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Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY
ADVANCED MANUFACTURING OFFICE

Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Carbon Fiber Reinforced Polymer Manufacturing

September 2017

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Preface

Reducing energy consumption through investment in advanced technologies and practices can enhance American manufacturing competitiveness. Energy bandwidth studies of U.S. manufacturing sectors serve as general data references to help understand the range (or *bandwidth*) of potential energy savings opportunities. [1] The U.S. Department of Energy (DOE)'s Advanced Manufacturing Office (AMO) has commissioned a series of bandwidth studies to analyze the manufacturing of products that can be used for lightweighting applications, and provide hypothetical, technology-based estimates of potential energy savings opportunities in the manufacturing process. The consistent methodology used in the bandwidth studies provides a framework to evaluate and compare energy savings potentials within and across manufacturing sectors at the macro-scale.

This study is being released as part of a series of six studies focusing on energy use in the manufacture of the following lightweight structural materials: carbon fiber reinforced polymer composites, glass fiber reinforced polymer composites, advanced high-strength steel alloys, aluminum alloys, magnesium alloys, and titanium alloys. It should be noted that the boundaries of these analyses were drawn based on features of the manufacturing processes that are unique to each material. Therefore, the results of the lightweight materials bandwidth studies cannot be directly compared. In a separate study, these boundaries are redrawn to consistently include energy consumption for all phases of the product manufacturing life cycle, from the energy embodied in the raw materials through finished part fabrication (for selected applications); energy associated with end-of-life recycling is also considered. This allows the data to be integrated and compared across all six materials. This separate study also develops a framework for comparing manufacturing energy intensity on a material performance (e.g., effective weight) basis for illustrative applications.

Four different energy *bands* (or measures) are used consistently in this series to describe different levels of on-site energy consumption to manufacture specific products and to compare potential energy savings opportunities in U.S. manufacturing facilities (see figure below). **Current typical** (CT) is the energy consumption in 2010; **state of the art** (SOA) is the energy consumption that may be possible through the adoption of existing best technologies and practices available worldwide; **practical minimum** (PM) is the energy consumption that may be possible if applied research and development (R&D) technologies under development worldwide are deployed; and the **thermodynamic minimum** (TM) is the least amount of energy required under ideal conditions, which typically cannot be attained in commercial applications. CT energy consumption serves as the benchmark of manufacturing energy consumption. TM energy consumption serves as the baseline (or theoretical minimum) that is used in calculating energy savings potential. Feedstock energy (the nonfuel use of fossil energy) is not included within the energy consumption estimates.

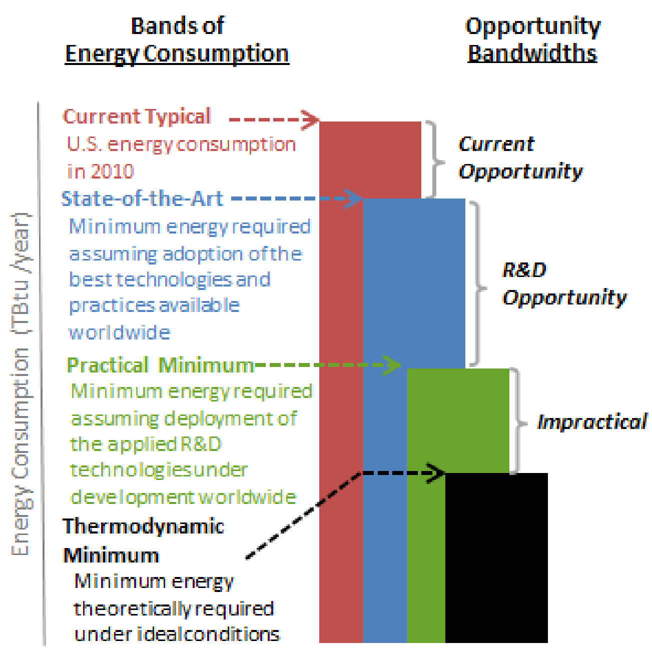

Figure P-1. Energy consumption bands and opportunity bandwidths estimated in this study
Source: EERE

Two on-site energy savings opportunity *bandwidths* are estimated: the ***current opportunity*** spans the bandwidth from CT energy consumption to SOA energy consumption, and the ***R&D opportunity*** spans the bandwidth from SOA energy consumption to PM energy consumption. The total opportunity is

[1] The concept of an energy bandwidth, and its use as an analysis tool for identifying potential energy saving opportunities, originated in AMO in 2002 (when it was called the Office of Industrial Technologies). Most recently, revised and consistent versions of bandwidth studies for the *Chemicals, Petroleum Refining, Iron and Steel*, and *Pulp and Paper* sectors were published in 2015.

the sum of the R&D and the current opportunities. The difference between PM energy consumption and TM energy consumption is labeled as *impractical*. The term *impractical* is used because the PM energy consumption is based on today's knowledge of R&D technologies tested between laboratory and demonstration scale; further decreases in energy intensity have not been displayed at any physical scale. However, decreasing the PM energy consumption with future R&D efforts and emerging technologies being investigated through modeling and theoretical calculations may eventually bring the PM energy consumption closer to the TM energy consumption. Significant investment in technology development and implementation would be needed to fully realize the energy savings opportunities estimated. The costs associated with achieving SOA and PM energy consumption are not considered in this report; a techno-economic analysis of the costs and benefits of future R&D technologies was not in the scope of this study.

For each lightweighting material studied in the series, the four energy bands are estimated for select individual subareas of the material manufacturing process. The estimation method involved a detailed review and analytical synthesis of data from diverse industry, governmental, and academic sources. Where published data were unavailable, best engineering judgment was used.

Acknowledgments

Joseph Cresko of DOE/AMO led the conceptual development of the bandwidth study series, with support from Dr. Alberta Carpenter at the National Renewable Energy Laboratory. AMO recognizes the efforts of Dr. Heather Liddell, Caroline Dollinger, Dr. Aaron Fisher, and Sabine Brueske of Energetics Incorporated, who conducted the research and analysis and wrote this report. Sujit Das of Oak Ridge National Laboratory is also acknowledged with appreciation for supplying valuable facility energy data for carbon fiber production, and for his useful input during discussions. AMO wishes to acknowledge the contributions made by George Husman of Husman Consulting, Inc. and Sanjay Mazumdar of Lucintel for their work reviewing this study.

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List of Acronyms and Abbreviations

ACC	American Chemistry Council
AMO	Advanced Manufacturing Office
Btu	British thermal unit
CF	Carbon fiber
CFRP	Carbon fiber reinforced polymer
CT	Current typical energy consumption or energy intensity
DOE	U.S. Department of Energy
EERE	DOE Office of Energy Efficiency and Renewable Energy
EIA	U.S. Energy Information Administration
EPA	U.S. Environmental Protection Agency
HDPE	High-density polyethylene
IEA	International Energy Agency
K	Kelvin
LBNL	Lawrence Berkeley National Laboratory
NREL	National Renewable Energy Laboratory
ORNL	Oak Ridge National Laboratory
PAN	Polyacrylonitrile
PEEK	Polyether ether ketone
PM	Practical minimum energy consumption or energy intensity
PP	Polypropylene
PS	Polystyrene
PU	Polyurethane
PVC	Polyvinyl chloride
R&D	Research and development
SOA	State of the art energy consumption or energy intensity
TBtu	Trillion British thermal units
TM	Thermodynamic minimum energy consumption or energy intensity
TP	Thermoplastic (resin)
TS	Thermoset (resin)
VSD	Variable speed drive (motor)

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Executive Summary

With their high strength-to-weight ratios, carbon fiber reinforced polymer (CFRP) composites have strong technical potential for lightweighting in structural applications; however, manufacturing challenges such as high costs, variable performance, poor repairability, and low process throughput currently limit their use in commercial applications. One of the most significant challenges for composite materials is their high energy intensity compared to other structural materials such as steel and aluminum.[2] In this report, the manufacturing energy consumption associated with the production of CFRP composites is investigated in detail. This study is limited to four energy-critical structural application areas (automotive, wind energy, aerospace, and pressure vessels), which together comprise about 51% of the total carbon fiber market.

This study explores the energy intensity and energy consumption associated with CFRP manufacturing, breaking down energy use by sub-process. Energy savings opportunities are identified and quantified for each of the six manufacturing sub-processes considered:

- *Polymerization:* the chemical polymerization of the carbon fiber precursor material
- *Spinning:* the process that produces fibers from the precursor
- *Oxidation/Carbonization:* a series of thermal processes that stabilize the precursor fibers and burn off non-carbon atoms, producing tightly bonded, carbon-rich fibers
- *Finishing:* the application of surface treatments and coatings (called "sizing") to protect the fibers and promote bonding with the plastic matrix, and the spooling of the fibers
- *Resin Production:* the manufacture of the polymer resin that will serve as a matrix material in the final composite product
- *Composite Product Forming:* the process of integrating the fibers into the polymer matrix and producing a finished composite product.

The purpose of this data analysis is to provide macro-scale estimates of energy savings opportunities for each CFRP manufacturing subarea. This is a step toward understanding the processes that could most benefit from technology and efficiency improvements to realize energy savings.

Study Organization and Approach: After providing an overview of the methodology and boundaries in Chapter 1, the 2010 production volumes for CFRP composites are estimated in Chapter 2. Current typical (CT) energy intensity and consumption are estimated for six sub-processes in Chapter 3. The state of the art (SOA) energy intensity and consumption for these processes (assuming the adoption of best technologies and practices available worldwide) is estimated in Chapter 4, and the practical minimum (PM) energy intensity and consumption for these processes (assuming the deployment of the applied research and development (R&D) technologies available worldwide) is assessed in Chapter 5. The thermodynamic minimum (TM) energy (that is, the minimum amount of energy theoretically required for these processes assuming ideal conditions) is estimated in Chapter 6; in some cases, this is less than zero. The difference between the energy consumption *bands* (CT, SOA, PM, TM) are the estimated energy savings opportunity *bandwidths*. These opportunity bandwidths are presented in Chapter 7.

Study Results: Two energy savings opportunity *bandwidths*—current opportunity and R&D opportunity—are presented in Table ES-1 and Figure ES-1.[3] The current opportunity is the difference between the 2010 current typical (CT) energy consumption and the state of the art (SOA) energy consumption; the R&D opportunity is the difference between the SOA energy consumption and the practical minimum (PM) energy consumption. Potential energy savings opportunities are presented as a total and broken down by manufacturing sub-process. The savings total reflects a representative composite formulation, with epoxy resin assumed as the polymer matrix material and resin transfer molding assumed as the forming method. Note that the energy savings opportunities presented reflect the estimated production of CFRP composites for selected application areas in

[2] See the other reports in this series, *Energy Use and Potential Energy Saving Opportunities in the Manufacturing of Lightweight Materials*, for energy intensity estimates for other lightweight structural materials.

[3] The energy estimates presented in this study are for macro-scale consideration; energy intensities and energy consumption values do not represent energy use in any specific facility or any particular region in the United States. The costs associated with achieving energy savings are not considered in this study. All estimates are for onsite energy use (i.e., energy consumed within the facility boundary). Energy used as feedstocks (non-fuel inputs) to production is excluded.

baseline year 2010. Lightweight composite materials have seen enormous growth in the past several years, especially in energy-critical applications such as automotive and wind energy. Therefore, it is important to note that the total energy opportunities would scale with increasing production.

Table ES-1. Potential Energy Savings Opportunities (On-site Energy Consumption) for CRFP Composite Manufacturing in the United States (Considering Production for Selected Lightweighting Application Areas Only)[4]

Opportunity Bandwidths	Estimated Energy Savings Opportunity for CFRP Composite Manufacturing (per year)
Current Opportunity – energy savings if the best technologies and practices available are used to upgrade production	**1.21 TBtu**[5] (22.1% energy savings)[6]
R&D Opportunity – additional energy savings if applied R&D technologies under development worldwide are successfully deployed	**3.43 TBtu**[7] (62.6% energy savings)[8]

[4] Calculated using the production values for lightweight structural application areas considered in this study only (see Section 1.4.), and not all carbon fiber composites. Energy savings are measured from the current typical energy consumption. Note that the thermodynamic minimum (TM) is used as the baseline (rather than zero) for energy savings percent calculations.
[5] Current opportunity = CT – SOA, as shown in Table 4-5..
[6] Current opportunity (or SOA) percentage = $\left(\frac{CT-SOA}{CT-TM}\right) x100$, as shown in Table 4-5.
[7] R&D opportunity = SOA – PM, as shown in Table 5-6.
[8] R&D opportunity percentage = $\left(\frac{SOA-PM}{CT-TM}\right) x100$, as shown in Table 5-6.

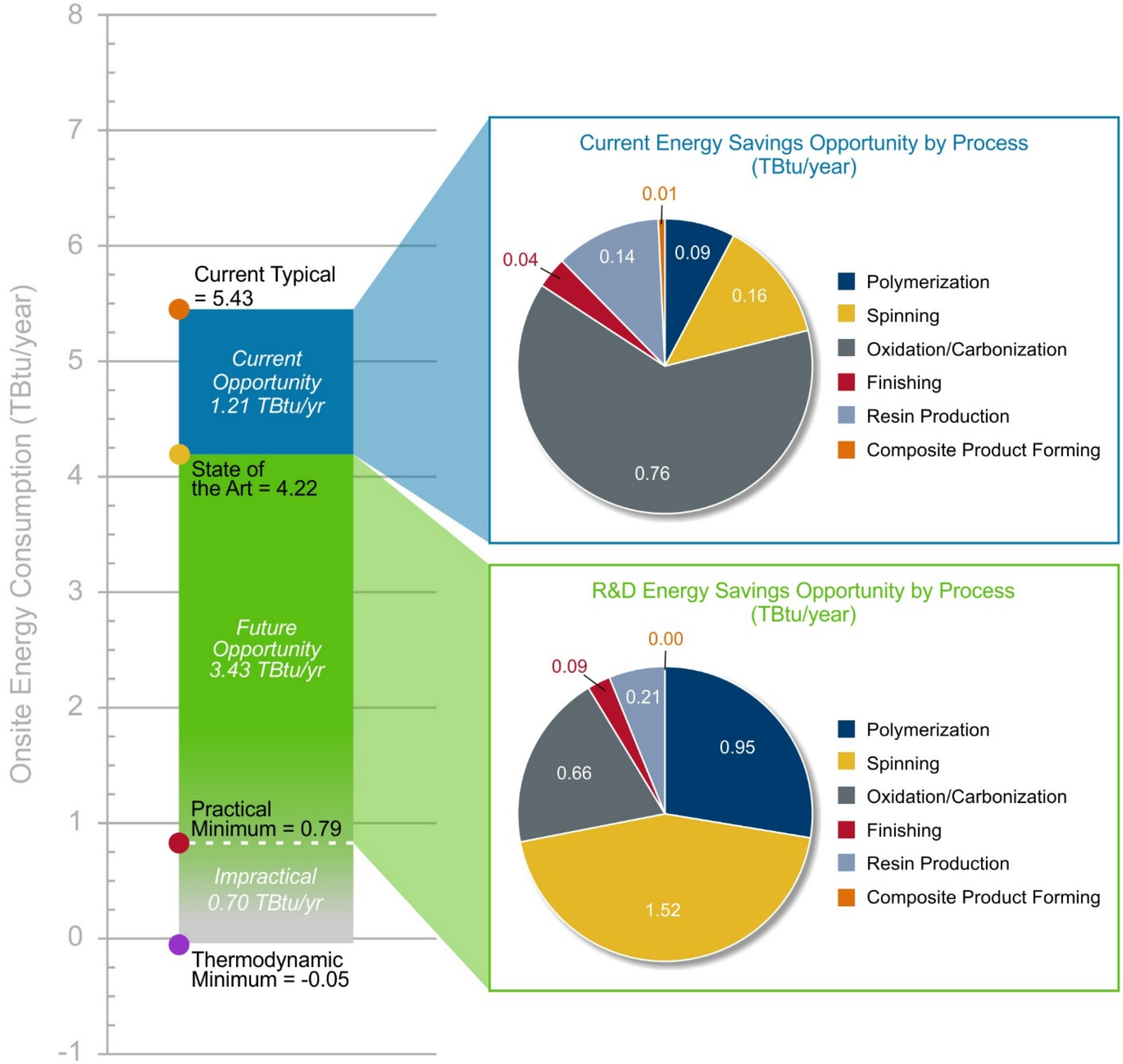

Figure ES-1. Current and R&D energy savings opportunities for CFRP composite manufacturing (on-site energy consumption) by process, based on 2010 carbon fiber production for structural applications
Source: EERE

The PM energy consumption estimates are speculative because they are based on unproven technologies. The estimates assume the successful deployment of R&D technologies that are under development; where multiple technologies were considered for a similar application, only the most energy efficient technology was considered in the energy savings estimate. The difference between PM and TM is labeled “impractical” in Figure ES-1 because the PM energy consumption is based on today’s knowledge of R&D technologies tested between laboratory and demonstration scale; further decreases in energy intensity have not been displayed at any physical scale. However, it is shown as a dashed line with color fading because emerging technologies being investigated through modeling and theoretical calculations may eventually bring the PM energy consumption further into the faded region and closer to the TM energy consumption.

An estimated 5.43 TBtu of energy was consumed in 2010 to manufacture CFRP composites in the United States for the four key structural applications considered in this study. Based on the results of this study, an estimated 1.21 TBtu of energy could be saved each year if state of the art technologies and manufacturing equipment available worldwide are used to upgrade CFRP manufacturing practices in the subareas studied. An additional 3.43 TBtu could be saved through the adoption of applied R&D technologies under development worldwide. Together, these results suggest that it is potentially feasible to reduce the energy consumption associated with CFRP manufacturing by 85% compared to typical practices used today.

The top three current energy savings opportunities for CFRP composites are as follows:

- **Oxidation/Carbonization,** representing 63% of the current opportunity (0.76 TBtu/year).
- **Spinning,** representing 13% of the current opportunity (0.21 TBtu/year).
- **Resin Production,** representing 12% of the current opportunity (0.16 TBtu/year).

The top three R&D energy savings opportunities are as follows:

- **Spinning**, representing 36% of the R&D opportunity (1.68 TBtu/year).
- **Oxidation/Carbonization**, representing 31% of the R&D opportunity (1.43 TBtu/year).
- **Polymerization**, representing 22% of the R&D opportunity (1.04 TBtu/year).

DOE researchers will continue to evaluate the energy consumption and opportunity bandwidths in U.S. carbon fiber reinforced polymer composites manufacturing, along with bandwidth study results from other manufacturing sectors.

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1. Introduction

1.1. Overview

The U.S. Department of Energy (DOE)'s Advanced Manufacturing Office (AMO) has commissioned a series of bandwidth studies to analyze processes and products that are highly energy intensive, and provide hypothetical, technology-based estimates of energy savings opportunities. Reducing energy consumption through investment in advanced technologies and practices can enhance American manufacturing competitiveness. Manufacturing energy bandwidth studies serve as general data references to help understand the range (or *bandwidth*) of energy savings opportunities. DOE AMO commissioned this bandwidth study to analyze the most energy consuming processes in manufacturing carbon fiber-reinforced polymer (CFRP) composites.

This bandwidth study is one in a series of six bandwidth studies characterizing energy use in manufacturing lightweight structural materials in the United States. The other materials, studied in parallel, include: aluminum alloys, magnesium alloys, titanium alloys, advanced high strength steel alloys, and glass fiber reinforced composites. Separate studies are available for these materials. As a follow-up to this work, an integrating analysis will be conducted to compare results across all six studies.

Similar energy bandwidth studies have also been prepared for four U.S. manufacturing sectors: petroleum refining (Energetics (2015a)), chemicals (Energetics (2015b)), iron and steel (Energetics (2015c)), and pulp and paper (Energetics (2015d)). These studies followed the same analysis methodology and presentation format as the six lightweight structural material energy bandwidth studies.

1.2. Definitions of Energy Consumption Bands and Opportunity Bandwidths

The consistent methodology used in the bandwidth studies provides a framework to evaluate and compare energy savings potentials within and across manufacturing sectors at the macro-scale.

Four different energy *bands* (or measures) are used consistently in this series to describe different levels of on-site energy consumption to manufacture specific products and to compare energy savings opportunities in U.S. manufacturing facilities. **Current typical** (CT) is the energy consumption in 2010; **state of the art** (SOA) is the energy consumption that may be possible through the adoption of existing best technologies and practices available worldwide; **practical minimum** (PM) is the energy consumption that may be possible if applied R&D technologies under development worldwide are deployed; and the **thermodynamic minimum** (TM) is the least amount of energy required under ideal conditions, which typically cannot be attained in commercial applications.

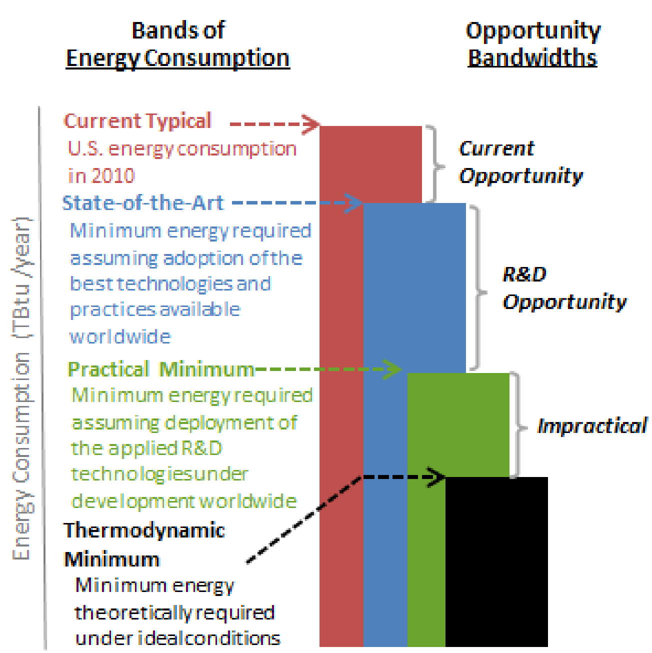

Figure 1-1. Energy consumption bands and opportunity bandwidths estimated in this study
Source: EERE

CT energy consumption serves as the benchmark of manufacturing energy consumption. TM energy consumption serves as the baseline (or theoretical minimum) that is used in calculating energy savings potential. Feedstock energy (the nonfuel use of fossil energy) is not included in the energy consumption estimates.

Two on-site energy savings opportunity *bandwidths* are estimated: the ***current opportunity*** spans the bandwidth from CT energy consumption to SOA energy consumption, and the ***R&D opportunity*** spans the bandwidth from SOA energy consumption to PM energy consumption. These bandwidths are estimated for processes and products studied and for all manufacturing within a sector based on extrapolated data. The difference between PM energy consumption and TM energy consumption is labeled as *impractical*. The term *impractical* is used because the PM energy consumption is based on today's knowledge of R&D technologies tested between laboratory and demonstration scale; further decreases in energy intensity have not been displayed at any physical scale. However, decreasing the PM energy consumption with future R&D efforts and emerging technologies being investigated through modeling and theoretical calculations may eventually bring the PM energy consumption closer to the TM energy consumption. Significant investment in technology development and implementation would be needed to fully realize the energy savings opportunities estimated. The costs associated with achieving SOA and PM energy consumption are not considered in this report; a techno-economic analysis of the costs and benefits of future technologies was not within the scope of this study.

1.3. Bandwidth Analysis Method

This section describes the method used in this bandwidth study to estimate the four bands of energy consumption and the two corresponding energy savings opportunity bandwidths. This section can also be used as a guide to understanding the structure and content of this report.

In this study, U.S. energy consumption is labeled as either "on-site energy" or "primary energy" and defined as follows:

- **On-site energy** (sometimes referred to as site or end use energy) is the energy consumed within the manufacturing plant boundary (i.e., within the plant gates). Non-fuel feedstock energy is not included in the on-site energy consumption values presented in this study.
- **Primary energy** (sometimes referred to as source energy) includes energy that is consumed both offsite and on-site during the manufacturing process. Offsite energy consumption includes generation and transmission losses associated with bringing electricity and steam to the plant boundary. Non-fuel feedstock energy is not included in the primary energy values. In some cases references do not differentiate steam from fuel as an energy source, and without a better estimate it is difficult to determine what portion of steam losses should be accounted for in primary energy. Primary energy is frequently referenced by governmental organizations when comparing energy consumption across sectors.

The four bands of energy consumption described above were quantified for process subareas and for the material total. **The bands of energy consumption and the opportunity bandwidths presented herein consider on-site energy consumption; feedstocks[9] are excluded.** To determine the total annual CT, SOA, PM, and TM energy consumption (TBtu per year), energy intensity values per unit weight (Btu per pound of material manufactured) were estimated and multiplied by the annual production total (pounds of material manufactured per year). The year 2010 was used as a base year since it was the most recent year for which consistent energy consumption and production data were available for all six lightweight materials analyzed in this series of bandwidth studies. Unless otherwise noted, 2010 production data were used.

Chapter 2 presents the **U.S. production** (million pounds per year) for 2010, including an overview of major application areas. Four structural application areas for CFRP composites are included within the scope of this bandwidth report. The production volumes for these application areas are estimated from market data.

[9] Feedstock energy is the nonfuel use of combustible energy.

Chapter 3 presents the estimated on-site **CT energy intensity** (Btu per pound) and **CT energy consumption** (TBtu per year) for the process subareas studied and material total (along with sources and assumptions).

Chapter 4 presents the estimated on-site **SOA energy intensity** (Btu per pound) and **SOA energy consumption** (TBtu per year) for the process subareas studied and material total (along with sources and assumptions).

Chapter 5 presents the estimated on-site **PM energy intensity** (Btu per pound) and **PM energy consumption** (TBtu per year) for the process subareas studied and material total (along with sources and assumptions).

Chapter 6 presents the estimated on-site **TM energy intensity** (Btu per pound) and **TM energy consumption** (TBtu per year) for the process subareas studied and material total (along with sources and assumptions).

Chapter 7 provides a summary of **current and R&D opportunity** analysis based on bandwidth study results.

1.4. Boundaries of the Study

The U.S. CFRP composites manufacturing sector is the physical boundary of this study. It is recognized that the major benefits of using CFRP composites as lightweight materials often occur *outside* of the manufacturing sector—for example, the energy benefits of a lightweight automobile component are typically realized primarily through fuel savings during the vehicle's use phase. Economic impacts are also important: an advanced lightweight aerospace component may be more expensive than the conventional choice. While such impacts are recognized as important, they will not be quantified as this is not a life cycle assessment study. Instead, this report focuses exclusively on the energy use directly involved in the production of carbon fiber composites from the relevant input materials. The focus of this bandwidth study is thus the *on-site* use of process energy (including purchased energy and on-site generated steam and electricity) that is directly applied to CFRP manufacturing at a production facility.

This study does not consider life cycle energy consumed during raw material extraction, off-site treatment, transportation of materials, product use, or disposal. For consistency with previous bandwidth studies, feedstock energy and the energy associated with delivering feedstocks to the plant gate (e.g., producing, conditioning, and transporting feedstocks) are *excluded* from the energy consumption bands in this analysis.

Carbon fibers and fiber-reinforced composites are used in many diverse applications that differ substantially in product use, performance requirements, and relevance to energy use. CFRP materials have strong lightweighting potential in transportation applications, where mass reductions in structural and semi-structural parts can provide substantial energy savings through improved fuel economy. These applications are of high relevance to the DOE because of the potential life cycle energy savings. Other applications, however, are less relevant to the DOE; for example, carbon fibers are becoming increasingly popular for use in consumer products such as smartphone covers, home décor, and even apparel. In order to focus exclusively on structural applications with strong relevance to energy use, this study was limited to four key application areas:

1) Automotive lightweighting (e.g., vehicle chassis, body, doors);
2) Compressed gas storage (e.g., hydrogen fuel tanks for electric vehicles);
3) Wind turbines (e.g., lighter and longer turbine blades); and
4) Aerospace (e.g., aircraft fairings, fuselages, floor panels).

The first three of these application areas are consistent with the areas of interest outlined in the DOE *Composite Materials and Structures* Funding Opportunity Announcement (DOE (2014)). The last application area (aerospace) is an additional high value-add market for lightweight structural materials. Together, the four application areas considered in this study account for approximately 51% of overall carbon fiber production in the United States, as shown in Figure 1-2.[10] Amongst these four application areas, wind energy and aerospace represent the two largest markets, collectively accounting for 42% of carbon fiber production overall and 81% of production for the four structural application areas considered in this report.

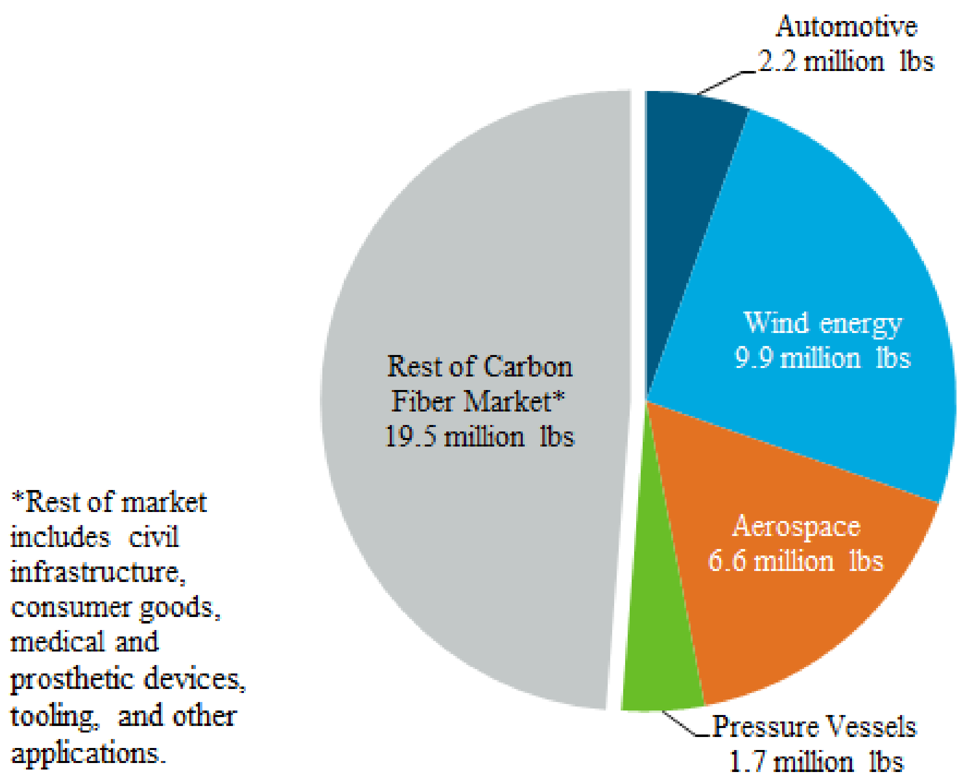

Figure 1-2. Estimated makeup of the carbon fiber market in 2010
Source: EERE

Production of CFRP composites for applications that are outside of the boundaries of this study will be discussed briefly in Chapter 2, but energy consumption will not be quantified. These other applications may include medical devices, electronics and communications, computers and electrical equipment, construction and infrastructure materials, and consumer goods and packaging.

[10] Data sources: JEC (2009) for production data; Holmes (2014) and Black (2012) for application breakdown data. Since JEC reported production capacities only, fiber production was estimated by assuming output coefficients for the manufacturing facilities. An output coefficient of 0.7 was assumed for small tow fibers; 0.9 for large tow; and 0.7 for pitch fibers. Market breakdowns from Holmes and Black were in good agreement. Data from the two sources were averaged to come up with the application breakdown used in this study.

2. Carbon Fiber Reinforced Polymer Composite Production

2.1. Manufacturing Overview

In 2010, United States carbon fiber manufacturers had a total nameplate capacity of 53.2 million pounds,[11] representing about 28% of global production capacity (JEC (2009)). Two general manufacturing methods for carbon fibers have been commercialized to date: the first involves the production of carbon fibers from a polyacrylonitrile (PAN) precursor, while the second method involves the conversion of a petroleum pitch precursor. The PAN process is by far the most common method used, accounting for approximately 98% of U.S. production capacity in the UNITED STATES by weight (JEC (2009)). In this study, the PAN process was considered as the current typical and state of the art manufacturing method for carbon fibers. The pitch process was not considered in this analysis (though alternate, low-energy precursors were included in the practical minimum analysis; see Chapter 6).

Figure 2-1 shows the CFRP composite manufacturing process schematically, assuming the use of PAN as a precursor. The manufacturing process can be divided into six main process steps:

- *Polymerization:* the chemical polymerization of the carbon fiber precursor material (in this case, PAN)
- *Spinning:* the process that produces fibers from the precursor, generally through a wet solution spinning process
- *Oxidation/Carbonization:* a series of thermal processes that stabilize the precursor fibers and burn off non-carbon atoms, producing tightly bonded, carbon-rich fibers
- *Finishing:* the application of surface treatments and coatings (called “sizing”) to protect the fibers and promote bonding with the plastic matrix, and the spooling of the fibers
- *Resin Production:* the manufacture of the polymer resin that will serve as a matrix material in the final composite product
- *Composite Product Forming:* the process of integrating the fibers into the polymer matrix and producing a finished composite product.

[11] This capacity includes fiber production only (not the production of CFRP composites, which would utilize the carbon fibers as an input).

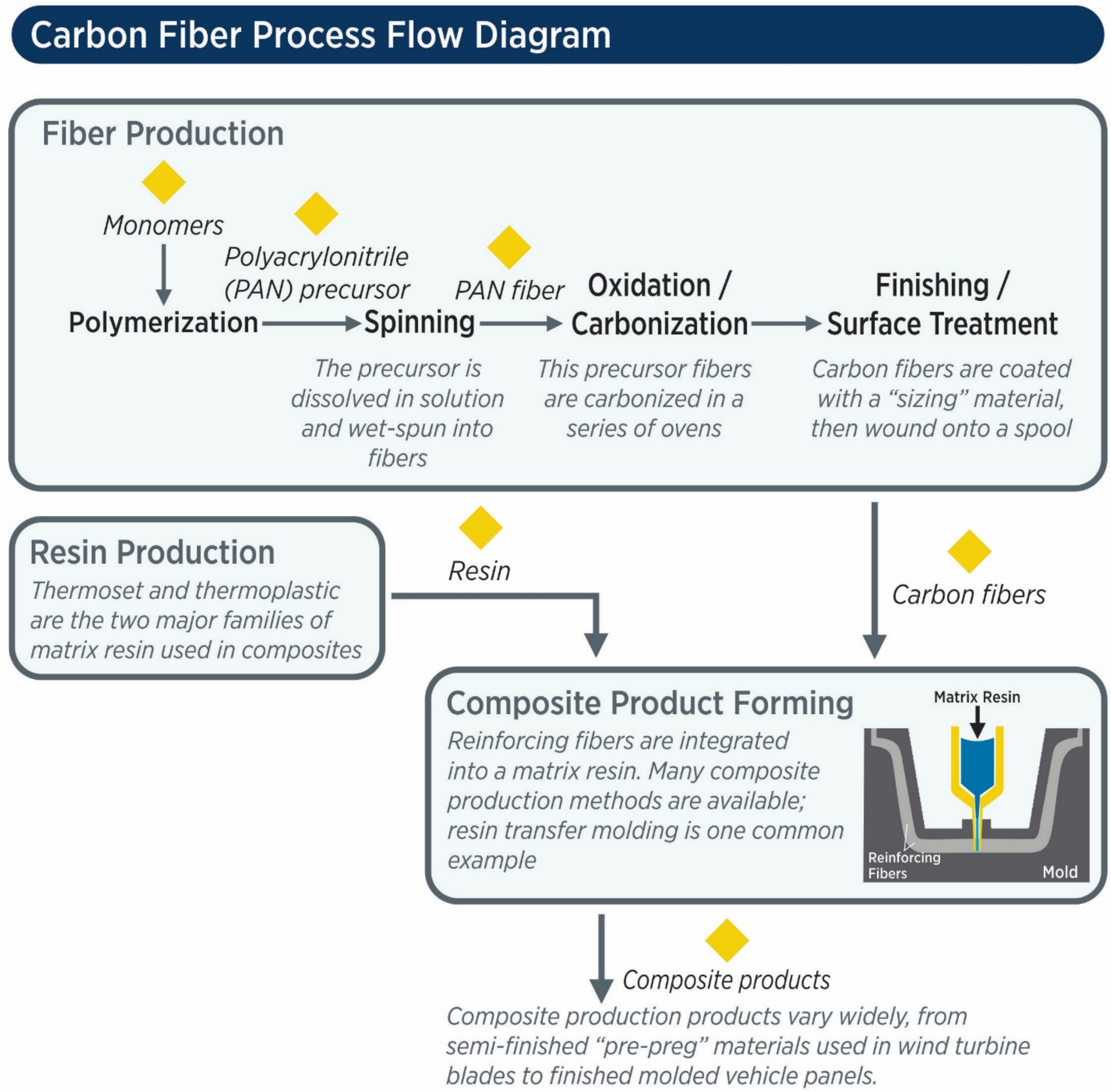

Figure 2-1. Process flow diagram for carbon fiber reinforced polymer composite manufacturing
Source: EERE

These process steps are further identified in Table 2-1, noting that the first four process steps listed (polymerization, spinning, oxidation/carbonization, and finishing) are sub-processes of carbon fiber production. Six different polymer matrix materials were considered in this study, including two thermosetting polymers (epoxy[12] and polyurethane[13]) and four thermoplastic polymers (polypropylene, high-density polyethylene, polyvinyl chloride,[14] and polystyrene[15]). Ten composite forming techniques were considered, including two intermediate (semi-finished) manufacturing techniques (pre-impregnated fabric or "prepreg," and sheet or bulk molding compounds), and eight direct forming methods (hand lay up or spray up, filament

[12] The epoxy system considered was bisphenol-A and epichlorohydrin. Epoxy hardeners were not considered.
[13] The polyurethane material considered was rigid polyurethane foam.
[14] The polyvinyl chloride material considered was produced via bulk polymerization.
[15] The polystyrene material considered was general-purpose polystyrene (GPPS) produced via continuous-mass radical polymerization.

winding, pultrusion, injection molding, compression molding, resin transfer molding [including vacuum-assisted resin infusion], thermoforming, and cold press). Direct molding processes result in a finished component, whereas intermediate manufacturing techniques result in a semi-finished product (typical a fabric, molding compound, or tape) that must undergo additional process steps to form the finished component. The energy consumed in these further process steps, which are often carried out offsite by an end-use manufacturer, was not considered in this analysis.

Additional resin materials and product forming techniques that are commonly used in composites manufacturing, but that were not included in this Bandwidth analysis, are listed in Table 2-1 for reference.

Energy intensity and consumption are evaluated by process area and sub-process for CT, SOA, PM, and TM in Chapters 3 through 6 of this report. Appendix A1 provides a summary of all data. To determine the total energy consumption for a given composite product, it is necessary to first sum the energy consumption for all four sequential carbon fiber production steps, then add the energy consumption for the selected resin material and product forming technique in a "mix-and-match" fashion. In this report, epoxy is used as the resin material and resin transfer molding is used as the product forming technique anywhere a total energy intensity or consumption is presented. However, readers may substitute values for other resins or processes into the formulae provided in this report to determine totals for other combinations.

Table 2-1. Carbon Fiber Reinforced Composites Manufacturing Process Subareas and Sub-Processes Considered in the Bandwidth Analysis

Subareas	Sub-processes/products
Carbon Fiber Production *(four sequential steps)*	- Polymerization - Spinning - Oxidation/Carbonization - Finishing
Resin Production	Thermosetting Resins: - Epoxy - Polyurethane - Vinyl ester* - Polyester* - Phenolic* - Polyimide* Thermoplastic Resins: - Polypropylene (PP) - High-density polyethylene (HDPE) - Polyvinyl chloride (PVC) - Polystyrene (PS) - Polyether ether ketone (PEEK)* - Polyamide (e.g., Nylon)*
Composite Product Forming	Intermediate (Semi-finished) Manufacturing Methods: - Prepreg - Sheet or bulk molding compound Direct Forming Methods: - Open molding (hand lay up or spray up) - Filament winding - Pultrusion - Injection molding - Compression molding - Resin transfer molding (including vacuum infusion) - Thermoforming - Cold press

2.2. Production Values

Production data for 2010 are summarized in Table 2-2, which shows the global production, U.S. production, and estimated U.S. production for the boundary applications. A 2009 market survey by JEC Composites (JEC (2009)) was used as the source for global and U.S. production capacity data for carbon fibers.[16] Note that 2010 data were projected from 2008 in this study. Total fiber production was broken down by application area (see Figure) using data from additional market reports (Black (2012), Holmes (2014)) to estimate the quantity of carbon fibers produced for the four boundary applications (automotive, wind energy, compressed gas storage, and aerospace).

Resin and composite production values were calculated by assuming a 50:50 weight ratio of fiber reinforcement to polymer matrix.[17] The resin production numbers, therefore, are an estimate of the production of polymer resins for use in carbon fiber composites only, and do not reflect the total production of these materials in the UNITED STATES for all applications. Global and U.S. production values for resins and composites were calculated only for the boundary applications, as some carbon fibers outside of the boundary applications were not used in the production of fiber-reinforced polymer composites. For example, carbon fibers are used in the construction industry for cement reinforcement; such fibers would not be integrated into a polymer matrix and thus are not included in the production totals.

Table 2-2. Global and U.S. Production of Carbon Fiber Composites in 2010

Subarea	Product	2010 Total Global Production (million lbs/yr)	2010 Total U.S. Production (million lbs/yr)	2010 Estimated U.S. Production for Boundary Applications (million lbs/yr)
Carbon Fiber Production	Carbon fiber	140.8	39.9	20.5
Resin Production for Structural CFRP Composites	Matrix resin	n/a*	n/a*	20.5
Structural Composite Production**	Composite product	n/a*	n/a*	40.9

* Not calculated because some fibers outside of the boundary applications were not used in the production of fiber-reinforced polymer composites.
** Structural composite production represents the sum of carbon fiber reinforcement production (for boundary applications) and resin production (for boundary applications, assuming a 50:50 weight ratio of fibers to polymer); independent rounding explains why the values do not sum in this summary table.

[16] Since JEC Composites reported production capacities only, fiber production was estimated by assuming output coefficients for the manufacturing facilities. An output coefficient of 0.7 was assumed for small tow fibers; 0.9 for large tow; and 0.7 for pitch fibers. These coefficients are consistent with published sources (Shin (2014), Moore (2012)).
[17] It is noted that fiber ratio in a CFRP composite can vary widely depending on the specific performance requirements in the application, but a 50:50 weight ratio is considered representative of structural lightweighting applications. This weight ratio was the median value in seven CFRP lightweighting case studies for automotive applications identified in a literature review (see Appendix A2 for details).

3. Current Typical Energy Intensity and Energy Consumption

This chapter presents energy intensity and consumption data for CFRP manufacturing processes, based on 2010 production data for the boundary application areas. It is noted that energy consumption in a manufacturing process can vary widely for diverse reasons, including production volume, differences in equipment, and the specific processing techniques employed at any given facility. The energy intensity estimates reported herein are considered representative of typical processes used to produce CFRP composites in the United States today; they do not represent energy consumption in any specific facility or any particular region in the United States.

3.1. Current Typical Energy Intensity

Table 3-1 presents the estimated CT energy intensities for carbon fibers. Energy intensities for all sub-processes are presented in terms of Btu per pound (Btu/lb) of finished carbon fibers. Facility energy data for carbon fiber production from a PAN precursor were provided by Oak Ridge National Laboratory (ORNL), including a detailed energy breakdown by sub-process. The PAN-based process used at ORNL is considered representative of commercial manufacturing processes. On-site CT energy intensity data were converted to primary energy data using process-specific energy mix assumptions, taking into account the relative use of electricity and fuel in each sub-process. Primary energy includes offsite energy generation and transmission losses. These assumptions are described in Appendix A3.

Table 3-1. Current Typical Energy Intensity for Production of Carbon Fibers

Carbon Fiber Production Sub-Process	On-site CT Energy Intensity (Btu/lb)	Primary* CT Energy Intensity (Btu/lb)	Data Source
Polymerization	50,756	67,064	Das & Warren (2014)
Spinning	83,664	91,139	Das & Warren (2014)
Oxidation/Carbonization	83,966	183,567	Das & Warren (2014)
Finishing	10,414	32,243	Das & Warren (2014)
Total Energy Intensity for Carbon Fibers**	**228,800**	**374,013**	

*Primary energy accounts for offsite electricity generation and transmission losses, assuming a grid efficiency of 32.3%. Process-specific energy mix data were used to determine the ratio of fuel and electricity consumed on site. See Appendix A3 for energy mix assumptions.

**Note: totals may not sum due to independent rounding.

Table 3-2 presents the estimated CT energy intensities for the six matrix resin materials studied. Energy intensities are presented in terms of Btu per pound (Btu/lb) of resin. For polypropylene (PP), high-density polyethylene (HDPE), polyvinyl chloride (PVC), and polystyrene (PS), data were drawn from the 2011 American Chemistry Council report, *Cradle-to-Gate Life Cycle Inventory of Nine Plastic Resins and Four Polyurethane Precursors*. This report quantified average energy use for resin manufacturing based on primary energy data submitted by 80 different resin/precursor manufacturing plants in North America. These data are considered very high quality, and representative of U.S. production. For epoxy resin and polyurethane resin, ACC data were not available. For these materials, data were drawn from the PlasticsEurope *Eco-Profiles.* The energy data reported in the *Eco-Profiles* are representative of average production processes in Europe, and are similarly high quality. Where data were available from both sources, ACC and PlasticsEurope energy intensity data were in good agreement (≤10% difference between values), indicating that energy use in U.S. and

European plants are generally similar for the resins considered. Note that feedstock energy is not included in the energy intensities reported here for consistency with past bandwidth reports.[18]

Table 3-2. Current Typical Energy Intensity for Production of Matrix Resins

Matrix Polymer	On-site CT Energy Intensity (Btu/lb)	Primary* CT Energy Intensity (Btu/lb)	Data Source
Thermosetting Resins			
Epoxy resin	34,256	40,105	PlasticsEurope (2006)
Polyurethane resin	11,398	27,355	PlasticsEurope (2005b)
Thermoplastic Resins			
Polypropylene (PP)	5,227	11,822	ACC (2011)
High density polyethylene (HDPE)	6,845	14,617	ACC (2011)
Polyvinyl chloride (PVC)	9,158	15,261	ACC (2011)
Polystyrene (PS)	10,751	18,099	ACC (2011)

*Primary energy accounts for offsite electricity generation and transmission losses, assuming a grid efficiency of 32.3%. Process-specific energy mix data were used to determine the ratio of fuel and electricity consumed on site. See Appendix A3 for energy mix assumptions.

Current typical energy intensity values for composite product forming are presented in Table 3-3, along with the sources used. Energy intensities are presented in terms of Btu per pound (Btu/lb) of composite product (fibers and resin).

[18] Feedstock energies were given in both ACC and PlasticsEurope data, but were subtracted from the totals in this analysis.

Table 3-3. Current Typical Energy Intensity for Composite Product Forming

Forming Method	On-site CT Energy Intensity (Btu/lb)	Primary* Energy Intensity (Btu/lb)	Data Source
Intermediate (Semi-Finished) Manufacturing Methods			
Prepreg	17,196	53,238	Suzuki & Takahashi (2005)
Sheet or bulk molding compound	1,505	4,658	Suzuki & Takahashi (2005)
Direct Forming Methods			
Open molding (hand lay up or spray up)	2,237	5,805	USLCI (2012)
Filament winding	1,161	3,594	Suzuki & Takahashi (2005)
Pultrusion	1,333	4,126	Suzuki & Takahashi (2005)
Injection molding	2,794	8,651	MFI (2016)
Compression molding	2,632	7,790	USLCI (2012)
Resin transfer molding (including vacuum infusion)	1,093	2,014	USLCI (2012)
Thermoforming	11,048	33,935	Franklin (2011)
Cold press	5,073	15,705	Suzuki & Takahashi (2005)

*Primary energy accounts for offsite electricity generation and transmission losses, assuming a grid efficiency of 32.3%. Process-specific energy mix data were used to determine the ratio of fuel and electricity consumed on site. See Appendix A3 for energy mix assumptions.

3.2. Current Typical Energy Consumption

Table 3-4 presents the calculated on-site and primary CT energy consumption for the CFRP production subareas studied. In these summary data, epoxy resin was assumed as the polymer matrix material and resin transfer molding was assumed as the composite production method. These selections are considered representative of current typical CFRP systems for structural applications. Energy consumption values were calculated by multiplying energy intensity (Btu/lb) by 2010 production (lbs). As described in the previous section, on-site energy intensities were converted to primary (and vice versa) using process-specific energy mix data. Electricity losses were calculated by subtracting the on-site energy consumption from the primary energy consumption.

Table 3-4. Calculated Current Typical Energy Consumption for Carbon Fiber Reinforced Polymer Composite Manufacturing: Application Areas Studied (2010)

Subarea (product)	On-site CT Energy Intensity (Btu/lb)	Primary CT Energy Intensity (Btu/lb)	Production (million lbs)	On-site CT Energy Consumption (TBtu/yr)	Offsite Losses, Calculated (TBtu/yr)	Primary CT Energy Consumption (TBtu/yr)
Carbon Fiber Production (carbon fibers)						
Polymerization	50,756	67,064	20.5	1.04	0.33	1.37
Spinning	83,664	91,139	20.5	1.71	0.15	1.87
Oxidation/Carbonization	83,966	183,567	20.5	1.72	2.04	3.76
Finishing	10,414	32,243	20.5	0.21	0.45	0.66
Resin Production* (matrix polymer)	34,256	40,105	20.5	0.70	0.12	0.82
Composite Product Forming** (composite product)	1,093	2,014	40.9	0.04	0.04	0.08
Total* **				**5.43**	**3.13**	**8.56**

* Assumes thermosetting epoxy resin.

** Assumes resin transfer molding.

***Note: totals may not sum due to independent rounding.

4. State of the Art Energy Intensity and Energy Consumption

This chapter estimates the energy savings possible if U.S. carbon fiber, resin, and composites manufacturers were to adopt the best technologies and practices available worldwide. State of the art (SOA) energy intensity is considered the minimum amount of energy needed for a specific process, assuming use of best-available commercial technologies and practices. The SOA energy intensity estimates reflect the use of a combination of state-of-the-art technologies, and do not represent energy consumption or manufacturing practices in any specific facility or any particular region in the United States or globally.

4.1. State of the Art Energy Intensity

CFRP composites are seeing a rapid evolution in state of the art technologies and practices. Carbon fiber producers utilize many proprietary processes and custom equipment, and facilities vary widely in size, efficiency, and in the types and amounts of products produced. As a result, there is no "standard" CFRP manufacturing protocol with known energy requirements. A wide range of energy intensities is assumed to exist among U.S. carbon fiber producers, though there is little published information about this topic.

In this study, the PAN carbon fiber production process (i.e., the current typical process) is used as the baseline for the SOA process. It is reasonable that the PAN process would be assumed for both measures of energy intensity, as 98% of U.S. carbon fiber producers utilize this manufacturing method (JEC (2009)). However, the CT energy intensity values are representative of typical processing, and do not necessarily incorporate energy savings from the best-available commercial technologies and practices. SOA energy intensity was therefore estimated by applying assumed energy savings percentages for applicable SOA technologies to the CT value. The SOA technologies considered in this analysis and assumed energy savings were are described as below. Each technology was considered individually initially (and not additively), acknowledging that the effects of some technologies may overlap if more than one technology is applicable to a subarea or sub-process. See Appendix A4 for more details.

- **Carbon fiber recycling:** 9% savings in the polymerization, spinning, oxidation/carbonization, and finishing processes
- **Motor re-sizing and/or use of variable-speed drives (VSD):** 12% savings in the spinning and finishing processes (applied to the electricity component only)
- **More efficient furnaces:** 10% savings in the oxidation/carbonization process
- **Improved heat transfer/heat containment:** 20% savings in the oxidation/carbonization process
- **Process heating control systems:** 3% savings in the oxidation/carbonization process
- **Waste heat recovery systems:** 13% savings in the oxidation/carbonization process.

For further discussion of these technologies and energy savings estimates, including references, see Appendix A4. Table 4-1 presents the estimated SOA energy intensities for carbon fibers.

Table 4-1. State of the Art Energy Intensity for Production of Carbon Fibers

Carbon Fiber Production Sub-Process	On-site SOA Energy Intensity (Btu/lb)	Primary* SOA Energy Intensity (Btu/lb)	Data Source
Polymerization	46,188	61,029	Calculated; see Appendix A4
Spinning	75,761	82,530	Calculated; see Appendix A4
Oxidation/Carbonization	46,659	102,006	Calculated; see Appendix A4
Finishing	8,387	25,966	Calculated; see Appendix A4
Total Energy Intensity for Carbon Fibers**	**176,995**	**271,531**	

State of the Art (SOA)
*Primary energy accounts for offsite electricity generation and transmission losses, assuming a grid efficiency of 32.3%. Process-specific energy mix data were used to determine the ratio of fuel and electricity consumed on site. See Appendix A3 for energy mix assumptions.
** Note: totals may not sum due to independent rounding.

For resin production, SOA energy intensity values were estimated by assuming a 20% energy savings over the lower of the current average primary energy intensity values reported for U.S. plants (based on ACC data) and European plants (based on PlasticsEurope data). The 20% savings figure is consistent with the ACC report (ACC (2011)), which stated that "individual plant results varied as much as 25 percent on either side of the average total energy." Table 4-2 presents the estimated SOA energy intensities for the six matrix polymer materials studied. Note that feedstock energy is not included in the energy intensities reported here for consistency with past bandwidth reports.[19]

[19] Feedstock energies were given in both ACC and PlasticsEurope data, but were subtracted from the totals in this analysis.

Table 4-2. State of the Art Energy Intensity for Production of Matrix Resins

Matrix Polymer	On-site SOA Energy Intensity (Btu/lb)	Primary* SOA Energy Intensity (Btu/lb)	Data Source
Thermosetting Resins			
Epoxy resin	27,405	32,084	Best engineering judgment (PlasticsEurope (2006) + 20% savings)
Polyurethane resin	9,118	21,884	Best engineering judgment (PlasticsEurope (2005a) + 20% savings)
Thermoplastic Resins			
Polypropylene (PP)	4,182	9,458	Best engineering judgment (ACC (2011) + 20% savings)
High density polyethylene (HDPE)	4,461	9,527	Best engineering judgment (ACC (2011) + 20% savings)
Polyvinyl chloride (PVC)	6,666	11,109	Best engineering judgment (PlasticsEurope (2005b) + 20% savings)
Polystyrene (PS)	8,249	13,887	Best engineering judgment (PlasticsEurope (2012) + 20% savings)

State of the Art (SOA)
*Primary energy accounts for offsite electricity generation and transmission losses, assuming a grid efficiency of 32.3%. Process-specific energy mix data were used to determine the ratio of fuel and electricity consumed on site. See Appendix A3 for energy mix assumptions.

SOA energy intensity values for composite product forming are presented in Table 4-3. For injection molding, a best practice energy intensity was available from a literature source. For the other processes, no best practice/best plant values were available in the literature; for these processes, the SOA intensity was assumed to be 20% lower than the current typical intensity. These values represent the authors' best engineering judgment.

Table 4-3. State of the Art Energy Intensity for Composite Product Forming

Production Method	On-site SOA Energy Intensity (Btu/lb)	Primary* SOA Energy Intensity (Btu/lb)	Data Source
Intermediate (Semi-Finished) Manufacturing Methods			
Prepreg	13,757	42,591	Best engineering judgment (20% savings)
Sheet or bulk molding compound	1,204	3,727	Best engineering judgment (20% savings)
Direct Forming Methods			
Open molding (*hand lay up or spray up)*	1,696	3,506	USLCI (2012)
Filament winding	929	2,875	Best engineering judgment (20% savings)
Pultrusion	1,066	3,301	Best engineering judgment (20% savings)
Injection molding	925	2,863	Thiriez (2006)
Compression molding	2,106	6,232	Best engineering judgment (20% savings)
Resin transfer molding (including vacuum infusion)	874	1,611	Best engineering judgment (20% savings)
Thermoforming	8,839	27,148	Best engineering judgment (20% savings)
Cold press	4,058	12,564	Best engineering judgment (20% savings)

*Primary energy accounts for offsite electricity generation and transmission losses, assuming a grid efficiency of 32.3%. Process-specific energy mix data were used to determine the ratio of fuel and electricity consumed on site. See Appendix A3 for energy mix assumptions.

4.2. State of the Art Energy Consumption

Table 4-4 presents the calculated on-site and primary SOA energy consumption for the CFRP production subareas studied. In these summary data, epoxy resin was assumed as the polymer matrix material and resin transfer molding was assumed as the composite product forming method. These selections are considered representative of current state of the art CFRP systems for structural applications. Energy consumption values were calculated by multiplying energy intensity (Btu/lb) by 2010 production (lbs). On-site energy intensities were converted to primary (and vice versa) using process-specific energy mix data, as described in Appendix A3. Some data sources provide primary values and others provide on-site values; offsite losses attributed to electricity generation and transmission are accounted for and either subtracted or added to convert between the onsite and primary.

Table 4-4. Calculated State of the Art Energy Consumption for Carbon Fiber Reinforced Polymer Composite Manufacturing: Application Areas Studied

Subarea (product)	On-site SOA Energy Intensity (Btu/lb)	Primary SOA Energy Intensity (Btu/lb)	Production (million lbs)	On-site SOA Energy Consumption (TBtu/yr)	Offsite Losses, Calculated (TBtu/yr)	Primary SOA Energy Consumption (TBtu/yr)
Carbon Fiber Production (carbon fibers)						
Polymerization	46,188	61,029	20.5	0.95	0.31	1.25
Spinning	75,761	82,530	20.5	1.55	0.75	1.69
Oxidation/Carbonization	46,659	102,006	20.5	0.95	2.03	2.09
Finishing	8,387	25,966	20.5	0.17	0.39	0.53
Resin Production* (matrix polymer)	27,405	32,084	20.5	0.56	0.10	0.66
Composite Production** (composite product)	874	1,611	40.9	0.04	0.03	0.07
Total* **				**4.22**	**2.06**	**6.28**

State of the Art (SOA)
* Assumes thermosetting epoxy resin.
** Assumes resin transfer molding
*** Note: totals may not sum due to independent rounding.

Table 4-5 presents a comparison of the on-site CT energy consumption and SOA energy consumption for each process subarea and as a total. The difference between the CT and SOA energy consumption values is presented as the SOA energy savings (or *current opportunity*).

The SOA energy savings percent in Table 4-5 is the percent of energy saved with SOA energy consumption compared to CT energy consumption, while referencing the thermodynamic minimum as the baseline energy consumption. Thermodynamic minimum (TM), discussed further in Chapter 6, is considered to be equal to zero in an ideal case with perfect efficiency (i.e., energy input to a system is considered fully recoverable with no friction losses or change in surface energy). For manufacturing processes where there is an irreversible change to the material, resulting in a change to the embodied free energy content of the material (i.e., chemical reaction or permanent crystalline change due to deformation), TM is not necessarily equal to zero; in some cases the change in theoretical free energy content of the material requires energy input (TM > 0) and in other cases the change creates a theoretical free energy gain (TM < 0). Referencing TM as the baseline in comparing bandwidths of energy consumption and calculating energy savings percent provides the most accurate measure of absolute savings potential. The equation for calculating on-site SOA energy savings percent is:

$$SOA\ Savings\ \% = current\ opportunity\ \% = \frac{CT - SOA}{CT - TM}$$

It is useful to consider both TBtu energy savings and energy savings percent when comparing energy savings opportunities. Both are good measures of opportunity; however, the conclusions are not always the same. A small percent energy reduction in a process that consumes a large amount of energy may result in a larger total savings than a large percent reduction in a process that consumes a relatively smaller amount of energy. Among the processes studied, the greatest *current opportunity* is oxidation/carbonization at 44.0% energy savings (0.76 TBtu per year). This sub-process represented the largest opportunity both in terms of percent energy savings and in terms of net TBtu savings.

If all U.S carbon fiber, resin, and composites producers (based on the 2010 production level of CFRP composites for application areas considered) were able to attain SOA energy intensities, it is estimated that a total of 1.34 TBtu of on-site energy could be saved annually, corresponding to a 22% energy savings overall for the application areas considered in this report. This energy savings estimate is based on adopting available SOA technologies and practices without accounting for future gains in energy efficiency from R&D. This is a simple estimate for potential savings; not all existing plants could necessarily achieve these state of the art values. No assessment was made in this study regarding whether the improvements would prove to be cost effective in all cases.

Table 4-5. Calculated State of the Art Energy Savings for Carbon Fiber Composite Manufacturing: Application Areas Studied

Subarea (product)	On-site CT Energy Consumption, Calculated (TBtu/yr)	On-site SOA Energy Consumption, Calculated (TBtu/yr)	SOA Energy Savings* (CT – SOA) (TBtu/yr)	SOA Energy Savings Percent** (CT-SOA)/(CT-TM)
Carbon Fiber Production (carbon fibers)				
Polymerization	1.04	0.95	0.09	8.7%
Spinning	1.71	1.55	0.16	9.4%
Oxidation/Carbonization	1.72	0.95	0.76	44.0%
Finishing	0.21	0.17	0.04	19.5%
Resin Production (matrix polymer)	0.70	0.56	0.14	19.9%
Composite Product Forming** (composite product)	0.04	0.04	0.01	20.0%
Total* **	**5.43**	**4.22**	**1.21**	**22.1%**

State of the Art (SOA)

* SOA energy savings is also called *Current Opportunity.*

** SOA energy savings percent is the SOA energy savings opportunity from transforming carbon fiber composite production processes through the adoption of state of the art equipment and practices. Energy savings percent is calculated using the TM energy consumption shown in Table 6-4 as the minimum energy consumption. The energy savings percent, with TM as the minimum, was calculated as follows: SOA Energy Savings Percent = (CT-SOA)/(CT-TM)

***Note: totals may not sum due to independent rounding.

5. Practical Minimum Energy Intensity and Energy Consumption

Technology innovation is the driving force for economic growth. Across the globe, R&D is underway to make CFRP composites in new ways, improving energy efficiency as well as composite performance. Commercialization of these improvements will drive the competitiveness of U.S. CFRP composites manufacturing. In this chapter, the energy savings possible through R&D advancements in CFRP composites manufacturing are estimated. Practical minimum (PM) is the minimum amount of energy required assuming the successful deployment of applied R&D technologies under development worldwide.

5.1. Practical Minimum Energy Intensity

R&D progress is difficult to predict, and the realization of potential gains in energy efficiency can depend on financial investments and market priorities. To estimate PM energy consumption for this bandwidth analysis, a review of R&D activities in carbon fiber manufacturing, polymer resin manufacturing, and composites production techniques was conducted. The focus of this search was applied research, defined as the investigation and development of new technologies with the intent of accomplishing a particular commercial objective. Basic science research, involving experimentation and modeling to expand understanding of fundamental mechanisms and principles without a direct link to commercial objectives, was not considered. Further, applied R&D technologies without a clear connection to manufacturing energy consumption (improved damage detection or multi-material joining techniques, for example) were not considered in this study.

An active area of CFRP composites R&D is precursor development. As discussed in Chapter 2.1. , two carbon fiber precursors are used in commercial production today: PAN and petroleum pitch. Several alternate fiber precursors are currently under development, including polyolefin and biomass lignin. Currently, fibers produced from these precursor materials do not match the strength and performance of PAN- and pitch-based fibers—but they are less energy intensive and less costly, and represent an important R&D area.

Facility energy data for carbon fiber production from polyolefin and lignin precursors were provided by Oak Ridge National Laboratory (ORNL), including a detailed energy breakdown by sub-process. In this study, the polyolefin carbon fiber production process was used as the baseline for the PM process. Biomass lignin precursors were also considered, but were not ultimately included in the PM model because the energy intensity baseline for the lignin process was higher than that of the polyolefin process. Compared to the conventional PAN precursor process, the polyolefin process offers energy advantages including a lower-embodied energy raw material, the ability to melt-spin rather than solution-spin, and increased carbonization yield.

PM energy intensity was estimated for carbon fibers by applying assumed energy savings percentages for applicable PM technologies to the baseline energy intensities for the polyolefin process. The PM technologies included in this analysis and assumed energy savings were:[20]

- **Polyolefin precursor:** baseline carbon fiber manufacturing process for PM calculation
- **Carbon fiber recycling:** 35% savings in the polymerization, spinning, oxidation/carbonization, and finishing processes
- **Microwave carbonization:** 45% savings in the oxidation/carbonization process
- **Process integration/pinch analysis:** 4% savings across all processes (cross-cutting technology).

The energy savings from the PM technologies essentially “stack” with the SOA technologies described earlier, and are not double-counted in the analysis. For a discussion of these technologies and energy savings estimates, see Appendix A5. Appendix A5 also provides details of additional technologies that were

[20] Note that three of the technologies listed (carbon fiber recycling, motor re-sizing or VSDs, and process heating control systems) were also included in the SOA model described in Chapter 4. These technologies are considered part of the *current opportunity* rather than the *R&D opportunity*. However, energy savings for these technologies were re-applied in the PM calculation because the baseline data for the polyolefin process did *not* include the use of all of the SOA technologies described in this study. For one technology (carbon fiber recycling), different applicability rates were assumed for the SOA and PM cases. See Appendices A4 and A5 for further details.

considered but not included in the final PM model. The excluded technologies were considered incompatible with the polyolefin production process or with PM technologies already included in the model. For example, energy savings opportunities from waste heat recovery were not included in the PM model because it was assumed that savings would be negligible when using a selective heating process (microwave heating) for the oxidation/carbonization process step. Table 5-1 presents the estimated PM energy intensities for carbon fibers. Note that the Polymerization sub-process is not applicable in the PM case because the input material for the polyolefin precursor process (polyethylene) does not require further polymerization prior to the spinning sub-process.

Table 5-1. Practical Minimum Energy Intensity for Production of Carbon Fibers

Carbon Fiber Production Sub-Process	On-site PM Energy Intensity (Btu/lb)	Primary** PM Energy Intensity (Btu/lb)	Data Source
*Polymerization**	0	0	
Spinning	1,610	5,868	Calculated; see Appendix A5
Oxidation/Carbonization	14,271	60,917	Calculated; see Appendix A5
Finishing	4,141	15,089	Calculated; see Appendix A5
Total Energy Intensity for Carbon Fibers* **	**20,022**	**81,874**	

Practical Minimum (PM)
* Polymerization step not required for Practical Minimum process.
**Primary energy accounts for offsite electricity generation and transmission losses, assuming a grid efficiency of 32.3%. Process-specific energy mix data were used to determine the ratio of fuel and electricity consumed on-site. See Appendix A3 for energy mix assumptions.
***Note: totals may not sum due to independent rounding.

For resin manufacturing and composite product forming processes, the baseline energy intensity for the practical minimum calculation was the SOA intensity. PM energy intensity was again estimated by applying assumed energy savings percentages for applicable PM technologies to the baseline energy intensities. The PM technologies and assumed energy savings were:

For resin manufacturing:

- **Plastics recycling and recovery:** 49% savings for thermoplastic resins and 35% savings for thermosetting resins
- **Process integration/pinch analysis:** 4% savings across all processes (cross-cutting technology).

For composite product forming:

- **Barrel insulation to reduce thermal losses:** 10% savings for injection molding, resin transfer molding, and vacuum-assisted resin infusion
- **Infrared heating with emissivity matching:** 50% savings for pultrusion and thermoforming
- **Improved die design:** 5% savings for pultrusion
- **Process integration/pinch analysis:** 4% savings across all processes (cross-cutting technology).

For a discussion of these technologies and energy savings estimates, including references, see Appendix A5. Table 5-2 and Table 5-3 present the estimated PM energy intensities for the six matrix polymer materials and the twelve composites production techniques studied, respectively.

Table 5-2. Practical Minimum Energy Intensity for Production of Polymer Matrix Resins

Matrix Polymer	On-site PM Energy Intensity (Btu/lb)	Primary* PM Energy Intensity (Btu/lb)	Data Source
Thermosetting Resins			
Epoxy resin	17,101	20,021	Calculated; see Appendix A5
Polyurethane resin	5,690	13,655	Calculated; see Appendix A5
Thermoplastic Resins			
Polypropylene (PP)	2,047	4,631	Calculated; see Appendix A5
High density polyethylene (HDPE)	2,184	4,664	Calculated; see Appendix A5
Polyvinyl chloride (PVC)	3,264	5,439	Calculated; see Appendix A5
Polystyrene (PS)	4,039	6,799	Calculated; see Appendix A5

Practical Minimum (PM)
*Primary energy accounts for offsite electricity generation and transmission losses, assuming a grid efficiency of 32.3%. Process-specific energy mix data were used to determine the ratio of fuel and electricity consumed on site. See Appendix A3 for energy mix assumptions.

Table 5-3. Practical Minimum Energy Intensity for Composite Production

Production Method	On-site PM Energy Intensity (Btu/lb)	Primary* PM Energy Intensity (Btu/lb)	Data Source
Semi-Finished Production Methods			
Prepreg	13,207	40,887	Calculated; see Appendix A5
Sheet or bulk molding compound	1,156	3,578	Calculated; see Appendix A5
Direct Forming Methods			
Open molding (hand lay up or spray up)	1,628	3,366	Calculated; see Appendix A5
Filament winding	891	2,760	Calculated; see Appendix A5
Pultrusion	486	1,505	Calculated; see Appendix A5
Injection molding	799	2,474	Calculated; see Appendix A5
Compression molding	2,021	5,983	Calculated; see Appendix A5
Resin transfer molding (including vacuum infusion)	755	1,392	Calculated, see Appendix A5
Thermoforming	4,243	13,031	Calculated; see Appendix A5
Cold press	3,896	12,062	Calculated; see Appendix A5

Practical Minimum (PM)
*Primary energy accounts for offsite electricity generation and transmission losses, assuming a grid efficiency of 32.3%. Process-specific energy mix data were used to determine the ratio of fuel and electricity consumed on site. See Appendix A3 for energy mix assumptions.

5.2. Practical Minimum Energy Consumption

Table 5-4 presents the calculated on-site and primary PM energy consumption for the CFRP production subareas studied. In these summary data, epoxy resin was assumed as the polymer matrix material and resin transfer molding was assumed as the composite product forming method. Energy consumption values were calculated by multiplying energy intensity (Btu/lb) by 2010 production (lbs). On-site energy intensities were converted to primary (and vice versa) using process-specific energy mix data, as described in Appendix A3. Some data sources provided primary values and others provided on-site values; offsite losses attributed to electricity generation and transmission are accounted for in the conversion between the onsite and primary.

Table 5-4. Calculated Practical Minimum Energy Consumption for Carbon Fiber Reinforced Composite Manufacturing: Application Areas Studied

Subarea (product)	On-site PM Energy Intensity (Btu/lb)	Primary PM Energy Intensity (Btu/lb)	Production (million lbs)	On-site PM Energy Consumption (TBtu/yr)	Offsite Losses, Calculated (TBtu/yr)	Primary PM Energy Consumption (TBtu/yr)
Carbon Fiber Production (carbon fibers)						
Polymerization*	0	0	0	0	0	0
Spinning	1,610	5,868	20.5	0.03	0.09	0.12
Oxidation/Carbonization	14,271	60,917	20.5	0.29	0.95	1.25
Finishing	4,141	15,089	20.5	0.08	0.22	0.31
Resin Production** (matrix polymer)	17,101	20,021	20.5	0.35	0.06	0.41
Composite Product Forming*** (composite product)	755	1,392	40.9	0.03	0.03	0.06
Total******				**0.79**	**1.35**	**2.14**

Practical Minimum (PM)
* Polymerization step not required for Practical Minimum process.
** Assumes thermosetting epoxy resin.
*** Assumes resin transfer molding.
****Note: totals may not sum due to independent rounding.

Table 5-5 presents a comparison of the on-site CT energy consumption and PM energy consumption for each process subarea and as a total. The difference between the CT and PM energy consumption values is presented as the PM energy savings (or the sum of the *Current Opportunity* plus the *R&D Opportunity*). Table 5-6 calculates the R&D opportunity for the process subareas studied.

Among the processes studied, the greatest *current* plus *R&D opportunity* is spinning, at 98.1% energy savings (1.68 TBtu). This sub-process represented the largest *current* plus *R&D opportunity* both in terms of percent energy savings and in terms of net TBtu savings.

If all U.S carbon fiber, resin, and composites producers (based on the 2010 production level of CFRP composites for application areas considered) were able to attain PM energy intensities, it is estimated that a total of 4.64 TBtu of on-site energy could be saved annually, corresponding to a 84.6% energy savings overall. This energy savings estimate assumes the adoption of the PM technologies and practices described in this report. This is a simple estimate for potential savings, as many of the PM technologies considered are unproven, and not all existing plants could necessarily deploy all of the practices considered. No assessment was made in this study regarding whether the improvements would prove to be cost effective in all cases, nor whether satisfactory CFRP performance could be achieved via the PM processes.

Table 5-5. Calculated Practical Minimum Energy Savings for Carbon Fiber Reinforced Polymer Composite Manufacturing: Application Areas Studied

Subarea (product)	On-site CT Energy Consumption, Calculated (TBtu/yr)	On-site PM Energy Consumption, Calculated (TBtu/yr)	PM Energy Savings** (CT – PM) (TBtu/yr)	PM Energy Savings Percent*** (CT-PM)/ (CT-TM)
Carbon Fiber Production (carbon fibers)				
Polymerization	1.04	0*	1.04	97.0%
Spinning	1.71	0.03	1.68	98.1%
Oxidation/Carbonization	1.72	0.29	1.43	82.2%
Finishing	0.21	0.08	0.13	60.2%
Resin Production (matrix polymer)	0.70	0.35	0.35	49.9%
Composite Product Forming (composite product)	0.04	0.03	0.01	30.9%
Total****	**5.43**	**0.79**	**4.64**	**84.6%**

Practical Minimum (PM)
* Polymerization step not required for Practical Minimum process.
** PM energy savings is the *Current Opportunity* plus the *R&D Opportunity*.
*** PM energy savings percent is the PM energy savings opportunity from transforming carbon fiber composite production processes through the adoption of state of the art equipment and practices. Energy savings percent is calculated using the TM energy consumption shown in Table 6-4 as the minimum energy consumption. The energy savings percent, with TM as the minimum, was calculated as follows: PM Energy Savings Percent = (CT-PM)/(CT-TM)
****Note: totals may not sum due to independent rounding.

The R&D savings percent is the percent of energy saved with SOA energy consumption compared to CT energy consumption. The PM energy savings percent in Table 5-5 is the percent of energy saved with PM energy consumption compared to CT energy consumption, while referencing the thermodynamic minimum as the baseline energy consumption. Thermodynamic minimum (TM), discussed further in the following section, is considered to be equal to zero in an ideal case with perfect efficiency (i.e., energy input to a system is considered fully recoverable with no friction losses or change in surface energy). For manufacturing processes where there is an irreversible change to the material, resulting in a change to the embodied free energy content of the material (i.e., chemical reaction or permanent crystalline change due to deformation), TM is not necessarily equal to zero; in some cases the change in theoretical free energy content of the material requires energy input (TM > 0) and in other cases the change creates a theoretical free energy gain (TM < 0). Referencing TM as the baseline in comparing bandwidths of energy consumption and calculating energy savings percent provides the most accurate measure of absolute savings potential. The equation for calculating on-site R&D opportunity and PM energy savings percent are:

$$R\&D\ Opportunity\ \% = \frac{SOA - PM}{CT - TM}$$

$$PM\ Savings\ \% = \frac{CT - PM}{CT - TM}$$

R&D opportunity represents the opportunities for energy savings from technologies currently an R&D stage of development (early TRL) and are not ready for deployment to manufacturing. It represents the energy savings opportunities that can be achieved if the R&D is put into those technologies to get them to a high enough TRL level that they can be deployed in the manufacturing sector. Table 5-6 shows the R&D opportunity totals and percent for the evaluated process subareas.

Table 5-6. Calculated Practical Minimum Energy Consumption, R&D Opportunity, and R&D Opportunity Percent for Carbon Fiber Reinforced Polymer Composite Manufacturing: Application Areas Studied

Subarea (product)	On-site SOA Energy Consumption (TBtu/yr)	On-site PM Energy Consumption (TBtu/yr)	R&D Opportunity (SOA – PM) (TBtu/yr)	R&D Opportunity Savings Percent* (SOA-PM)/ (CT-TM)
Total**	4.22	0.79	3.43	62.6%

Current Typical (CT), State of the Art (SOA), Practical Minimum (PM), Thermodynamic Minimum (TM)
* Energy savings percent is calculated using TM energy consumption shown in Chapter 6 as the minimum energy consumption. The energy savings percent, with TM as the minimum, is calculated as follows: (SOA- PM)/(CT- TM).
** Totals may not sum due to independent rounding.

6. Thermodynamic Minimum Energy Intensity and Energy Consumption

Real-world manufacturing does not occur under theoretically ideal conditions; however, understanding the theoretical minimal amount of energy required to manufacture CFRP composites can provide a more complete understanding of the realistic opportunities for energy savings. This baseline can be used to establish more realistic projections (and bounds) for the future R&D energy savings that may be achieved. This chapter presents the thermodynamic minimum (TM) energy consumption required for the subareas studied.

TM energy consumption, which is based on Gibbs free energy calculations, assumes ideal conditions that are unachievable in real-world applications. TM energy consumption assumes that all energy is used productively, that there are no energy losses, and that energy is ultimately perfectly conserved by the system (i.e., when cooling a material to room temperature or applying work to a process, the heat or work energy is fully recovered – perfect efficiency). It is not anticipated that any manufacturing process would ever attain this value in practice. A reasonable long-term goal for energy efficiency would be the practical minimum (see Chapter 5).

For manufacturing processes where there is an irreversible change to the material, resulting in a change to the embodied free energy content of the material (i.e., chemical reaction or permanent crystalline change due to deformation), TM is not necessary equal to zero; in some cases the change in theoretical free energy content of the material requires energy input (TM > 0) and in other cases the change creates a theoretical free energy gain (TM < 0).

6.1. Thermodynamic Minimum Energy Intensity

The thermodynamic minimum energy intensity was calculated for each sub-process by determining the Gibbs free energy associated with the chemical transformations involved, under ideal conditions for a manufacturing process.[21] The TM energy intensity is *negative* when the chemical reaction is net-exergonic and *positive* when the chemical reaction is net-endergonic.[22] Changes in surface energy were not considered in the TM analysis. The change in entropy was calculated based on the relative change in the number of molecules, and the change in enthalpy was calculated based on the change in bond energy.[23]

TM energy intensity calculations are path independent (state function), but are directly related to the relative energy levels of the substrate reactants and the products. The reported value depends only on the starting material and the end product, and would not change if the process had greater or fewer process steps or if a catalyst were involved. For polymerization reactions, the starting material is assumed to be the relevant monomers (not crude petroleum). It is important to note that a negative TM value does not imply that the reaction will occur without being forced by a manufacturing process.

In this report, TM energy consumption is referenced as the baseline (or minimum amount of energy) when calculating the absolute energy savings potential. The equations used to determine the absolute energy savings for current opportunity (SOA), R&D, and PM are defined below. PM savings percent is the sum of the current opportunity percent and the R&D opportunity percent.

$$Current\ opportunity\ \% = \frac{CT - SOA}{CT - TM}$$

$$R\&D\ opportunity\ \% = \frac{SOA - PM}{CT - TM}$$

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[21] Unless otherwise noted, “ideal conditions” means a pressure of 1 atmosphere and a temperature of 77°F.

[22] Exergonic (reaction is favorable) and endergonic (reaction is not favorable) are thermodynamic terms describing the total change in Gibbs free energy (delta G). This differs from exothermic (reaction is favorable) and endothermic (reaction is not favorable) terminology that are used in describing change in enthalpy (delta H).

[23] Note that the bond energy values are averages, not specific to the molecule in question.

$$PM\ Savings\ \% = \frac{CT - PM}{CT - TM}$$

For processes requiring an energy intensive transformation (e.g., polymerization, which has a high CT energy intensity but a negative TM energy intensity), this percent energy savings approach results more realistic and comparable energy savings estimates. Using zero as the baseline (or minimum amount of energy) would exaggerate the total bandwidth to which SOA energy savings and PM energy savings are compared to determine the energy savings percent. When TM energy consumption is referenced as the baseline, SOA energy savings and PM energy savings are relatively more comparable, resulting in more accurate energy savings percentages.

For carbon fiber manufacturing, only the polymerization and oxidation/carbonization processes had nonzero TM energy intensities. These values are presented in Table 6-1. The polymerization TM energy intensity is based on polymerization of a PAN precursor from acrylonitrile, assuming a polymer chain 1000 units in length. The TM energy intensity for oxidation/carbonization was estimated by using carbon black combustion as a proxy for the process. Note that primary energy intensity was not calculated for TM because energy conversion is assumed to be perfect in the theoretical minimum case.

Table 6-1. Thermodynamic Minimum Energy Intensity for Production of Carbon Fibers

Carbon Fiber Production Sub-Process	TM Energy Intensity (Btu/lb)	Data Source
Polymerization	-1,563	Calculated*
Spinning	0	Calculated*
Oxidation/Carbonization	-803	Calculated*
Finishing	0	Calculated*
Total Energy Intensity for Carbon Fibers**	**-2,366**	

Thermodynamic Minimum (TM)
* See preceding discussion in text for description of methodology.
** Note: totals may not sum due to independent rounding.

The TM energy intensity values for the matrix polymers reflect polymerization of the resin from its monomers, assuming a polymer chain 1000 repeat units in length.[24] TM values for the polymer materials are presented in Table 6-2.

For composite production there is no change to the embodied free energy content of the materials being produced, no chemical reactions or phase changes are involved in the processes; the TM energy intensity was therefore assumed to be zero for all methods, as shown in Table 6-3.

[24] The exception was epoxy, which is based upon a chain consisting of 25 units of bisphenol-A and 26 units of epichlorohydrin.

Table 6-2. Thermodynamic Minimum Energy Intensity for Production of Matrix Resins

Matrix Polymer	TM Energy Intensity (Btu/lb)	Data Source
Thermosetting Resins		
Epoxy resin	-115	Calculated*
Polyurethane resin	-188	Calculated*
Thermoplastic Resins		
Polypropylene (PP)	-1,163	Calculated*
High density polyethylene (HDPE)	-1,744	Calculated*
Polyvinyl chloride (PVC)	-969	Calculated*
Polystyrene (PS)	-470	Calculated*

Thermodynamic Minimum (TM)
* Calculated based on polymerization of the resin from its monomers; see discussion in text for details of methodology used.

Table 6-3. Thermodynamic Minimum Energy Intensity for Composite Product Forming

Production Method	TM Energy Intensity (Btu/lb)	Data Source
Intermediate (Semi-Finished) Manufacturing Methods		
Prepreg	0	Best engineering judgment*
Sheet or bulk molding compound	0	Best engineering judgment*
Direct Forming Methods		
Open molding (hand lay up or spray up)	0	Best engineering judgment*
Filament winding	0	Best engineering judgment*
Pultrusion	0	Best engineering judgment*
Injection molding	0	Best engineering judgment*
Compression molding	0	Best engineering judgment*
Resin transfer molding (including vacuum infusion)	0	Best engineering judgment*
Thermoforming	0	Best engineering judgment*
Cold press	0	Best engineering judgment*

Thermodynamic Minimum (TM)
*See discussion in text for details of methodology used.

6.2. Thermodynamic Minimum Energy Consumption

Table 6-4 presents the calculated TM energy consumption for the CFRP production subareas studied. In these summary data, epoxy resin was assumed as the polymer matrix material and resin transfer molding was assumed as the composite product forming method. Energy consumption values were calculated by multiplying energy intensity (Btu/lb) by 2010 production volume (lbs).

Table 6-4. Calculated Thermodynamic Minimum Energy Consumption for Carbon Fiber Reinforced Polymer Composite Manufacturing: Application Areas Studied

Subarea (product)	**TM Energy Intensity** (Btu/lb)	**Production** (million lbs)	**TM Energy Consumption** (TBtu/yr)
Carbon Fiber Production (carbon fibers)			
Polymerization	-1,563	20.5	-0.03
Spinning	0	20.5	0
Oxidation/Carbonization	-803	20.5	-0.02
Finishing	0	20.5	0
Resin Production* (matrix polymer)	-115	20.5	-0.002
Composite Production** (composite product)	0	40.9	0
Total* **			**-0.05**

Thermodynamic Minimum (TM)
* Assumes thermosetting epoxy resin.
** Assumes resin transfer molding.
***Note: totals may not sum due to independent rounding.

7. Current and R&D Opportunity Analysis/Bandwidth Summary

Table 7-1 summarizes the *current opportunity* and *R&D opportunity* energy savings for the subareas studied, based on CFRP composite production in 2010 for the four boundary application areas. Carbon fiber production is broken down into its four sub-processes. The carbon fiber production methods, polymer matrix materials, and composite production methods assumed for each energy band are shown in Table 7-2. For all energy bands, summary calculations were made based an epoxy matrix resin, a 50% (by weight) fiber fraction, and resin transfer molding as the forming technique. Readers wishing to estimate energy savings for other composite material formulations may do so by substituting data for other resins, fiber fractions, and forming methods (using energy intensity values presented in this report) in a mix-and-match fashion.

Table 7-1. Current and R&D Opportunities for CFRP Manufacturing (On-site Energy Consumption): Application Areas Studied

Subarea (product)	Current Energy Savings Opportunity (CT – SOA) (TBtu/year)	R&D Energy Savings Opportunity (SOA – PM) (TBtu/year)
Carbon Fiber Production (carbon fibers)		
Polymerization	0.09	0.95
Spinning	0.16	1.52
Oxidation/Carbonization	0.76	0.66
Finishing	0.04	0.09
Resin Production – epoxy resin (matrix polymer)	0.14	0.21
Composite Production – resin transfer molding (composite product)	0.01	0.00
Total*	**1.21**	**3.43**

Current typical (CT), state of the art (SOA), practical minimum (PM)
* Note: totals may not sum due to independent rounding.

Table 7-2. Manufacturing Process Assumptions for Current Typical, State of the Art, and Practical Minimum Energy Bands

Energy Band	Fiber Fraction (weight %)	Carbon Fiber Production Method	Polymer Matrix Material	Composite Product Forming Method
Current Typical	50%	PAN process	Epoxy resin	Resin transfer molding
State of the Art	50%	PAN process	Epoxy resin	Resin transfer molding
Practical Minimum	50%	Polyolefin process	Epoxy resin	Resin transfer molding
Thermodynamic Minimum	50%	Polyolefin process	Epoxy resin	Resin transfer molding

In this study, two hypothetical opportunity bandwidths for energy savings were estimated (as defined in Chapter 1). The analysis shows the following:

- *Current Opportunity* – 1.21 TBtu per year of energy savings could be realized if state of the art technologies and practices are deployed
- *R&D Opportunity* – 3.43 TBtu per year of additional energy savings could be attained in the future if applied R&D technologies under development worldwide are successfully deployed (i.e., reaching the practical minimum).

Figure 7-1 depicts these two opportunity bandwidths graphically. The area between *R&D opportunity* and *impractical* is shown as a dashed line with color fading because the PM energy savings impacts are based on today's knowledge of research tested between laboratory and demonstration scale; emerging technologies being investigated through modeling and theoretical calculations may eventually bring the PM energy consumption further into the faded region and closer to the TM energy consumption. The *impractical* bandwidth, or the difference between PM energy consumption and TM energy consumption, represents the area that would require fundamental changes in CFRP manufacturing. The term *impractical* is used because the PM energy consumption is based on current knowledge of R&D technologies tested between laboratory and demonstration scale; further decreases in energy intensity have not been displayed at any physical scale.

Based on the bandwidth analysis, the greatest *current* energy savings opportunity for CFRP composites involves upgrading oxidation/carbonization equipment and processes. The greatest *R&D* energy savings opportunities could be achieved through improved, energy-efficient spinning techniques. Examples of technologies that could be deployed to achieve these opportunities were detailed in this report and its appendices.

It is noted that this report assumes the same composite formulation (an epoxy resin matrix, a 50% fiber fraction by weight, and resin transfer molding) in all summary calculations to ensure comparability between the energy bands presented. Additional energy savings could be achieved by altering these parameters. For example, small adjustments in the fiber fraction can significantly alter the energy intensity of a composite material because it is much more energy-intensive to manufacture a pound of carbon fibers than it is to manufacture a pound of a typical resin. Polymer materials and composite forming techniques vary widely in energy intensity, and substituting one material or method for another also alters the energy intensity of a composite. While major energy savings are potentially available from these types of changes, the reader is cautioned that the resulting composite products may not be comparable on a performance basis. Careful attention to application-specific component design and requirements is needed to understand these additional potential energy savings opportunities.

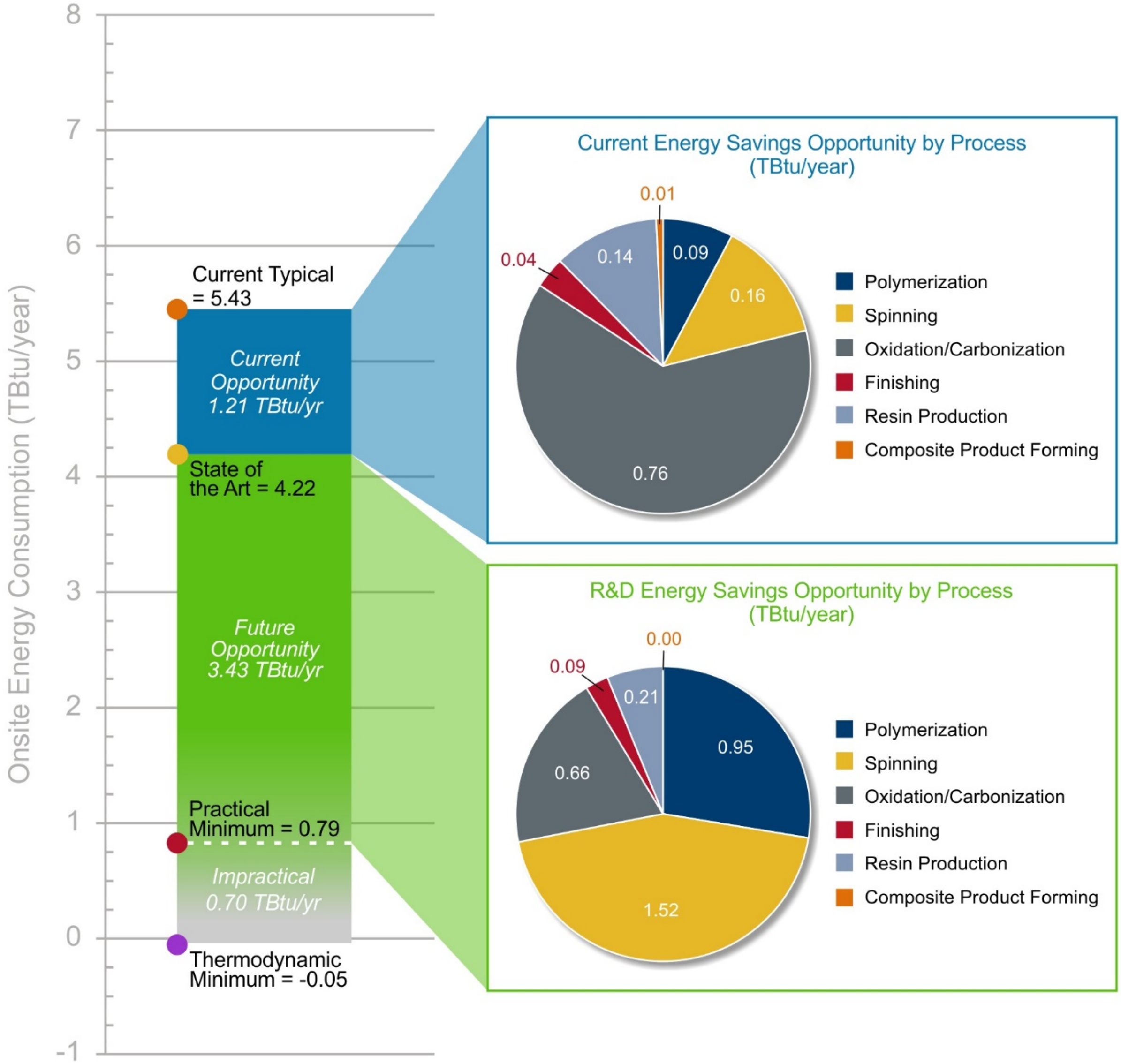

Figure 7-1. Current and R&D energy savings opportunities for CFRP composite manufacturing by process, based on 2010 carbon fiber production for structural applications
Source: EERE

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Appendix A1. Master CFRP Composite Summary Tables

Table A1-1. On-site Energy Intensity and Energy Consumption Estimates for CFRP Composite Manufacturing for the Four Bandwidth Measures, Based on 2010 Production of CFRP Composites for Structural Application Areas

Process Subarea or Sub-Process	2010 Application Area Production* (million lbs)	Estimated On-site Energy Intensity** (Btu/lb)				Calculated On-site Energy Consumption (TBtu/yr)			
		CT	SOA	PM	TM	CT	SOA	PM	TM
Carbon Fiber Production									
Polymerization	20.5	50,756	46,188	0	-1,563	1.04	0.95	0.00	-0.03
Spinning		83,664	75,761	1,610	0	1.71	1.55	0.03	0.00
Oxidation/Carbonization		83,966	46,659	14,271	-803	1.72	0.95	0.29	-0.02
Finishing		10,414	8,387	4,141	0	0.21	0.17	0.08	0.00
Overall – Fiber Production		**228,800**	**176,995**	**20,022**	**-2,366**	**4.68**	**3.62**	**0.41**	**-0.05**
Resin Production									
Epoxy resin	20.5	**34,256**	**27,405**	**17,101**	**-115**	**0.70**	**0.56**	**0.35**	**0.00**
Polyurethane resin		11,398	9,118	5,690	-188	0.23	0.19	0.12	0.00
Polypropylene (PP)		5,227	4,182	2,047	-1,163	0.11	0.09	0.04	-0.02
High density polyethylene (HDPE)		6,845	4,461	2,184	-1,744	0.14	0.09	0.04	-0.04
Polyvinyl chloride (PVC)		9,158	6,666	3,264	-969	0.19	0.14	0.07	-0.02
Polystyrene (PS)		10,751	8,249	4,039	-470	0.22	0.17	0.08	-0.01
Composite Product Forming									
Prepreg	40.9	17,196	13,757	13,207	0	0.70	0.56	0.54	0.00
Sheet or bulk molding compound		1,505	1,204	1,156	0	0.06	0.05	0.05	0.00
Open molding (hand lay up or spray up)		2,237	1,696	1,628	0	0.09	0.07	0.07	0.00
Filament winding		1,161	929	891	0	0.05	0.04	0.04	0.00
Pultrusion		1,333	1,066	486	0	0.05	0.04	0.02	0.00
Injection molding		2,794	925	799	0	0.11	0.04	0.03	0.00
Compression molding		2,632	2,106	2,021	0	0.11	0.09	0.08	0.00
Resin transfer molding (including vacuum infusion)		**1,093**	**874**	**755**	**0**	**0.04**	**0.04**	**0.03**	**0.00**
Thermoforming		11,048	8,839	4,243	0	0.45	0.36	0.17	0.00
Cold press		5,073	4,058	3,896	0	0.21	0.17	0.16	0.00
Total for Carbon Fiber Reinforced Polymer Manufacturing****	**40.9**	**132,621**	**103,074**	**19,317**	**-1,240**	**5.43**	**4.22**	**0.79**	**-0.05**

* Carbon fiber production data reflect the total production of finished fibers used in automotive, wind energy, pressure vessel, and aerospace applications. Resin production data indicate the estimated production of all resins for CFRP composites in the application areas, assuming 50 wt% carbon fibers. Composites production indicates the total production of CFRP composites (all methods) calculated from the above data.

** Energy intensities reported in terms of Btu per pound of fibers for carbon fiber production (all sub-processes), Btu per pound of resin for resin production, and Btu per pound of composite product (fibers and resin) for composites production. The total energy intensity for CFRP composites is reported in Btu per pound of composite product. Feedstock energy is excluded in all values.

*** Total is a representative value assuming a fiber fraction of 50 wt% carbon fibers (the median value in seven automotive case studies considered; see Appendix A2). The polymer material was assumed to be epoxy and the composite production method was assumed to be resin transfer molding. The values included in the total are shown in bold in the table. The formula used for the calculation was: Total CFRP Energy = (0.50*[Fiber Production Energy] + 0.50*[Resin Production Energy] + Product Forming Energy). To determine the total for another GFRP composition, the material-specific energy intensity can be calculated by substituting other table values in this formula.

Table A1-2. Primary Energy Intensity and Energy Consumption Estimates for CFRP Composite Manufacturing for the Four Bandwidth Measures, Based on 2010 Production of CFRP Composites for Structural Application Areas

Process Subarea or Sub-Process	2010 Application Area Production* (million lbs)	Estimated Primary Energy Intensity** (Btu/lb)				Calculated Primary Energy Consumption (TBtu/yr)			
		CT	SOA	PM	TM***	CT	SOA	PM	TM***
Carbon Fiber Production									
Polymerization		67,064	61,029	0	-1,563	1.37	1.25	0.00	-0.03
Spinning		91,139	82,530	5,868	0	1.87	1.69	0.12	0.00
Oxidation/Carbonization	20.5	183,567	102,006	60,917	-803	3.76	2.09	1.25	-0.02
Finishing		32,243	25,966	15,089	0	0.66	0.53	0.31	0.00
Overall – Fiber Production		**374,013**	**271,531**	**81,874**	**-2,366**	**7.65**	**5.56**	**1.68**	**-0.05**
Resin Production									
Epoxy resin		**40,105**	**32,084**	**20,021**	**-115**	**0.82**	**0.66**	**0.41**	**0.00**
Polyurethane resin		27,355	21,884	13,655	-188	0.56	0.45	0.28	0.00
Polypropylene (PP)	20.5	11,822	9,458	4,631	-1,163	0.24	0.19	0.09	-0.02
High density polyethylene (HDPE)		14,617	9,527	4,664	-1,744	0.30	0.19	0.10	-0.04
Polyvinyl chloride (PVC)		15,261	11,109	5,439	-969	0.31	0.23	0.11	-0.02
Polystyrene (PS)		18,099	13,887	6,799	-470	0.37	0.28	0.14	-0.01
Composite Product Forming									
Prepreg		53,238	42,591	40,887	0	2.18	1.74	1.67	0.00
Sheet or bulk molding compound		4,658	3,727	3,578	0	0.19	0.15	0.15	0.00
Open molding (hand lay up or spray up)		5,805	3,506	3,366	0	0.24	0.14	0.14	0.00
Filament winding		3,594	2,875	2,760	0	0.15	0.12	0.11	0.00
Pultrusion		4,126	3,301	1,505	0	0.17	0.14	0.06	0.00
Injection molding	40.9	8,651	2,863	2,474	0	0.35	0.12	0.10	0.00
Compression molding		7,790	6,232	5,983	0	0.32	0.26	0.24	0.00
Resin transfer molding (including vacuum infusion)		**2,014**	**1,611**	**1,392**	**0**	**0.08**	**0.07**	**0.06**	**0.00**
Thermoforming		33,935	27,148	13,031	0	1.39	1.11	0.53	0.00
Cold press		15,705	12,564	12,062	0	0.64	0.51	0.49	0.00
Total for Carbon Fiber Reinforced Polymer Manufacturing*****	**40.9**	**209,073**	**153,419**	**52,339**	**-1,240**	**8.56**	**6.28**	**2.14**	**-0.05**

* Carbon fiber production data reflect the total production of finished fibers used in automotive, wind energy, pressure vessel, and aerospace applications. Resin production data indicate the estimated production of all resins for CFRP composites in the application areas, assuming 50 wt% carbon fibers. Composites production indicates the total production of CFRP composites (all methods) calculated from the above data.

** Energy intensities are reported in terms of Btu per pound of fibers for carbon fiber production (all sub-processes), Btu per pound of resin for resin production, and Btu per pound of composite product (fibers and resin) for composites production. The total energy intensity for CFRP composites is reported in Btu per pound of composite product. Feedstock energy is excluded in all values. The conversion from on-site energy intensity to primary was made using process-specific energy mix assumptions (see Appendix A3).

*** For TM, primary energy is equal to the on-site energy because electric conversion is assumed to be perfect in the theoretical minimum case.

**** Total is a representative value assuming a fiber fraction of 50 wt% carbon fibers (the median value in seven automotive case studies considered; see Appendix A2). The polymer material was assumed to be epoxy and the composite production method was assumed to be resin transfer molding. The values included in the total are shown in bold in the table. The formula used for the calculation was: Total CFRP Energy = (0.50*[Fiber Production Energy] + 0.50*[Resin Production Energy] + Product Forming Energy). To determine the total for another GFRP composition, the material-specific energy intensity can be calculated by substituting other table values in this formula.

Appendix A2. Fiber Ratios in Structural Lightweighting Applications

To determine a representative carbon fiber (CF) to matrix resin ratio for lightweight structural applications, seven automotive case studies were compiled from literature sources (see Table A2-1). Each source referenced was an automotive lightweighting study that described the use of a CFRP component in a specific lightweighting application (e.g., a vehicle door or chassis). These case studies would fall under the automotive structural application area considered in this bandwidth report.

Table A2-1. Carbon Fiber (CF)/Matrix Polymer Ratios: Automotive Case Studies

Case Study	Polymer Type*	CF Ratio, by Weight %	CF Ratio, by Volume %	Data Source
Automotive door	Epoxy	55 wt%	50 vol%	Rocky Mountain Institute (2013)
Automotive body	Epoxy	55 wt%	50 vol%	Duflou et al. (2009)
Automotive chassis	Epoxy	69 wt%	64 vol%	Suzuki & Takahashi (2005)
Automotive body	PP	46 wt%	32 vol%	Suzuki & Takahashi (2005)
Automotive floor pan	Polyester	31 wt%	34 vol%	Das (2011)
Automotive energy absorber (low)	Epoxy	40 wt%	35 vol%	Jacob et al. (2005)
Automotive energy absorber (high)	Epoxy	50 wt%	45 vol%	Jacob et al. (2005)

* assumed densities were 1.6 g/cm^3 for CF; 1.3 g/cm^3 for epoxy resin; 0.9 g/cm^3 for polypropylene; and 1.9 g/cm^3 for polyester.

The CFRP composites described in these seven case studies ranged in composition from 31% to 69% carbon fiber by weight (32 to 64% by volume). The average value was 49 wt% CF and the median value was 50 wt% CF. Based on these statistics, a 50:50 ratio of fibers to polymer resin (by weight) was assumed to be representative of structural composites for the purposes of this study.

Appendix A3. Energy Mix Assumptions

The fuel and electricity requirements for manufacturing processes depend strongly on the specifics of the process: motor-driven processes such as conveyer belts and mixers typically use mostly electric energy, whereas thermal processes generally use mostly fuel energy. In this study, energy mixes were assumed for each sub-process to maximize the accuracy of conversions between on-site and primary energy intensity and consumption (Table A3-1). These energy mixes were generally drawn from the same sources that were used for baseline energy intensity data. Normally the steam generation and transmission losses would be accounted for when converting from on-site to primary energy consumption, but the sources used in this report did not provide that level of detail for the fuel energy data provided. Consequently, the primary energy intensities may be considered conservative as they only contain offsite electricity generation and transmission losses. Unless otherwise specified in the reference, composite product forming processes were assumed to be 100% electric, which is consistent with several sources (Schepp (2006), Das (2011), Thiriez (2006)).

An electricity generation efficiency of 32.3% was used to calculate offsite electricity generation losses. This value was calculated by dividing the total electricity sales to the industrial sector in 2010 by the sum of electricity sales and electricity generation losses, based on data from the U.S. Energy Information Administration's Monthly Energy Review (EIA (2016)). The formula used to convert between on-site and primary consumption was as follows:

$$E_{primary} = E_{onsite}\left(f_{fuel} + \frac{f_{elec}}{\varepsilon}\right)$$

where $E_{primary}$ and $E_{on\text{-}site}$ are the primary and on-site energy consumption values (or energy intensities), respectively, f_{fuel} and f_{elec} are the fractions of fuel and electricity usage for the process, respectively, and ε is the electricity generation efficiency.

Table A3-1. Energy Mix Assumptions for CFRP Composite Manufacturing Processes

Process Subarea or Sub-Process	Fuel %	Electric %	Data Source
Carbon Fiber Production: PAN Precursor			
Polymerization	84.7%	15.3%	*Best engineering judgment**
Spinning	95.7%	4.3%	Das (2014)
Oxidation/Carbonization	43.4%	56.6%	Das (2014)
Finishing	0.0%	100.0%	*Best engineering judgment***
Overall – Fiber Production	84.7%	15.3%	Das (2014)
Carbon Fiber Production: Polyolefin Precursor			
Polymerization	n/a	n/a	*Polymerization not required*
Spinning	0.0%	100.0%	Das & Warren (2014)
Oxidation/Carbonization	43.4%	56.6%	Das & Warren (2014)
Finishing	0.0%	100.0%	Das & Warren (2014)
Overall – Fiber Production	34.7%	65.3%	Das & Warren (2014)
Resin Production: Thermosetting Resins			
Epoxy resin	91.9%	8.1%	PlasticsEurope (2006)
Polyurethane resin	33.2%	66.8%	PlasticsEurope (2005a)
Resin Production: Thermoplastic Resins			
Polypropylene (PP)	39.8%	60.2%	PlasticsEurope (2014a)
High density polyethylene (HDPE)	45.8%	54.2%	PlasticsEurope (2014b)
Polyvinyl chloride (PVC)	68.2%	31.8%	PlasticsEurope (2005b)

Process Subarea or Sub-Process	Fuel %	Electric %	Data Source
Polystyrene (PS)	67.4%	32.6%	PlasticsEurope (2012)
Composite Production: Intermediate (Semi-finished) Manufacturing Methods			
Prepreg	0.0%	100.0%	*Best engineering judgment****
Sheet or bulk molding compound	0.0%	100.0%	*Best engineering judgment****
Composite Production: Direct Forming Methods			
Open molding (hand lay-up or spray up)	23.9%	76.1%	USLCI (2012)
Filament winding	0.0%	100.0%	*Best engineering judgment****
Pultrusion	0.0%	100.0%	*Best engineering judgment****
Injection molding	0.0%	100.0%	*Best engineering judgment****
Compression molding	6.5%	93.5%	USLCI (2012)
Resin transfer molding (including vacuum infusion)	59.8%	40.2%	USLCI (2012)
Thermoforming	0.0%	100.0%	*Best engineering judgment****
Cold press	0.0%	100.0%	*Best engineering judgment****

* Not reported; assumed the same as the overall energy mix
** Assumed the same energy mix for PAN precursor finishing step as for polyolefin precursor finishing.
***Unless otherwise specified in the reference, all composite production methods were assumed to be 100% electric, which is consistent with several sources (Schepp (2006), Das (2011), Thiriez (2006)).

Appendix A4. State of the Art Technologies Considered for Carbon Fiber Production

The SOA energy intensity for carbon fiber production (and its sub-processes) was determined based on the technologies outlined in Table A4-1. The applicability column indicates the subarea/sub-process where the technology is considered for application. Percent savings over CT baseline is estimated, along with a brief explanation.

Table A4-1. Details of State of the Art Technologies Considered for Carbon Fiber Production

Technology Name	Description	Applicability	Explanation of energy savings assumptions	Percent savings (over baseline energy)	Reference
Carbon fiber recycling	Use of recycled carbon fiber content in products reduces energy requirements, as production of virgin carbon fibers is highly energy intensive.	Carbon Fiber Production (all sub-processes)	Kim compared virgin and recycled carbon fiber composite energy intensity, and found that recycled CFRP offered an 86% energy advantage for thermoset composites and a 90% energy advantage for thermoplastic composites. An 88% energy savings was assumed for each kilogram of carbon fiber replaced by recycled content. The state of the art recycling rate was assumed to be 10%, which is the fraction of recycled material in BMW i vehicles (see Gardiner 2014), for a total energy savings of 9%.	9%	Gardiner (2014); Kim (2014)
Motor re-sizing or VSDs	Motors and pumps that are improperly sized cause energy losses that could be avoided with an appropriately sized motor or a variable speed drive motor.	Spinning; Finishing	Worrell *et al.* estimated a typical energy savings of 8-15% from VSDs for conveyer belt systems used in glass batching. Similar energy savings were assumed for carbon fiber spinning and finishing. The range was averaged to come up with an overall savings of 12%, applied only to the electricity portion of the spinning and finishing processes.	1% (spinning); 12% (finishing)	Worrell (2008); Worrell (2010)
More efficient furnaces	Furnaces with improved thermal efficiency could save energy in the intensive oxidation and carbonization steps.	Oxidation/ Carbonization	Worrell *et al.* estimated that the average thermal efficiency of furnaces is between 75% and 90%, and that the theoretical maximum efficiency is 92%, suggesting possible savings of 2% to 17% from improved furnace design. Assuming a typical efficiency of 80% and a 90% SOA efficiency, a 10% energy savings was assumed.	10%	Worrell (2010)
Improved heat transfer/ containment	Energy losses could be minimized through improved furnace technologies, including better insulation, sealing, and pressure control.	Oxidation/ Carbonization	Worrell *et al.* reported typical savings of 5-10% from cleaning heat transfer surfaces, 4-12% from ceramic-coated furnace tubes, 2-5% from better insulation, 5-10% from controlling furnace pressure, and 0-5% from maintaining door and tube seals. Carbonization ovens are assumed to be carefully pressure-controlled already due to process requirements. Summation of the remaining savings opportunities gives a range of 11-29% savings. This was averaged to come up with an energy savings of 20%.	20%	Worrell (2010)

Technology Name	Description	Applicability	Explanation of energy savings assumptions	**Percent savings** (over baseline energy)	Reference
Process heating control systems	Advanced sensors and control systems enable continuous monitoring and optimization of heat inputs for fuel savings.	Oxidation/ Carbonization	Worrell *et al.* reported energy savings of 2 to 3% for glass melting furnaces; these savings are assumed to be applicable to carbonization furnaces as well. A 3% savings was assumed.	3%	Worrell (2008)
Waste heat recovery	Recovery of flue gases to preheat air in lower-temperature furnaces is an effective way to improve system efficiency.	Oxidation/ Carbonization	Worrell *et al.* estimated that typical fuel savings range from 8% to 18% for waste heat recovery. This range was averaged to come up with an estimated 13% savings for oxidation/carbonization.	13%	Worrell (2010)

In cases where more than one technology was considered for a given subarea/sub-process, the following calculation was used:

$$SOA = CT * [(1 - S_1) * (1 - S_2) * \dots * (1 - S_n)]$$

where *SOA* is the SOA energy intensity, *CT* is the current typical (baseline) energy intensity, and S_1, S_2, … S_n are the percent savings for each of the *n* SOA technologies included in the model. Energy savings from different technologies were not considered additive; rather, this formula considers technologies as compounding when more than one is applicable to a certain subarea.

Appendix A5. Practical Minimum (R&D) Technologies Considered for Carbon Fiber Production

The PM energy intensity for carbon fiber composite manufacturing was determined based on the technologies outlined in Table A5-1. The applicability column indicates the subarea/sub-process where the technology is considered for application. The percent savings over the PM baseline is estimated, along with a brief explanation (Note that the PM baseline energy intensity is based on the polyolefin process energy intensity for carbon fiber production, and on the SOA energy intensity for resin and composite production). Some technologies in Table A5-1 were considered but not included in the final PM model. The excluded technologies were considered incompatible with PM technologies already included in the model, or it was determined that the additional energy savings from the technology were negligible. For example, energy savings opportunities from waste heat recovery were not included in the PM model because it was assumed that savings would be negligible when using a selective heating process (microwave heating) for the melting process step.

Table A5-1. Details of Practical Minimum Technologies Considered

Technology Name	Description	Applicability	Explanation of energy savings assumptions	Percent savings (over baseline energy)	Included in PM model?	Reason for excluding (if applicable)	Reference
Polyolefin carbon fiber precursor	Polyolefin offers a lower-embodied-energy starting material (polyethylene), melt spinning rather than solution spinning, and higher conversion yield compared to PAN	Carbon Fiber Production (all sub-processes)	Energy intensities reported explicitly. This process was used as the PM baseline (see Chapter 5).	n/a	Yes		Das & Warren (2014)
Lignin carbon fiber precursor	Biomass lignin (softwood) precursors could provide energy savings and other environmental benefits compared to conventional PAN.	Carbon Fiber Production (all sub-processes)	Energy intensities reported explicitly.	n/a	No	Polyolefin process provides a lower baseline energy use.	Das & Warren (2014)

Carbon fiber recycling	Use of recycled carbon fiber content in products reduces energy requirements, as production of virgin carbon fibers is highly energy intensive.	Carbon Fiber Production (all sub-processes)	Kim compared virgin and recycled carbon fiber composite energy intensity, and found that recycled CFRP offered an 86% energy advantage for thermoset composites and a 90% energy advantage for thermoplastic composites. An 88% energy savings was assumed for each kilogram of carbon fiber replaced by recycled content. The practical minimum recycling rate was assumed to be 40%, corresponding to an overall savings of 35%.	35%	Yes		Gardiner (2014); Kim (2014)
Melt spinning	Melt spinning converts precursor materials directly into fiber form without the use of solvents. This is not currently possible with PAN because it thermally decomposes below its melting temperature.	Spinning	30% savings assumed, based on personal communication with Sujit Das of ORNL.	30%	No	Melt spinning implicit in polyolefin precursor process.	Paiva (2003)
Motor re-sizing or VSDs	Motors and pumps that are improperly sized cause energy losses that could be avoided with an appropriately sized motor or a variable speed drive motor.	Spinning; Finishing	Worrell *et al.* estimated a typical energy savings of 8-15% from VSDs for conveyer belt systems used in glass batching. Similar energy savings were assumed for carbon fiber spinning and finishing. The range was averaged to come up with an overall savings of 12%, applied to the electricity portion of the spinning and finishing processes.	12% (spinning); 12% (finishing)	Yes		Worrell (2008); Worrell (2010)
More efficient furnaces	Furnaces with improved thermal efficiency could save energy in the intensive oxidation and carbonization steps.	Oxidation/ Carbonization	Worrell *et al.* estimated that the average thermal efficiency of furnaces is between 75% and 90%, and that the theoretical maximum efficiency is 92%, suggesting possible savings of 2% to 17% from improved furnace design. Assuming a typical efficiency of 80% and a 92% PM efficiency, a 12% energy savings was assumed.	12%	No	Not compatible with microwave carbonization	Worrell (2010)

Improved heat transfer/ containment	Energy losses could be minimized through improved furnace technologies, including better insulation, sealing, and pressure control.	Oxidation/ Carbonization	Worrell *et al.* reported typical savings of 5-10% from cleaning heat transfer surfaces, 4-12% from ceramic-coated furnace tubes, 2-5% from better insulation, 5-10% from controlling furnace pressure, and 0-5% from maintaining door and tube seals. Carbonization ovens are assumed to be carefully pressure-controlled already due to process requirements. Summation of the remaining savings opportunities gives a range of 11-29% savings. This was averaged to come up with an energy savings of 20%.	20%	No	Benefit assumed negligible for selective (e.g., microwave) heating	Worrell (2010)
Microwave carbonization	Microwave-generated plasma is used to selectively heat fibers during carbonization.	Oxidation/ Carbonization	Huang *et al.* reported a 67% reduction in PAN carbonization time for the microwave process. For a polyolefin precursor, carbonization represents approximately 67% of the oxidation/ carbonization step (Das & Warren (2014)). Energy savings were therefore assumed to be 67% with a 67% applicability for the oxidation/ carbonization step, or 45% total.	45%	Yes		Huang (2009)
Process heating control systems	Advanced sensors and control systems enable continuous monitoring and optimization of heat inputs for fuel savings.	Oxidation/ Carbonization	Worrell *et al.* reported energy savings of 2 to 3% for glass melting furnaces; these savings are assumed to be applicable to carbonization furnaces as well. A 3% savings was assumed.	3%	Yes		Worrell (2008)
Waste heat recovery	Recovery of flue gases to preheat air in lower-temperature furnaces is an effective way to improve system efficiency.	Oxidation/ Carbonization	Worrell *et al.* estimated that typical fuel savings range from 8% to 18% for waste heat recovery. This range was averaged to come up with an estimated 13% savings for oxidation/ carbonization.	13%	No	Benefit assumed negligible for selective (e.g., microwave) heating	Worrell (2010)
Plastics recycling and recovery	Recycling of plastics is currently very limited in composites, but mechanical and other separation technologies could enable reuse.	Polymer Production	Martin *et al.* reported a 70% energy savings with a 70% applicability for thermoplastic (TP) polymer production (49% savings). Thermosets are more difficult to recycle, but technologies exist; see e.g. Yang (2012). A 70% savings with an applicability of 50% (35% savings) was assumed for thermoset (TS) polymer production.	49% (TP); 35% (TS)	Yes		Martin (2000); Hopewell (2009); Yang (2012)

Barrel insulation	Barrel insulation in closed molding systems enables shorter start-up times and reduces energy use through mitigation of thermal losses.	Injection Molding; Resin Transfer Molding; Vacuum-Assisted Resin Infusion	Schepp *et al.* estimated that barrel insulation could reduce heating energy by 7% to 25%. A 10% savings was assumed for the applicable composite molding techniques.	10%	Yes	Schepp (2006)
Infrared heating with emissivity matching	Infrared (radiant) heaters can save heating energy when the IR emissivity is well matched to the thermal characteristics of the polymer material	Pultrusion; Thermoforming	Schepp *et al.* estimated that radiant heaters could reduce energy use by 50%.	50%	Yes	Schepp (2006)
Improved die design	Proper die design (e.g., achieved through simulation) could reduce scrap rates and improve throughput.	Pultrusion	Schepp *et al.* estimated that rejected product (and the corresponding energy use) could be reduced by 5% through improved die design.	5%	Yes	Schepp (2006)
Process integration/ pinch analysis	Process intensification leverages synergies in systems of components working together. Strategies include size and performance matching to reduce bottlenecks (the "pinch")	Cross-Cutting (all subareas and sub-processes)	Martin *et al.* estimated an energy savings of 10% with 40% applicability, or 4% savings overall.	4%	Yes	Martin (2000)

In cases where more than one technology was considered for a given subarea/sub-process, the following calculation was used:

$$PM = PMBaseline * [(1 - P_1) * (1 - P_2) * \ldots * (1 - P_n)]$$

where *PM* is the practical minimum energy intensity, *PMBaseline* is the baseline energy intensity (the polyolefin process for carbon fiber production, and the SOA intensity for resin and composite production), and P_1, P_2, … P_n are the percent savings for each of the *n* PM technologies included in the model. Energy savings from different technologies were not considered additive; rather this formula considers technologies as compounding when more than one is applicable to a certain subarea. Energy savings from cross-cutting technologies were applied across all subareas and sub-processes as part of the compounded savings estimate.

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