Advanced Composites Materials and their Manufacture Technology Assessment

Contents

1. Introduction to the Technology/System

Lightweight, high-strength, and high-stiffness composite materials have been identified as a key cross-cutting technology in U.S. clean energy manufacturing with the potential to reinvent an energy efficient transportation sector, enable efficient power generation, provide new mechanisms for storing and transporting reduced carbon fuels, and increase renewable power production.[1] In order to fulfill this promise, advanced manufacturing techniques are required that will enable an expansion of cost-competitive production at commercial volumes. This Technology Assessment identifies where manufacturing operations – from constituent materials production to final composite structure – can benefit from technological advances. By reaching cost and performance targets at required production volumes, these advances have the potential to transform supply chains for these 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 than the constituents alone.[2] Fiber-reinforced polymer (FRP) composites are made by combining a polymer resin with strong, reinforcing fibers. These lightweight composites enable many applications where the potential energy savings and carbon emissions reduction occurs in the use phase. Primary examples of these use phase savings derive from opportunities such as fuel savings in lighter weight vehicles, efficient operation at a lower installed cost in wind turbines that displace non-renewable energy sources, and use of compressed gas tanks for natural gas and, ultimately, hydrogen as fuels storage with lower environmental impact than petroleum-derived fuels.

Typically, a composite material is made of reinforcement and a matrix. The reinforcement material provides the mechanical strength and transfers loads in the composite. The matrix binds and maintains the alignment or spacing of the reinforcement material and protects the reinforcement from abrasion or the environment. The combination of a matrix material with a strong reinforcement material enables lighter weight products relative to monolithic materials (like metals) with similar or better performance properties. Resin and fibers can be combined in a multitude of ways and further processed through a series of forming and consolidation steps. The specific manufacturing technique is dependent on the resin material, the shape and size of the component, and the structural properties required by the end use application. This technology assessment will address limitations to material, manufacturing and recycling processes to make FRP composites for several critical clean energy applications. FRP composites for

[1] The Minerals, Metals and Materials Society (2012). *Materials: Foundation for the Clean Energy Age.* Retrieved from http://energy.tms.org/docs/pdfs/Materials_Foundation_for_Clean_Energy_Age_Press_Final.pdf
[2] Structural Composite Materials. Campbell, F.C. (2010) ASM International. www.asminternational.org

automotive, wind turbine blade, and compressed gas storage applications are highlighted as primary examples for clean energy applications, but are not exhaustive. There are other applications including industrial equipment and components such as heat exchangers and pipelines, geothermal energy production, structural materials for buildings, fly-wheels for electricity grid stability, hydrokinetic power generation, support structures for solar systems, shipping containers and other systems which can also benefit from lower cost, high strength and stiffness, corrosion resistant, and lightweight composite materials to impact national energy goals.

A number of these applications benefit specifically from carbon fiber reinforced plastic (CFRP) composites, which offer a higher strength-to-weight ratio and stiffness-to-weight ratio than many structural materials, as seen in Figure 1. These lightweight materials can deliver significant energy savings during the use phase or facilitate performance that cannot be attained with materials that do not have the high strength and stiffness characteristics.

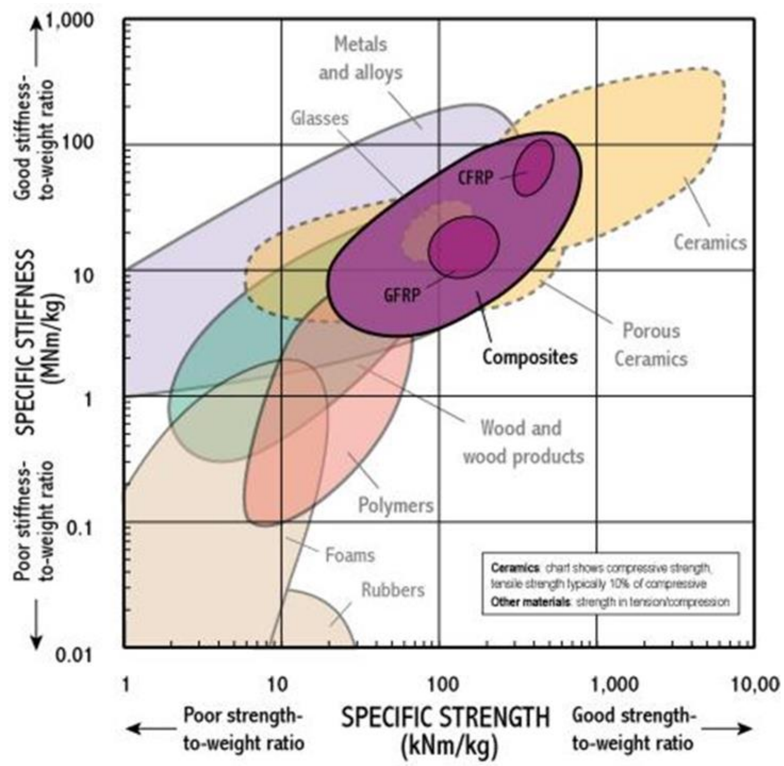

Figure 1: Specific stiffness and specific strength for various materials, the figure highlights Carbon Fiber Reinforced Polymer (CFRP) Composites and Glass Fiber Reinforced Polymer (GFRP) Composites.[3]

While composites encompass a wide range of matrix/reinforcement options, advanced FRP composites and specifically carbon FRP composites have been targeted by DOE as a priority (Figure 2). Some other types of composites, such as metal-matrix composites, are addressed in the Advanced Materials Technology Assessment and the Innovation Impact Report[4].

[3] University of Cambridge, Department of Engineering Website. http://www-materials.eng.cam.ac.uk/mpsite/interactive_charts/spec-spec/basic.html
[4] http://energy.tms.org/docs/pdfs/InnovationImpactReport2011.pdf

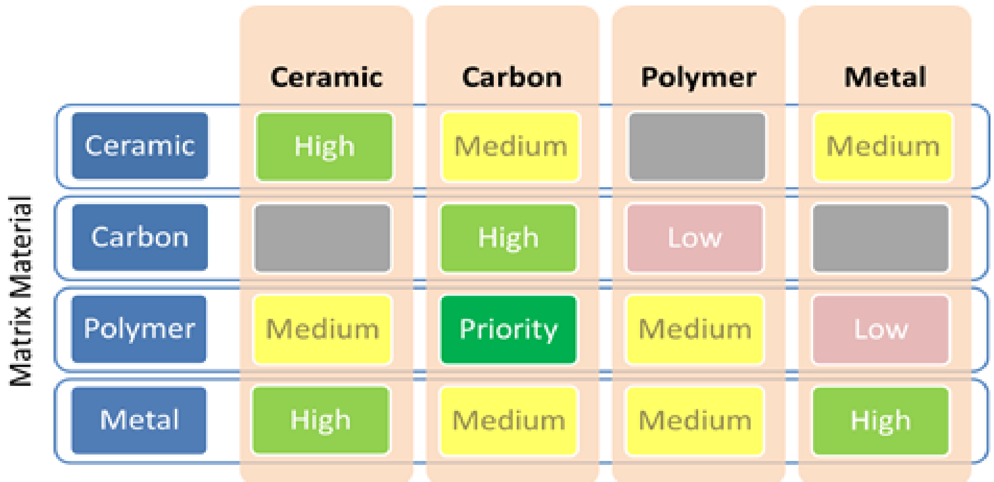

Figure 2: Preliminary prioritization of different classes of composites based on their potential impact on clean energy goals and the mission of the Department of Energy.[5]

One industry analysis predicts the global carbon fiber polymer composite market alone to grow to $25.2 billion by 2020[6] and, in the next 10 years, there is a projected growth of 310% growth in carbon fiber use in industrial applications—primarily for energy applications.[7] Research will be needed to overcome the challenges associated with advanced carbon FRP composite materials and their manufacture. [8] High priority challenges include the high cost, low production speed, energy intensity of composite materials, recyclability as well as improved design, modeling, and inspection tools.[9] 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.

2. Technology Potential and Assessment

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

2.1 The Potential for Advanced Composites for Clean Energy Application Areas

2.1.1 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 6%–8% for conventional internal combustion engines, or increase the range of a battery-electric vehicle by up to 10%.[10] A 10% reduction in the weight of all vehicles in the U.S. car and light-duty truck fleet could result in a 1,060 TBTU annual reduction in

[5] DOE internal analysis.
[6] Industry Experts. Website. *Carbon Fibers and Carbon Fiber Reinforced Plastics (CFRP) – A Global Market Overview.* http://industry-experts.com/verticals/chemicalsandplastics/carbon-fibers-and-carbon-fiber-reinforced-plastics-a-global-market-overview.html
[7] Sara Black (2012).“Carbon Fiber Gathering Momentum,” Composites World. 29 February. Accessed Oct. 21, 2014.
[8]The Minerals, Metals and Materials Society (2011). *Linking Transformational Materials and Processing for an Energy Efficient and Low-Carbon Economy: Creating the Vision and Accelerating Realization, Innovation Impact Report*. Retrieved from http://energy.tms.org/docs/pdfs/Phase_III_Report.pdf
[9] Request for Information (RFI): Clean Energy Manufacturing Topics Suitable for a Manufacturing Innovation Institute (2014), DE-FOA-0001122
[10]U.S. Department of Energy (2011), *Quadrennial Technology Review.* p.39. Retrieved from http://energy.gov/sites/prod/files/QTR_report.pdf

energy and a 72 MMT reduction in CO_2 emissions.[11] The DOE Vehicles Technology Office (VTO) estimates savings of more than 5 billion gallons 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 Corporate Average Fuel Economy (CAFE) standard for cars and light-duty trucks set forth by the U.S. Environmental Protection Agency will increase fuel economy to the equivalent of 54.5 mpg by model year 2025.[13] Lightweighting has been identified as a potential new technology approach with significant potential to achieve this standard. The U.S. Drive Materials Technical Team identified carbon fiber composites as the most impactful material to reducing vehicle mass in their 2013 Roadmap.[14] Composites can offer a range of mass reductions over steel ranging from 25–30% (glass fiber systems) up to 60–70% (carbon fiber systems).[15] 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 can be used where the ability to consolidate parts, corrosion resistance and damping properties are beneficial.[16]

Carbon fiber composites have had limited adoption in the commercial automotive sector over the past forty years in primarily semi-structural (i.e. hood, roof) [17] and non-structural (i.e. seat fabric) for low volume production runs. However, they offer the most significant impact to vehicle lightweighting and use in vehicle structural applications. The typical body structure for a light duty vehicle accounts for 23-28% of the weight.[18] The DOE Vehicle Technologies Program sets a goal of a 50% weight reduction in passenger-vehicle body and chassis systems.[19] While one foreign manufacturer recently released a low volume electric vehicle with a primarily carbon fiber body,[20] as indicated by VTO workshop participants, the structural and safety requirements for body structures requires additional failure mode information, materials with equal or better performance at equivalent cost, better design tools and dependable joining technology for composites, all at adequate manufacturing speeds and consistency for more common vehicle models.[21]

The benefits of lightweighting extends to military vehicles as well for improved fuel economy, increased performance, the ability to better support operationally and improved survivability, according to the 2012 National Research Council report on the *Application of Lightweighting Technology to Military Vehicles, Vessels and Aircraft*.[22] The report also recognizes that "robust manufacturing processes for fabricating

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[11] The Minerals, Metals and Materials Society (2011). *Linking Transformational Materials and Processing for an Energy Efficient and Low-Carbon Economy: Creating the Vision and Accelerating Realization, Innovation Impact Report*. p.92. Retrieved from http://energy.tms.org/docs/pdfs/Phase_III_Report.pdf

[12] http://www1.eere.energy.gov/vehiclesandfuels/technologies/materials/index.html

[13] National Highway Traffic Safety Administration. Press Release. August 28, 2012. http://www.nhtsa.gov/About+NHTSA/Press+Releases/2012/Obama+Administration+Finalizes+Historic+54.5+mpg+Fuel+Efficiency+Standards

[14] US DRIVE (2013). *Materials Technical Team Roadmap*. Figure 1. http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/mtt_roadmap_august2013.pdf

[15] U.S. Drive (2013). Materials Technical Team Roadmap. p.4 Accessed October 31, 2013. http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/mtt_roadmap_august2013.pdf

[16] Massachusetts Institute of Technology. Laboratory for Energy and the Environment (2008). *On the Road in 2035*. Table 14.

[17] Massachusetts Institute of Technology. Laboratory for Energy and the Environment (2008). *On the Road in 2035*. p.48

[18] U.S. Department of Energy, Vehicles Technology Office (2012). *Lightduty Vehicles Workshop Report*. p.9. Retrieved from http://www1.eere.energy.gov/vehiclesandfuels/pdfs/wr_ldvehicles.pdf.

[19] US Department of Energy, Vehicle Technologies Office (2010), Materials Technologies: Goals, Strategies, and Top Accomplishments.

[20] Composites World. Accessed October 3, 2013. http://www.compositesworld.com/news/bmw-formally-launches-i3-manufacture-and-assembly

[21] U.S. Department of Energy, Vehicles Technology Office (2012). *Lightduty Vehicles Workshop Report*. p.9. Retrieved from http://www1.eere.energy.gov/vehiclesandfuels/pdfs/wr_ldvehicles.pdf.

[22] National Research Council (2012). *Application of Lightweighting Technology to Military Aircraft, Vessels and Vehicles*. p.122. The National Academies Press. Retrieved from http://www.nap.edu/catalog.php?record_id=13277

complex structural components from continuous-fiber-reinforced composites have not yet achieved the rate and consistency of steel stamping."[23]

2.1.2 Wind Turbines

Supplying 20% of U.S. electricity from wind could reduce carbon dioxide emissions from electricity generation by 825 million metric tons by 2030.[24] In wind energy, high strength and stiffness, fatigue-resistant lightweight materials like carbon fiber composites can support development of lighter, longer blades and increased power generation.[25] In addition, "using lighter blades reduces the load-carrying requirements for the entire supporting structure and saves total costs far beyond the material savings of the blades alone."[26] Not only could there be cost savings for land-based wind applications by reducing the structure of the turbine tower, but significant savings in reducing the support structure for offshore wind applications, where larger more efficient turbines are possible.

While high performance carbon fiber has been used for highly loaded areas (i.e. spar caps) by some manufacturers,[27] glass fiber composites with lower specific properties are the dominant materials for the overall blade due to lower cost. Capital cost of turbine structures and blade is a significant contributor to the levelized cost of electricity (LCOE) for wind generation. As a result, any enhancement in 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 is favorable due to the possible weight reduction of the blade. One study estimates a 28% reduction for a 100m carbon fiber spar cap blade design compared to the glass fiber equivalent.[28] Materials account for similar relative proportion of cost based on models by Sandia National Laboratory for a 100m all glass (72%) or all carbon (75%) blade; however, carbon fiber cost would need to drop 34% to be competitive.[36] A combination of material optimization and lower costs could enable use of carbon fiber in future blades.[29]

[23] National Research Council (2012). *Application of Lightweighting Technology to Military Aircraft, Vessels and Vehicles*. p.2. The National Academies Press. Retrieved from http://www.nap.edu/catalog.php?record_id=13277

[24] U.S. Department of Energy (2008). *20% Wind Energy by 2030*.p13. Retrieved from http://www1.eere.energy.gov/wind/pdfs/41869.pdf

[25] The Minerals, Metals and Materials Society (2012). *Materials: Foundation for the Clean Energy Age.* p.24. Retrieved from http://energy.tms.org/docs/pdfs/Materials_Foundation_for_Clean_Energy_Age_Press_Final.pdf

[26] U.S. Department of Energy (2008). *20% Wind Energy by 2030.* p.32. Retrieved from http://www1.eere.energy.gov/wind/pdfs/41869.pdf

[27] http://www.compositesworld.com/articles/wind-turbine-blades-glass-vs-carbon-fiber

[28] Griffith, T. et.al. (2012). *Challenges and Opportunities in Large Offshore Rotor Development: Sandia 100-meter Blade Research.* AWEA Windpower 2012 Conference and Exhibition, Scientific Track Paper, June 3-6,2012. Table 8. Retrieved from http://energy.sandia.gov/wp/wp-content/gallery/uploads/Griffith_WindPower-SAND2012-4229C.pdf

[29] Sandia National Laboratories (2013). SAND2013-2734. *Large Blade Manufacturing Cost Studies Using the Sandia Blade Manufacturing Cost Tool and Sandia 100-meter Blades*. http://energy.sandia.gov/wp/wp-content/gallery/uploads/dlm_uploads/SAND_SNLLargeBladeManufacturingCostTrendsAnalysis_SAND2013-2734.pdf

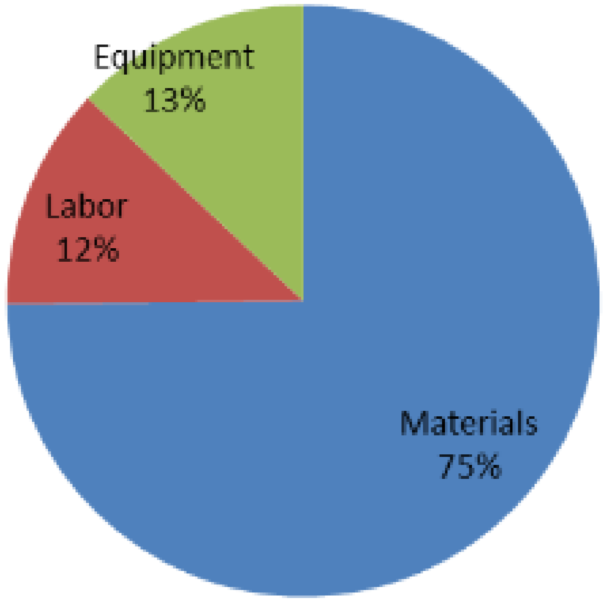

Figure 3: 100m Carbon Spar Blade (SNL100-01) Major Cost Components Breakdown

Further advances in manufacturing techniques, improved quality control, innovations for glass-carbon fiber hybrid composites and reduced costs for carbon fiber composite materials and manufacturing will support production of larger turbines and enable continued growth of wind. One industry analyst predicts wind could be the largest consumer of carbon fiber composites by 2018.[30] The U.S. has a strong position in manufacturing of wind energy equipment[31] and innovative manufacturing techniques could further strengthen U.S. competitiveness in this market segment.

2.1.3 Compressed Gas Storage

According to the Fuel Cells Technologies Office (FCTO), analysis has shown that Fuel Cell Electric Vehicles using hydrogen can reduce oil consumption in the light-duty vehicle fleet by more than 95% when compared with today's gasoline internal combustion engine vehicles, by more than 85% when compared with advanced hybrid electric vehicles using gasoline or ethanol, and by more than 80% when compared with advanced plug-in hybrid electric vehicles.[32] Full commercialization of fuel cell systems using hydrogen will require advances in hydrogen storage technologies. Lightweight, compact and cost competitive hydrogen storage will help make fuel cell systems competitive for mobile and stationary applications. Early markets for fuel cells include portable, stationary, back-up and material handling equipment (i.e. fork trucks) applications.

Many storage technologies for hydrogen are similar to those needed for natural gas applications. As compressed gas storage for hydrogen and natural gas demand grows, lower cost materials and manufacturing methods for storage tanks will be required. High pressure storage tanks are typically made with high strength (>700ksi 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

[30] Red, C. (2012). "Global Market for Carbon Fiber Composites: Maintaining Competitiveness in the Evolving Materials Market." Presentation. Composites World 2012, La Jolla, CA, Dec 4-6.
[31] U.S. Department of Energy (2013). *2012 Wind Technologies Market Report*. p.14. Retrieved from http://www1.eere.energy.gov/wind/pdfs/2012_wind_technologies_market_report.pdf
[32] U.S. Department of Energy (2011). Hydrogen and Fuel Cells Program Plan. p.3. Retrieved from http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/program_plan2011.pdf

systems.[33] FCTO has set ultimate cost targets of $8/kWhr ($267/kg H_2 stored). For Type IV storage tanks with 5.6kg of hydrogen storage at 700bar to meet these cost targets carbon fiber composite costs will need to drop to $10-$15/kg.[34] The U.S. Drive Hydrogen Storage Technical team indicates that when manufactured in high volumes (500,000 units per year) the largest cost reductions to achieve their 2020 system target of $10/kWhr is expected to come from improvements in carbon fiber manufacturing and utilization of material use, as shown in Figure 4.

The FCTO continues to support R&D to lower carbon fiber costs including the use of alternative feedstock materials, advanced processing techniques for fiber conversion, as well as the use of fillers or additives as well as innovative tank design and manufacturing techniques.

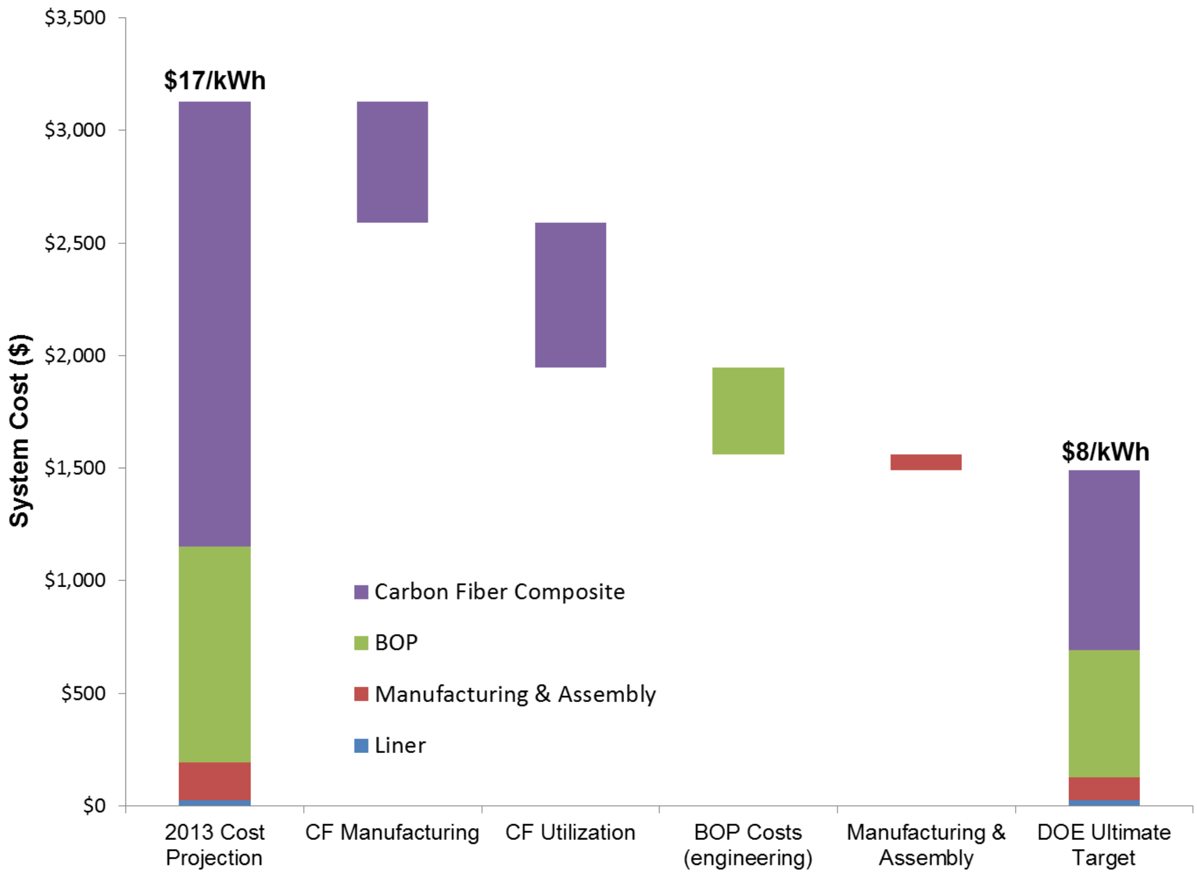

Figure 4: Potential Cost Reduction Strategy for Compressed Vessels to Meet the 2020 U.S. Drive Cost Target (BOP = Balance of Plant).[35]

2.2 Technology Assessment

[33] U.S. Department of Energy (2013). Fuel Cells Technology Office Fact Record #13013: *Onboard Type IV Compressed Hydrogen Storage Systems – Current Performance and Cost.* Retrieved from http://www.hydrogen.energy.gov/pdfs/13010_onboard_storage_performance_cost.pdf

[34] Advanced Manufacturing Office estimate based on U.S. Department of Energy (2013). Fuel Cells Technology Office Fact Record #13013: *Onboard Type IV Compressed Hydrogen Storage Systems – Current Performance and Cost.* Retrieved from http://www.hydrogen.energy.gov/pdfs/13010_onboard_storage_performance_cost.pdf

[35] Ned Stetson (2013), "Hydrogen Storage Session Introduction", 2013 Annual Merit Review Proceedings – Hydrogen Storage, http://www.hydrogen.energy.gov/pdfs/review13/st000_stetson_2013_o.pdf

An in-depth discussion of the state-of-the-art and limitations to the specific technologies for the steps in producing composite parts is included in the sections below. The discussion follows the supply chain for composites, starting with reinforcement and matrix materials, then manufacturing techniques, curing/polymerization processes and recycling followed by a discussion of enabling technologies such as design, modeling and inspection tools.

2.2.1 Barriers

Several sources indicate that there are several major barriers to the use of composites in key application areas for clean energy applications.

Responses to a Request for Information (RFI) release by AMO in 2013 support indicated the top five most important R&D areas (combined responses to questions 1 and 2) [36] 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.

Respondents to the AMO RFI also identified a lack of knowledge and high capital costs (re-tooling/equipment costs) as the most significant obstacles they face to increase investement and/or adoption of this technology. Further details in these responses point to 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 also identified by RFI respondents as an obstacle to broader use of fiber reinforced composite materials and structures.

Additionally responses indicated that a certified manufacturing/technical workforce including both professional level, re-education of designers and engineers and community college/trade school programs for manufacutring with hands on training and an increased focus at universities at both the undergraduate and graduate levels for a range of knowledge areas relevant to composite manufacturing were needed to support an adequate workforce.

A separate analysis indicates that the material cost for carbon fiber and high-rate composites manufacturing have been identified as top among ten obstacles to the market growth for high volume applications.[37] Additional obstacles identified through this particular assessment including proven crashworthiness, design tools, sunk capital, workforce resistance, standards, a lack of assured supply, reparability, and compatibility with commodity resin systems. [38]

The U.S. Drive Materials Technology Team also 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.[39] The American Chemistry Council further identifies in the Plastics in Automotive Markets Technology Roadmap, “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

[36] U.S. Department of Energy. Advanced Manufacturing Office. RFI DE-FOA-0000980 Results Summary Document. http://www1.eere.energy.gov/manufacturing/pdfs/composites_rfi_results_summary.pdf

[37] Warren, D. and Eberle, C. (2013). “Barriers to Widespread Adoption of Carbon Fibers in High Volume Applications,” presented to Southern Advanced Materials in Transportation Alliance (SAMTA), Oak Ridge, TN, Feb.

[38] Warren, D. and Eberle, C. (2013). “Barriers to Widespread Adoption of Carbon Fibers in High Volume Applications,” presented to Southern Advanced Materials in Transportation Alliance (SAMTA), Oak Ridge, TN, Feb.

[39] US DRIVE (2013). *Materials Technical Team Roadmap*. Figure 1. Retrieved from http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/mtt_roadmap_august2013.pdf

designing with plastics and innovating new applications for plastics and polymer composites, especially in light of evolving safety performance criteria and energy efficiency goals."[40]

The critical barriers to the broader adoption and increased potential impact for carbon fiber reinforced composites are cost, speed, energy and recyclability.

2.2.2 Cost

Carbon fiber composites currently cost 1.5 – 5.0 times steel's cost.[41] High fiber-production cost inhibits high volume deployment; thus, there is a need to reduce precursor and processing costs. And as previously discussed is a limitation for larger scale wind as well. With major advancements in the next 15 years, the cost is expected to drop from $22/kg to $11/kg.[42] Oil prices have driven raw material cost and supply-demand imbalances have driven periodic price swings up to twice the cost, encouraging research in non-petroleum based resin and fiber precursors.

2.2.3 Manufacturing Speed

Process throughput or manufacturing speed is another primary cost driver for composites and a critical decision criterion for the adoption of composites for 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 as one way to address complex tooling generation.[43] The tradeoff of lower tooling and setup costs versus process throughput gives rise to a part count threshold beyond which the advantage moves to metal parts. To achieve cost parity with metal at higher production levels, cycle times for composites manufacturing must be reduced. Emerging fast-curing resins and thermoforming process with long-fiber reinforcement in thermoplastic matrix polymers comprise direct approaches to shorten cycle times for 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. The automotive industry, where this is a particular barrier to adoption, suppliers have been working on reducing cure time to improve throughput speed. As examples, in 2011, Momentive Specialty Chemicals introduced a five-minute-cure epoxy and in 2014, Hexcel introduced a snap cure pre-preg with a two-minute cycle.[44]

2.2.4 Energy

Life-cycle energy advantages are a balance between highly energy-intensive advanced composites production and the energy savings and greenhouse gas emissions reductions that mainly occur in the use phase. Savings in the use phase derive from opportunities such as fuel savings in lightweight vehicles, efficient operation at a lower installed cost in wind turbines that displace non-renewable energy sources, and use of compressed gas tanks for natural gas and, ultimately, hydrogen as fuels storage with lower environmental impact than petroleum-derived fuels.

Raw materials are typically derived from energy intensive petroleum processing for reinforcement and matrix constituents of FRPs. In the production phase, high temperatures are required in the manufacture of both carbon and glass fibers. One study estimates that carbon fiber composites are 3-5 times more

[40] American Chemistry Council (2009). *Plastics in Automotive Markets Technology Roadmap*. Retrieved from http://www.plastics-car.com/roadmap_fullversion

[41] Warren, C.D. Das, S. and Jeon. S. (2014). "Carbon Fiber Composites in High Volume Ground Transportation: Competition Between Material Alternatives," paper presented at the LCA XIV conference, held in San Francisco, CA, Oct. 6-8.

[42] http://energy.tms.org/docs/pdfs/InnovationImpactReport2011.pdf

[43] Reference Additive Manufacturing Technology Assessment.

[44] Composites 2014: A Multitude of Markets. Compositesworld.com

energy intensive than conventional steel on a weight basis.[45] To reduce the energy intensity of FRP, high-quality lower energy raw materials and lower energy production technologies are needed.

Additionally, if FRP costs and manufacturing challenges are addressed, resulting in commodity application use of these materials with no corresponding decrease in the manufacturing energy this could potentially increase total energy use in applications where there are no life cycle or renewable energy benefits.

2.2.5 Recycling

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 cost.[46] Cost-effective recycling technologies of FRP composites need to be developed which would save a significant amount of energy—particularly if the process enables repeated recycling without loss of quality and recycling represents a fraction of the original manufacturing energy use and emissions. It is estimated that secondary carbon fiber FRP would require only about 25% of the primary material manufacturing energy use. Recycling of composites occurs now, but only to a limited extent, including 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.[47]

2.2.6 Goals

The wider application of advanced composites in clean energy industries can support major DOE goals. Application of composites can lead to *increased energy productivity* due to improvements in lifecycle energy and domestic production of clean energy products. Use of composites can support reduction of the cost of energy for large scale wind and other potential renewable sources (geothermal, solar) to move toward the DOE goal to *double renewable power generation* by 2030. Finally increased deployment of composites for transportation applications can support *vehicle lightweighting goals* and *diversify fuel sources* for the transportation sector.

To enable these objectives, the Advanced Manufacturing Office has identified the following goals for composites technology.

- i) Reduce life cycle energy use and associated greenhouse gas emissions for supported composites R&D efforts;
- ii) Reduce production cost of finished carbon fiber composites for targeted applications by 50% over ten years;[48]
- iii) Reduce the embodied energy[49] (and associated greenhouse gas emissions) of carbon fiber composites by 75% reduction in ten years;[50] and
- iv) Improve recyclability of composites >95% in in ten years.

[45] Suzuki and Takahashi (2005). *Prediction of Energy Intensity of Carbon Fiber Reinforced Plastics for Mass-Produced Passenger Cars.*

[46] Suzuki and Takahashi (2005). *Prediction of Energy Intensity of Carbon Fiber Reinforced Plastics for Mass-Produced Passenger Cars.*

[47] Mazumdar, S. (2014). "Opening the Door for Composites: New Ways to Compete", paper presented at the *CAMX 2014 Conference,* Orlando, FL, October 13-16, 2014.

[48] Data for key application areas for clean energy are provided in Table 2 with more specific proposed cost targets for carbon fiber composites at representative performance requirements and production volumes.

[49] 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.

[50] Literature estimates that thermoset composites (234 MJ/kg) have higher embodied energy than thermoplastics (155 MJ/kg), indicating further energy reduction is required for thermoset composites. Data Source: Suzuki and Takahashi (2005). *Prediction of Energy Intensity of Carbon Fiber Reinforced Plastics for Mass-Produced Passenger Cars.* pp.16-17.

2.3 Matrix Materials

When viewing the entire market for plastic and composite materials, that is, all products employing polymeric resins, thermoplastics represent about 80% of the total. Thermosets represent the remaining 20%. This is largely because thermoplastics have much faster molding times. The market for just reinforced materials, that is, the composite materials, is about 20% of the entire plastics and composites marketplace. Within this more narrow composites market, thermosets represent about 80% of the total material used, just the reverse from the entire marketplace.[51] The most common thermosetting resin used today is polyester resin, followed by vinyl ester and epoxy.[52] However, there has been increasing interest in developing non-petroleum, bio-based resins. In 2001, John Deere began using ENVIREZ 1807, a resin composed of 13% soybean oil and 12% corn ethanol. One batch (17,000 kg/37,478 lb) of ENVIREZ 1807 used in an application represents 10 barrels of crude petroleum saved and a 15,000 kg/33,069 lb reduction in CO_2 emissions during manufacturing, farming and processing soybeans and corn into oil and ethanol respectively.[53] Information on the technological potential to improve the energy footprint of organic chemicals fundamental to matrix materials can be found in the Chemical Bandwidth Study.[54]

Since thermosets polymerize via irreversible cross-linking reactions, and thermoplastic polymers can be re-melted above a transition temperature, there are not only differences in physical properties but also differences in the manufacturing processes for composites comprised of these matrices.

Many carbon fiber and glass fiber composites today use thermoset polymer matrix materials. Thermoset polymer matrix materials or 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. The composites processing goal is to completely saturate dry fibers with resin without voids or dry sports in the fiber preform as fast as possible for increased production speeds. If the viscosity is too high, the processing times required to completely wet out composite preforms would be too high and not economical for sufficient part manufacturing.

Thermoset resin based composites are difficult to recycle 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, the thermoset resin constituent material is typically broken down at the elevated temperatures used to remove it from fibers. Note, many thermoset resins are designed to be used a high temperatures – thus the temperatures needed to remove them from fibers for recycling can be very high and of high energy/financial costs. Since the thermosets break down during fiber separation, they would not be available for use in recycling purposes.

The increased use of thermoplastic matrix materials offers the potential for improved recyclability but face technical challenges with respect to temperature stability, moisture sensitivity, mechanical stability and final surface quality, among other issues. Thermoplastic resins can liquefy and be separated from fibers at lower temperatures compared to thermoset resins. This is due to thermoplastics being a mix of amorphous and crystalline polymers versus highly cross-linked polymers in thermoset resins. A primary barrier for the widespread use of thermoplastic resin is the high viscosity versus processability.

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 (i.e. composite

[51] Fundamentals of Composite Manufacturing Materials, Methods, and Applications by A Brent Strong. (2008)

[52] http://composite.about.com/od/aboutcompositesplastics/a/Thermoplastic-Vs-Thermoset-Resins.htm

[53] http://www.compositesworld.com/articles/bio-composites-update-bio-based-resins-begin-to-grow

[54] Chemical Bandwidth study, U.S. DOE, expected publication Spring 2015

material stress concentrations at porosity sites). Elevated temperatures reduce the thermoplastic viscosity, but not sufficiently enough. If the temperature is too elevated, the resin will begin to degrade and lose integrity. Future work is on the development of thermoplastic resins that can be processed at temperatures and viscosities similar to thermoset resins, without breaking down.

There is significant research and development in the use of nano-material based resin additives for material property improvement in composite materials. The market value of polymer nanocomposite technologies is expected to increase at the average rate of 5% per year for the next 10 years.[55] Examples of nanomaterial resin additives include carbon nanotubes (CNT), nanoclays, nano-platelets, and graphene. Nano-material based resin additives hold promise in providing 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 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 provide significant impact on new composite material applications, such as damage sensing structures or self-healing structures. Current status is how to reduce the material and processing costs of resin nano-additives by finding applications where they can make significant impact in composite material performance.

2.4 Reinforcement Materials

Reinforcements 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 fiber-reinforced plastics (FRP) are glass, carbon, aramid and boron.

Figure 5 shows the manufacturing processes to create carbon fiber. The precursor is produced at first through the polymerization process where the monomers of the selected materials combine chemically forming stable covalent chemical bonds between the monomer sets. After the polymerization process is complete, a filtration process is carried out followed by 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: where the PAN precursor is first 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 to give 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 1500-3000°C at the next graphitization step, which improves the ordering, and orientation of the crystallites in the direction of the fiber axis. The fibers are then wound into appropriate size and packed for further processing[56].

[55] Linking Transformational materials and processing for an energy efficient and low-carbon economy: creating the vision and accelarationg realization. www..tms.org

[56] Masuelli, M. A (2013.) Introduction of Fibre-Reinforced Polymers – Polymers and Composites: Concepts, Properties and Processes. New York: InTech.

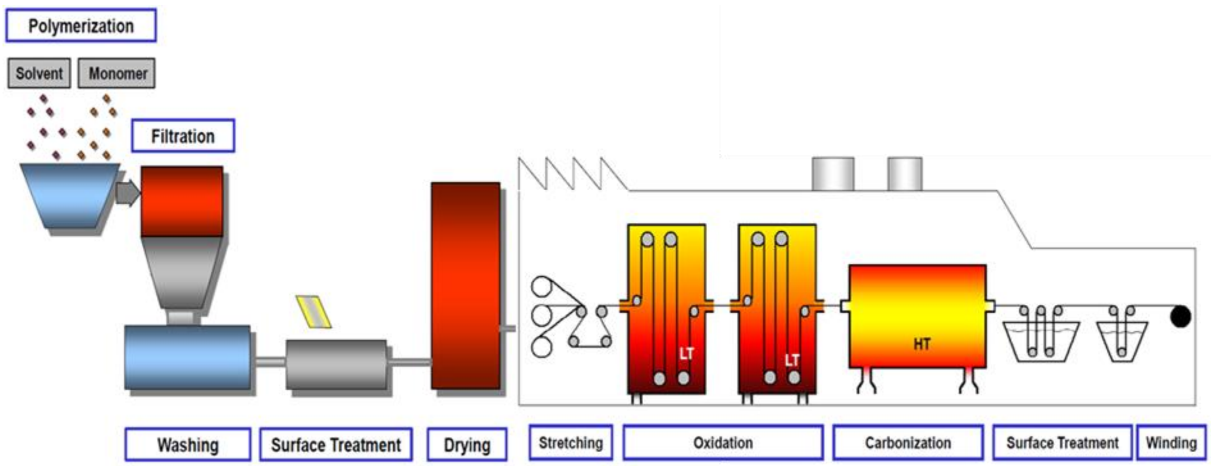

Figure 5: Current carbon fiber production steps. Intensification and energy reduction are necessary to achieve low-cost carbon fiber production.

Roughly 90% of precursors used today are derived from polyacrylonitrile (PAN). The remaining 10% are made from rayon or petroleum pitch. Opportunities to reduce embodied energy and the cost of today's advanced carbon FRPs technology hinge on R&D-enabled modifications to the production processes. An important step in this process is the production of the precursor, the raw material used to produce the fiber. Precursor cost accounts for the largest share of overall fiber cost, at around 50%.[57,58] Novel precursors, such as polyolefin, lignin, or pitch-based materials 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.[59,60]

Lignin is a heterogeneous polymer from plants that has a relatively unpredictable structure that varies between feedstock sources, complicating its processing into renewable materials. 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.[61] Various methods for producing carbon fibers from lignin have been tested, with melt-blowing of soluble lignin emerging as the favored method.[62] Lignin has also been used to displace a percentage of PAN in conventional carbon fibers, but the resulting material did not meet targets for quality.[63] The challenges associated with direct conversion of lignin to finished carbon fibers, including meeting structural specifications and developing new manufacturing processes and lines, mean that it could take longer for its commercial potential to be realized than drop-in bio-ACN.

Another opportunity involves new fiber spinning methods: melt spinning of carbon fiber precursors is both an 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

[57] Trutzschler Man-Made Fibers. New Prospects for the Manufacturing of Carbon Fibers, Dresden.
[58] Das, S. and Warren, D. (2012). "Technical Cost Modeling – Life Cycle Analysis Basis for Program Focus," Oak Ridge National Laboratory, Oak Ridge, TN, May.
[59] Draft Technology Assessment: Composite Materials, November 2014
[60] Warren, C.D. (2012). "Lower Cost Carbon Fiber Precursors," 2012 DOE Vehicle Technologies Office Annual Merit Review, http://www1.eere.energy.gov/vehiclesandfuels/pdfs/merit_review_2012/lightweight_materials/lm004_warren_2012_o.pdf
[61] Baker and Rials, Recent advances in low-cost carbon fiber manufacture from lignin. Journal of Applied Polymer Science, 2013, 130: 713
[62] Baker et al. On the characterization and spinning of an organic-purified lignin toward the manufacture of low-cost carbon fiber. Journal of Applied Polymer Science, 2012, 124, 227
[63] http://www1.eere.energy.gov/vehiclesandfuels/pdfs/merit_review_2012/lightweight_materials/lm048_husman_2012_o.pdf

manufacturing energy requirements and fiber cost by 30%.[64,65] 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%[66] and 25%[67] respectively. The technique is currently being scaled to a pilot-line scale at the DOE-funded Oak Ridge National Laboratory Carbon Fiber Technology Facility. In addition, a Weyerhaeuser (a lignin-based carbon fiber manufacturer) and Zoltek (a high-volume PAN carbon fiber manufacturer) partnership has successfully demonstrated low-cost commercial-scale trial fibers that incorporate the natural polymer lignin precursor (a byproduct of manufacturing wood products and paper) into the conventional PAN-based precursors.

Figure 6 shows a breakdown of energy usage in the fabrication of polymer-reinforced carbon fiber composites. Each step represents potential improvement opportunities in reducing the total needed manufacturing energy.

An alternative approach to reducing energy intensity could be through the use of alternative raw materials that require less energy to produce. The Bioenergy Technology Office's (BETO) *Renewable, Low-Cost Carbon Fiber for Lightweight Vehicles: Summary Report* discusses potential alternative materials and technical challenges to drop in bio-based and unconventional fiber materials that may have lower embodied energy (and potentially cost) relative to existing PAN based technologies.[68]

As summarized in the Bioenergy Technology Office's recent FOA (DE-FOA-0000996: Renewable Carbon Fibers),[69] their goal is to enable technologies that can produce bio-based acrylonitrile (ACN) at a modeled cost of $1/pound or less, to enable the overall manufacturing of carbon fiber at less than or equal to $5.00/lb by 2020 that are suitable for vehicle structural components. If met the anticipated outcomes are: (1) Enabling the use of cellulosic sugars or lignin in the production of millions of metric tons of higher value commodity chemicals, such as bio-ACN, thereby avoiding an equivalent amount of fossil fuel derived chemicals and generating more than $57B of new revenue throughout the renewable carbon fiber supply chain; (2) Enabling the substantial market penetration of the resulting renewable lightweight carbon fiber to assist in reducing the average weight of passenger cars by 10%, thereby reducing annual petroleum consumption by more than 5 billion gallons in the United States.

As such, these technologies would address the following key performance metrics for EERE:

- Dramatically reduce dependence on foreign oil;
- Increase the viability and deployment of renewable energy technologies;
- Increase the energy efficiency of industry; and
- Spur the creation of a domestic bio-industry.

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[64] Das, S. and Warren, J. "Cost modeling of Alternative Carbon Fiber Manufacturing Technologies – Baseline Model Demonstration." Presented to DOE, Washington, DC, Apr. 5, 2012.

[65] Unpublished analysis by Kline and Co., 2007.

[66] Das, S. and Warren, J. "Cost modeling of Alternative Carbon Fiber Manufacturing Technologies – Baseline Model Demonstration." Presented to DOE, Washington, DC, Apr. 5, 2012.

[67] U.S. Department of Energy ARPA-E (2013). *Modern Electro/Thermochemical Advances in Light-metal Systems (METALS), Funding Opportunity No. DE-FOA-0000882*

[68] U.S. Department of Energy, Bioenergy Technology Office (2013). *Renewable, Low-Cost Carbon Fiber for Lightweight Vehicles: Summary Report.* Retrieved from http://www1.eere.energy.gov/bioenergy/pdfs/carbon_fiber_summary_report.pdf

[69] https://eere-exchange.energy.gov/FileContent.aspx?FileID=d1c02657-a04e-420b-ae6d-6585a611b8f4

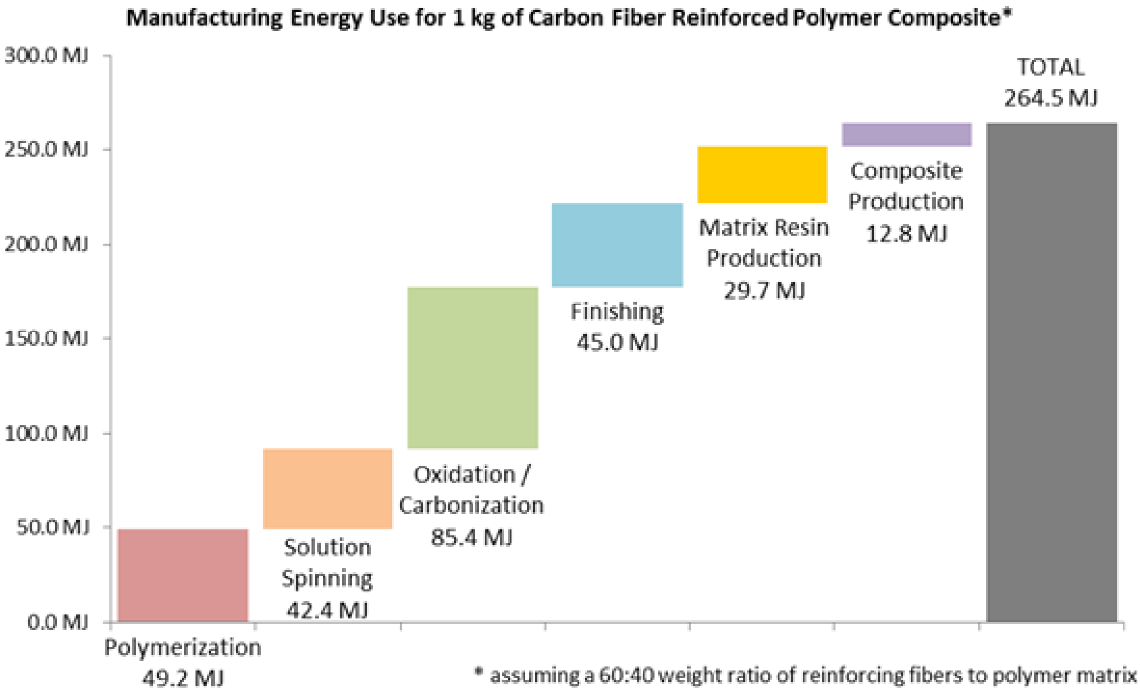

Figure 6: A breakdown of energy usage in the fabrication of carbon fiber composites. Each step represents potential improvement opportunities in reducing the total needed manufacturing energy.[70]

Glycerol, a by-product of biorefineries, is a potential raw material for biobased acrylonitrile. 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.[71,72] The resulting acrylonitrile can be polymerized to form polyacrylonitrile (PAN) fibers for subsequent conversion to carbon fiber.[73]

These technology development insights have led to the development of the following technical priorities for the renewable carbon fiber effort:

- Highly efficient, scalable and integrated process to convert biomass into intermediates that are suitable for further upgrading to bio-ACN;
- Highly efficient, scalable and integrated process to convert biomass intermediates into bio-ACN;
- Highly effective separations and products recovery processes at each of the material junctions that are able to be integrated with the conversion technologies; and,
- Manufacturing process validation of the bio-ACN technical performance attributes as manifested in the final PAN white fiber.

To address this technology, two funding awards up to $11.3 million from DOE-BETO were announced on July 30, 2014[74]: (1) Southern Research Institute (SRI) of Birmingham, Alabama will receive up to $5.9 million to innovate on a multi-step catalytic process for conversion of sugars from non-food biomass to acrylonitrile; (2) National Renewable Energy Laboratory (NREL) of Golden, Colorado will receive up to

[70] Lightweight Materials Bandwidth Study, prepared by Energetics Incorporated for the DOE Advanced Manufacturing Office (2015), to be published.
[71] Liebig et al., Glycerol conversion to acrylonitrile by consecutive dehydration over WO_3/TiO_2 and ammoxidation over Sb-(Fe,V)-O, Applied Catalyst B: Environmental, 2013, Volumes 132-133, 170-182.
[72] Dubois, Method for the synthesis of acrylonitrile from glycerol. US Patent Application, Pub. No. US2010/0048850 A1, Pub. Date Feb. 25, 2010.
[73] Plee, Method of manufacturing carbon fibres, US Patent Application, Pub. No. US2010/0047153 A1, Pub. Date Feb. 25, 2010.
[74] http://www.energy.gov/eere/articles/energy-department-announces-11-million-advance-renewable-carbon-fiber-production

$5.3 million to investigate and optimize multiple pathways to bio-acrylonitrile. The two projects seek to demonstrate new biomass conversion technologies that enable acrylonitrile manufacturing for high performance carbon fiber feedstock at less than $1 per pound.

2.5 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 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 50K tow carbon fibers commonly used for less demanding non-aerospace applications. Standard modulus carbon fibers are generally of 12K-50K tow size range and constitute 80-90% of the total carbon fiber market today.[75] A filament 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 but must be cold stored to prevent complete curing. Bulk Molding Compounds (BMC) are primarily the crosslinking thermoset materials which are widely used in low-end composite applications today. Sheet Molding Compounds (SMC) are thin sheets of fibers precompounded with a thermoset resin and are primarily used in compression molding processes. Figure 7 shows currently available manufacturing technologies associated with semi-finished carbon fiber products.

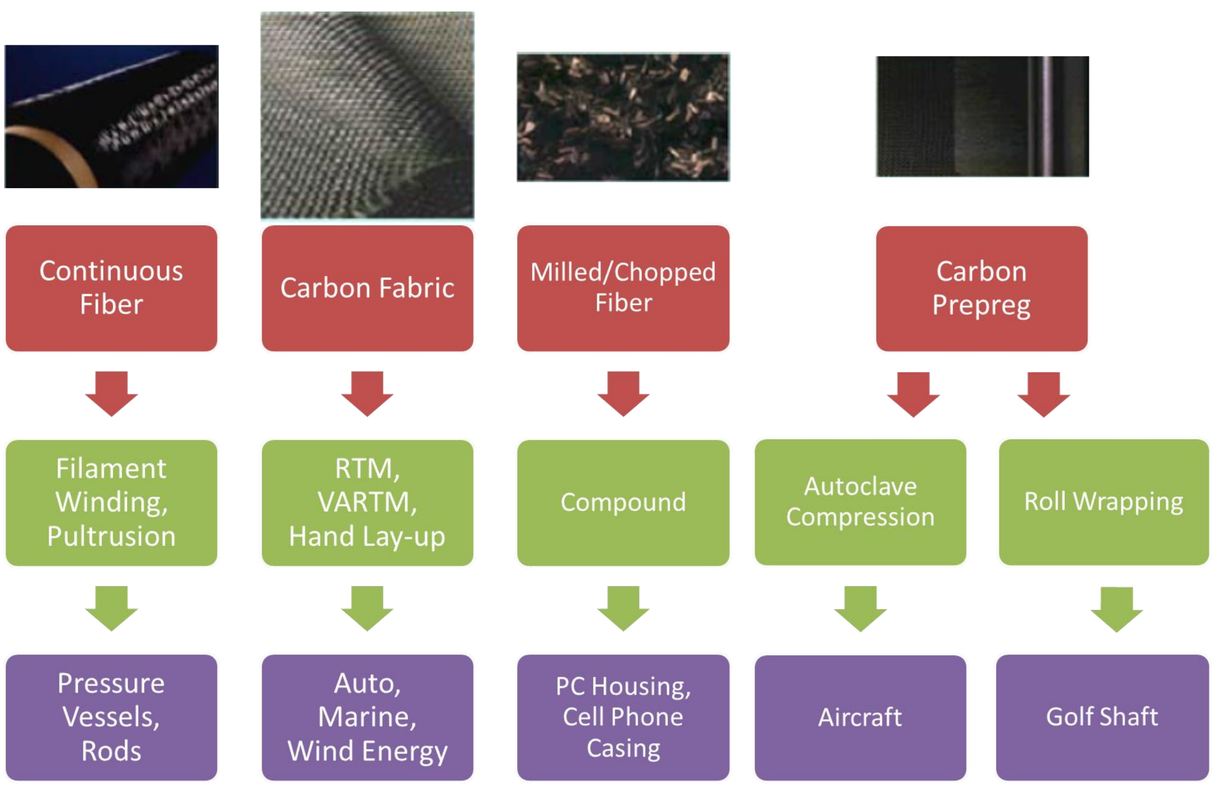

Figure 7: Currently available carbon fiber composite manufacturing technologies and their applications.

2.6 Manufacturing Techniques

[75] Red, C. (2012). 2012 Global Market for Carbon Fiber Composites: Maintaining Competitiveness in the Evolving Materials Market. CW2012, La Jolla, CA, Dec. 4-6, 2012.

The end 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. The most common manufacturing methods used for composite parts are summarized in Table 1. A detailed assessment of the most promising composite manufacturing methods based on their ability to produce high quality, large volume of parts with a fast cycle time and lower capital costs relative to the current state of the art is presented in the following paragraphs.

The challenges associated with the processes and their limitations in meeting the energy efficiency goals, for example, in the transportation sector, wind power generation, and storing and transporting reduced carbon fuels applications are also 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 which requires cycle times less than 3 minutes for carbon fiber reinforced materials and less than 5 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 for fast and cost effective manufacturing processes. Use of composites in compressed gas cylinders for storing fuels requires that the associated manufacturing processes be 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 2.

Table 1: Manufacturing Techniques for Carbon Fiber Reinforced Polymer

Thermoset (including epoxy)		**Thermoplastic**	
Semi-Finished Fabrication	**Technology Stage**	**Semi-Finished Fabrication**	**Technology Stage**
Thermoset Pre-preg	Widely used	*Thermoplastic Pre-preg*	Uncommon
Thermoset Sheet Molding Compound (SMC) / Bulk Molding Compound (BMC)	Widely used	*Thermoplastic Sheet Molding Compound (SMC) / Bulk Molding Compound (BMC)*	Uncommon
Open Forming	**Technology Stage**	**Open Forming**	**Technology Stage**
Hand Lay Up	Widely used	*Hand Lay Up*	Widely used
Spray Up	Widely used	*Robotic Lay Up*	Widely used
Robotic Lay Up	Widely used	*Filament Winding*	Widely used
Filament Winding	Widely used	*Pultrusion*	Uncommon
Pultrusion	Widely used	*Fused Deposition Modeling (Additive Manufacturing)*	R&D
Honeycomb Core	Widely used	*Honeycomb Core*	Uncommon
Closed Forming	**Technology Stage**	**Closed Forming**	**Technology Stage**
Injection Molding	Uncommon	*Injection Molding*	Widely used
Resin Transfer Molding	Widely used	*Resin Transfer Molding*	R&D
Vacuum Assisted Resin Infusion	Widely used	*Vacuum Assisted Resin Infusion*	R&D
Compression Molding	Widely used	*Compression Molding*	Uncommon
Autoclave Forming	Widely used	*Autoclave Forming*	Uncommon
Cold Press	Widely used	*Balanced Pressure Fluid Molding ("Quickstep")*	*New comer technology*
Balanced Pressure Fluid Molding ("Quickstep")	New comer technology		
Thermal Press Curing	R&D		

Another consideration driving improvements in the manufacturing methods is the energy intensity of these various manufacturing techniques. A comparison of the energy intensities inherent in these methods at the current state of the art is shown in Figure 8. The high energy intensity requirement of the autoclave based processes has driven the current increased focus on processes such as resin transfer molding and out-of-autoclave (OOA) curing of thermosets. Out-Of-Autoclave pre-pregs has also recently been effectively used for tooling manufacturing. The process ensures even resin distribution, avoiding the dry spots and resin-rich pockets common with infusion processes. Additionally, OOA pre-pregs can be cured at lower pressures and temperatures (vacuum pressure vs. a typical autoclave pressure of 85 psi and cure at 200°F/93°C or 250°F/121°C vs. a traditional 350°F/ 177°C autoclave cure). Therefore, tooling for large composite structures with integrated stiffeners that can be co-cured in a single cycle, which is typically very complex and expensive, can now be fabricated much more simply and cost-effectively through this process. Further, mismatches between tool and part coefficients of thermal expansion are smaller at lower temperatures and, therefore, more easily managed, positioning OOA pre-pregs as a potential solution for part cracking caused by cure-temperature differentials and achieving faster, more agile manufacturing.

Table 2: Comparison of the Most Commonly Used Composite Molding Process[76]

Molding Process	Advantages	Disadvantages	Cycle Time
Pre-preg	Better 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 and large scrap generated when fiber mats used	45-75 secs. Compform Process 4-5 mins Vacuum forming
RTM	Inside and outside finish possible with thickness control, more complex parts possible with vacuum assisted	Low viscosity resin necessary and the possibility of voids formation without vacuum assisted	8-10 mins for large parts 3-4 mins for vacuum assisted
Liquid Compression Molding	Favored method for mass production with high fiber volumes	Expensive set up cost for low production	1-2 mins.
SMC	Cost effective for production volume 10K-80K/year.	Minimum weight savings potential	50-100 secs
RIM	Low cost tooling where prototypes can be made with soft tools	Difficult to control the process	1-2 mins
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 with the good surface finish capability	Difficult to control the process particularly with low viscosity resin and longer cure cycle time.	4 mins
CFRTP	Easily recycled, faster consolidation	high viscosity which forces users to utilize equipment involving high temperature (200-400 °C)	1 Min

As presented in Table 1, the methods have been grouped by forming processes, the curing methods for thermosets, and consolidation methods for thermoplastics. Forming processes combine the matrix and reinforcement materials to produce the desired shape. These processes are generally grouped into two general classes: open forming and closed forming. Unlike thermoplastic composites, thermosets additionally need to be cured under heat and pressure. Curing in thermosets refers to the cross-linking of polymer chains of the resin matrix that result in a hardened finished part. Many methods can be used for curing. Some of these include the use of heat, chemical additives or electron beams. An assessment of the curing methods and their applicability are discussed shortly.

[76] Das. S. "The cost of the automotive polymer composites: A review and assessment of the DOE's lightweight materials composite research". ORNL/TM-2000/383

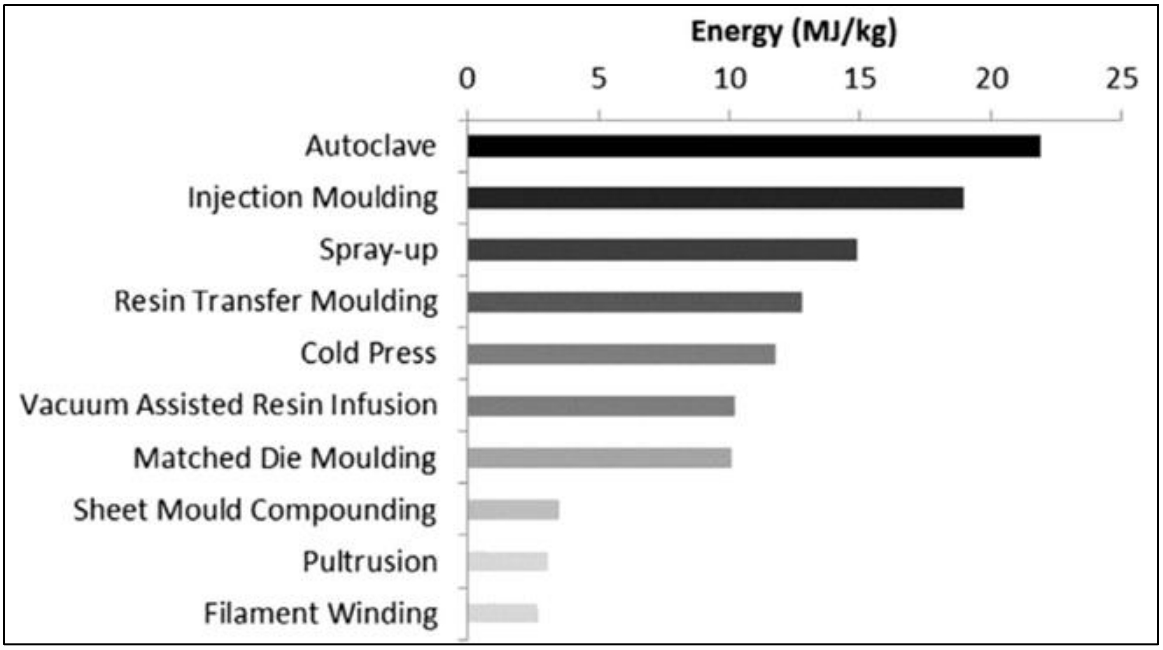

Figure 8: Energy intensity of composite manufacturing techniques.[77]

2.6.1 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 the all goods manufactured nowadays use injection molding due to its versatility and low cost.[78] Solid pellets of resin containing the fibers are fed through a hopper 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, usually of the order of a few seconds. Together these allow for the possibility of high volume production. The main disadvantages are the high initial costs of the capital equipment and the molds and the variation in part properties due to lack of control of fiber orientation and distribution. Additionally, due to the melt viscosity limitations of the current thermoplastic resins, injection molding is capable of producing short fiber reinforced composites which are suited to applications in automobiles such as interior components (e.g. seat backs, dashboard components), closures, and miscellaneous parts like electronic throttle control valves.

Long cycle times for part molding are a primary drawback to use of fiber reinforced polymers in all high volume markets, including mainstream vehicle applications. Long cycle times are governed by resin rate of cure, timescale of resin flow, timescale needed to avoid the creation of bubbles in the resin that turn into voids upon cure and lead to structural weaknesses. To be competitive in the automotive industry, the necessary cycle times are 2 minutes, significantly faster than the conventional state-of-the art autoclave pre-preg process with a cycle time of greater than one hour. Current composites applications typically employ glass fiber reinforcement and compression or injection molding and thermoplastic matrix to

[77] Song, Y.S., Young, J.R., Gutowski, T.G., 2009 Life cycle energy analysis of fiber-reinforced composites. Compos. Part Appl. Sci. Manuf. 40, 1257-1265.
[78] Advani, S. G., & Sozer, E. M. (2003). *Process modeling in composites manufacturing*. New York: Marcel Dekker.

circumvent thermoset cure times. Developments are underway to modify thermoplastics chemistry whereby the tailored low melt viscosity of the resin will enable injection molding of long fiber reinforced composites. This high volume production method will remain the method of choice for non-structural parts in automotive applications. 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.[79]

Resin Transfer Molding

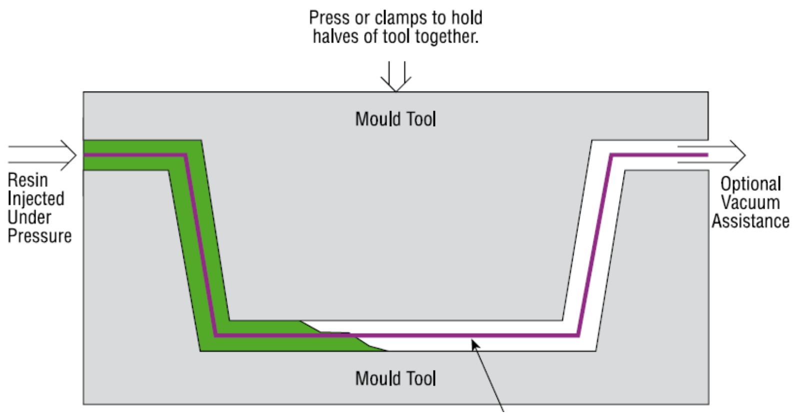

Figure 10: Resin Transfer Molding. Image from Gurit's Guide to Composites.

In Resin Transfer Molding, fiber preform or dry fiber reinforcement is packed into a mold tool that has the desired shape of the composite part. 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 very expensive scrap parts. This composites manufacturing method offers the highest potential of all methods in the fabrication of complex, large scale integrated automobile structural parts. The current BMW i3 uses 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 the 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 practice, a 20 minute cycle time[80] 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 under two-minute cycle times, such as low viscosity fast curing resins by Dow Chemical[81] to make 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 the next challenge in this arena that is being addressed.

Vacuum-Assisted Resin Infusion

[79] http://www.tohotenaxamerica.com/. Accessed on Oct. 28, 2014

[80] Composites World. Accessed October 3, 2013. http://www.compositesworld.com/news/plasan-sheds-light-on-its-automotive-composites-work-in-michigan

[81] Dow Automotive Systems. YouTube Video Published October 1, 2013. Live demonstration of Dow Automotive Systems VORAFORCE 5300 epoxy formulation for high-speed mass production of light-weight structural carbon-fiber automotive composites, via high-pressure resin transfer molding (RTM) process. Demonstration part: 540 x 290 x 2mm, 50vol% carbon fiber content. Total cycle time ~80 seconds. http://www.youtube.com/watch?v=lgtjkpySvhY

There are several slight modifications to Resin Transfer Molding where the second (upper) mold tool is replaced by a vacuum bag. These modified processes include SCRIMP, RIFT, and VARTM. A permeable layer, such as peel ply or a knitted type of non-structural fabric, is often introduced to facilitate the distribution of the resin throughout the part quickly.

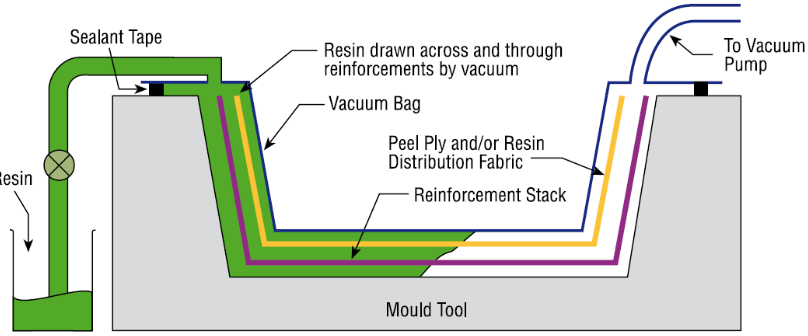

Figure 11: Infusion Schematic. Image for Gurit's Guide to Composites.

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.

Land-based and offshore utility-scale wind turbine blades currently employing vacuum-assisted resin transfer molding (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 content, and frequent rework. To reduce the labor content of blade production, automated fiber placement and inspection processes are necessary. Thermoplastic use will reduce blade weight, cost, and cure cycle times and will facilitate recycling of plastic composites 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.[82] 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 (i.e. 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 that will enable economical use of this method is directed towards developing low viscosity, fast curing resins to 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 2000 psi are applied,[83] 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 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 minor defects as a result of 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 sheet molding compounds (SMCs) and bulk molding compounds (BMCs). Development efforts are underway to enable

[82] Frank, M. Zhu, S. and Peters, F. (2014). "Automated Composite Fabric Layup for Wind Turbine Blades," *CAMX 2014 Conference Proceedings*, Orlando, FL, June 2-5, 2014.
[83] http://www.moldedfiberglass.com/sites/default/files/user/images/MFG_compression%20molding.jpg

long carbon fiber reinforced SMCs to take advantage of their improved strength and stiffness-to-weight ratios. SMC formulation improvements are underway to 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 UV, impact and moisture resistance and have surface-quality demands that drive the need for customized material development.

A subset of compression molding described as matched die 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 also known as the blank, unidirectional and/or woven, is pressed into final shape in a matched die mold and cured (thermosets) or consolidated/stamped (thermoplastics) to rapidly produce parts. The blank design has to be highly engineered because the fiber drapes into the final shape causing changes in fiber orientation and thus the blank design and the press process affect properties. The cure or consolidation cycle time depends on the material selection, with thermoplastic parts consolidated in seconds and thermoset matrix parts in minutes with 17 minutes being the current state of the art. As mentioned in the preceding developments are underway to develop thermoset resins with cure times as fast as 2 minutes, making this process a strong competitor to the RTM process if the dies can be re-used multiple times without any shape distortions or loss of integrity.

2.6.2 Open Forming Processes

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 creates 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. The use of high styrene resins has the potential to be hazardous.

A challenge in this method of part fabrication is managing the VOCs (volatile organic compound) 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 lay up process and, therefore, their use has been limited to the repair of damaged parts, including parts made form other commonly used materials, such as steel and concrete.

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 low viscosity resins usually need to be used. This is a predominant composites manufacturing process for axisymmetric composites – 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.

At high-volume production for storage tanks using filament winding of carbon fiber in an epoxy matrix over a high-density polyethylene liner, carbon fiber materials cost constitutes 60% of the total tank cost.[84] Cost reduction and the fast process cycle times to produce 500,000 parts per year can 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 to extend the tank's useful life.

Pultrusion

Fibers are pulled from a creel through a resin bath and then on through a heated die. As the fiber passes through the die, the resin cures. This process is limited to components with constant, or near constant, cross-sections. Additionally, the cost of the heated die can be high.

Pultrusion yields smooth finished parts that typically do not require post processing. A wide range of continuous, consistent, solid and hollow profiles are pultruded, and the process can be custom-tailored to fit specific applications such as the constant cross-section spar in some windmill blade applications.

Automated Fiber Placement

Automated tow placement and tape placement are subsets of this method with the differences being in the starting materials and the material laydown rates feasible.

The fiber placement process automatically places multiple individual pre-preg tows onto a mandrel at high speed, using a numerically controlled, articulating robotic placement head to dispense, clamp, cut and restart as many as 32 tows simultaneously. Minimum cut length (the shortest tow length a machine can lay down) is the essential ply-shape determinant. The fiber placement heads can be attached to a 5-axis gantry, retrofitted to a filament winder or delivered as a turnkey custom system. Machines are available with dual mandrel stations to increase productivity. Advantages of fiber placement include processing speed, reduced material scrap and labor costs, parts consolidation and improved part-to-part uniformity. Often, the process is used to produce large thermoset parts with complex shapes.

Automated tape laying (ATL) is an even speedier automated process in which pre-preg tape, rather than single tows, is laid down continuously to form parts. It is often used for parts with highly complex contours or angles. Tape layup is versatile, allowing breaks in the process and easy direction changes, and it can be adapted for both thermoset and thermoplastic materials. The head includes a spool or spools of tape, a winder, winder guides, a compaction shoe, a position sensor and a tape cutter or slitter. In either case, the head may be located on the end of a multi-axis articulating robot that moves around the tool or mandrel to which material is being applied, or the head may be located on a gantry suspended above the tool. Alternatively, the tool or mandrel can be moved or rotated to provide the head access to different sections of the tool. Tape or fiber is applied to a tool in courses, which consist of one row of material of any length at any angle. Multiple courses are usually applied together over an area or pattern and are defined and controlled by machine-control software that is programmed with numerical input derived from part design and analysis. Capital expenditures for computer-driven, automated equipment can be significant.

[84] Advanced Manufacturing Office estimate based on US Department of Energy (2013). Fuel Cells Technology Office Fact Record #13013

Although ATL generally is faster than AFP and can place more material over longer distances, AFP is better suited to shorter courses and can place material more effectively over contoured surfaces. The latest equipment trend enables both AFP and ATL, switching between the two, in a matter of minutes, by swapping out dockable heads. Another development area is the pursuit of out of autoclave (OOA) in-situ consolidation of high-performance thermoplastic ATL/ATP parts using laser heating and strategically placed mechanical rollers for consolidation. Both methods suffer, however, from the high capital cost of the equipment and facilities required. The payoffs with these methods for automobile applications are in large scale integrated, complex part fabrication where the lower assembly costs due to the reduced part count and reduced tooling fixture requirements can offset the capital costs.

2.6.3 Curing/Polymerization Processes

Fiber-reinforced plastic (FRP) composite structures require the polymer matrix to attain and maintain solid-state characteristics in service. Since thermosets polymerize via irreversible cross-linking reactions, and thermoplastic polymers can be re-melted above a transition temperature, there are not only differences in physical properties but also differences in the manufacturing processes for composites comprised of these matrices.

Historically, advanced composite structures have been based on thermosetting systems, and approximately 80% of composites are based on a thermoset matrix,[51] requiring a cure step to attain desired properties. Due to exacting specifications and certification processes, aerospace composite structures are 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. The development and demonstration of improved selective heating/polymerization techniques, optimized cure cycles and further advancement of out-of-the-autoclave techniques are potential 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[85] that utilize radiative energy transfer methods that provide energy only where it is required, but requires components within the system that are responsive to the applied frequencies. This can include, for example:

- 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. Considerations include ensuring that depth of penetration appropriate for the size and geometry of the part; tooling is 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 has 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

[85] Note – Electrotechnologies as a form of process heating are covered in more depth in the "Process Heating Technology Assessment."

penetration, with the most promising applications being relatively thin, uniform and planar components and/or structures.

- Induction heating methods are 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 - as an example, a previous 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.[86] Others have demonstrated the potential to directly couple with composites containing sufficiently conductive components, such as carbon fiber.[87] Considerations include the requirement that the composite structure's geometry is of a form that the induction coil can be placed with a uniform, close proximity to the part; and that heat losses are mitigated to ensure uniform heating profiles.
- MW heating technology for curing CFRP. Once considered intractable for curing composites comprised of conductive materials like carbon fiber (due to problems including arcing and dielectric breakdown), advanced multimode MW applicator designs initially investigated at the University of Karlsruhe[88] have been commercialized[89] 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 have the potential to drive chemical reactions; this can happen indirectly, as with ultraviolet (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, making 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 from exposure to energetic particles.

As composites systems expand to include new chemistries, there are additional post-processing techniques that can provide the opportunity for 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, which can enable modification of the physical properties after parts are manufactured. While SPP of nylon via convection techniques is 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.[90] This has the potential to enable faster processing of composites structures with lower viscosity, then post-processing to achieve higher performance specifications.

2.6.4 Intensifying and Optimizing Composites Manufacturing Processes

Technical and non-technical limitations to manufacturing composites at high speed (throughput) contribute to the high cost of composite components that restricts their broader application. The

[86] U.S. Department of Energy (2011). Industrial Technologies Office Report DOE/EE-0389. Retrieved from http://www1.eere.energy.gov/manufacturing/intensiveprocesses/pdfs/eip_report.pdf

[87] Cresko, J.W; Roberts, P.L., "Method of induction curing conductive carbon fiber composites with radio frequency energy;" 3rd World Congress on Microwave and Radio frequency applications. Sydney, 2002. https://inis.iaea.org/search/search.aspx?orig_q=RN:35028342

[88] Feher, L; Flach, A.; Nuss, V.; Pozzo, P.; Seitz, T. "HEPHAISTOS - A novel 2.45 GHz Microwave System for Aerospace Composite Fabrication," 9th International Conference on Microwave and R F Heating, Loughborough University, Loughborough, 2003.

[89] http://www.voetsch-ovens.com/en/products/industrial_microwave_system/schunk01.c.59509.en?_pid=51758

[90] Cresko, J.W.; Phipps, L.M.; Mavretic, A.; "Development of an Industrial Solid Phase Polymerization Process Using Fifty-Ohm Radio Frequency Technology," Advances in Microwave and Radio Frequency Processing," Springer. Report from the 8th International Conference on Microwave and High Frequency Heating held in Bayreuth, Germany, 2001

integration, intensification and optimization of tailored manufacturing operations designed for materials/parts is necessary to achieve production rates at volumes that meet cost targets acceptable for increased market penetration.

As an example, carbon fiber composite components are currently in use on higher end vehicles in smaller production runs (<50,000 units/yr). Wider adoption is limited by the inability of manufacturing processes to meet the <3 minute cycle time needed for incorporation into larger vehicle production runs (>100,000 units/yr). One current technology used today for low to mid production volume vehicle parts has a <20min cycle time,[91] although <2mins cycle time has been shown at lab scale.[92] Current glass fiber composite manufacturing is also not competitive with the production throughput rates of metal stamping and a target of <5 minute cycle times for glass fiber composites by 2025 has been identified for high-volume automotive applications.[93] Reduction cycle time by the introduction of high-end processes has been identified as a cost-driver to enable increased use of glass and carbon fiber composites for wind turbine applications.[94]

Improvements in automation, with high repeatability and further advancements of continuous processes such as tape and fiber placement systems, high speed resin transfer systems, pultrusion, high speed molding systems and new innovative processes with faster lay-up times and cure cycles to meet manufacturing rates and quality requirements are needed and will be an important RD&D focus area. Use of innovative curing technologies (e.g. microwave, ultraviolet, electron beam, etc.) and integrated manufacturing approaches are also potential areas of R&D.

2.7 Recyclability

Table 3 shows the embodied energies of common composite constituent materials, aluminum, and steel. When compared to composite manufacturing techniques in Figure 8, the carbon fiber energy production is roughly an order of magnitude more energy intensive. This is largely due to the high temperatures required for graphitization. The embodied energies in the resins are less than half that of the carbon fiber but still significantly higher than any of the composite manufacturing techniques. Recovery of materials with high embodied energy, such as carbon fiber, presents particularly compelling pathway to save energy and benefits the environment because recycling avoids energy consumption associated with the production of new materials.

Table 3: Embodied Energies of Common Composite Constituent Materials and Two Common Metals[95]

Material	Embodied Energy (MJ/kg)
Carbon Fiber	183 to 286
Glass Fiber	13 to 32

[91] Composites World. Accessed October 3, 2013. http://www.compositesworld.com/news/plasan-sheds-light-on-its-automotive-composites-work-in-michigan

[92] Dow Automotive Systems. YouTube Video Published October 1, 2013. Live demonstration of Dow Automotive Systems VORAFORCE 5300 epoxy formulation for high-speed mass production of light-weight structural carbon-fiber automotive composites, via high-pressure resin transfer molding (RTM) process. Demonstration part: 540 x 290 x 2mm, 50vol% carbon fiber content. Total cycle time ~80 seconds. http://www.youtube.com/watch?v=lgtjkpySvhY

[93] U.S. Department of Energy, Vehicles Technology Office (2012). Lightduty Vehicles Workshop Report. http://www1.eere.energy.gov/vehiclesandfuels/pdfs/wr_ldvehicles.pdf P.32 Table 10.

[94] Watson, J. and Serrano, J. (2010). *Composite Materials for Wind Blades.* p.51 http://windsystemsmag.com/article/detail/149/composite-materials-for-wind-blades

[95] Song, Y.S., Young, J.R., Gutowski, T.G., 2009 Life cycle energy analysis of fiber-reinforced composites. Compos. Part Appl. Sci. Manuf. 40, 1257-1265.

Polyester Resin	63 to 78
Epoxy Resin	76 to 80
Aluminum Alloys	196 to 257
Stainless Steel	110 to 210

There are very limited commercial recycling operations for carbon FRP composites due to economic and technical constraints. Lack of markets, high recycling cost, and lower quality of the recyclates versus virgin materials are major commercialization barriers.[96] The technical difficulty is in liberating the homogeneous particles from the composite material. 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 with poor mechanical properties can be produced using this method. Chemical recycling involves chemical depolymerization by 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 would be known. However, with post-consumer composite scrap, there is a mixture of various composites.

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 the reinforcement fibers and fillers. One option for thermal recycling is fluidized-bed combustion that combusts the resin matrix as energy and recovers the carbon fibers. The high temperatures of the combustion, roughly $550^{o}C$, result in degradation of the carbon fibers, typically a 20% loss in stiffness and a 25% loss in tensile strength[97]. Another option for thermal recycling is pyrolysis. Pyrolysis is thermal depolymerisation at temperatures between $300\text{-}800^{o}C$ 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 also recovered as secondary fuels or feedstock polymers. The world's first commercial scale continuous recycled carbon fiber operation was in 2009 by Recycled Carbon Fibre Ltd in the UK using pyrolysis. Unlike thermoset composites, thermoplastics can also be recycled directly by remelting and remolding.

[96] Yang, Y., et al. (2012). "Recycling of composite materials." Chemical Engineering and Processing: Process Intensification **51** pp. 53-68.

[97] Yang, Y., et al. (2012). "Recycling of composite materials." Chemical Engineering and Processing: Process Intensification **51** pp. 53-68.

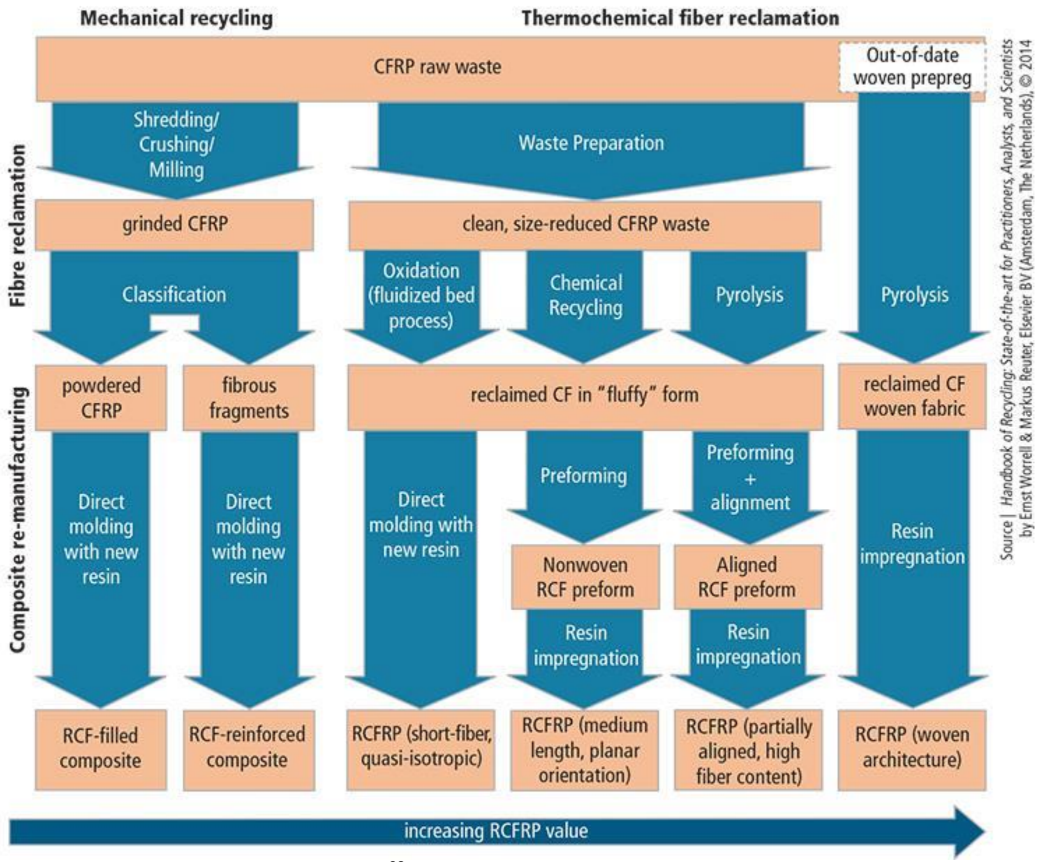

Figure 12: Diagram of CFRP recycling pathways[98]

Current fiber-reinforced composite manufacturing generates 15-25% scrap.[99] 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 a fruitful RD&D pathway. Carbon fiber recovery demands only about 10% of the energy needed to produce virgin material. Since current fiber recovery approaches produce discontinuous fibers retaining >90% of virgin carbon fiber mechanical properties,[100] recycling technology and recycled product streams needs to be developed to effectively use fibers of differing lengths. Boeing, in partnership with Adherent Technologies and MIT-RCF, has performed limited recycle 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.[101]

2.8 Enabling Technologies

To overcome additional challenges identified as barriers to the adoption of composites additional enabling technologies need to be further developed.

[98] http://www.compositesworld.com/articles/supply-and-demand-advanced-fibers-2015
[99] Gosau, J-M, Alfred, RE, and Shoemaker, JM (2001). "Recycling Process for carbon/epoxy composites. In SAMPE 2001Symposium and Exhibition. Long Beach, CA. May.
[100] Gosau, J-M. Wesley, TF, and Allred, RE (2006). "Integrated Composite Recycling Process." In SAMPE Technical Conference, Dallas, TX. November 7-9.
[101] Sustainable Cement Production – Co-processing of Alternative Fuels and Raw Materials in the European Cement Industry." (2009), released by the European Cement Association (CEMBUREAU)

2.8.1 Innovative Design Concepts

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. Composite systems are often overdesigned, adding cost and weight, due to the variability in material properties and lack of information and validated design models. Examples of innovative design approaches that could impact cost, manufacturability and energy use might include, material optimization, structural redesign, multi-functionality of parts, (for example use of 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. Fire mitigation concepts may also need to be considered. Design tools that address reliability trade-offs without increasing composite part cost will be essential in cost-sensitive applications.

2.8.2 Modeling and Simulation Tools

Modeling and simulation tools for materials as well as the process can speed the development cycle for new manufacturing processes, innovative designs and assembly techniques. In addressing modeling and simulation development, the Institute should leverage past work and other ongoing efforts supported by DOE, other federal agencies and programs to the greatest practical extent. One example of significant progress in this area is the Composite Materials Handbook 17, a compilation of data, standards and design practices for composite materials and structures primarily for aircraft though expanding into automotive.[102] Another example is modeling and simulation work sponsored by the DOE VTO to develop predictive engineering tools for injection-molded long-carbon-fiber thermoplastic composites.[103] While progress has been made in the modeling of composites, additional development is still needed, as even for mature industries "existing gaps in modeling 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."[104] Design automation tools that address reliability trade-offs without increasing the composite part cost will be essential in these cost-sensitive applications.

2.8.3 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, reduced strength, joint performance and reparability, directionality of composite materials, nondestructive evaluation of bonded joints, the need for surface preparation, and long times to complete joining. Technology development is needed for fast, reliable techniques for joining materials and structures.[105] Such new joining methods must also avoid degradation of the resulting composite structure for broad applications. Joining techniques should contribute to the reduction in life-cycle energy use and be compatible with processes and manufacturing rates on the factory floor.

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[102] Composite Materials Handbook 17 Website. Accessed October 3, 2013. http://www.cmh17.org/documents.aspx

[103] Pacific Northwest National Laboratory (2013). Report PNNL-22301. *Predictive Engineering Tools for Injection-Molded Long-Carbon-Fiber Thermoplastic Composites.* Retrieved from http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-22301.pdf

104 National Research Council (2012). *Application of Lightweighting Technology to Military Aircraft, Vessels and Vehicles.* p120. The National Academies Press.

[105] U.S. Department of Energy, Vehicles Technology Office (2012). Lightduty Vehicles Workshop Report. Retrieved from http://www1.eere.energy.gov/vehiclesandfuels/pdfs/wr_ldvehicles.pdf p.11.

2.8.4 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 in non-destructive evaluation methods to understand as-manufactured part performance and in-situ sensors for process control to prevent defect formation is required. Technologies exist for non-destructive evaluation of composites but new thinking may be required to adapt to specific material sets and improvements. Defect detection and remediation at high manufacturing throughputs is a significant product quality and cost challenge in many technologies and improvements will need to be made to accommodate high speed production and larger size components, in particular for wind blades.

3. Program Considerations to Support R&D

3.1 Public Considerations

Numerous activities in the public sector are addressing the challenges faced by the composites industry. Within the U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy (EERE), the focus of research activity focus has been broad, ranging from manufacturing technologies focus by the Advanced Manufacturing Office to the development of a renewable-based carbon fiber precursor material by the Bioenergy Technology Office (BETO). The Clean Energy Manufacturing Initiative (CEMI) technology team will be working to share best practice information across DOE offices and 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 composites.

BETO has recently announced selection of two projects, one to be led by Southern Research Institute of Birmingham, Alabama and a second by National Renewable Energy Laboratory (NREL) that aim 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.[106] Both of these projects seek to demonstrate new biomass conversion technologies that enable the manufacturing of acrylonitrile—an essential feedstock for high performance carbon fiber—for less than $1 per pound. The former organization aims to innovate on a multi-step catalytic process for conversion of sugars from non-food biomass to acrylonitrile, whereas the latter one will optimize multiple pathways to bio-acrylonitrile. DOE's Vehicle Technologies Office (VTO) has supported numerous lightweight material projects to reduce cost, demonstrate feasibility, and address multi-material joining and crashworthiness, among others. VTO is supporting integrated computational tools to accelerate the product development cycle times for vehicle components as well as R&D for the next generation of lightweight materials—such as magnesium and carbon-fiber composites—to meet its 2015 goal of demonstration of a cost-effective 50% weight reduction in passenger vehicle body and chassis systems.[107] The Fuel Cell Technologies Office is focused on high strength-grade carbon fiber composites for use in hydrogen storage vessels.

Beyond the Department of Energy, numerous federal agencies are supporting technical activities to move composites technology forward. Traditionally FRP composites have be utilized in high performance applications such as aircraft and spacecraft. The Department of Defense through numerous programs has supported tremendous advances in the use of FRP composites for military and commercial applications.

[106] Green Car Congress (2014). "DOE Awarding $11M to Advance Renewable Carbon Fiber Production from Biomass." Web. Accessed Oct. 28, 2014.
[107] Vehicle Technologies Program (2010). *Materials Technologies: Goals, Strategies, and Top Accomplishments.* U.S. Department of Energy, Energy Efficiency & Renewable Energy. Web. Accessed Oct. 28, 2014.

DOD efforts are coordinated through the Joint Defense Manufacturing Technology Panel, Composites Processing and Fabrication Subpanel and 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 Institute of Standards and Technology (NIST) is supporting the development of technology roadmaps and has recently awarded consortiums led by University of Massachusetts, Lowell and Georgia Institute of Technology to develop executable roadmaps for a course of future research, workforce development, and technology transfer efforts to advance the state of the U.S. advanced composites industry. The Consortium for Accelerated Innovation and Insertion of Advanced Composites (CAIIAC) is led by Georgia Institute of Technology, while the UMass, Lowell-led consortium is called Facilitating Industry by Engineering, Roadmapping and Science (FIBERS).

3.2 Private Considerations

Private sector engagement has focused on application and component design. The automotive and wind energy industries have more experience and more wide-scale adoption of glass fiber reinforced composites, but an increasing interest and application of carbon fiber reinforced composites. For the automotive industry, focus has increased with CAFÉ standards, while the wind industry's interest has grown as larger blades are explored. Estimates are that about 33% of the worldwide pressure vessel industry is involved in manufacturing CFRP pressure vessels.

There has been a lack of international cooperation 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. The only goods exempt from licensing requirements are those specially designed for purely civilian applications, i.e., sporting goods, automotive industry, machine tool industry, and medical applications.[108]

3.3 Future Considerations

With carbon fiber composites having several emerging potential high-volume applications across several industrial manufacturing sectors, closely coordinating the carbon fiber and composites R&D portfolio at all TRL levels and across DOE program offices could produce strategic benefit 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, process energy intensity, and product use-phase factors.

To support the advancement of technologies towards the goals identified and support US leadership in Advanced Composites for Clean Energy Applications, the DOE through the Advanced Manufacturing Office has launched a Clean Energy Manufacturing Innovation Institute for Composite Materials and Structures. The focuses of the Institute are 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 creation of a national network of manufacturing institutes.

Because cost is the most significant barrier to the technology adoption, both the DOE Advanced Manufacturing Office (AMO) and the Vehicle Technologies Office (VTO) have continued support for

[108] US Code of Federal Regulations. Title 15, Part 774. The Commerce Control List. Also available at: http://www.bis.doc.gov/index.php/regulations/export-administration-regulations-ear

development and validation of low-cost, high performance carbon fiber materials. VTO will validate the low-cost manufacturing of carbon fiber using innovative manufacturing processes and low-cost source materials. As a part of this effort, a prototype manufacturing facility for carbon fiber of 25 tonnes/year capacity was created with $34.7 million from the American Recovery and Reinvestment Act of 2009 (ARRA) at Oak Ridge National Laboratory. The latest demonstration for melt-stable PAN having 4,500 MPa tensile strength is on schedule for 2016 at this facility.[109]

The Plastics Division of 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. Corporate Average Fuel Economy (CAFÉ) standards.[110] 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. Other consortiums previously mentioned, i.e., CAIIAC and FIBERS supported by the NIST AmTech grant, are beginning to develop the industry roadmap. American Composites Manufacturers Association is also beginning the composites growth initiative roadmapping.

4. Risk and Uncertainty, and Other Considerations

The extent of application of FRPs will depend on the balance among the characteristics and performance of the material, first costs, and life cycle costs (Table 4). It is particularly risky for a large scale penetration of any immature technology such as carbon fiber polymer composites. Due to high part cost from a lack of economies of scale and learning, most applications are initially seen in niche, premium markets. The safety liability of composite structures is one of the greatest concerns for vehicle 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 a tradeoff with parts integration advantage of composite parts. Insurability requires repairability. Unless consumers are comfortable with cost-effective repair options during the component use phase, wide scale composites technology adoption is too risky.

[109] C. Eberle et al., “Commercialization of New Carbon Fiber Materials Based on Sustainable Resources for Energy Applications,” Report ORNL/TM-2013/54, Mar. 2013. Accessed at http://info.ornl.gov/sites/publications/Files/Pub41318.pdf.

[110] American Chemistry Council (Plastics Division) (2014). Technology Roadmap: Plastics and Polymer Composites for Automotive Markets. Mar. Also available at: http://www.plastics-car.com/Tomorrows-Automobiles/Plastics-and-Polymer-Composites-Technology-Roadmap/Plastics-and-Polymer-Composites-Technology-Roadmap-for-Automotive-Markets-Full-Report.pdf

Table 4. Typical Virgin Material Performance and Cost

	GFRP	CFRP	Steel	Aluminum	Magnesium	Titanium
Specific Strength (kNm/kg)[111,112]	150	400	38	130	158	120
Density (kg/m^3)[113,114]	1800	1590	7870	2700	1800	4500
Embodied Energy (MJ/kg)[115,116]	33	236	45	227	416	474
Domestic Production Cost ($/kg)[117,118]	2.5	27	0.47	2	3.31	9

Two major policies have had particular influence on the composites industry. The CAFÉ standard targeting 54.5 mpg by 2025 is driving 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 resin transfer molding (RTM) and carbon fiber fabric to produce the passenger compartment of its ~30,000 units/year niche i3 electric car, saving more than 230 kg compared to conventional metal construction. Several federal financial incentives have supported wind projects in the United States, including the Production Tax Credit (PTC), 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 which include a 3 GW wind farm proposal. Although policies such as these facilitate industry growth by creating market growth, they also have been responsible for surges and contractions in industry growth. For example, in 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 the domestic consumption.

5. Sidebars and Case Studies

5.1 Case Study: Novel Low-Cost Carbon Fibers for High-Volume Automotive Applications

The CAFÉ standard targeting 54.5 mpg by 2025 is driving increasing industrial interest in a range of light-weighting technologies including high performance composites as a means to achieve required mass

[111] University of Cambridge, Department of Engineering Website. http://www-materials.eng.cam.ac.uk/mpsite/interactive_charts/spec-spec/basic.html Note: Composite material performance will vary based on the type of matrix material, fiber and fiber volume fraction and laminate construction. Values in this chart are more closely representative of quasi-isotropic composites, unidirectional composites may have even higher properties.

[112] U.S. Department of Energy ARPA-E (2013). *Modern Electro/Thermochemical Advances in Light-metal Systems (METALS), Funding Opportunity No. DE-FOA-0000882*, https://arpa-e-foa.energy.gov/Default.aspx?Archive=1%20-%20FoaId7494c8b3-e88e-48f2-b4c8-e4c093bbe077#FoaId7494c8b3-e88e-48f2-b4c8-e4c093bbe077

[113] U.S. Department of Energy ARPA-E (2013). *Modern Electro/Thermochemical Advances in Light-metal Systems (METALS), Funding Opportunity No. DE-FOA-0000882*, https://arpa-e-foa.energy.gov/Default.aspx?Archive=1%20-%20FoaId7494c8b3-e88e-48f2-b4c8-e4c093bbe077#FoaId7494c8b3-e88e-48f2-b4c8-e4c093bbe077

[114] University of Cambridge, Department of Engineering Website. http://www-materials.eng.cam.ac.uk/mpsite/interactive_charts/strength-density/basic.html.

[115] Song. Y.S., *et.al*. "Life Cycle Energy Analysis of Fiber-Reinforced Composites." *Composites: Part A* 40 (2009) 1257-1265. Note: Averages of data from table 1 and 2.

[116] Rankin, W.J. (2011). *Minerals, Metals and Sustainability: Meeting Future Energy Needs.* Table 9.5.

[117] Note: Average value from data in Table 2 in this document.

[118] U.S. Department of Energy ARPA-E (2013). *Modern Electro/Thermochemical Advances in Light-metal Systems (METALS), Funding Opportunity No. DE-FOA-0000882*, https://arpa-e-foa.energy.gov/Default.aspx?Archive=1%20-%20FoaId7494c8b3-e88e-48f2-b4c8-e4c093bbe077#FoaId7494c8b3-e88e-48f2-b4c8-e4c093bbe077

reductions. A 10% reduction in vehicle mass can yield a 6-8% reduction in fuel consumption.[119] Carbon fiber polymer composites has the most weight savings potential in the range of 50-60%, but they are more energy-intensive and also 1.5-5.0X more expensive compared to conventional steel.[120] Conventional polyacrylonitrile (PAN)-based carbon fiber precursors used in carbon fiber polymer composites are energy-intensive and expensive. A novel polyolefin (PO) precursor and proprietary process technology developed at a laboratory scale has a higher carbon fiber yield potential of 65-80% compared to PAN precursor fibers (~48% yield), a lower cost, and reduced energy consumption.

The LIGHTEn-UP cross-sectoral life cycle analysis tool developed by Lawrence Berkeley National Laboratory was used to estimate the lifecycle energy impacts through the use phase for hypothetical automotive parts by comparing three manufacturing pathways, i.e., PAN CFRP, PO CFRP, and conventional stamped steel – when substituting 22 kg of CFRP for 44 kg of steel (Low scenario) and 55 kg of CFRP for 110 kg of steel (High scenario) in gasoline internal combustion engine light duty vehicles (LDVs). The PAN CFRP pathway begins with the polymerization of acrylonitrile (AN) and utilizes solutions spinning and the PO CFRP pathway begins with the polymerization of ethylene to polyethylene (PE) and uses melt spinning; these two pathways merge at the two subsequent high temperature carbonization steps. It is the energy-efficient and high yield carbon fiber conversion manufacturing steps that creates energy-efficiency and cost-effectiveness for the PO CFRP pathway.

Life cycle energy benefits of CFRP light-weighting of the LDV fleet occurs only after significant use phase energy benefits are realized with a significant penetration of lightweight vehicles. Industrial carbon fiber manufacturing energy consumption increases, and both industrial steel sector and transportation sector demand decrease. Using conventional PAN CFRP, the energy benefits occur in 2038; using low energy PO CFRP, the energy benefits occur in 2030. Capturing LDV fleet light-weighting benefits can begin eight years earlier because of PO CFRP. After 2030, net energy savings of low-energy PO CFRP LDV would grow and reach 70-175 TBty/year by 2050.

[119] US Department of Energy (2011). Quadrennial Technology review. P. 39. Accessed from http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/mtt_roadmap_august2013.pdf

[120] Warren, C.D. (2012). High Volume Vehicle Materials. US Low Carbon Vehicles Workshop. Georgia Technological University, Atlanta, Georgia.

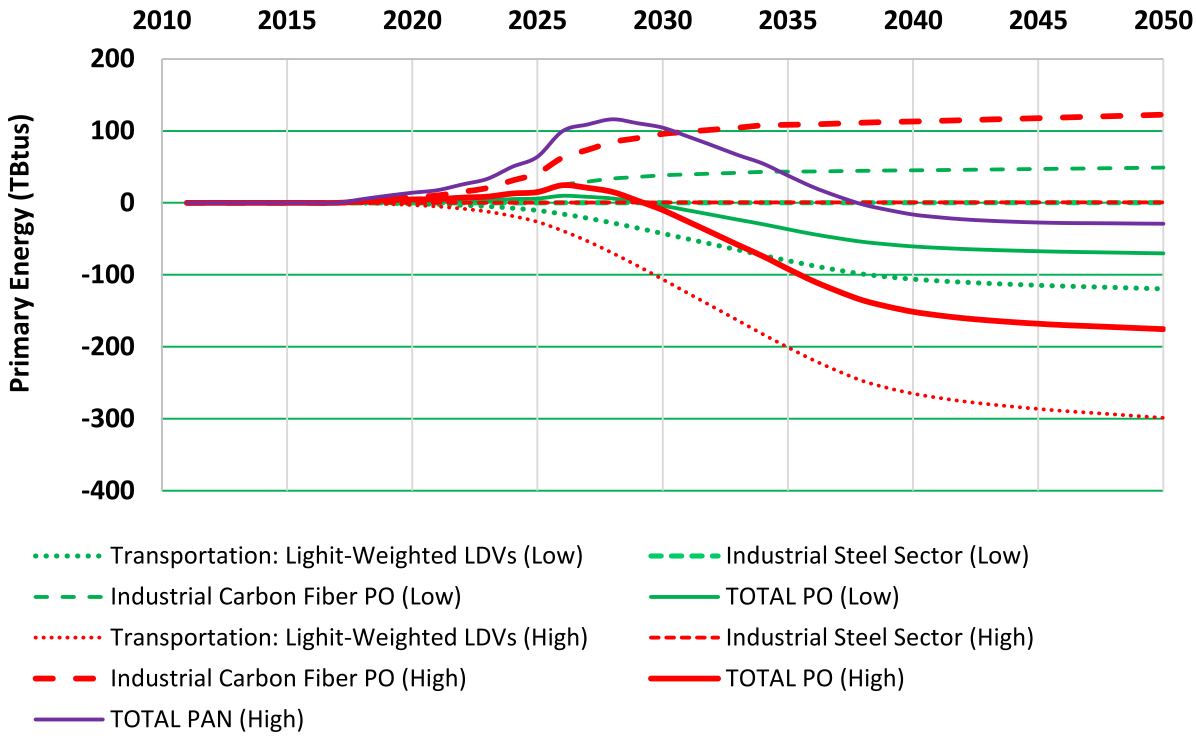

Figure 13: Estimates of the lifecycle energy impacts through the use phase for hypothetical automotive parts by comparing three manufacturing pathways and conventional stamped steel.