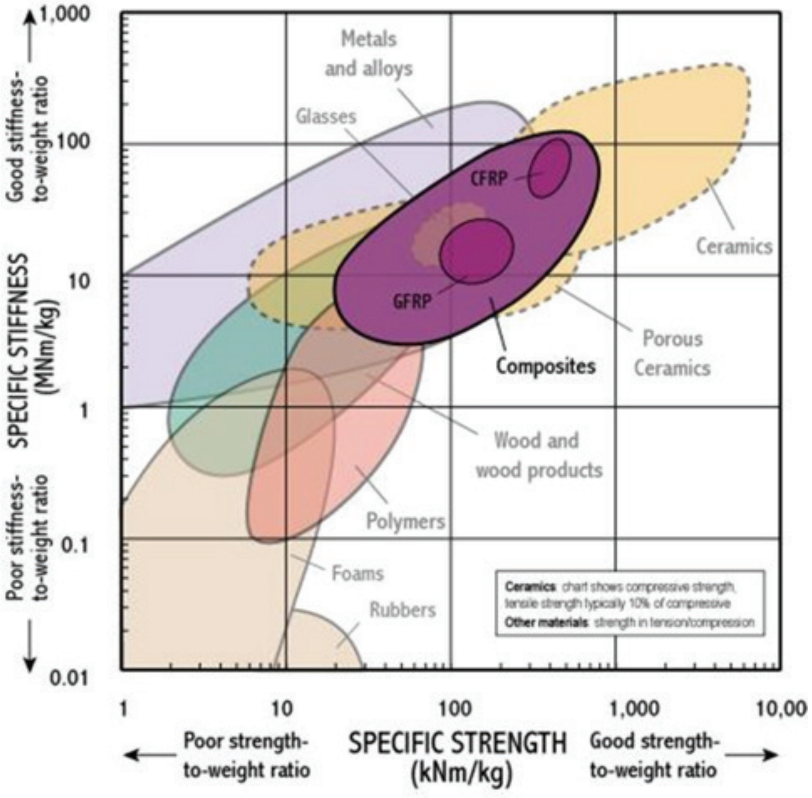
FRP composites are made by combining a polymer resin with strong, reinforcing fibers. These lightweight composites can enable energy savings in applications where large amounts of energy use and carbon emissions occur in the use phase, such as fuel savings in lighter-weight vehicles. Other energy benefits of FRP composites include more-efficient wind turbine operation at a lower installed cost, and compressed gas storage tanks for natural gas (and ultimately, hydrogen) that enable increased use of fuels with a lower life cycle environmental impact. This is not an exhaustive list of potential application areas. Lower cost, high strength and stiffness, corrosion resistant, and lightweight composite materials could also provide benefits in diverse applications including industrial equipment and components, pipelines, structural materials for buildings, fly-wheels for energy storage, support structures for solar energy systems, shipping containers, and continued use of FRP composites in aerospace applications.

Many of the applications listed above may benefit specifically from carbon fiber reinforced plastic (CFRP) composites, which can offer a higher strength-to-weight ratio and stiffness-to-weight ratio than other structural materials, as shown in Figure 6.E.1. These lightweight materials may deliver energy savings during the use phase or facilitate performance that cannot be attained with materials that do not have such high strength and stiffness characteristics.

As shown in Figure 6.E.1, high-strength materials are not necessarily high stiffness and vice versa. Depending on the application, a high-strength and/or high-stiffness material may be preferred. For example, a high-strength material is desired for compressed gas storage tanks, whereas a high-stiffness material is desired for wind turbine blades. One important advantage of composite materials such as CFRP composites is that the material properties can be tailored to the application. Unlike most metals and ceramics that are isotropic (the mechanical properties are the same in all orientations), composites can be anisotropic, which results in a different response to the applied force depending on fiber orientation and load direction. Carbon fibers are stiffest and strongest in the direction of the fibers. By tailoring the orientation of the fibers in the composite, the mechanical properties can be optimized for a specific application. Additionally, performance can be tailored by choice and relative quantity of constituent materials, fiber matrix interface, composite structure design, and manufacturing and joining processes.

Figure 6.E.1 Relationship Between Specific Stiffness and Specific Strength for Various Materials. The figure highlights carbon fiber reinforced polymer (CFRP) composites and glass fiber reinforced polymer (GFRP) composites.[5]

Credit: University of Cambridge - Department of Engineering



The actual lightweighting potential of various materials is application specific; the mass savings potential for a given material depends not only on its material properties, but also on whether the application is stiffness- or strength-critical, as shown in Table 6.E.1. A key performance criterion for stiffness-critical applications is the specific stiffness (the ratio of the modulus to the first, second, or third power of density, depending on the application); a key performance criterion for strength-critical applications is the specific strength (the ratio of the strength to the first, second, or third power of density). As shown in Table 6.E.1, for certain applications, the greatest theoretical mass savings could be achieved using carbon fiber composites—although in all material cases, the estimated theoretical mass savings cannot be fully achieved due to manufacturing technology limitations.

FRP composites were originally developed and used primarily in the aerospace industry on both military and commercial aircraft, with glass FRP composites entering the market in the 1940s and carbon FRP composites in the 1960s.[7] Since then, the applications for composite materials have become more diverse and the market has grown significantly. Research will be needed to overcome the challenges associated with carbon FRP composite materials and their manufacture, including high costs, low production speeds, high energy intensity, and poor recyclability as well as needs for improved design, modeling, and inspection tools.[8,9] This technology assessment will discuss limitations to material, manufacturing, and recycling processes to make FRP composites for several targeted clean energy applications.

As FRP composites become more broadly utilized and tailored for the application areas, performance standards for these materials will be driven by the application need, and may result in FRP composites becoming more

Table 6.E.1 Mass Savings Potential of Various Lightweight Materials[6]

Material	Density (g/cm^3)	Young's Modulus (GPa)	Strength (MPa)	Mass Savings (% Relative to Mild Steel)	
				Stiffness Application	Strength Application
Mild Steel	7.9	205	350	0%	0%
Advanced High Strength Steel	7.9	205	1000	0%	24–42%
Aluminum	2.7	72	190	3–52%	37–54%
Magnesium	1.8	45	140	51–62%	43–64%
Glass Fiber Composites	2.0	25	300	28–49%	71–73%
Carbon Fiber Composites	1.6	80	1300	48–72%	90–95%

commodity based materials. Today, these materials remain, in particular CFRP, niche materials due to the limitations discussed in this assessment. Addressing the technical challenges may enable U.S. manufacturers to capture a larger share of the high-value-added segment of the composites market and could support domestic manufacturing competitiveness.

Technology Potential and Assessment

CFRP composite technologies, and to some extent glass fiber reinforced polymer (GFRP) composite technologies, were developed for structural applications by the aerospace industry because of the high specific strength, high specific stiffness, and tailorability advantages they offered relative to other lightweight materials such as aluminum. These technology developments were sponsored by the Department of Defense (DoD) and the National Aeronautics and Space Administration (NASA), and began with early applications in aircraft secondary structures that were not safety critical. As the technology matured, CFRP composites were increasingly used in military aircraft, with the B-2 bomber representing the maximum use of these materials in flight safety critical, ultra-lightweight structures.[10]

The increasing demands of military aircraft performance and NASA's anticipation of commercial aircraft needs led to significant CFRP materials and manufacturing technology advancements. These include analytical tools; strictly controlled CFRP materials composition; manufacturing processes such as resin transfer molding (RTM); automated manufacturing methods such as robotic layup and automated tow placement; non-destructive inspection methods; reduced part count structures for assembly cost savings; and certification criteria, compliance methods and databases. These materials, processes and design technology developments increased the attractiveness of CFRP to the commercial aircraft industry, resulting in their extensive use in Boeing's 787 airliner and several Airbus models.

In these aerospace applications, aircraft weight savings justified the significant cost per kilogram premium paid for CFRP materials and manufacturing. The business case for CFRP and GFRP composite use in automotive, wind turbine, and compressed gas storage applications, however, may require cost parity with state-of-the-art materials and manufacturing methods. This technology assessment, therefore, describes the constraints to which composite materials would be subject (such as $/kg manufactured part cost), assesses the current state of the art in composites technologies with respect to these constraints, and delineates the expected improvements and trends in the near-term based on the planned and in-progress RD&D activities directed toward U.S. clean energy manufacturing.

Throughout this technology assessment, the use of FRP composites for vehicles, wind turbines, and compressed gas storage are highlighted as primary examples for clean energy applications where composite materials could have a significant impact. Additional industrial and clean energy applications are also discussed below.

Potential of FRP Composites for Clean Energy Applications

Vehicles

Lightweighting is an important end-use energy efficiency strategy in transportation. For example, a 10% reduction in vehicle weight can improve fuel efficiency by an estimated 6%–8% for conventional internal combustion engines, or increase the range of a battery-electric vehicle by up to 10%.[11] A 10% reduction in the weight of all vehicles in the U.S. car and light-duty truck fleet could result in a 1.06 quad (1.12 exajoule [EJ]) annual reduction in energy use and a 72 million metric ton (MMT) reduction in CO_2 emissions.[9] The DOE Vehicles Technology Office (VTO) estimates savings of more than 5 billion gallons (19 billion liters) of fuel annually by 2030 if one quarter of the U.S. light duty fleet utilizes lightweight components and high-efficiency engines enabled by advanced materials.[12]

In 2012, the U.S. Environmental Protection Agency (EPA) and the National Highway Traffic Safety Administration (NHTSA) set new Corporate Average Fuel Economy (CAFE) standards for cars and light-duty trucks that are projected to increase fleetwide average fuel economy to the equivalent of 54.5 mpg (0.043 liters/km) by model year 2025.[13,14] Lightweighting has been identified as a technology approach with significant potential to help achieve this standard. The U.S. DRIVE (Driving Research and Innovation for Vehicle efficiency and Energy sustainability) Materials Technical Team identified carbon fiber composites as the most impactful material to reduce vehicle mass in their 2013 Roadmap.[15] Composites can offer mass reductions over conventional steel ranging from 28–73% in glass fiber systems and 48–95% in carbon fiber systems, as shown in Table 6.E.1. Glass fiber composites can be found in closures or semi-structural components, such as rear hatches, roofs, doors and brackets, which make up 8–10% of the typical light duty vehicle weight. Glass fiber composites are especially useful in applications where the ability to consolidate parts and provide corrosion resistance and vibration damping properties are beneficial.[16]

Carbon fiber composites have had limited adoption in the commercial automotive sector over the past forty years, and have primarily been used in semi-structural (e.g., hoods and roofs)[16] and non-structural (e.g., seat fabric) applications for low-volume production runs. However, they have significant technical potential for vehicle lightweighting in structural applications. The typical body structure for a light duty vehicle accounts for 23–28% of the weight.[17] VTO set a goal of a 50% weight reduction in passenger-vehicle body and chassis systems.[18] One foreign manufacturer recently released a low-volume electric vehicle with a primarily carbon fiber body.[19] To expand carbon fiber use to more vehicle models, VTO workshop participants indicated that key needs include additional failure mode information regarding the structural and safety requirements for body structures, materials with equal or better performance at equivalent cost, better design tools, and dependable joining technology for composites, all at adequate manufacturing speeds with consistent performance.[17]

The benefits of lightweighting military vehicles include improved fuel economy, increased performance, improved survivability, and the ability to better support operations, according to the 2012 National Research Council report on the *Application of Lightweighting Technology to Military Vehicles, Vessels and Aircraft*.[20]

The report also recognizes that "…robust manufacturing processes for fabricating complex structural components from continuous-fiber-reinforced composites have not yet achieved the rate and consistency of steel stamping."[20]

For load-limited, heavy-duty vehicles, lightweighting can result in increased freight capacity, thereby reducing the number of trucks required to ship a given tonnage. In volume-limited shipping, weight reduction impacts on heavy-duty vehicles are similar to those for light-duty vehicles. VTO's SuperTruck program recently demonstrated a 115% freight efficiency improvement relative to the 2009 baseline by using a spectrum of technologies, including CFRP composites for lightweighting.[20] In addition, Walmart released the WAVE (Walmart Advanced Vehicle Experience), a concept truck with a trailer made almost exclusively of fiber composites that reduces the weight by around 4,000 pounds (1800 kg).[22]

According to the *VTO Workshop Report: Trucks and Heavy-Duty Vehicles Technical Requirements and Gaps for Lightweight and Propulsion Materials*, the three most significant technical gaps impeding widespread implementation of carbon fiber composites are:[23]

1. A lack of low-cost precursors and energy efficient conversion processes for carbon fiber;
2. Inadequate design methods and predictive modeling capabilities; and
3. A lack of high volume manufacturing methods amenable to non-epoxy resin systems.

Wind Turbines

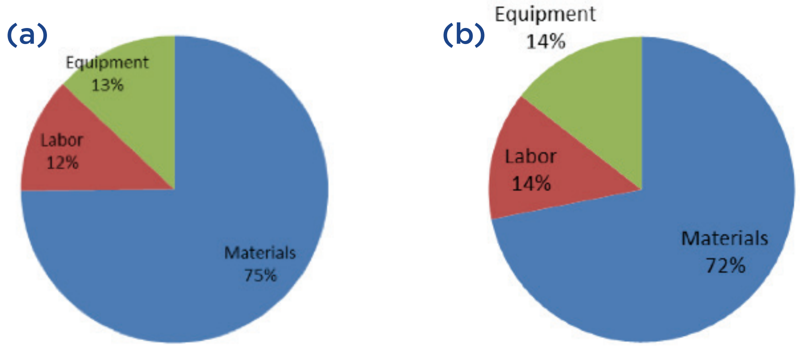
DOE's recently released Wind Vision study develops a central scenario for potential future wind deployment to estimate costs, benefits, and other impacts. The study estimates that if current manufacturing capacity is maintained via pathways that include aggressive cost reductions, 35% wind energy as a share of national end-use electricity demand can be achieved by 2050, compared against a baseline scenario, and that supplying 35% of U.S. electricity from wind could reduce cumulative GHG emissions from electricity generation by 12.3 gigatonnes CO_2 equivalents by 2050.[24] In wind energy generation, high strength and stiffness, fatigue-resistant lightweight materials like carbon fiber composites can support development of lighter, longer blades and increased power generation.[1] Blade designers are increasingly using lighter weight materials such as industrial carbon fiber laminates, modular prepreg members, and automated fiber placement production technologies to achieve longer, stiffer blades, including the use of carbon fiber in structural spar caps. The use of lighter blades also reduces loading on support structures, and can result in material and cost savings beyond the blades alone.[25] Advances in composites materials and production methods will be needed to achieve the aggressive cost reductions required meet these targets.

While high performance carbon fiber has been used for components subject to the highest loads (i.e., spar caps) by some manufacturers,[26] glass fiber composites with lower specific properties are the dominant materials for the overall blade due to lower cost. The capital cost of turbine structures and blades is a significant contributor to the levelized cost of electricity (LCOE) for wind generation. As a result, any enhancement to the structural properties of materials must be balanced against the increased cost to ensure the overall system costs do not increase disproportionately with the increased power capacity and energy production.

For longer blades, the use of carbon fiber can reduce the weight of the blade. One study estimates a 28% mass reduction for a 100m carbon fiber spar cap blade design compared to the glass fiber equivalent.[27] Materials account for a similar relative proportion of blade costs based on models by Sandia National Laboratories for a 100m all glass (72%) or all carbon (75%) reinforced blades, as shown in Figure 6.E.2; however, carbon fiber cost would need to drop by an estimated 34% to be competitive.[36] A combination of material optimization and lower costs could enable the use of carbon fiber in future blades.[28]

Figure 6.E.2 Major cost components breakdown for 100m wind turbine blades for (a) a carbon fiber spar blade design (Sandia SNL100-01 design) and (b) an equivalent glass fiber design, based on Sandia cost models.[28]

Credit: Sandia National Laboratories



Further advances in blade manufacturing techniques, improved quality control, innovations for glass-carbon fiber hybrid composites, and reduced costs of carbon fiber composite materials and manufacturing will support production of larger turbines and continued growth of wind power. The U.S. has a strong position in manufacturing of wind energy equipment,[29] and innovative manufacturing techniques could further strengthen U.S. competitiveness in this market segment.

Compressed Gas Storage

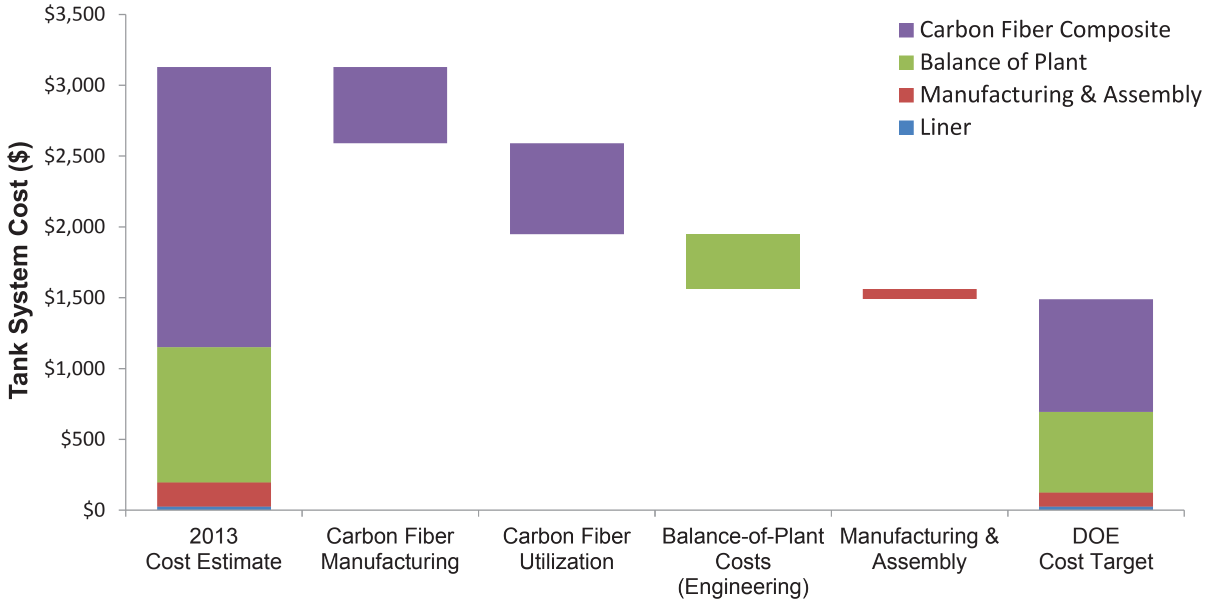
According to an analysis by the Fuel Cell Technologies Office (FCTO), fuel cell electric vehicles using hydrogen can reduce oil consumption in the light-duty vehicle fleet by more than 95% compared to today's gasoline internal combustion engine vehicles; by more than 85% compared to advanced gasoline hybrid electric vehicles; and by more than 80% compared to advanced plug-in hybrid electric vehicles. Full commercialization of fuel cell systems using hydrogen will require advances in hydrogen storage technologies including lightweighting and cost reduction. Early markets for hydrogen fuel cells include portable, stationary, and back-up generation systems as well as material handling equipment (e.g., forklift trucks).

Many storage technologies for hydrogen are similar to those needed for natural gas applications. As the demand grows for compressed gas storage of hydrogen and natural gas, lower cost materials and manufacturing methods for storage tanks will be required. High pressure storage tanks are typically made with high strength (>5,000 MPa tensile strength) carbon fiber filament in a polymer matrix wound over a metallic or polymeric liner. Carbon fiber composites can account for over 60% of the cost of these systems.[31] FCTO has set a capital cost target at $333/kg H_2 stored,[32] which will provide sufficient hydrogen storage capacity to enable light duty vehicles (LDV) to meet consumer expectations for driving range between refueling stops. To achieve this cost target for type IV storage tanks with 5.6kg of hydrogen storage at 700bar, CFRP costs will need to drop to $10–$15/kg.[31] The U.S. DRIVE Hydrogen Storage Technical Team estimates that when storage tanks are manufactured in high volumes (500,000 units per year), the largest cost reductions are expected to come from improvements in carbon fiber manufacturing (e.g., use of alternative precursors or advanced conversion techniques) and utilization of materials (e.g., use of fillers or resin substitution), as shown in Figure 6.E.3.

Industrial and Other Applications

In addition to automotive, wind turbine, and pressure vessel applications, industrial applications also merit some review. According to the World Corrosion Organization, the annual cost of corrosion and its prevention worldwide is $2.2 trillion, more than 3% of the world's economy,[34] and a 2002 study by the Federal Highway Administration estimated U.S. corrosion costs at approximately 3.1% of GDP, approximately $276 billion at

Figure 6.E.3 Potential Cost Reduction Strategy for Compressed Hydrogen Pressure Vessels to Meet the 2020 DOE Cost Target. Innovations in carbon fiber manufacturing and utilization can play key roles in reducing overall system cost.[33]



that time.[35] CFRP composites offer corrosion resistance and could potentially replace metals in structures such as tanks, piping, cooling towers, and railcars used for chemical transport and other applications.[36] In addition to being lightweight, the ability to withstand corrosive environments has led to increased use of composites in deep-water drilling and hydraulic fracturing. In March 2014, Lucintel reported that the oil & gas and chemical segments together accounted for more than 55% of the U.S. fiber-reinforced plastic pipe market.[36]

Other applications could benefit from high strength and stiffness, corrosion resistant, and lightweight composite materials. In addition to the uses identified previously—including structural materials for buildings, fly-wheels for energy storage, and support structures for solar energy systems, other potential applications include heat exchangers, equipment for geothermal energy production, hydrokinetic power generation. Examples of nonstructural applications of FRP composites include electric arc furnace (EAF) electrodes, insulation materials, engine components, and power lines.

Barriers to Increased Utilization of Composites in Clean Energy Applications

Responses to a Request for Information (RFI) released by U.S. Department of Energy (DOE) Advanced Manufacturing Office (AMO) in 2013[37] indicated that the top five most important R&D areas for composites are:

- high speed production (low cycle times);
- low cost production (noted by respondents as highly connected to production speed);
- energy efficient manufacturing;
- recycling/downcycling technologies; and
- innovative design concepts.

A separate analysis identified the high material cost for carbon fibers and low production rates for composites manufacturing as the most critical obstacles to market growth in high volume applications.[38] Additional

obstacles identified in this assessment include unproven crashworthiness for composite parts, a lack of design tools, sunk capital in other technologies, workforce resistance, a lack of standards, a lack of assured supply, insufficient repairability, and poor compatibility with commodity resin systems.[38]

The U.S. DRIVE Materials Technology Team identified carbon fiber cost, high volume manufacturing, recycling, predictive modeling and other enabling technologies as some of the most critical challenges to the further adoption of carbon fiber composites.[15] The American Chemistry Council (in the *Plastics in Automotive Markets Technology Roadmap*) summarized the main challenges by stating "…the industry's manufacturing infrastructure must become fully effective while working with plastics and combining multiple materials into a functional whole. Simultaneously, the industry's developmental infrastructure must become fully adept at designing with plastics and innovating new applications for plastics and polymer composites, especially in light of evolving safety performance criteria and energy efficiency goals."[39]

Four critical barriers to the broader adoption of carbon fiber reinforced composites (cost, speed, energy intensity, and recyclability) are further explored in the following sections.

Cost

For equivalent material performance, carbon fiber composites currently cost 1.5 to 5 times the cost of steel,[40] limiting use primarily to relatively low-volume and niche applications. To expand market use, the costs of fiber precursors and processing need to be reduced. Fluctuating oil prices and supply-demand imbalances have driven raw material costs up for petroleum-based precursors,[41] encouraging research in renewable resin and fiber precursors. As shown in Table 6.E.2, GFRP composites are typically more expensive than steel but lower in cost than CFRP. They face similar processing and recyclability challenges.

Table 6.E.2 Typical Virgin Material Cost and Performance

	GFRP	CFRP	Steel	Aluminum	Magnesium	Titanium
Domestic Production Cost ($/kg)[42,43]	2.5	27	0.47	2	3.31	9
Specific Strength (kNm/kg)[5,43]	150	400	38	130	158	120
Density (kg/m^3)[43,44]	1800	1590	7870	2700	1800	4500

Manufacturing Speed

Process throughput (or manufacturing speed) is another primary cost barrier for composites and a critical decision criterion impacting adoption of composites in high-volume applications. Conversely, tooling and setup costs usually favor composite parts of the same shape and function compared to conventional metal parts. Advances in additive manufacturing are being explored to address complex tooling requirements.[45] The tradeoff of lower tooling and setup costs and low process throughput for composites versus the higher tooling costs and higher throughput for metals gives rise to a part count threshold beyond which the advantage moves to metal parts. To achieve cost parity with metal parts at higher production levels, cycle times for composites manufacturing must be reduced. Emerging fast-curing resins and thermoforming processes with long-fiber reinforcement in thermoplastic matrix polymers are two approaches to shorten cycle times compared to existing processes. Process automation, such as robotic material deposition systems, adaptive tooling and transport of preforms or subcomponents between unit operations, can help meet higher throughput objectives. In the automotive industry, where manufacturing speed is a particular barrier to adoption, suppliers have been working on reducing cure times. For example, Momentive Specialty Chemicals, Inc. introduced a five-minute-cure epoxy in 2011 and Hexcel Corporation introduced a quick cure pre-preg with a two-minute cycle in 2014.[36]

Energy Intensity

Life-cycle energy advantages are a balance between energy-intensive advanced composites production and the energy savings and greenhouse gas emissions reductions that mainly occur in the application end-use phase, such as from fuel savings in lightweight vehicles. Manufacturing energy intensity can be an important barrier in the overall life cycle energy balance. One study estimates that carbon fiber composites are three to five times more energy intensive than conventional steel on a weight basis.[46] As a result of the highly energy-intensive manufacturing process, it can take years before the use phase energy benefits of lightweight composites offset the added manufacturing energy. This tradeoff is explored for adoption of CFRP composites in light-duty vehicles in the *Novel Low-Cost Carbon Fibers for High-Volume Automotive Applications* case study.

Conventional steel is produced by well-established processes that have undergone over 150 years of optimization and energy intensity improvements, while FRP composites are currently produced by relatively new processes that have promising opportunities for optimization and energy intensity improvements. Raw materials for reinforcement and matrix constituents are often derived from energy-intensive petroleum processing, and high temperatures are required in the manufacture of both carbon and glass fibers. To reduce the energy intensity of FRP composites, high-quality, lower energy raw materials and lower energy production technologies are needed. Figure 6.E.5 illustrates potential energy savings opportunities in the fabrication

Novel Low-Cost Carbon Fibers for High-Volume Automotive Applications

Conventional polyacrylonitrile (PAN)-based carbon fiber precursors used in carbon fiber polymer composites are energy intensive and expensive. If an alternative lower cost precursor can be developed with a higher carbon fiber yield (> 65 % yield) compared to PAN precursor fibers (~48% yield), energy consumption of carbon fiber polymer composites could then be significantly reduced.

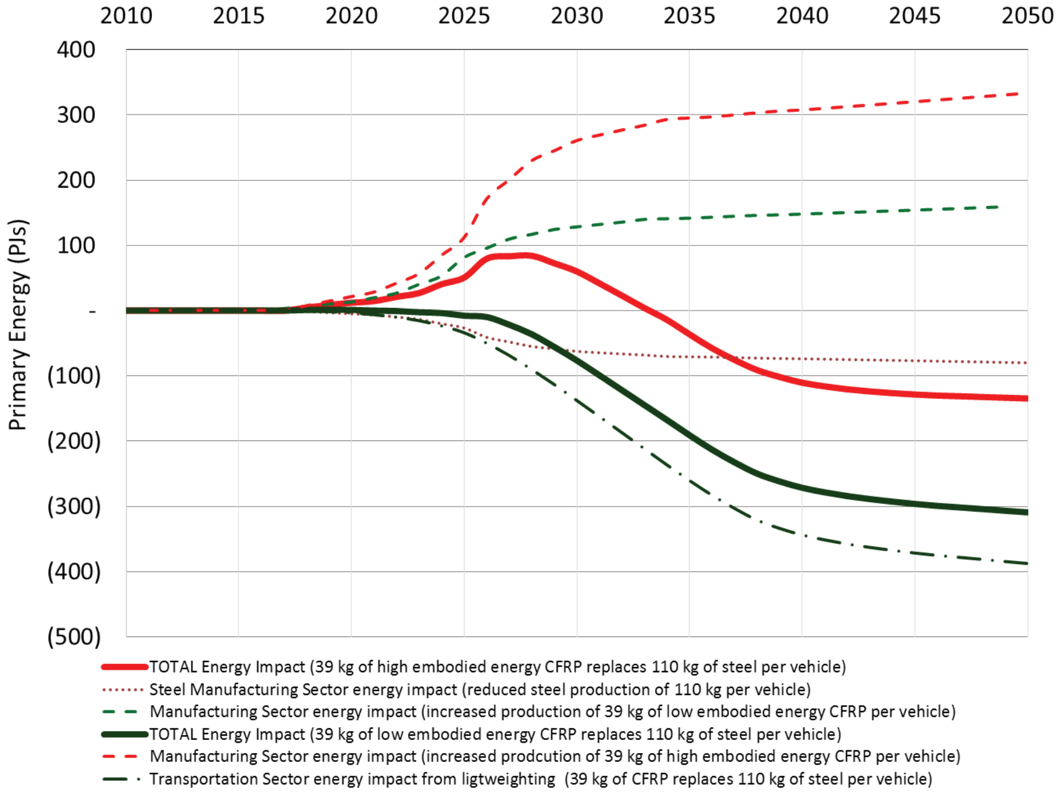
The Lifecycle Industry GreenHouse gas, Technology and Energy through the Use Phase (LIGHTEn-UP) cross-sectoral energy life cycle analysis tool developed by Lawrence Berkeley National Laboratory was used to explore the long-term, net energy impacts associated with the deployment of lightweight CFRP automotive parts across the light-duty vehicle (LDV) fleet in the U.S. Two manufacturing pathways using CFRP parts (40% fiber by weight) were compared against a business-as-usual baseline of conventional stamped steel. The first CFRP manufacturing pathway is based on a conventional, high-embodied-energy PAN carbon fiber precursor. The PAN CFRP pathway begins with the polymerization of acrylonitrile (AN) and utilizes solution spinning. The second manufacturing pathway was a hypothetical low-energy CFRP manufactured with an alternate precursor. The low energy CFRP pathway begins with the polymerization of an alternative high-yield precursor raw material and uses melt spinning. Both pathways include two subsequent high-temperature carbonization steps. For this case study, it was assumed that the low-energy manufacturing pathway can attain a 70% reduction in embodied energy in the CF as compared to conventional, PAN-based CF.

A mass reduction of 65% was assumed for a 110-kg steel part replaced with a 39-kg CFRP part in the gasoline internal combustion engine (ICE) LDV fleet. Mass substitution factors for automotive parts are application specific, as part design depends on loading conditions, geometry, and other factors. For this scenario, a generic mass substitution was assumed, based on a theoretical correlation between fiber mass fraction and mass savings when CFRP replaces steel for a panel in bending for a 150 GPa fiber modulus.[6] Further key assumptions include a vehicle lifetime driving distance of 250,000 km and a mass reduction induced change in fuel consumption of -0.38 liters/100 km driven per 100 kg of steel replaced by CFRP. Recycling was not considered in this analysis.

As shown in Figure 6.E.4, net-positive life cycle energy benefits of CFRP lightweighting of the LDV fleet are observed only after significant use phase energy benefits are realized from the penetration of lightweight vehicles into the U.S. fleet. As the use of CFRP parts in vehicles increases over time, industrial carbon fiber manufacturing energy consumption increases while industrial steel sector and transportation sector energy use decrease.

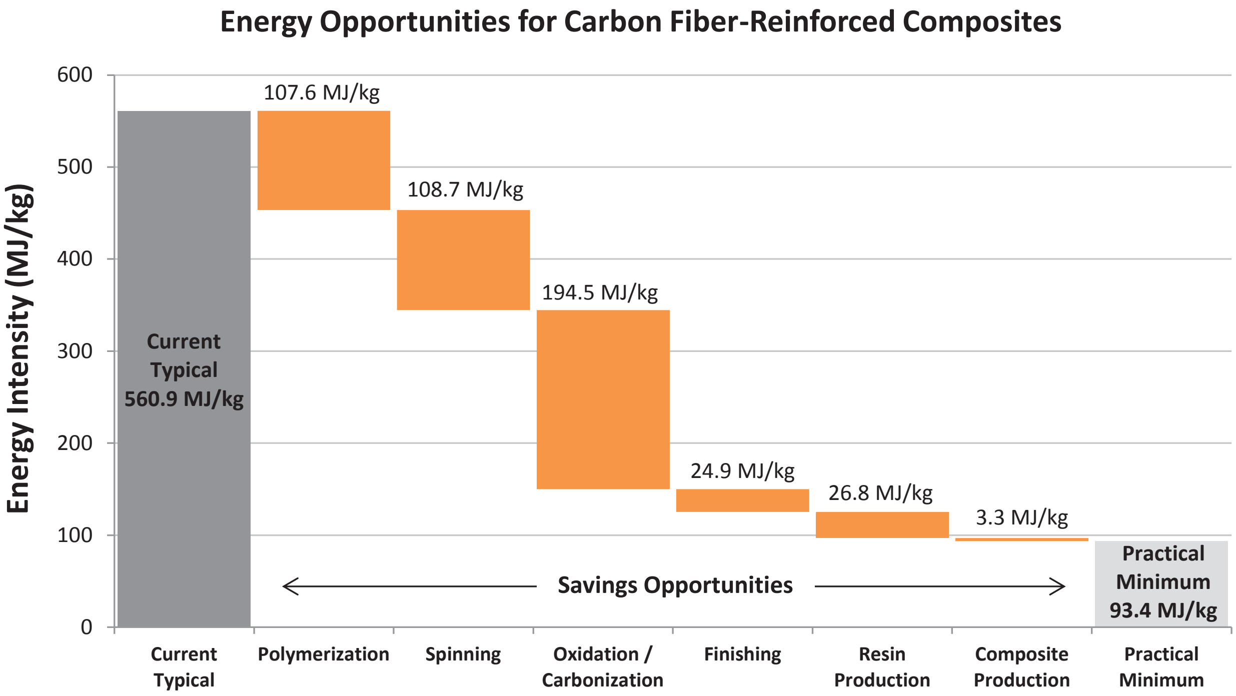
Using conventional PAN-based CFRP, break-even energy benefits occur after 2033; using low energy CFRP, the energy benefits begin approximately thirteen years earlier as a result of the lower energy requirements for CF manufacturing. Net energy savings for low-energy CFRP were predicted to reach approximately 135–310 PJ/year by 2050.

Figure 6.E.4 Estimates of the net annual life cycle energy impacts of replacing 110 kg of conventional steel parts with 39 kg of CFRP parts (40% fiber by weight) in the U.S. LDV fleet, comparing two manufacturing pathways (conventional PAN-based CF and an alternative, low-energy CF).



of 1 kg of carbon fiber-reinforced polymer composite based on a review of state-of-the-art and applied R&D technologies under development.[47] It is noted that manufacturing energy intensity—and therefore the magnitude of potential savings opportunities—depends strongly on fabrication parameters such as component design, fiber content, use of recycled material, choice of matrix polymer, and consolidation method. In addition, life cycle energy benefits for lightweighting depend on factors such as substitution factors and use phase parameters such as vehicle travel distance.[48] A key goal of the recently announced Institute for Advanced Composites Manufacturing Innovation (IACMI) is to reduce the embodied energy of CFRP by 50% in five years to ensure and accelerate the use-phase benefits of these materials.[49]

Figure 6.E.5 Estimated onsite energy savings opportunities for 1 kg of carbon-fiber reinforced polymer composite, broken down by sub-process. Energy intensities and savings opportunities are based on a 40 wt% epoxy – 60 wt% carbon fiber composite part fabricated via resin transfer molding.[47] Note that manufacturing energy intensity depends on the precursor, ratio of fibers to polymer, the type of resin, and manufacturing process chosen.



Recyclability

The ability to reuse fibers and a strong recycling and reuse market can have a significant positive impact on the life-cycle energy and greenhouse gas footprint for composites, as well as on the cost.[46] Cost-effective recycling technologies for FRP composites and collection supply chains need to be developed to save a significant amount of energy—particularly if the process enables repeated recycling without loss of quality or downcycling. It is estimated that secondary CFRP would require only about 25% of the primary material manufacturing energy used.[50] Recycling of composites occurs now, but only to a limited extent (for example, in the aerospace sector and some applications in the automotive sector; e.g., ~10% of the carbon fiber in BMW's i3 model is recycled material).[51] A more detailed discussion of recyclability is provided below.

Materials and Manufacturing Techniques for Fiber-Reinforced Composites

An in-depth discussion of state-of-the-art methods for composite part production and the current technology limitations is included in this section. The review follows the composites supply chain, starting with reinforcement and matrix materials, then manufacturing techniques, curing/polymerization processes, and finally recycling. This section concludes with a discussion of enabling technologies such as design, modeling, and inspection tools.

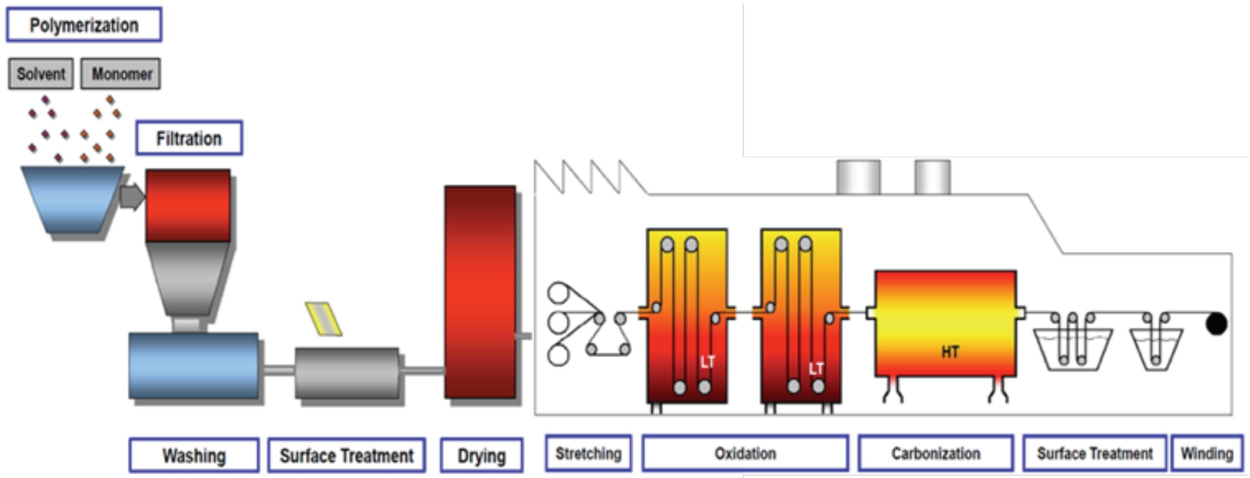
Reinforcement Materials

Reinforcement materials give the necessary stiffness and strength to the composite. Fibers for composite materials can come in many forms: continuous and discontinuous, long and short, organic and inorganic. The most widely used fiber materials in FRP composites are glass, carbon, aramid, and boron.

Glass fibers are popular for large scale structures (e.g., wind blades, boat hulls) and consumer products (e.g., bathtubs / showers, non-structural automotive panels) because of their low cost compared to other fiber reinforcements. Research is underway to enhance the performance of glass fibers while capitalizing on its lower cost compared to carbon or aramid fibers. For example, PPG Industries from Greensboro, North Carolina, recently won a competitive cost-shared R&D project from DOE to demonstrate a novel high strength glass fiber that is stronger than the carbon fibers used today at half the cost.[52] This work will focus on the application of glass fibers to on-board hydrogen storage vessels for fuel cell electric vehicles.

Figure 6.E.6 shows the manufacturing processes involved in the production of carbon fibers from polyacrylonitrile (PAN), the most common precursor used today. First, the precursor is produced through a polymerization process. This step is followed by filtration and washing to remove any excess solvents and impurities. The conversion of the precursor (PAN) into high performance carbon fibers involves successive stages of oxidative stabilization wherein the PAN precursor is stretched and simultaneously oxidized in a temperature range of 200–300°C. This treatment converts thermoplastic PAN to a non-plastic cyclic or ladder compound. Fibers are then carbonized at about 1000°C without tension in an inert atmosphere (normally nitrogen) for a few hours. During this process, the non-carbon elements are removed as volatiles leaving carbon fibers with a yield of about 50% of the mass of the original PAN precursor material. Depending on the final fiber property requirements, the fibers are treated at temperatures between 1500 to 3000°C at the next

Figure 6.E.6 Current Carbon Fiber Production Steps (Assuming a PAN Precursor). Process intensification and energy reductions are necessary to achieve low-cost carbon fiber production.



graphitization step, which improves the ordering and orientation of the crystallites in the direction of the fiber axis. The fibers are then wound to an appropriate size and packed for further processing.[53]

R&D-enabled modifications to today's production processes could reduce embodied energy and the cost of advanced CFRP technology. One approach to reducing energy intensity could be through the use of alternative raw materials that require less energy to produce. Roughly 90% of precursors used today are derived from PAN. The remaining 10% are made from rayon or petroleum pitch. Precursor cost accounts for the largest share of overall fiber cost, typically around 50%.[54,55] Novel precursors, such as polyolefin or lignin, could reduce fiber cost and manufacturing energy use by up to 70%. Some novel precursors, such as lignin, are based on less-expensive renewable feedstocks, whereas inexpensive traditional plastics such as polyolefin can substantially reduce the amount of precursor material required for carbon fiber conversion.[56]

Bio-based precursor options, including bio-derived acrylonitrile (bio-ACN) and lignin, are of interest as renewable materials that may have lower embodied energy (and potentially lower cost) relative to conventional PAN.[41,57] Bio-ACN involves the conversion of biomass materials to PAN, providing a "drop-in" renewable substitute for conventional PAN. Glycerol, a by-product of biorefineries, is one potential raw material for bio-ACN. The indirect ammoxidation of glycerol to acrylonitrile was demonstrated in a tandem reactor where glycerol dehydration formed an acrolein intermediate followed by the ammoxidation of acrolein to acrylonitrile.[58,59] The resulting acrylonitrile can be polymerized to form PAN fibers for subsequent conversion to carbon fiber.[60] The DOE Bioenergy Technology Office (BETO) has set a goal to produce bio-ACN at a modeled cost of $1.00/pound ($2.20/kg) or less to enable the manufacture of carbon fibers suitable for vehicle structural components at a cost of $5.00/lb ($11.00/kg) or less by 2020.[57] In 2014, BETO announced two competitively-won funding awards to advance bio-ACN technology:[61] Southern Research Institute (SRI) in Birmingham, Alabama, will develop a multi-step catalytic process for conversion of sugars from non-food biomass to acrylonitrile; and the National Renewable Energy Laboratory (NREL) in Golden, Colorado will investigate and optimize multiple pathways to bio-acrylonitrile.

Lignin, a heterogeneous plant-based polymer, is another biomass precursor option, though its processing is complicated by its relatively unpredictable structure that varies between feedstock sources. Through a half-century of research and development, key parameters for spinning lignin into carbon fibers, including the range of molecular weights and compositions best suited for production, have been identified.[62] Various methods for producing carbon fibers from lignin have been tested, with melt-blowing of soluble lignin emerging as the favored method.[63] A partnership between Weyerhaeuser (a lignin-based carbon fiber manufacturer) and Zoltek (a high-volume PAN carbon fiber manufacturer) has successfully demonstrated low-cost commercial-scale trial fibers that incorporate lignin into conventional PAN-based precursors.[64] The challenges associated with direct conversion of lignin to finished carbon fibers include difficulties meeting structural specifications consistently and the need for new manufacturing processes and lines for lignin-based production. As a result, it may take longer to commercialize lignin-based carbon fibers than drop-in bio-ACN.[41]

Another opportunity involves new fiber spinning methods. Melt spinning of carbon fiber precursors is both a more environmentally sound and cost-effective method compared to the conventional, capital-intensive and highly corrosive solvent-based solution spinning method. Optimized melt-spun PAN precursors, which enable automated spinning operations for higher throughput, have the potential to reduce manufacturing energy requirements and fiber cost by 30%.[65,66] Further gains are possible in the carbonization stage, the process of converting precursor fibers to crystallized, carbon-rich fibers in an inert (oxygen-free) environment—typically using a series of specially-designed furnaces. Microwave-assisted plasma carbonization could potentially replace this high-temperature, energy-intensive process for energy and cost savings of up to 50%[65] and 25%[43] respectively. The technique is currently being scaled to a pilot-line scale at the DOE-funded Oak Ridge National Laboratory (ORNL) Carbon Fiber Technology Facility (CFTF).

Matrix Materials

Most carbon fiber and glass fiber composites today use thermoset polymer matrix materials, with thermosets representing about 80% of the total reinforced polymer composites market.[67] Thermosets are attractive for composites manufacturers due to their relatively low viscosity at room or elevated processing temperatures. Resin viscosity is important to consider for composites applications, because it controls the timescale of the liquid resin impregnation into the dry fiber preform. During composites processing, it is important to completely saturate dry fibers with resin without voids or dry spots in the fiber preform—and this must be done as quickly as possible to achieve the high production speeds desired for commercial applications. If the viscosity is too high, the processing times required to completely wet the composite preform would be too high and not economical for part manufacturing.

A drawback of thermoset resin based composites is that they are difficult to recycle using thermal techniques while maintaining continuous fiber integrity because the temperatures required to separate the matrix material from the fiber can damage the fibers and leave residue that makes the fibers more difficult to reprocess. In addition, because thermosets polymerize via irreversible cross-linking reactions, the thermoset resin constituent material is typically broken down at the elevated temperatures used to remove it from fibers; the polymer, therefore, cannot be recovered for reuse. Many thermoset resins are designed for use at high temperatures—thus the temperatures needed to remove them from fibers for fiber recycling can be very high, with high associated energy/financial costs. Other mechanisms discussed below on recyclability may be appropriate, but result in chopped or lower quality material.

The increased use of thermoplastic matrix materials offers the potential for improved recyclability, but presents other technical challenges including temperature stability, moisture sensitivity, mechanical stability and final surface quality, among other issues. Unlike thermosets, which polymerize via irreversible cross-linking reactions, thermoplastic polymers can be re-melted above a transition temperature. Thermoplastic resins can liquefy and separate from fibers at lower temperatures compared to thermoset resins, enabling recycling of both fibers and polymer. However, a primary barrier for the widespread use of thermoplastic resin is the high viscosity. At typical processing temperatures, the thermoplastic resin is very viscous and does not readily impregnate fiber preforms and tows. Lack of sufficient impregnation increases the likelihood of trapped air bubbles and porosity—which upon resin hardening, leads to decreased part quality due to stress concentrates at voids and porosity sites. Elevated temperatures reduce the thermoplastic viscosity, but not sufficiently. If the temperature is too high, the resin will begin to degrade and lose integrity. Future work is needed for the development of thermoplastic resins that can be processed at temperatures and viscosities similar to thermoset resins, without breaking down.

A recent development in promising thermoplastic matrix materials for molding processes is Arkema's, Inc. liquid thermoplastic resin Elium.[68] Elium's low viscosity at room temperature makes it suitable for continuous fiber resin transfer molding (RTM) and vacuum-assisted resin transfer molding (VARTM) applications. The current developmental version is cured like a thermoset at 80°C in 20-30 minutes. Once cured, the composite matrix behaves like a thermoplastic that can be thermoformed to any shape and joined to other thermoplastics by induction welding. These qualities facilitate recycling because the resin can be melted and stripped from the composite and used again along with the fibers. Significant research and development has been conducted to improve the material properties of composite materials using nano-material based resin additives. Examples include carbon nanotubes (CNT), nanoclays, nano-platelets, and graphene. Nano-material based resin additives could provide significant material property modification.

As fibrous materials reinforce the matrix at micron length scales, resin nano-additives provide reinforcement at nano length scales. Multi-scale reinforcement of the matrix can lead to improved mechanical performance, such as better distribution of transverse shear to reduce delamination failure and increasing fracture toughness to arrest the progression of micro-cracking. In addition, some nano-additives can influence other material properties such as electrical and thermal conductivity. Their use could significantly impact new composite material applications, such as damage sensing structures or self-healing structures. For example, at the Beckman Institute at the University of Illinois at Urbana-Champaign, researchers demonstrated high-performance composite materials that can heal autonomously and repeatedly using a three dimensional vascular network filled with microcrack healing chemistries.[69] Currently, efforts are underway to identify applications where resin nano-additives can significantly impact composite material performance and, therefore, justify the added material and processing costs.

Thermoset and thermoplastic polymers are both largely derived from petroleum-based feedstocks, leading to high embodied energies for these materials. However, there has been increasing interest in non-petroleum, bio-based resins to reduce energy intensity and reliance on non-renewable fuel resources. In 2001, John Deere began using ENVIREZ 1807, a resin composed of 13% soybean oil and 12% corn ethanol. One batch (17,000 kg) of ENVIREZ 1807 saves the equivalent of 10 barrels of crude petroleum and reduces CO_2 emissions by 15,000 kg after considering the energy requirements of farming and processing soybeans and corn into oil and ethanol respectively, and manufacturing the resin. Information on the technological potential to improve the energy footprint of organic chemicals fundamental to matrix materials can be found in the 2015 *Bandwidth Study on Energy Use and Potential Energy Savings in U.S. Chemical Manufacturing.*[71]

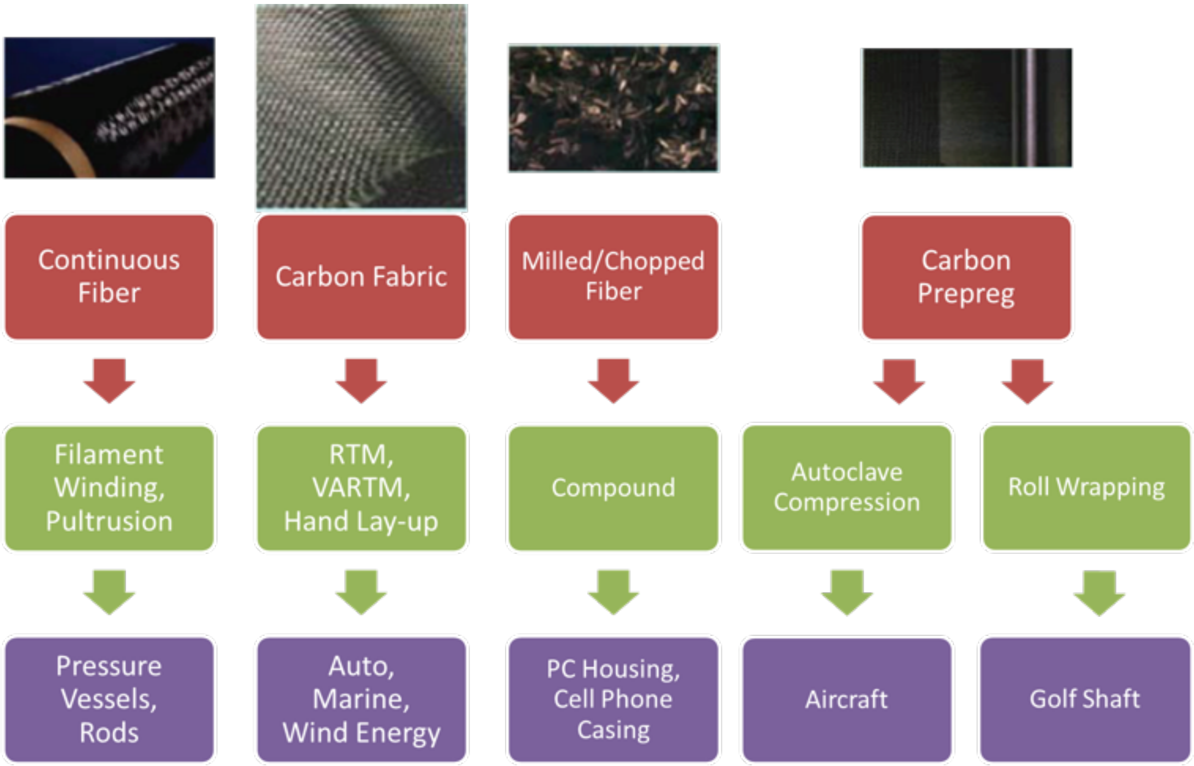
Semi-Finished Products

A filament is a single segment of reinforcement. Tow count is the number of filaments in the carbon fiber bundle (which can vary depending on the product, such as 3K, 6K, 12K, 24K, and 50K tow fibers). Smaller tow count carbon fibers are generally of higher strength and modulus compared to standard modulus, higher tow count carbon fibers, which are commonly used for less demanding non-aerospace applications. Standard modulus carbon fibers are generally of 12K to 50K tow size range and constitute 80–90% of the total carbon fiber market today.[72] Continuous filaments can be used in continuous fiber processes such as filament winding and pultrusion. Filaments may also be woven or stitched into fabrics. Preforms are three-dimensional fabric forms designed to conform to a specific shape to meet specific mechanical and structural requirements. A pre-impregnated composite, or pre-preg, is where fibers, often in the form of a weave or fabric, are held together with a matrix resin. The matrix is partially cured to allow easy handling and often must be cold stored to prevent complete curing. Bulk molding compounds (BMC) and sheet molding compounds (SMC) are made up of fibers pre-compounded with a thermoset resin, and are primarily used in compression molding processes. Figure 6.E.7 shows currently available manufacturing technologies associated with semi-finished carbon fiber products.

Consolidation Techniques

The final properties of a composite part depend not only on the matrix, reinforcement materials, and their starting product forms, but also the processes used to consolidate them into final parts for assembly. Forming processes combine the matrix and reinforcement materials to produce the desired shape. These manufacturing processes are generally grouped into two classes: open forming and closed forming. The most common manufacturing methods used for composite parts are summarized in Table 6.E.3. In this section, a detailed assessment of the most promising composite manufacturing methods is presented based on their ability to produce high quality parts at large production volumes, fast cycle times, and low capital costs relative to the current state of the art.

Figure 6.E.7 Currently Available Carbon Fiber Composite Manufacturing Technologies and Their Applications.



The challenges associated with composites manufacturing processes and their limitations in meeting the energy efficiency goals in key energy applications are presented. For automotive applications, the processes and the associated material systems need to be developed with a capability to produce 100,000 parts per year, requiring cycle times of less than three minutes for carbon fiber reinforced materials, and less than five minutes for glass fiber reinforced materials. Comparable goals for wind blade production are 10,000 units per year with automated material deposition rates of 1500 kg/hr. A goal for the use of composites in compressed gas cylinders is a manufacturing process capable of producing 500,000 units per year with the finished part cost in the $10–15/kg range. Typical cycle times for various molding processes are shown in Table 6.E.4.

The energy intensity of various manufacturing techniques is another consideration driving improvements in composite manufacturing methods. A comparison of the energy intensities of the current state-of-the-art methods is shown in Figure 6.E.8. The high energy intensity of autoclave based processes has driven the current increased focus on processes such as resin transfer molding and out-of-autoclave (OOA) curing of thermosets. Curing refers to the cross-linking of polymer chains in the resin with the matrix, resulting in a hardened finished part. Many methods can be used for curing including the use of heat, chemical additives, or electron beams. OOA pre-pregs can be cured at lower pressures and temperatures (vacuum pressure vs. a typical autoclave pressure of 586 kPa, and cure at 93°C or 121°C vs. a traditional 177°C autoclave cure). Out-of-autoclave pre-pregs have also recently been effectively used for tooling manufacturing. Using OOA technology, integrated stiffeners in large composite structures can be co-cured in a single cycle, simplifying a process that

Table 6.E.3 Manufacturing Techniques for Carbon Fiber Reinforced Polymer Composites

	Thermoset (e.g., epoxy)	Thermoplastic (e.g., polypropylene)
Semi-Finished Fabrication	Technology Stage	Technology Stage
Pre-preg	Widely used[73, 74, 75]	Uncommon[76, 77, 78]
Sheet Molding Compound (SMC) / Bulk Molding Compound (BMC)	Widely used[79, 80]	Uncommon[80, 81, 82]
Open Forming	Technology Stage	Technology Stage
Hand Lay Up	Widely used[83]	Widely used[83]
Spray Up	Widely used[83]	Not used
Robotic Lay Up	Widely used[83, 84]	Widely used[83]
Filament Winding	Widely used[83]	Widely used[83]
Pultrusion	Widely used[83]	Uncommon[83, 85]
Fused Deposition Modeling (Additive Manufacturing)	Not used	R&D[86, 87]
Honeycomb Core	Widely used[88, 89]	Uncommon[90]
Closed Forming	Technology Stage	Technology Stage
Injection Molding	Uncommon[91]	Widely used[83]
Resin Transfer Molding	Widely used[83]	R&D[92, 93]
Vacuum Assisted Resin Infusion	Widely used[83]	R&D[92]
Compression Molding	Widely used[83]	Uncommon[83]
Autoclave Forming	Widely used[94]	Uncommon[83]
Cold Press	Widely used[95]	Not used
Balanced Pressure Fluid Molding ("Quickstep")	New commercial technology[96]	New commercial technology[96]
Thermal Press Curing	R&D[97]	Not used

is typically very complex and expensive. Further, coefficient of thermal expansion (CTE) mismatches between tool and part play a smaller role at lower temperatures and are therefore more easily managed. As a result, OOA pre-pregs are a potential solution for part cracking caused by cure-temperature differentials and could help achieve faster, more agile manufacturing.

Table 6.E.4 Comparison of the Most Commonly Used Composite Molding Processes[98]

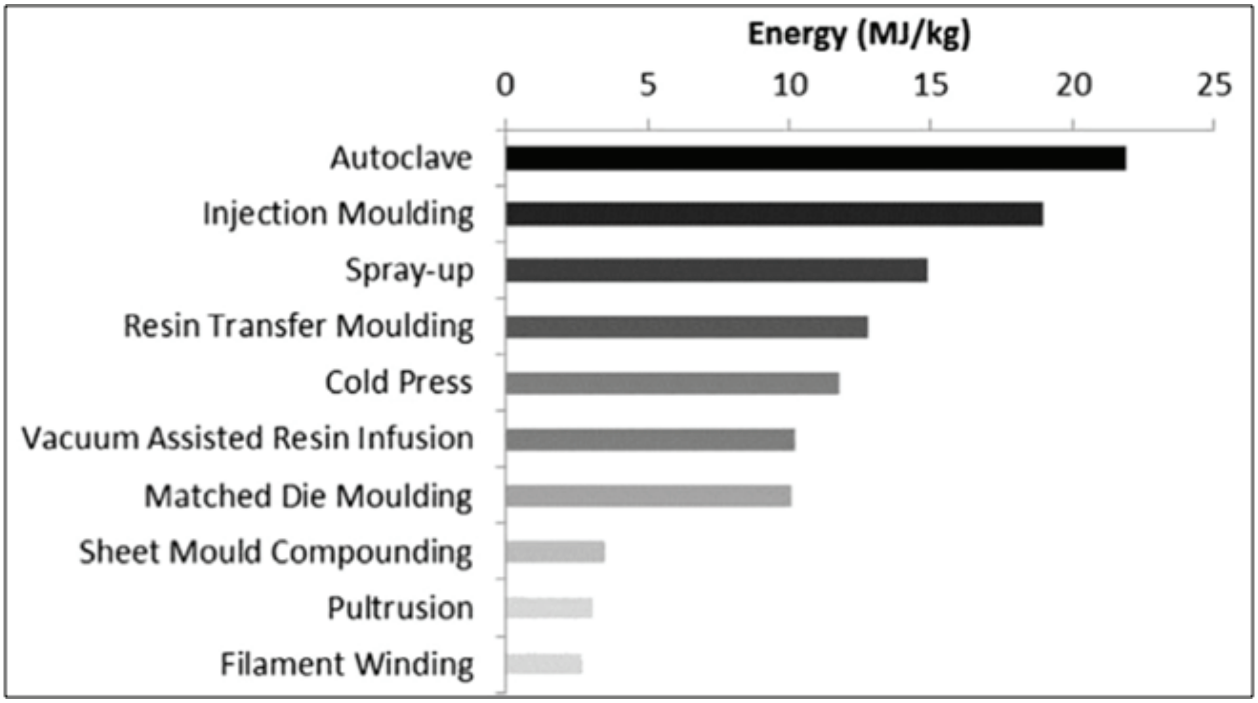
Molding Process	Advantages	Disadvantages	Cycle Time
Pre-preg	Good resin/fiber control	Labor intensive for large complex parts	5–10 hrs
Preforming	Good moldability with complicated shapes and the elimination of trimming operation	Cost effective only for large, complicated shape parts; large scrap generated when fiber mats used	45–75 secs (Compform process) 4–5 mins (vacuum forming)
Resin Transfer Molding (RTM)	Inside and outside finish possible with thickness control, more complex parts possible with vacuum assisted	Low viscosity resin necessary; voids formation possible without vacuum assist	45–75 secs (Compform process) 4–5 mins (vacuum forming)
Liquid Compression Molding	Favored method for mass production with high fiber volumes	Expensive set-up cost for low production	1–2 mins
Sheet Molding Compound (SMC)	Cost effective for production volume 10K–80K/year.	Minimum weight savings potential	50–100 secs
Resin Injection Molding (RIM)	Low-cost tooling; prototypes can be made with soft tools	Difficult to control the process	1–2 mins
Bulk Molding Compound (BMC)	Low-cost base material	Low fiber content; randomly oriented; low structural quality; poor surface finish	30–60 secs
Extrusion Compression Molding	Fully automated; variety of polymers and fibers can be used with fiber volumes up to 60% by weight	Not for surface finish parts without paint film or similar process	3–6 mins
Structural Reaction Injection Molding	Low tooling cost; good surface finish capability	Difficult to control the process, particularly with low viscosity resins and longer cure cycle times.	4 mins for thermosetting resins; a few seconds for thermoplastic matrices
Carbon Fiber Reinforced Thermoplastics (CFRTP)	Easily recycled; fast consolidation	High viscosity which forces users to utilize equipment involving high temperature (200–400 °C)	1 min

Closed Forming Processes

Injection Molding

Injection molding is the most common and widely used manufacturing process for high-volume production of thermoplastic resin parts reinforced with fibers. Nearly 20% of all goods manufactured today use injection molding due to its versatility and low cost.[100] Solid pellets of resin containing the fibers are fed through a hopper

Figure 6.E.8 Energy Intensity of Composite Manufacturing Techniques (shaded by energy intensity)[99]



into a heated barrel with a rotating screw. The rotating screw generates heat by viscous shearing against the barrel, melting the resin. The screw also acts as a piston and forces the mixture of fibers and molten resin into a matched-metal mold where the mixture cools and solidifies. The mold cavity is then opened and the composite part is ejected. The main advantages of injection molding are the ease of automating the process and the short cycle times, which together enable high volume production. The main disadvantages are the high initial costs of the capital equipment and the molds and material property variation in the part due to the inability to control fiber orientation and distribution. Additionally, due to the melt viscosity limitations of the current thermoplastic resins, injection molding generally produces only short fiber reinforced composites. These composites are suited to nonstructural applications in automobiles such as interior components (e.g., seat backs, dashboard components), closures, and miscellaneous parts like electronic throttle control valves. Research is underway to modify thermoplastic chemistry to tailor the melt viscosity of the resin, which could enable injection molding of long fiber reinforced composites for structural applications.

Long cycle times for part layup and cure associated primarily with thermosetting resins are a primary drawback to the use of fiber reinforced polymers in all high volume markets, including mainstream vehicle applications. Long cycle times are determined by the timescale of resin flow and by the process speeds needed to avoid the creation of bubbles in the resin, which can lead to structural weaknesses in the finished parts. To be competitive in the automotive industry, the necessary cycle times are two minutes, significantly faster than the conventional state-of-the art autoclave pre-preg process with a cycle time of greater than one hour. While injection molding offers lower cycle times, throughputs are still below automotive standards for thermosetting resins; even injection molding of chopped fiber reinforced resin requires as much as 4 minutes to consolidate a composite part. A carbon fiber reinforced thermoplastic technology recently developed by Toho Tenax is projected to have a cycle time of less than 1 minute for potential high-volume use in GM cars, trucks, and crossovers.[101]

While injection molding is a relatively mature process, its compatibility with long fiber reinforcements has mostly restricted its use thus far to cosmetic and other non-structural parts. Resin transfer molding, a newer process evolved from the same concept, can be used to fabricate continuous carbon fiber reinforced composites with broader applicability in structural and semi-structural components.

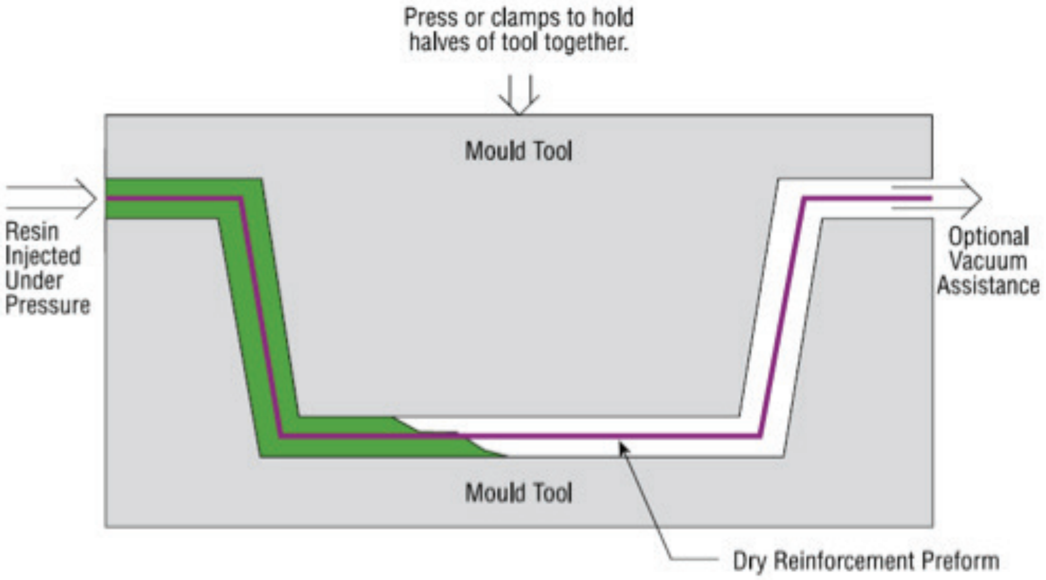
Resin Transfer Molding

In resin transfer molding (RTM), fiber preform or dry fiber reinforcement is packed into a mold tool that has the desired shape of the composite part, as shown in Figure 6.E.9. A second mold tool is clamped over the first and resin is injected into the cavity. A vacuum may be used to assist in drawing the resin through the cavity in a process called vacuum assisted resin injection (VARI). The main disadvantage of this method is that matched tooling capable of withstanding the elevated pressures is expensive and generally limited to smaller components. Additionally, un-impregnated areas can occur, resulting in costly scrap. This composites manufacturing method has the greatest potential (compared to other methods) for fabricating complex, large-scale integrated automobile structural parts. The BMW i3 hatchback car, introduced in 2013, uses the RTM process in conjunction with robotic laydown of preforms to manufacture the body frame of the car. The method is also a strong candidate for chassis/suspension, roof, and hood applications in automobiles.

The key to rapid manufacturing of thermoset parts via RTM, compression, infusion or spray processes is the development of fast curing thermoset resins; in particular, epoxies and polyurethanes which have demonstrated excellent performance in carbon fiber composites. High pressure resin transfer molding in combination with thermoforming is a promising innovation currently underway to improve the cycle time of the RTM process. At the current state-of-the-art practice, a 20–minute cycle time[103] has been demonstrated for the RTM process with the use of high pressure injection of resin to reduce the infusion time to seconds instead of minutes and allows for the use of fast-reacting thermoset resins. All the major global suppliers of thermoset resins have developed laboratory-scale resin systems with cycle times under two-minutes,[104] making the target of less than 3 minute cycle time for automobile parts feasible. Scale up of the RTM process for high pressure injection and fast curing resins is a challenge that is being addressed.

Figure 6.E.9 Resin Transfer Molding.[102]

Credit: Image courtesy of Gurit

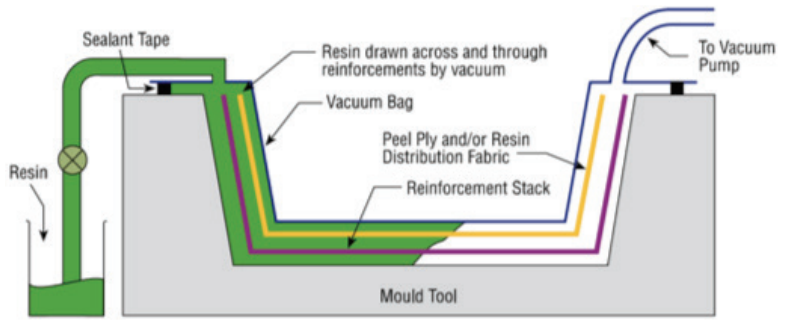


Vacuum-Assisted Resin Infusion

The VARI process involves several slight modifications to the RTM process, including replacement of the second (upper) mold tool by a vacuum bag, as shown in Figure 6.E.10. VARI processes include the Seemann Composites Resin Infusion Molding Process (SCRIMP),[105] the resin infusion under flexible tooling (RIFT) process, and vacuum assisted resin transfer molding (VARTM). A permeable layer, such as a peel ply or knitted non-structural fabric, is often introduced to facilitate the distribution of the resin throughout the part quickly. These processes have replaced resin transfer molding for some applications due to the simplicity, the low initial capital investment from using only one tool surface, and the ability to manufacture large structures such as bridge sections and rail carriages. The major disadvantages of these processes are poor surface finish on the bagging side, limitation to nearly flat structures, time involved in material preparation, poor dimensional tolerances, and lack of automation.

Figure 6.E.10 Vacuum-Assisted Resin Infusion Schematic[102]

Credit: Image courtesy of Gurit



Current manufacturing processes for land-based and offshore utility-scale wind turbine blades that employ VARTM or low-temperature-cure pre-preg containing 90–100% glass fiber reinforcement suffer from long manufacturing cycle times of 35–40 hours for a 45m blade, high labor requirements, and frequent rework. Automated fiber placement and inspection processes could reduce the labor requirements of blade production. Thermoplastic use is expected to reduce blade weight, cost, and cure cycle times and facilitate recycling at the end of their service life. A novel automated fabric layup solution based on a new method to manipulate fiberglass fabric for wind turbine blades manufacturing is being developed at Iowa State University.[106] Due to high cost, carbon fiber use has been limited to spar cap applications today. Using pultruded carbon fiber sheet material in blade spars has also been considered to enable larger, lighter rotors that will increase energy capture. This method is well suited to wind blade applications where larger blades (in the range of 100 m) can be fabricated in the field without the need for autoclaves. As in the case of RTM, future research to enable economical use of this method is directed towards the development of low viscosity, fast curing resins that reduce the cycle times from the current state of the art.

Compression Molding

The principle in compression molding is very simple and has been utilized for decades. The material (called the charge) is placed inside the mold cavity. The material charge is often a mixture of resin and fibers, sometime in a mat preform. The mold is closed and pressures up to 14 MPa are applied,[107] forcing the material charge to deform to the shape of the cavity. Low pressure compression molding is called cold press molding. The mold is opened and the part is ejected. The advantages of compression molding include its simplicity, relatively fast cycle times, high repeatability, tight tolerances and high-volume production. The major disadvantages are the large initial capital investments in molds and presses and defects resulting from residual stresses, delamination, warpage, and flow orientation of fibers.

This process is currently widely used in non-structural automobile applications such as interiors, closures and miscellaneous parts. The primary starting materials are short glass fiber reinforced SMCs and BMCs. Development efforts are underway to enable long carbon fiber reinforced SMCs to take advantage of their improved strength and stiffness-to-weight ratios. SMC formulation improvements are underway that will toughen the materials to prevent surface micro cracking.

Composites manufacturers in industrial markets are formulating their own resins and compounding SMCs in-house to meet needs in specific applications that require ultraviolet (UV), impact, and moisture resistance. The surface-quality requirements drive the need for customized material development.

Matched die molding, a subset of compression molding, holds strong promise to produce continuous carbon fiber reinforced parts for structural applications in automobiles such as the car body, chassis, and suspension. In this process, a continuous fiber ply stack (known as the blank) that is unidirectional and/or woven is pressed into its final shape in a matched die mold and cured (thermosets) or consolidated/stamped (thermoplastics) to rapidly produce parts. The blank design must be highly engineered because the fibers drape into the final shape, causing changes in fiber orientation; thus, the blank design and press process affect the properties of the finished part. The cure time, or consolidation cycle time, depends on the material selection. Thermoplastic parts are consolidated in seconds and thermoset matrix parts in minutes, with 17 matrix parts in minutes, with significant reductions in cycle time achieved in the last few years. For example, state-of-the-art in 2011 was on the order of 17 minutes[131] and the next generation of the technology can achieve 8 minute cycle time.[132] As mentioned in the preceding sections, research to develop thermoset resins with cure times as fast as two minutes is underway. The matched die molding process would be a strong competitor to the RTM process if the dies can be re-used multiple times without any shape distortions or loss of integrity.

Open Forming Processes

Hand Lay Up

Resins are impregnated by hand into fibers in the form of weaves and fabrics. Rollers or brushes are typically used. The composite is left to cure under standard atmospheric conditions. The major disadvantage is the lack of consistency; the quality of the product is highly dependent on the skill of the laminator. Resins need to be low in viscosity to be workable by hand. This generally compromises the mechanical and thermal properties of the composite and can create a health risk for the laminator.

Spray Up

Chopped fiber and catalyzed resin are sprayed directly into a mold and left to cure under standard atmospheric conditions. Although this method is low-cost, there are several serious disadvantages. Laminates tend to be very resin-rich and, therefore, excessively heavy. Only short fibers and resins low in viscosity are able to be sprayed, which severely limits the mechanical properties. Additionally, exposure to high styrene resins is hazardous to the health of workers.

A challenge in this method of part fabrication is managing the volatile organic compounds and hazardous air pollutants released in the process. These are expensive to control in the spray up process, and, as a consequence, many composites manufacturers have migrated to closed mold, infusion-based processes which better contain and manage the pollutants. The part finish and precision obtained with other manufacturing methods cannot be achieved with either the spray up or the hand layup process. Therefore, the use of these open forming techniques has been mostly limited to large consumer goods such as bathtubs and swimming pools and to the repair of damaged parts.

Filament Winding

This process is most appropriate for hollow, circular, or oval sectioned components, such as pipes and tanks. Fiber tows are passed through a resin bath before being wound onto a mandrel. The main disadvantages are that fibers cannot be laid in the axial direction and that low viscosity resins usually need to be used. Filament winding is the predominant composites manufacturing process for axisymmetric composite products such as compressed gas storage tanks or pipeline sections. The process also offers speed and cost advantages for structural axisymmetric parts such as struts, axles, and drive shafts.

For compressed gas storage tanks, carbon fiber material costs constitute approximately 60% of the total tank cost in high-volume production, assuming carbon fiber filament winding in an epoxy matrix over a high-density polyethylene liner.[108] Cost reduction and the fast process cycle times needed to produce 500,000 parts per year may be achieved through lower material cost, novel braided preforms, manufacturing automation, reduced scrap, reduced energy cost through shorter cure times, and use of protective coatings and durable materials that extend the tank's useful life.

Pultrusion

In pultrusion forming, fibers are pulled from a creel through a resin bath and passed through a heated die. As the fiber passes through the die, the resin cures. Pultrusion yields smooth finished parts that typically do not require post processing. A wide range of continuous, consistent, solid and hollow profiles can be pultruded. The process can be custom-tailored to fit specific applications such as the constant cross-section spar in some windmill blade applications. However, this process is limited to components with constant, or near constant, cross sections. Additionally, the cost of the heated die can be high.

Automated Fiber Placement

Automated tow placement (ATP) and automated tape laying (ATL) are subsets of the automated fiber placement method. The differences are the starting materials (pre-preg tows vs. pre-preg tapes) and the material laydown rates feasible. Generally, ATL is faster than ATP and can place more material over longer distances. However, ATP is better suited to shorter courses and can place material more effectively over contoured surfaces.[109] These automated approaches offer several advantages over manual lay-up and spray-up techniques including reduced processing speed, reduced material scrap and labor costs, improved part consolidation, and improved part-to-part uniformity. However, capital expenditures for computer-driven, automated equipment can be significant.[109] Some of the recent improvements in automated fiber placement include: dockable heads, enabling equipment to function in both ATP and ATL modes; laser heating for OOA curing of high-performance thermoplastic ATL/ATP parts; and equipment integrated with real-time temperature controls.[109]

Curing/Polymerization Processes

Fiber-reinforced plastic (FRP) composite structures require the polymer matrix to attain and maintain solid-state characteristics in service. Thermosets polymerize via irreversible cross-linking reactions and thermoplastic polymers can be re-melted above a transition temperature. As a result, composites comprised of these matrices have different physical properties as well as different manufacturing processes.

Historically, advanced composite structures have been based on thermosetting systems; approximately 80% of composites use a thermoset matrix[67] that requires a cure step to attain desired properties. Due to exacting specifications and certification processes, aerospace composite structures are mostly based on epoxy systems in which the curing process must follow a precise temperature profile in an autoclave to ensure proper resin flow, de-gassing, consolidation, and eventually uniform degree of polymerization to achieve final properties.

The processes are typically slow (on the order of hours) and energy intensive, in part because the large thermal mass of the tooling and autoclave are also subject to the same thermal cycle. Autoclaving processes have been adopted across much of the composites industry beyond aerospace, resulting in an inefficient approach to produce composite structures. Improved selective heating/polymerization techniques, optimized cure cycles, and further advancement of out-of-the-autoclave techniques are potential development and demonstration pathways to reduce the energy used in composite manufacturing.

Methods that selectively target the heating and/or curing of composites systems are based on electrotechnologies[110] that utilize radiative energy transfer methods to provide energy only where it is required. These technologies require that the components within the system are responsive to the applied frequencies. The following are examples:

- **Dielectric heating methods based on microwave (MW) or radio frequency (RF) where the electromagnetic (EM) energy couples principally with the matrix.** For example, RF curing of epoxy-based GFRP is based on the dielectric response of the epoxy. In some cases, susceptors can be used to improve the heating response of materials. The depth of penetration needs to be appropriate for the size and geometry of the part, and tooling must be adapted for exposure to a high frequency EM environment.
- **Infrared (IR) as a low-cost, efficient method of pre-heating, heating, melting, and/or curing.** Long and medium-wave IR have a number of potential applications. Some have been successfully utilized by industry, including pre-heating of preforms and partial curing of composites structures as a method of temporarily fixturing during intermediate processing steps. As thermoplastic-based composites systems become more prevalent, the use of IR systems has the potential to provide faster heating rates at higher efficiencies than attainable with convection methods. Considerations include the “line-of-sight” nature of IR and its relatively short depth of penetration, with the most promising applications being relatively thin, uniform, and planar components and/or structures.
- **Induction heating methods.** Induction techniques can be used to heat conductive materials and are widely used in the metals industries for unit operations ranging from heat treating to melting. Some applications have targeted the selective heating of the tooling. For example, an R&D project sponsored by EERE demonstrated an induction heating technology for tooling that resulted in estimated manufacturing energy savings of 40–75% for representative wind, automotive, and aerospace parts.[111] Others have demonstrated the potential to directly couple with composites containing sufficiently conductive components, such as carbon fiber.[112] A limitation of induction heating methods is the requirement that the composite structure have a geometry that allows the induction coil to be placed within a uniform and close proximity to the part. Also, heat losses must be mitigated to ensure uniform heating profiles.
- **MW heating technology for curing CFRP.** MW heating was once considered an intractable method for curing composites comprised of conductive materials like carbon fiber (due to problems like arcing and dielectric breakdown). Advanced multimode MW applicator designs initially investigated at the University of Karlsruhe[113] have been commercialized[114] and are now being used to fabricate aircraft composites structures, demonstrating that even the most difficult market is amenable to adopting new technologies.
- **Ionizing sources of EM energy.** Ionizing sources have the potential to drive chemical reactions. This can happen indirectly, as with UV energy that activates a photoinitiator leading to polymerization, or directly with an electron beam technology that is energetic enough to drive polymerization reactions without an intermediary photoinitiator. Considerations include the very limited depth of penetration of UV, which make the technology more amenable to films and coatings; and the high cost and safety concerns with electron beam energy, which require extensive shielding to protect against exposure to energetic particles.

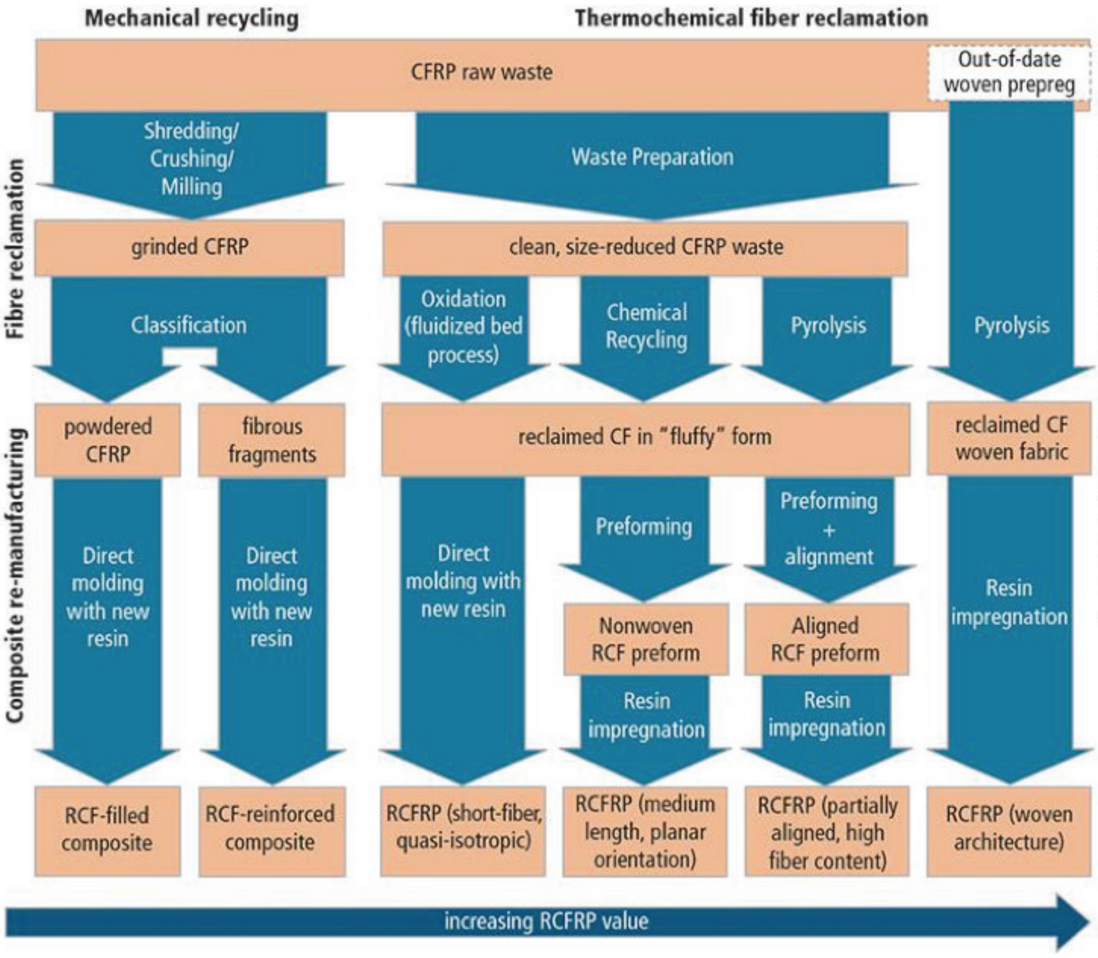
As composites systems expand to include new chemistries, there are additional post-processing techniques that can enable entirely new sequences of manufacturing operations to achieve final parts specifications. For example, solid phase polymerization (SPP) of nylon 6,6 can drive the molecular weight distribution higher and enable modification of the physical properties after parts are manufactured. While SPP of nylon via convection techniques has been commercialized for limited production for specialty applications, it requires extended thermal cycles. However, accelerated SPP has been demonstrated at the pilot scale through a radio frequency process. This has the potential to enable faster processing of composites structures with lower viscosity, then post-processing to achieve higher performance specifications.

Recycling

Recovery and re-use of materials with high embodied energy, such as carbon fibers, presents a particularly compelling pathway to save energy and benefits the environment because recycling avoids the energy consumption associated with production of virgin materials.

Commercial recycling operations for CFRP composites are limited today due to economic and technical constraints. Figure 6.E.11 illustrates the major recycling pathways for carbon fiber composites. Lack of markets, high recycling cost, and lower quality of the recovered materials versus virgin materials are major

Figure 6.E.11 Diagram of CFRP Recycling Pathways[117]



Source | *Handbook of Recycling: State-of-the-art for Practitioners, Analysts, and Scientists* by Ernst Worrell & Markus Reuter, Elsevier BV (Amsterdam, The Netherlands), © 2014 commercialization barriers.[116] The technical difficulty is in liberating the constituent materials from the composite. Current R&D activities can be grouped in the following categories: mechanical recycling, chemical recycling, and thermal recycling. Mechanical recycling involves the energy intensive process of shredding and grinding. Then, the fine particles are screened and classified as fiber-rich and matrix-rich fractions. Only short milled fibers can be produced using this method. Chemical recycling involves chemical depolymerization using chemical solvents. The efficiency of this process depends on the characteristics of the composite scrap, such as the type of organic resins used. In production scrap, these characteristics may be known. However, with post-consumer composite scrap, there is a mixture of composites and the specific composition is likely unknown. Other challenges to chemical recycling include generation of toxic effluents and use and disposal of alkaline catalysts.

Thermal recycling uses heat to decompose the resin and separate it from the reinforcement fibers and fillers. One option for thermal recycling is fluidized-bed combustion. In this process, the resin matrix is combusted and carbon fibers are recovered. The high temperatures of the combustion, roughly 550°C, result in degradation of the carbon fibers typically with a 20% loss in stiffness and a 25% loss in tensile strength.[116] Another option for thermal recycling is pyrolysis. Pyrolysis is thermal depolymerization at temperatures between 300–800°C in the absence of oxygen. Once again, the high temperatures cause degradation of the carbon fibers. However, unlike fluidized-bed combustion, the matrix resin is recovered as secondary fuels or feedstock polymers. The world's first commercial-scale continuous recycled carbon fiber operation was developed by Recycled Carbon Fibre Ltd in 2009 in the UK using pyrolysis. Unlike thermoset composites, thermoplastics can be recycled directly by remelting and remolding.

Current fiber-reinforced composite manufacturing generates 15–25% scrap.[118] This makes recycling and reuse of in-process waste streams a high priority and the development of new processes and designs that maximize material utilization an important RD&D pathway. Carbon fiber recovery demands only about 10% of the energy needed to produce virgin material. Pilot scale chemical recycling with a proprietary catalyst can produce discontinuous fibers retaining >90% of virgin carbon fiber mechanical properties; however, this method is difficult to scale-up. It requires high temperatures (>300°C) and pressures (>3 MPa) that would require custom autoclaves and exotic valve materials for continuous operations.[119] Additionally, recycling technology and recycled product streams needs to be developed to effectively recover continuous fibers. Boeing, in partnership with Adherent Technologies and MIT-RCF, has performed limited recycling of CFRP composites into useful new products. Glass fiber reinforced polymer composites recycling is challenged by the low residual value of glass fiber, but options exist for re-use in products such as insulation, ceramics, and concrete.[120]

Innovative Design, Modeling and Simulation Tools

The number of parts and the design of a system directly affect cost and manufacturability. Innovative design concepts that consolidate smaller parts into a single part may result in lower manufacturing costs. In addition, composite systems are often overdesigned, adding cost and weight, due to the variability in material properties and lack of information and validated design models. The additional cost and embodied energy penalties associated with overdesign of composite parts can be minimized by developing and applying more accurate predictive tools and validation data. These high accuracy design tools along with improved manufacturing simulation methods can be used to reduce part cost and weight. Examples of innovative design approaches that could impact cost, manufacturability, and energy use could include material optimization, structural redesign, and multi-functionality of parts (for example, use of a composite material for strength as well as electrical shielding of embedded electrical control circuits). Designing damage-tolerant composite structures is a standard practice for aerospace applications. As design requirements and concepts are developed for lower value-add applications, the effects of damage will need to be addressed. Flammability of composite materials may also need to be considered.

Modeling and simulation tools for composite materials and processes can speed the development cycle for new manufacturing processes, innovative designs, and assembly techniques. One example is the modeling and simulation work sponsored by the DOE VTO to develop predictive engineering tools for injection-molded long-carbon-fiber thermoplastic composites.[121] While progress has been made in the modeling of composites, additional development is still needed. Even mature industries have "existing gaps in modeling [that] preclude the goal of being able to predict a composite system's properties based purely on knowledge of the individual constituents and the processing history."[20] Design tools that address reliability trade-offs without increasing composite part cost will be essential in cost-sensitive applications.

Effective Joining

The use of multi-material structures and optimized designs can result in reduced weight or improved system performance. Joining different and novel materials presents challenges that include thermal expansion mismatch, limited temperature and load ranges for joined structures, joint performance and repairability, directionality of composite materials, lack of nondestructive evaluation techniques for bonded joints, the need for surface preparation, galvanic corrosion, and long time requirements to complete joining. Technology development is needed for fast, reliable techniques for joining materials and structures.[17] The new joining methods must not degrade the resulting composite structure in broad applications. Joining techniques also need to be compatible with processes and manufacturing rates on the factory floor.

Defect Detection

Identifying manufacturing defects in components and structures is an important issue for composite systems. The components (matrix, fiber) of a composite retain their original state when combined to form the new material, making it challenging to identify defects in the heterogeneous composite material. Since undetected manufacturing defects can significantly degrade part performance, advancements are needed in *in situ* sensors for process control to prevent defect formation and in non-destructive evaluation methods to understand as-manufactured part performance. Technologies exist for non-destructive evaluation of composites, but new thinking may be required to apply them to specific material sets and accommodate high speed production and larger size components.

For example, one of the most common defects in fiber reinforced composite materials is the presence of voids in the matrix around or inside fiber bundles. These voids are sourced from air bubbles that become entrapped during processing while the resin is liquefied. These voids lead to mechanical stress concentrations in the composite, which can lead to premature microcracking and decreased useful part life. Detection of voids is currently limited to inspection of finished parts via optical microcopy, ultrasound detection, and x-ray detection. Complete and thorough inspection for large scale parts (e.g., wind blades) is expensive and impractical. Also, if defects are detected, repair is often costly or not practical, leading to scrapped parts. Future work to address these challenges could include improving detection techniques for handling large scale parts at sufficient resolutions, improving understanding of the nucleation of potential defects during processing (i.e., when the resin is still liquid), and taking actions to prevent void defects once the resin hardens.

Program Considerations to Support R&D

Goals

The wider application of advanced composites in clean energy industries can support major national energy goals. The use of composites can lead to increased energy productivity due to improvements in life cycle energy and domestic production of clean energy products. Use of composites can also support a reduction in the cost of energy from large-scale wind and other potential renewable sources (geothermal, solar) and help move the United States toward doubling renewable power generation by 2030. Further, increased deployment of composites in transportation applications can support national goals to improve energy security by reducing the weight and increasing the efficiency of vehicles and by helping enable the use of new fuel sources such as hydrogen in the transportation sector, thus diversifying our fuel sources.

To enable these objectives, the following advances in composites technology are needed:

1. Reduce life cycle energy use and associated greenhouse gas emissions for supported composites R&D efforts;
2. Reduce production cost of finished carbon fiber composites for targeted applications by 50% over ten years;[122]
3. Reduce the embodied energy[123] (and associated greenhouse gas emissions) of carbon fiber composites by 75% in ten years;[124] and
4. Improve recyclability of composites >95% in ten years by both improved process development and design criteria and that the recycled materials would meet application design specifications.

Public Considerations

Activities in the public sector to help address the challenges faced by the composites industry are conducted through competitive cost-shared R&D with industry, universities, and national laboratories. Within the U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy (EERE), the focus has been broad, ranging from supporting R&D on manufacturing technologies by the Advanced Manufacturing Office (AMO), to the development of a renewable-based carbon fiber precursor material by the Bioenergy Technology Office (BETO), to the development of vehicle lightweighting technologies using composites by the Vehicle Technologies Office (VTO), among others. The Clean Energy Manufacturing Initiative (CEMI) technology team is sharing best practice information across DOE offices and plans to set a strategic course for R&D after identifying opportunities and barriers, with the goal of improving U.S. manufacturing competitiveness. One cross-cutting area under CEMI is fiber reinforced polymer composites.

As previously discussed, BETO announced last year the selection of two projects to advance the production of cost-competitive, high-performance carbon fiber material from renewable, non-food-based feedstocks such as agricultural residues and woody biomass. VTO has supported numerous lightweight material projects to reduce cost, demonstrate feasibility, and address multi-material joining and crashworthiness, among others. VTO is also supporting integrated computational tools to accelerate product development cycle times for the next generation of lightweight materials—such as magnesium and carbon-fiber composites—to meet its goal of demonstrating a cost-effective 50% weight reduction passenger vehicle body and chassis systems.[18] The Fuel Cell Technologies Office (FCTO) is focused on the development of high strength, low-cost carbon fiber composites for use in hydrogen storage vessels, and supports a range of related technologies including R&D on alternative feedstock materials, advanced processing techniques for fiber conversion, the use of fillers or additives, as well as innovative tank design and manufacturing techniques.

Beyond the DOE, numerous federal agencies are supporting technical activities to move composites technology forward. Traditionally, FRP composites have been utilized in high performance applications such as aircraft and spacecraft. The DoD through numerous programs has supported advances in the use of FRP composites for military and commercial applications. DoD efforts are currently coordinated through the Joint Defense Manufacturing Technology Panel, Composites Processing and Fabrication Subpanel, and are supported by many of the branch research divisions including the Defense Advanced Research Project Agency (DARPA). DARPA currently has focus areas on advanced structural fiber involving carbon nanotubes at the precursor level and on informatics and process modeling to build confidence in new manufacturing technologies. Current NASA programs are focused on composite cryotanks for space launch and development and regulatory acceptance of advanced composites structure for aeronautics vehicles. The National Science Foundation (NSF) invests in CFRP composites research. As of 2015, NSF had over a hundred active awards related to composites manufacturing. These awards cover a variety of topics including, but not limited to, nanofibers, organic fibers, low-energy curing processes, high-strength thermoplastics, improved joining techniques, and recycling of composites.[126]

The National Institute of Standards and Technology (NIST) supports the development of technology roadmaps and recently funded two consortiums to develop executable roadmaps for future research, workforce development, and technology transfer efforts to advance the U.S. advanced composites industry. The two consortiums are the Consortium for Accelerated Innovation and Insertion of Advanced Composites (CAIIAC) led by the Georgia Institute of Technology and the Facilitating Industry by Engineering, Roadmapping and Science (FIBERS) led by the University of Massachusetts, Lowell.

Private Considerations

Private sector engagement has focused on near-term application and component design. The automotive and wind energy industries have more experience with and more wide-scale adoption of glass fiber reinforced composites; they are now showing increasing interest in applications of carbon fiber reinforced composites. The automotive industry has increased its focus on lightweighting as a result of CAFE fuel economy standards, while the wind industry's interest has grown as larger blades are explored.

Respondents to the recent AMO Request for Information (RFI)[37] identified a lack of knowledge and high capital costs (re-tooling/equipment costs) as the most significant obstacles manufacturers face that limit increased investment and/or adoption of this technology.[37] Further details in their responses indicated a lack of integration with end users, lack of confidence and knowledge at the design stage, and high capital cost for scale up. High quality material properties data and validated part performance data combined with adequate predictive modeling and simulation tools, design capabilities and technical education could address a lack of knowledge were also identified by RFI respondents as an obstacle to broader use of fiber reinforced composite materials and structures. Longer-term, higher-performance materials and capabilities are also essential for this industry.

Additionally, responses to the RFI indicated that an adequate manufacturing/technical workforce is needed. To support this workforce, training and educational needs include professional level, re-education of designers and engineers; community college/trade school programs with hands-on training; and an increased focus at universities at both the undergraduate and graduate levels in a range of knowledge areas relevant to composite manufacturing

International cooperation has been minimal, particularly in the carbon fiber composites industry. The U.S. Commerce Department restricts the export of goods and technology that could contribute to the military potential or nuclear proliferation of other nations, including carbon fiber technologies. The only goods exempt from licensing requirements are those specially designed for purely civilian applications, such as sporting goods, automotive, machine tool, and medical applications.[127]

Future Considerations

Carbon fiber composites are an emerging technology in several potential high-volume applications in diverse industrial manufacturing sectors. Closely coordinating the carbon fiber and composites R&D portfolio at all technology readiness levels (TRLs) levels and across DOE program offices could produce strategic benefits for U.S. manufacturing. To achieve the desired national and international impact, the R&D strategy should characterize, leverage, and optimize opportunities through the complete lifecycle: feedstock carbon intensity, manufacturing energy intensity, and product use-phase.

To support the advancement of technologies towards the goals identified above and support U.S. leadership in advanced composites for clean energy applications, the DOE through the AMO has recently launched the Institute for Advanced Composites Manufacturing Innovation (IACMI). This Institute will target the development of low-cost, energy efficient manufacturing and recycling of FRP composites to support U.S. prosperity and security, further the mission of R&D in energy efficient and renewable technologies, and contribute to the national network of manufacturing institutes.

Because cost is the most significant barrier to the technology adoption, both the DOE AMO and the VTO have supported for development and validation of low-cost, carbon fiber materials through the use of cost-shared competitive R&D with industry, universities, and national laboratories. This includes support for validating the low-cost manufacturing of carbon fiber using innovative manufacturing processes and low-cost source materials. As a part of this effort, the Carbon Fiber Technology Facility, a prototype manufacturing facility for carbon fibers with a capacity of 25 metric tons/year,[128] was created at ORNL with $34.7 million from the American Recovery and Reinvestment Act of 2009. Recent work at the CFTF has targeted the production of low-cost precursors from textile-based PAN (T-PAN), which is a relatively low-cost commodity material. One challenge is to develop oxidation/carbonization protocols that will yield physical properties sufficient to meet application-specific performance demands. The CFTF has made progress improving the tensile performance of T-PAN derived fibers, exceeding 450 ksi tensile strength, almost doubling the initial test results.[129]

The Plastics Division of the American Chemistry Council has recently published a technology roadmap for plastics and polymer composites for automotive markets to address the latest issues facing the automotive marketplace and regulatory drivers, particularly the new U.S. CAFE standards.[130] In this roadmap, it is projected that by 2030, the automotive industry and society will recognize plastics and polymer composites as preferred solutions that meet, and in many cases set, automotive performance and sustainability requirements. To accomplish this, the roadmap outlines key initiatives and actions that should occur within each and across all aspects of the materials development and implementation process. Five key initiatives include industry-wide demonstrations, material selection and part design, manufacturing and assembly, continued materials development, and supporting initiatives. Critical to the success of this strategy is the ability of the plastics and polymer composites industry to work together with the automotive industry and its supply chain to implement the actions it contains in an appropriate, precompetitive environment. The consortia previously mentioned, CAIIAC and FIBERS supported by NIST AmTech grants, are beginning to develop industry roadmaps. American Composites Manufacturers Association is also beginning the composites growth initiative roadmapping effort.

Risk and Uncertainty, and Other Considerations

The extent of FRP applications will depend on the balance among the characteristics and performance of the material, first costs, and life cycle costs (see Table 6.E.2). The limited supply of material also restricts adoption. Due to high part cost from a lack of economies of scale and learning, most applications are initially in premium niche markets. The safety liability of composite structures is one of the greatest concerns for vehicle original equipment manufacturers (OEMs). Designers will select initial applications in non-crash critical components before the technology demonstration is proven at the full system and subsystem level. In addition, any new technology requires a significant level of investment, particularly for carbon fiber production facilities, and OEMs and suppliers have billions of dollars in capital investment already sunk into metal-based production equipment and facilities. Repairability is also a tradeoff for composite parts; insurability requires repairability, and until consumers are comfortable with cost-effective repair options during the component use phase, wide scale composites technology adoption is risky. Additionally, workforce training for technicians that repair these technologies is needed to support broader adoption.

The following policies are having a particular influence on the composites industry. The CAFE standard targeting 54.5 mpg (0.043 liter/km) by 2025 is spurring increasing industrial interest in a range of light-weighting technologies, including higher-performing composites as a means to achieve required mass reductions. For example, BMW utilizes RTM and carbon fiber fabric to produce the passenger compartment of its ~30,000 units/year niche i3 car, saving more than 230 kg per vehicle compared to conventional metal construction. Several federal financial incentives have supported wind projects in the United States, including the Production Tax Credit (PTC) (which expired in 2014), Accelerated Depreciation (and Bonus Depreciation which ended in 2013), and the Investment Tax Credit (also ended in 2013). In addition to the recent PTC reauthorization, the 2012 "We Can't Wait" Initiative supports seven nationally and regionally significant solar and wind energy projects, including a 3 GW wind farm. Although policies such as these are creating market growth, they also have been responsible for surges and contractions in industry growth. For example, in the 1980s, the legislation requiring procurement of carbon fiber materials by DoD to have high domestic content (at least 60%) spurred tremendous growth in the industry. However, due to export restrictions, most U.S. production was limited to domestic consumption.

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[123] Embodied energy refers to the energy required to make the materials and manufacture a composite part, it does not include distribution, use phase or end-of-life energy consumption of a product.

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Acronyms

ATP	Automated tow placement
ATL	Automated tape laying
Bio-ACN	Bio-derived acrylonitrile
BMC	Bulk molding compound
CAFE	Corporate Average Fuel Economy
CFRP	Carbon fiber reinforced plastic
CFTF	Carbon Fiber Technology Facility
EERE	Energy Efficiency & Renewable Energy (DOE Office of)
EM	Electromagnetic
EPA	Environmental Protection Agency
FCTO	Fuel Cell Technologies Office
FIBERS	Facilitating Industry by Engineering, Roadmapping and Science
FRP	Fiber-reinforced polymer
GFRP	Glass fiber reinforced plastic
IACMI	Institute for Advanced Composites Manufacturing Innovation
IR	Infrared
LCOE	Levelized cost of electricity
LDV	Light duty vehicle
LIGHTEn-UP Tool	Lifecycle Industry GreenHouse gas, Technology and Energy through the Use Phase
MMT	Million metric ton
MW	Microwave
NASA	National Aeronautics and Space Administration
NHTSA	National Highway Traffic Safety Administration
NIST	National Institute of Standards and Technology
NREL	National Renewable Energy Laboratory
NSF	National Science Foundation
OEM	Original equipment manufacturer
OOA	Out-of-autoclave
ORNL	Oak Ridge National Laboratory
PAN	Polyacrylonitrile

PTC	Production tax credit
RF	Radio frequency
RFI	Request for information
RIM	Resin injection molding
RTM	Resin transfer molding
SMC	Sheet molding compound
SPP	Solid phase polymerization
SRI	Southern Research Institute
U.S. DRIVE	Driving Research and Innovation for Vehicle efficiency and Energy
UV	Ultraviolet
VARI	Vacuum-assisted resin injection
VARTM	Vacuum-assisted resin transfer molding
VTO	Vehicle Technologies Office

Glossary

Composite	There are a range of definitions of composites; in broad terms a composite can be defined as a combination of two or more materials that retain their macro-structure, resulting in a material that can be designed to have improved properties compared to the constituents alone.[2] That definition applies for composites covered in this Technology Assessment; however, the target of this Assessment is the class of composites known as fiber-reinforced polymer (FRP).
Downcycling/ upcycling (recycling)	In materials recycling, the material may be reused for similar or different applications depending upon next-use requirements and properties of the recycled materials. Typically, materials are downcycled into lower value applications when material properties are compromised due to effects like contamination. Direct reuse as well as upcycling for higher value applications typically requires some amount of energy to be expended in post-processing and clean-up before the materials can be reused.
Fiber-reinforced polymer (FRP) composites	Composites that consist of a fibrous reinforcement material and a polymeric matrix material; they are typically used for structural applications where improved performance properties are desired. Glass fiber is the most commonly used reinforcement, and carbon fiber is used when very high stiffness and light weight are desired.

Life cycle phases	A full assessment of the energy impacts of technologies requires an accounting of the energy of: 1) extraction and processing of the raw materials; 2) the manufacturing phase; 3) freight and transportation; 4) the use phase of the product's useful life; and 5) the end-of-life (to recycle or dispose of the product). Lightweighting technologies (e.g., for vehicles) can be a trade-off between the additional energy required in the materials and manufacturing phases, versus the energy savings from reduced fuel consumption from a lighter vehicle that uses transportation fuel more efficiently.
Lightweighting	Reduction in mass by substitution of materials (e.g., steel replaced by composites) that can lead to performance improvements such as increased fuel economy of vehicles.
Melt spinning	Conversion of a polymer to a fiber form using thermal processes, which requires thermally stable thermoplastic polymers. The fiber forms as the temperature of the melt drops below the glass transition temperature.
Out-of-autoclave (OOA)	A generic term that refers to any process that obviates the need for the traditionally long cure cycles required to cure thermoset-based composites structures in autoclaves. This could include alternative curing technologies (e.g., microwave, electron beam) for thermoset based composites, as well as thermoplastic based composites structures that do not require curing. OOA processes are desirable for composites parts manufacturers as they can reduce the significant time, labor, and energy requirements needed for traditional autoclave-based production methods.
Pre-preg	A combination of polymer and resin in a semi-finished form (e.g., a fiber weave pre-impregnated with partially cured polymer resin) that is supplied to manufacturers of finished composites parts, enabling them to reduce the number of steps required to manufacture a final part.
Resin transfer molding	One method of composites manufacture, in which the resin component is introduced into a mold occupied by the fiber reinforcement component. A variant of the process is vacuum assisted resin transfer molding (VARTM), in which the mold under vacuum accelerates the resin transfer and de-airing processes.
Solution spinning	Conversion of a polymer precursor to a fiber form using solvents, typically by evaporation (dry spinning) or by coagulation in a solvent-compatible fluid (wet spinning).
Spar cap	A structural component of a wind turbine blade, which carries the bending loads applied to the blade. Blades are typically designed with two spar caps running at or near the blade surfaces, and one or two perpendicular connecting shear webs that act as either an I-beam or box-beam, respectively, to carry the loads along the length of the blade. Very lightweight, stiff spar caps are desirable as they can allow for more efficient wind energy generation and associated design benefits.

Tow	Sometimes referred to as a ribbon, a tow is an untwisted bundle of continuous fiber filaments (as opposed to yarns, which are twisted), designated by the number of filaments they contain—for example, 12K = 12,000 fibers. Tows come in a range of sizes, typically from 1 K (1,000 filaments) to 24K (24,000 filaments), with some large format 80K tows used in industry; ultra-large format tows (>600K) are being tested at the CFTF at ORNL. Generally, small-tow composites offer the highest strength-to-weight ratios, and are used in aerospace-grade applications with stringent property requirements, while large-tow composites are used in industrial-grade applications. Note that filament diameter is associated with strength—smaller diameter filaments result from longer oxidation processes and yield filaments of a higher strength, so physical properties are not dependent upon tow size alone. Tows are woven into fabrics, and supplied either dry (for wet lay-up) or impregnated into a semi-cured resin as prepregs.