U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in the Manufacturing of Lightweight Materials: Carbon Fiber Reinforced Polymer Composites

March 15, 2016

Prepared for: National Renewable Energy Laboratory and U.S. Department of Energy, Advanced Manufacturing Office

Prepared by: Energetics Incorporated

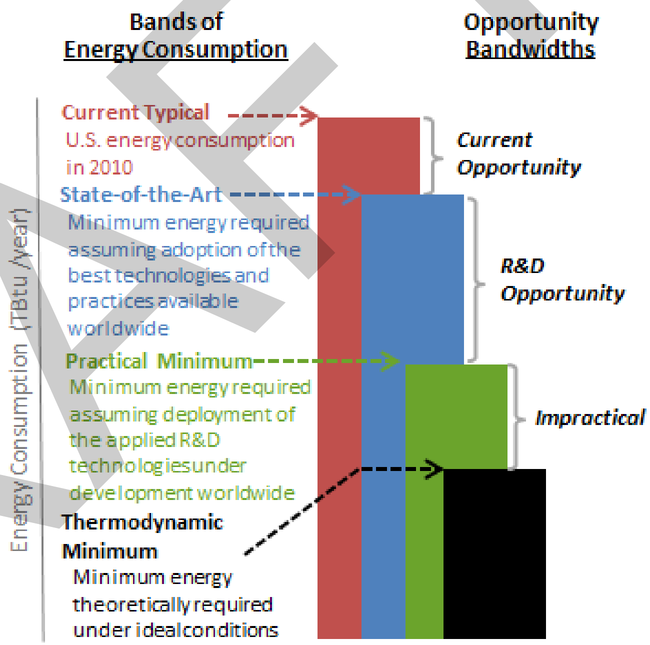
DRAFT REPORT

(This page intentionally left blank)

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.

AMO is releasing this energy bandwidth study in draft form in order to solicit input from the public as part of the peer review process. 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, aluminum, magnesium, and titanium. Reviewer feedback will be used to update the bandwidth reports with the best available data and assumptions prior to final publication, and to generate input to support further analysis. In the next phase of work, data will be integrated and compared across all six materials, including a comparison of manufacturing energy intensity on a material performance (e.g., effective weight) basis for key applications.



Energy Consumption Bands and Opportunity Bandwidths Estimated in this Study

[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.

Four different energy *bands* (or measures) are used consistently in this series to describe different levels of onsite energy consumption to manufacture specific products and to compare potential energy savings opportunities in U.S. manufacturing facilities (see figure). **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. 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.

Two onsite 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 difference between PM energy consumption and TM energy consumption is labeled as *impractical*. The term *impractical* is used because with today's knowledge of technologies in R&D, further investment may no longer lead to incremental energy savings and thermodynamic limitations impede technology opportunities. 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 Kramer, 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.

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. 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;
- *Polymer Production:* the manufacture of the polymer resin that will serve as a matrix material in the final composite product; and
- *Composite Production:* 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.[2] 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. Note that the energy savings opportunities presented reflect the estimated production of CFRP composites for selected application areas in 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 for CRFP Composite Manufacturing in the U.S. (Considering Production for Selected Lightweighting Application Areas only)*

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[3,4]**	2 TBtu (a 25% savings**)
R&D Opportunity **– additional energy savings if applied R&D technologies under development worldwide are successfully deployed[5,6]**	5 TBtu (a further 66% savings**)

* 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.

---

[2] 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.
[3] Current opportunity savings calculation: 8 TBtu – 6 TBtu = 2 TBtu.
[4] Current opportunity savings percentage = [(CT – SOA)/(CT – TM)]x100.
[5] R&D opportunity savings calculation: 6 TBtu – 1 TBtu = 5 TBtu.
[6] R&D opportunity savings percentage = [(SOA – PM)/(CT – TM)]x100

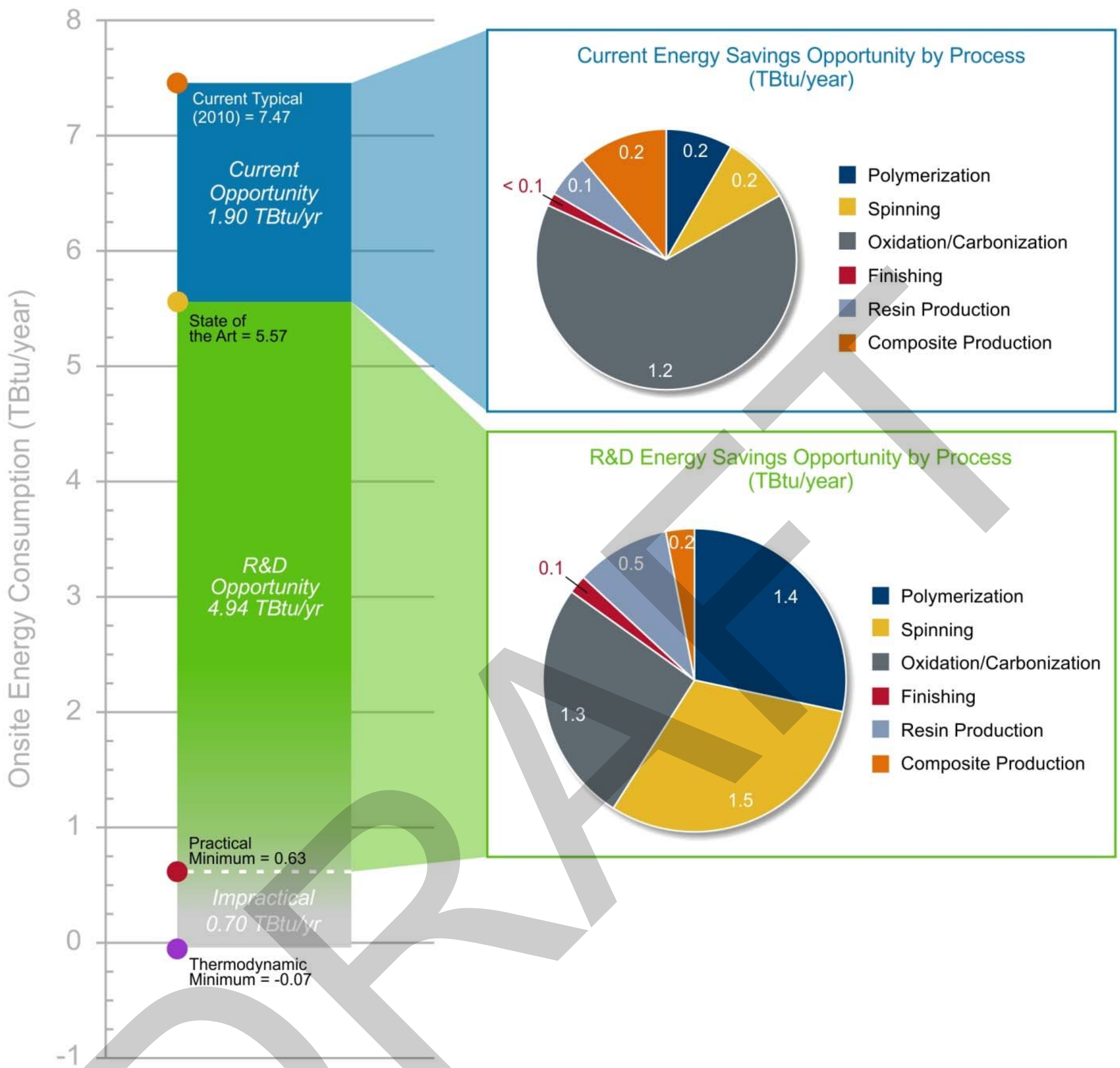


Figure ES-1. Current and R&D Energy Savings Opportunities for CFRP Composite Manufacturing by Process, Based on 2010 Carbon Fiber Production for Structural Applications

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 with today’s knowledge of technologies in R&D, further investment may no longer lead to incremental energy savings and thermodynamic limitations impede technology opportunities.

An estimated 7.47 TBtu of energy was consumed in 2010 to manufacture CFRP composites in the U.S. for the four key structural applications considered in this study. Based on the results of this study, an estimated 1.90 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 4.94 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 91% compared to typical practices used today.

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

- **Oxidation / Carbonization,** representing 65% of the Current Opportunity (1.23 TBtu/year). This opportunity is primarily attributed to carbon fiber recycling, improved furnace control systems, better heat transfer, and waste heat recovery.
- **Composite Production,** representing 11% of the Current Opportunity (0.21 TBtu/year). This opportunity is primarily attributed to the use of out-of-autoclave manufacturing methods.
- **Spinning,** representing 9% of the Current Opportunity (0.16 TBtu/year). This opportunity is primarily attributed to carbon fiber recycling and improved motor system design.

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

- **Spinning**, representing 31% of the R&D Opportunity (1.51 TBtu/year). This opportunity is primarily attributed to the replacement of solution spinning processes with melt spinning processes.
- **Polymerization**, representing 28% of the R&D Opportunity (1.40 TBtu/year). This opportunity is primarily attributed to the use of a polyolefin precursor rather than the conventional polyacrylonitrile (PAN) precursor.
- **Oxidation / Carbonization**, representing 26% of the R&D Opportunity (1.28 TBtu/year). This opportunity is primarily attributed to the use of selective microwave heating rather than traditional furnaces for thermal processing.

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
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)

Table of Contents

List of Tables

List of Figures

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 U.S. The other materials, studied in parallel, include: aluminum, magnesium, titanium, advanced high strength steel, 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.

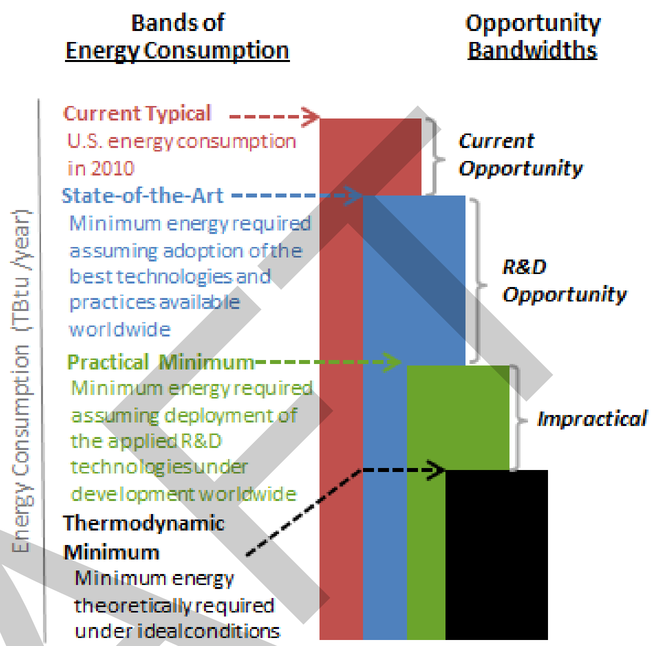
1.2 Definitions of Energy Consumption Bands and Opportunity Bandwidths

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 onsite 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.

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 onsite 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 with today's knowledge of technologies in R&D, further investment may no longer lead to incremental energy savings and thermodynamic limitations impede technology opportunities. 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.



Energy Consumption Bands and Opportunity Bandwidths Estimated in 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 "onsite energy" or "primary energy" and defined as follows:

- **Onsite 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 onsite energy consumption values presented in this study.

- **Primary energy** (sometimes referred to as source energy) includes energy that is consumed both offsite and onsite 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 onsite energy consumption; feedstocks[7] 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.

Chapter 3 presents the estimated onsite **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 onsite **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 onsite **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 onsite **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).

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

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. manufacturing sector is the physical boundary of this study. It is recognized that the major benefits of 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 *onsite* use of process energy (including purchased energy and onsite 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 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 U.S., as shown in Figure 1-1.[8]

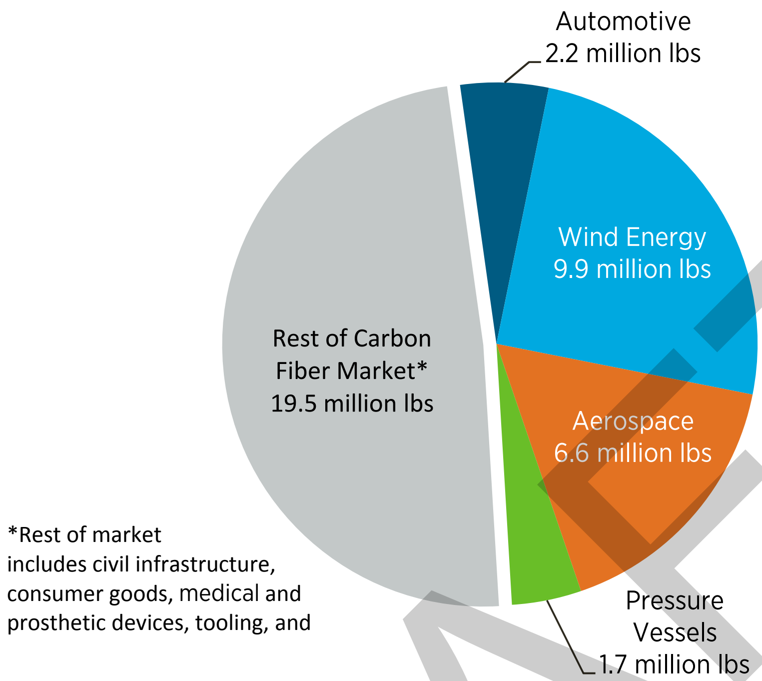


Figure 1-1. Estimated Makeup of the Carbon Fiber Market in 2010.

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.

[8] 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,[9] 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 U.S. 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;
- *Polymer Production:* the manufacture of the polymer resin that will serve as a matrix material in the final composite product; and
- *Composite Production:* the process of integrating the fibers into the polymer matrix and producing a finished composite product.

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

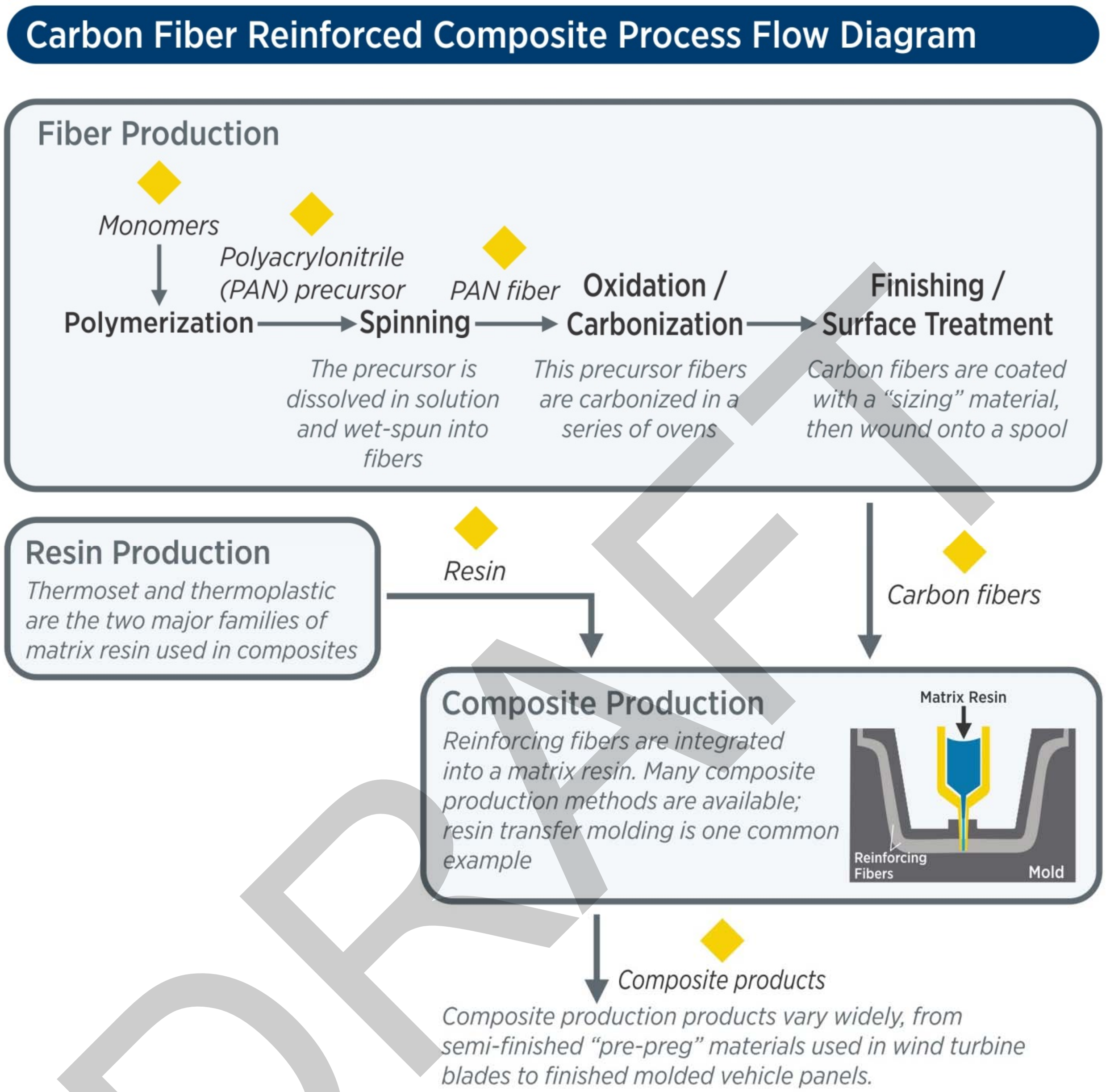


Figure 2-1. Process Flow Diagram for Carbon Fiber Reinforced Polymer Composite Manufacturing

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[10] and polyurethane[11]) and four thermoplastic polymers (polypropylene, high-density polyethylene, polyvinyl chloride,[12] and polystyrene[13]).

[10] The epoxy system considered was bisphenol-A and epichlorohydrin. Epoxy hardeners were not considered.
[11] The polyurethane material considered was rigid polyurethane foam.
[12] The polyvinyl chloride material considered was produced via bulk polymerization.

Twelve composite production techniques were considered, including two semi-finished production techniques (pre-impregnated fabric or "prepreg," and sheet or bulk molding compounds), four open forming methods (hand lay up, spray up, filament winding, and pultrusion), and six closed forming methods (injection molding, compression molding, resin transfer molding, vacuum-assisted resin infusion, autoclave forming, and cold press).

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	- Epoxy resin - Polyurethane resin - Polypropylene - High-density polyethylene - Polyvinyl chloride - Polystyrene
Composite Production	- Prepreg - Sheet or bulk molding compound - Hand lay up - Spray up - Filament winding - Pultrusion - Injection molding - Compression molding - Resin transfer molding - Vacuum-assisted resin infusion - Autoclave forming - Cold press

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 composite production technique in a "mix-and-match" fashion. In this report, the choice of resin material and composite production technique will be clearly noted anywhere a total energy intensity or consumption is presented.

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

[13] The polystyrene material considered was general-purpose polystyrene (GPPS) produced via continuous-mass radical polymerization.

data for carbon fibers.[14] Note that 2010 data were projected from 2008 in this study. Total fiber production was broken down by application area (see Figure 1-1) 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.[15] 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 U.S. 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 never 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	20.4
Resin Production	Matrix resin	n/a*	n/a*	20.4
Composite Production**	Composite product	n/a*	n/a*	40.7

* Not calculated because some fibers outside of the boundary applications were not used in the production of fiber-reinforced polymer composites.

** Composite production represents the sum of carbon fiber 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.

[14] 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).

[15] 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 differences in equipment and processing techniques employed. The energy intensity estimates reported herein are considered representative of typical processes used to produce CFRP composites in the U.S. 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. Onsite 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	Onsite CT Energy Intensity (Btu/lb)	Primary* CT Energy Intensity (Btu/lb)	Data Source
Polymerization	85,710	105,760	Das & Warren (2014)
Spinning	83,740	91,140	Das & Warren (2014)
Oxidation / Carbonization	135,900	183,570	Das & Warren (2014)
Finishing	10,740	32,240	Das & Warren (2014)
Total Energy Intensity for Carbon Fibers**	316,080	412,700	

*Primary energy accounts for offsite electricity generation and transmission losses, assuming a grid efficiency of 33.3%. Process-specific energy mix data were used to determine the ratio of fuel and electricity consumed onsite. 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 polymer materials studied. Energy intensities are presented in terms of Btu per pound (Btu/lb) of polymer material. For polypropylene (PP), high-density polyethylene (HDPE), and polyvinyl chloride (PVC), 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 plastics 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, polyurethane resin, and polystyrene, 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 for PP, HDPE, and PVC). Note that feedstock energy is not included in the energy intensities reported here for consistency with past bandwidth reports.[16]

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

Matrix Polymer	Onsite CT Energy Intensity (Btu/lb)	Primary* CT Energy Intensity (Btu/lb)	Data Source
Thermosetting Resins			
Epoxy resin	31,940	40,490	PlasticsEurope (2006)
Polyurethane resin	20,140	27,690	PlasticsEurope (2005b)
Thermoplastic Resins			
Polypropylene (PP)	5,370	11,840	ACC (2011)
High density polyethylene (HDPE)	5,710	11,900	ACC (2011)
Polyvinyl chloride (PVC)	9,710	15,270	ACC (2011)
Polystyrene (PS)	10,500	17,360	PlasticsEurope (2012)

*Primary energy accounts for offsite electricity generation and transmission losses, assuming a grid efficiency of 33.3%. Process-specific energy mix data were used to determine the ratio of fuel and electricity consumed onsite. See Appendix A3 for energy mix assumptions.

Current typical energy intensity values for composite production are presented in Table 4-3, along with the sources used. Energy intensities are presented in terms of Btu per pound (Btu/lb) of composite product (fibers and resin).

[16] 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 Production

Production Method	Onsite CT Energy Intensity (Btu/lb)	Primary* Energy Intensity (Btu/lb)	Data Source
Semi-Finished Production Methods			
Prepreg	17,200	51,640	Suzuki & Takahashi (2005)
Sheet or bulk molding compound	1,510	4,520	Suzuki & Takahashi (2005)
Open Forming Methods			
Hand lay up	8,250	24,790	Suzuki & Takahashi (2005)
Spray up	6,410	19,240	Suzuki & Takahashi (2005)
Filament winding	1,160	3,490	Suzuki & Takahashi (2005)
Pultrusion	1,330	4,000	Suzuki & Takahashi (2005)
Closed Molding Methods			
Injection molding	4,830	14,490	Schepp (2006)
Compression molding	4,910	14,730	Schepp (2006)
Resin transfer molding	5,500	16,530	Suzuki & Takahashi (2005)
Vacuum-assisted resin infusion	4,390	13,170	Suzuki & Takahashi (2005)
Autoclave forming	9,570	28,730	Schepp (2006)
Cold press	5,070	15,230	Suzuki & Takahashi (2005)

*Primary energy accounts for offsite electricity generation and transmission losses, assuming a grid efficiency of 33.3%. Process-specific energy mix data were used to determine the ratio of fuel and electricity consumed onsite. See Appendix A3 for energy mix assumptions.

3.2 Current Typical Energy Consumption

Table 3-4 presents the calculated onsite 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 autoclave forming 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, onsite energy intensities were converted to primary (and vice versa) using process-specific energy mix data. Electricity losses were calculated by subtracting the onsite energy consumption from the primary energy consumption.

Table 3-4. Calculated Current Typical Energy Consumption for Carbon Fiber Reinforced Polymer Composite Manufacturing – Application Areas Considered

Subarea (product)	Onsite CT Energy Intensity (Btu/lb)	Primary CT Energy Intensity (Btu/lb)	Production (million lbs)	Onsite CT Energy Consumption (TBtu/yr)	Offsite Losses, Calculated (TBtu/yr)	Primary CT Energy Consumption (TBtu/yr)
Carbon Fiber Production (carbon fibers)						
Polymerization	85,710	105,760	20.4	1.74	0.41	2.15
Spinning	83,740	91,140	20.4	1.70	0.15	1.86
Oxidation/Carbonization	135,900	183,570	20.4	2.77	0.97	3.74
Finishing	10,740	32,240	20.4	0.22	0.44	0.66
Resin Production* (matrix polymer)	31,940	40,490	20.4	0.65	0.17	0.82
Composite Production (composite product)**	9,570	28,730	40.7	0.39	0.78	1.17
Total* **				**7.47**	**2.92**	**10.40**

* Assumes thermosetting epoxy resin.
** Assumes autoclave forming.
***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.

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, 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	Onsite SOA Energy Intensity (Btu/lb)	Primary* SOA Energy Intensity (Btu/lb)	Data Source
Polymerization	77,990	96,240	Calculated; see Appendix A4
Spinning	75,820	82,520	Calculated; see Appendix A4
Oxidation / Carbonization	75,520	102,010	Calculated; see Appendix A4
Finishing	8,650	25,970	Calculated; see Appendix A4
Total Energy Intensity for Carbon Fibers**	237,980	306,730	

State of the Art (SOA)
*Primary energy accounts for offsite electricity generation and transmission losses, assuming a grid efficiency of 33.3%. Process-specific energy mix data were used to determine the ratio of fuel and electricity consumed onsite. See Appendix A3 for energy mix assumptions.
** Note: totals may not sum due to independent rounding.

For polymer 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.[17]

[17] 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 Polymer Matrix Resins

Matrix Polymer	Onsite SOA Energy Intensity (Btu/lb)	Primary* SOA Energy Intensity (Btu/lb)	Data Source
Thermosetting Resins			
Epoxy resin	26,880	32,390	Best engineering judgment (20% savings), ACC (2011), PlasticsEurope (2006)
Polyurethane resin	17,330	22,150	Best engineering judgment (20% savings), ACC (2011), PlasticsEurope (2005a)
Thermoplastic Resins			
Polypropylene (PP)	4,290	9,470	Best engineering judgment (20% savings), ACC (2011)
High density polyethylene (HDPE)	4,570	9,520	Best engineering judgment (20% savings), ACC (2011)
Polyvinyl chloride (PVC)	7,180	11,290	Best engineering judgment (20% savings), ACC (2011), PlasticsEurope (2005b)
Polystyrene (PS)	8,400	13,890	Best engineering judgment (20% savings), ACC (2011), PlasticsEurope (2012)

State of the Art (SOA)
*Primary energy accounts for offsite electricity generation and transmission losses, assuming a grid efficiency of 33.3%. Process-specific energy mix data were used to determine the ratio of fuel and electricity consumed onsite. See Appendix A3 for energy mix assumptions.

SOA energy intensity values for composite production 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 Production

Production Method	Onsite SOA Energy Intensity (Btu/lb)	Primary* SOA Energy Intensity (Btu/lb)	Data Source
Semi-Finished Production Methods			
Prepreg	13,760	41,310	Best engineering judgment (20% savings)
Sheet or bulk molding compound	1,200	3,620	Best engineering judgment (20% savings)
Open Forming Methods			
Hand lay up	6,600	19,830	Best engineering judgment (20% savings)
Spray up	5,120	15,390	Best engineering judgment (20% savings)
Filament winding	930	2,790	Best engineering judgment (20% savings)
Pultrusion	1,070	3,200	Best engineering judgment (20% savings)
Closed Molding Methods			
Injection molding	960	2,880	Thiriez (2006)
Compression molding	3,920	11,780	Schepp (2006)
Resin transfer molding	4,400	13,220	Best engineering judgment (20% savings)
Vacuum-assisted resin infusion	3,510	10,530	Best engineering judgment (20% savings)
Autoclave forming	7,650	22,990	Best engineering judgment (20% savings)
Cold press	4,060	12,190	Best engineering judgment (20% savings)

*Primary energy accounts for offsite electricity generation and transmission losses, assuming a grid efficiency of 33.3%. Process-specific energy mix data were used to determine the ratio of fuel and electricity consumed onsite. See Appendix A3 for energy mix assumptions.

4.2 State of the Art Energy Consumption

Table 4-4 presents the calculated onsite 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 production 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). Onsite 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 onsite 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 Considered

Subarea (product)	Onsite SOA Energy Intensity (Btu/lb)	Primary SOA Energy Intensity (Btu/lb)	Production (million lbs)	Onsite SOA Energy Consumption (TBtu/yr)	Offsite Losses, Calculated (TBtu/yr)	Primary SOA Energy Consumption (TBtu/yr)
Carbon Fiber Production (carbon fibers)						
Polymerization	77,990	96,240	20.4	1.59	0.37	1.96
Spinning	75,820	82,520	20.4	1.54	0.14	1.68
Oxidation/Carbonization	75,520	102,010	20.4	1.54	0.54	2.08
Finishing	8,650	25,970	20.4	0.18	0.35	0.53
Resin Production* (matrix polymer)	26,880	32,390	20.4	0.55	0.11	0.66
Composite Production** (composite product)	4,400	13,220	40.7	0.18	0.36	0.54
Total***				5.57	1.87	7.44

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 onsite 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 onsite SOA energy savings percent is:

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

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* in terms of percent energy savings is composite production at 54.0% energy savings; the greatest *current opportunity* in terms of TBtu savings is oxidation/carbonization at 1.23 TBtu per year 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 1.90 TBtu of onsite energy could be saved annually, corresponding to a 25% 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

Subarea (product)	Onsite CT Energy Consumption, Calculated (TBtu/yr)	Onsite 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	1.74	1.59	0.16	8.8%
Spinning	1.70	1.54	0.16	9.5%
Oxidation/Carbonization	2.77	1.54	1.23	44.2%
Finishing	0.22	0.18	0.04	19.5%
Resin Production (matrix polymer)	0.65	0.55	0.10	15.3%
Composite Production (composite product)**	0.39	0.18	0.21	54.0%
Total***	**7.47**	**5.57**	**1.90**	**25.2%**

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, 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:[18]

- **Polyolefin precursor:** baseline carbon fiber manufacturing process for PM calculation;
- **Carbon fiber recycling:** 35% savings in the polymerization, spinning, oxidation/carbonization, and finishing processes;
- **Motor re-sizing or VSDs:** 12% savings in the spinning and finishing processes (applied to the electricity component only);
- **Microwave carbonization:** 45% savings in the oxidation/carbonization process;
- **Process heating control systems:** 3% savings in the oxidation/carbonization process;
- **Modeling and process analysis to reduce off-spec material:** 14% savings across all processes (cross-cutting technology);
- **Process integration / pinch analysis:** 4% savings across all processes (cross-cutting technology).

For a discussion of these technologies and energy savings estimates, see Appendix A5. Appendix A5 also provides details of additional technologies that were 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.

[18] 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.

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

Carbon Fiber Production Sub-Process	Onsite PM Energy Intensity (Btu/lb)	Primary* PM Energy Intensity (Btu/lb)	Data Source
Polymerization	9,210	21,230	Calculated; see Appendix A5
Spinning	1,430	4,290	Calculated; see Appendix A5
Oxidation / Carbonization	12,620	26,930	Calculated; see Appendix A5
Finishing	3,880	11,640	Calculated; see Appendix A5
Total Energy Intensity for Carbon Fibers**	27,140	64,080	

Practical Minimum (PM)
*Primary energy accounts for offsite electricity generation and transmission losses, assuming a grid efficiency of 33.3%. Process-specific energy mix data were used to determine the ratio of fuel and electricity consumed onsite. See Appendix A3 for energy mix assumptions.
**Note: totals may not sum due to independent rounding.

For polymer and composite production 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 polymer production:

- **Plastics recycling and recovery:** 49% savings for thermoplastic resins and 35% savings for thermosetting resins;
- **Modeling and process analysis to reduce off-spec material:** 14% savings across all processes (cross-cutting technology);
- **Process integration / pinch analysis:** 4% savings across all processes (cross-cutting technology).

For composite production:

- **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 autoclave forming;
- **Improved die design:** 5% savings for pultrusion;
- **Modeling and process analysis to reduce off-spec material:** 14% savings across all processes (cross-cutting technology);
- **Process integration / pinch analysis:** 4% savings across all processes (cross-cutting technology).

For a discussion of these technologies and energy savings estimates, 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	Onsite PM Energy Intensity (Btu/lb)	Primary* PM Energy Intensity (Btu/lb)	Data Source
Thermosetting Resins			
Epoxy resin	11,320	13,640	Calculated; see Appendix A5
Polyurethane resin	7,300	9,330	Calculated; see Appendix A5
Thermoplastic Resins			
Polypropylene (PP)	2,310	5,080	Calculated; see Appendix A5
High density polyethylene (HDPE)	2,450	5,110	Calculated; see Appendix A5
Polyvinyl chloride (PVC)	3,850	6,060	Calculated; see Appendix A5
Polystyrene (PS)	4,510	7,450	Calculated; see Appendix A5

Practical Minimum (PM)
*Primary energy accounts for offsite electricity generation and transmission losses, assuming a grid efficiency of 33.3%. Process-specific energy mix data were used to determine the ratio of fuel and electricity consumed onsite. See Appendix A3 for energy mix assumptions.

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

Production Method	Onsite PM Energy Intensity (Btu/lb)	Primary* PM Energy Intensity (Btu/lb)	Data Source
Semi-Finished Production Methods			
Prepreg	11,360	34,110	Calculated; see Appendix A5
Sheet or bulk molding compound	990	2,980	Calculated; see Appendix A5
Open Forming Methods			
Hand lay up	5,450	16,370	Calculated; see Appendix A5
Spray up	4,230	12,710	Calculated; see Appendix A5
Filament winding	770	2,300	Calculated; see Appendix A5
Pultrusion	420	1,260	Calculated; see Appendix A5
Closed Molding Methods			
Injection molding	710	2,140	Calculated; see Appendix A5
Compression molding	3,240	9,730	Calculated; see Appendix A5
Resin transfer molding	3,270	9,820	Calculated; see Appendix A5
Vacuum-assisted resin infusion	2,610	7,830	Calculated; see Appendix A5
Autoclave forming	3,160	9,490	Calculated; see Appendix A5
Cold press	3,350	10,060	Calculated; see Appendix A5

Practical Minimum (PM)
*Primary energy accounts for offsite electricity generation and transmission losses, assuming a grid efficiency of 33.3%. Process-specific energy mix data were used to determine the ratio of fuel and electricity consumed onsite. See Appendix A3 for energy mix assumptions.

5.2 Practical Minimum Energy Consumption

Table 5-4 presents the calculated onsite and primary PM energy consumption for the CFRP production subareas studied. In these summary data, polypropylene was assumed as the polymer matrix material and injection molding was assumed as the composite production method. These selections reflect the current R&D interest in moving towards thermoplastic resins and low-energy composite production methods to reduce CFRP cost and energy requirements. Energy consumption values were calculated by multiplying energy intensity (Btu/lb) by 2010 production (lbs). Onsite 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 onsite 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 Considered

Subarea (product)	Onsite PM Energy Intensity (Btu/lb)	Primary PM Energy Intensity (Btu/lb)	Production (million lbs)	Onsite PM Energy Consumption (TBtu/yr)	Offsite Losses, Calculated (TBtu/yr)	Primary PM Energy Consumption (TBtu/yr)
Carbon Fiber Production (carbon fibers)						
Polymerization	9,210	21,230	20.4	0.19	0.24	0.43
Spinning	1,430	4,290	20.4	0.03	0.06	0.09
Oxidation/Carbonization	12,620	26,930	20.4	0.26	0.29	0.55
Finishing	3,880	11,640	20.4	0.08	0.16	0.24
Resin Production* (matrix polymer)	2,310	5,080	20.4	0.05	0.06	0.10
Composite Production (composite product)**	710	2,140	40.7	0.03	0.06	0.09
Total***				**0.63**	**0.87**	**1.50**

Practical Minimum (PM)
* Assumes thermoplastic polypropylene resin.
** Assumes injection molding.
***Note: totals may not sum due to independent rounding.

Table 5-5 presents a comparison of the onsite 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*).

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 onsite PM energy savings percent is:

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

Among the processes studied, the greatest *R&D opportunity* in terms of percent energy savings is spinning at 98.3% energy savings; the greatest *R&D opportunity* in terms of TBtu savings is oxidation/carbonization at 2.51 TBtu per year 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 6.85 TBtu of onsite energy could be saved annually, corresponding to a 90.7% 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 Considered

Subarea (product)	Onsite CT Energy Consumption, Calculated (TBtu/yr)	Onsite 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	1.74	0.19	1.56	87.7%
Spinning	1.70	0.03	1.68	98.3%
Oxidation/Carbonization	2.77	0.26	2.51	90.2%
Finishing	0.22	0.08	0.14	63.9%
Resin Production (matrix polymer)	0.65	0.05	0.60	89.5%
Composite Production ** **(composite product)**	0.39	0.03	0.36	92.6%
Total* **	**7.47**	**0.63**	**6.85**	**90.7%**

Practical Minimum (PM)
* 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.

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.[19] The TM energy intensity is *negative* when the chemical reaction is net-exergonic and *positive* when the chemical reaction is net-endergonic.[20] 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.[21]

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

---

[19] Unless otherwise noted, "ideal conditions" means a pressure of 1 atmosphere and a temperature of 77°F.
[20] 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).
[21] Note that the bond energy values are averages, not specific to the molecule in question.

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.

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	-1,560	Calculated*
Spinning	0	Calculated*
Oxidation / Carbonization	-800	Calculated*
Finishing	0	Calculated*
Total Energy Intensity for Carbon Fibers**	-2,370	

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.[22] 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**.

[22] 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 Polymer Matrix Resins

Matrix Polymer	TM Energy Intensity (Btu/lb)	Data Source
Thermosetting Resins		
Epoxy resin	-120	Calculated*
Polyurethane resin	-190	Calculated*
Thermoplastic Resins		
Polypropylene (PP)	-1,160	Calculated*
High density polyethylene (HDPE)	-1,740	Calculated*
Polyvinyl chloride (PVC)	-970	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 Production

Production Method	TM Energy Intensity (Btu/lb)	Data Source
Semi-Finished Production Methods		
Prepreg	0	Best engineering judgment*
Sheet or bulk molding compound	0	Best engineering judgment*
Open Forming Methods		
Hand lay up	0	Best engineering judgment*
Spray up	0	Best engineering judgment*
Filament winding	0	Best engineering judgment*
Pultrusion	0	Best engineering judgment*
Closed Molding Methods		
Injection molding	0	Best engineering judgment*
Compression molding	0	Best engineering judgment*
Resin transfer molding	0	Best engineering judgment*
Vacuum-assisted resin infusion	0	Best engineering judgment*
Autoclave forming	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, polypropylene was assumed as the polymer matrix material and injection molding was assumed as the composite production method. These selections reflect the current R&D interest in moving towards thermoplastic resins and low-energy composite production methods to reduce CFRP cost and energy requirements. 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 Considered

Subarea (product)	TM Energy Intensity (Btu/lb)	Production (million lbs)	TM Energy Consumption (TBtu/yr)
Carbon Fiber Production (carbon fibers)			
Polymerization	-1,560	20.4	-0.03
Spinning	0	20.4	0
Oxidation/Carbonization	-800	20.4	-0.02
Finishing	0	20.4	0
Resin Production* (matrix polymer)	-1,163	20.4	-0.02
Composite Production (composite product)**	0	40.7	0
Total***			**-0.07**

Thermodynamic Minimum (TM)
* Assumes thermoplastic polypropylene resin.
** Assumes injection 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**.

Table 7-1. Current and R&D Opportunities for CFRP Manufacturing (Onsite Energy Consumption)

Subarea (product)	Current Opportunity (CT – SOA) (TBtu/year)	R&D Opportunity (SOA – PM) (TBtu/year)
Carbon Fiber Production (carbon fibers)		
Polymerization	0.16	1.40
Spinning	0.16	1.51
Oxidation/Carbonization	1.23	1.28
Finishing	0.04	0.10
Resin Production (matrix polymer)	0.10	0.50
Composite Production (composite product)	0.21	0.15
Total*	1.90	4.94

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	Carbon Fiber Production Method	Polymer Matrix Material	Composite Production Method
Current Typical	PAN process	Epoxy resin	Autoclave forming
State of the Art	PAN process	Epoxy resin	Resin transfer molding
Practical Minimum	Polyolefin process	Polypropylene	Injection 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* – 1.90 TBtu per year of energy savings could be realized if state of the art technologies and practices are deployed; and
- *R&D Opportunity* – 4.94 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 speculative and based on unproven technologies. The *impractical* bandwidth—the difference between the PM and TM energy consumption—represents energy savings that could only be achieved through fundamental changes in CFRP manufacturing. The term *impractical* is used because the TM energy consumption is based on ideal conditions that are unattainable in commercial applications.

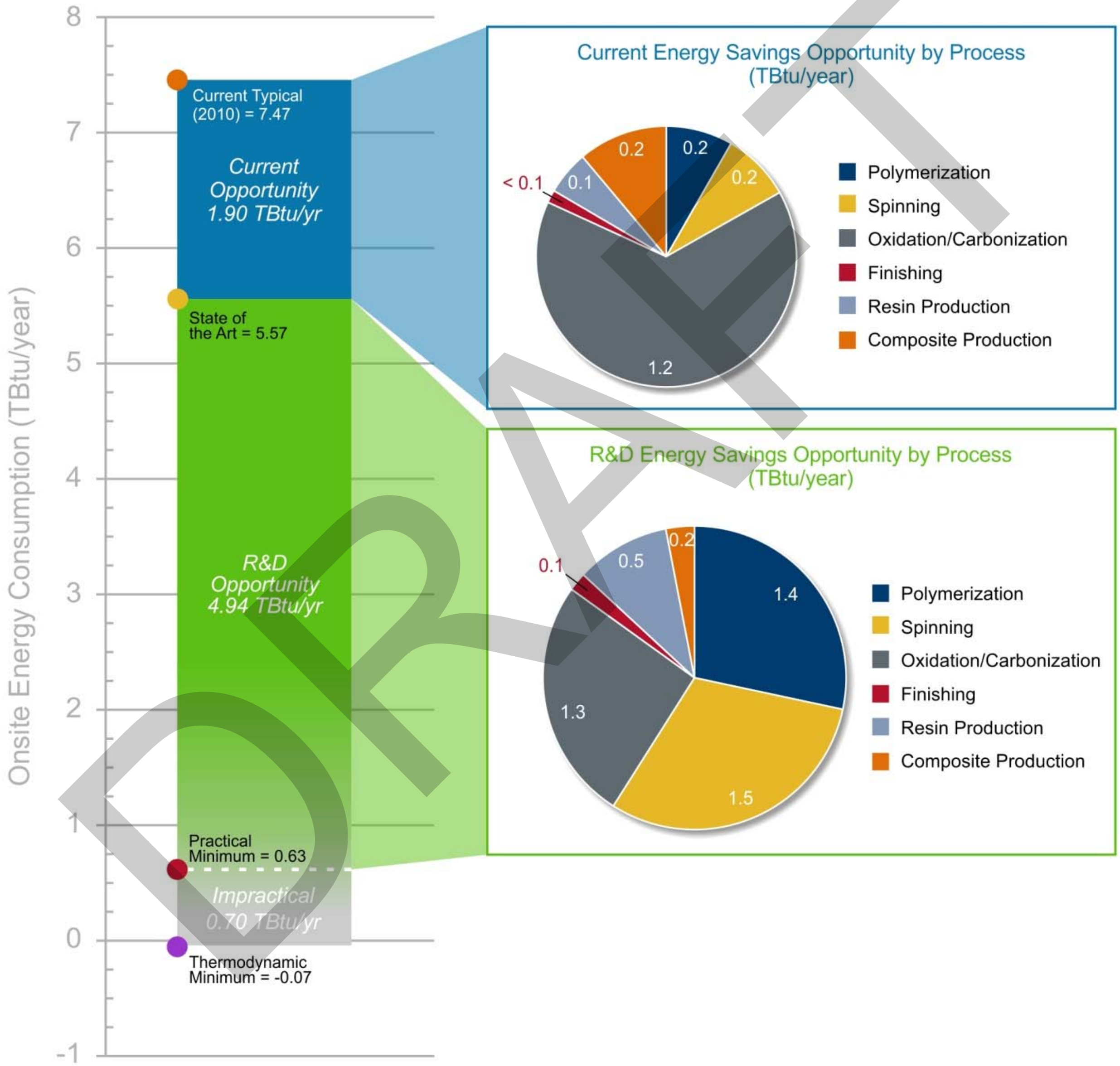


Figure 7-1. Current and R&D Energy Savings Opportunities for CFRP Composite Manufacturing by Process, Based on 2010 Carbon Fiber Production for Structural Applications

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 polymerization, spinning, and oxidation techniques. Examples of technologies that could be deployed to achieve these opportunities were detailed in this report and its appendices.

8. References

ACC (2011)	American Chemistry Council (2011), "Cradle-to-Gate Life Cycle Inventory of Nine Plastic Resins and Four Polyurethane Precursors," prepared by Franklin Associates for the Plastics Division of the American Chemistry Council.
Black (2012)	Black S., "Carbon fiber market: Gathering Momentum," CompositesWorld. 2012
Das (2011)	Das S. (2011), "Life Cycle Assessment of Carbon Fiber-Reinforced Polymer Composites," Int. Journal of Life Cycle Assessment 16, pp. 268-282
Das (2014)	Das, S., "IACMI Composite FOA Impact Assessment." Unpublished analysis. 2014.
Das & Warren (2014)	Das S. and Warren J., "Energy Analysis of Polyolefin-Based Carbon Fiber – Case Study for Lighten-Up Tool." Unpublished analysis. 2014.
DOE (2014)	Clean Energy Manufacturing Innovation Institute for Composite Materials and Structures. Funding Opportunity Announcement (FOA) Number DE-FOA-0000977. DOE/EERE. 2014. http://www1.eere.energy.gov/manufacturing/financial/solicitations_detail.asp?sol_id=760
Duflou (2009)	Duflou J.R., DeMoor J., Verpoest I., and Dewulf W. (2009), "Environmental Impact analysis of composite use in car manufacturing," CIRP Annals – Manufacturing Technology 58, pp. 9-12
Energetics (2015a)	Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Petroleum Refining. Prepared by Energetics Inc. for the U.S. DOE Advanced Manufacturing Office. 2015. http://www.energy.gov/eere/amo/downloads/bandwidth-study-energy-use-and-potential-energy-saving-opportunities-us-petroleum
Energetics (2015b)	Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Chemical Manufacturing. Prepared by Energetics Inc. for the U.S. DOE Advanced Manufacturing Office. 2015. http://www.energy.gov/eere/amo/downloads/bandwidth-study-energy-use-and-potential-energy-saving-opportunities-us-chemical
Energetics (2015c)	Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Iron and Steel Manufacturing. Prepared by Energetics Inc. for the U.S. DOE Advanced Manufacturing Office. 2015. http://www.energy.gov/eere/amo/downloads/bandwidth-study-energy-use-and-potential-energy-saving-opportunities-us-iron-and
Energetics (2015d)	Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Pulp and Paper Manufacturing. Prepared by Energetics Inc. for the U.S. DOE Advanced Manufacturing Office. 2015. http://www.energy.gov/eere/amo/downloads/bandwidth-study-energy-use-and-potential-energy-saving-opportunities-us-pulp-and

Gardiner (2014)	Gardiner G (2014), "Recycled carbon fiber update: closing the CFRP lifecycle loop," Composites World, 11/30/2014
Holmes (2014)	Holmes M., "Carbon fibre reinforced plastics market continues growth path (Part 1)," Reinforced Plastics. 2014.
Hopewell (2009)	Hopewell J., Dvorak R. and Kosior E. (2009), "Plastics recycling: challenges and opportunities," Philosophical Transactions of the Royal Society B 364, pp. 2115-2126
Huang (2009)	X. Huang (2009), "Fabrication and Properties of Carbon Fibers," Materials 2, pp. 2369-2403
Jacob (2005)	Jacob G.C., Starbuck J.M., Fellers J.F., and Simunovic S. (2005), "Effect of fiber volume fraction, fiber length, and fiber tow size on the energy absorption of chopped carbon fiber-polymer composites," Polymer Composites 26, pp. 293-305
JEC (2009)	"Carbon fibre: investing cautiously," JEC Composites Magazine. Vol. 51. 2009.
Kim (2014)	Kim S. (2014), "Engineering sustainability of mechanical recycling on carbon fiber composite materials," Undergraduate Research Paper, University of Minnesota - Duluth.
Krause (2008)	Krause F.L. (2008), "Energy Efficiency in Manufacturing: The Role of ICT," Report of the European Commission Smart Manufacturing Consultation Group.
Martin (2000)	Martin et al, "Emerging Energy-Efficient Industrial Technologies," Lawrence Berkeley National Laboratory (2000)
Moore (2012)	Moore, S., "Will a carbon fiber supply crunch emerge?" *Plastics Today*, July 9, 2012.
Paiva (2003)	M.C. Paiva, P. Kotasthane, D.D. Edie, and A.A. Ogale (2003), "UV stabilization route for melt-processible PAN-based carbon fibers," Carbon 41, pp. 1399-1409
PlasticsEurope (2005a)	Eco-Profiles of the European Plastics Industry: Polyurethane Rigid Foam. PlasticsEurope. 2005. http://www.plasticseurope.org/plastics-sustainability-14017/eco-profiles.aspx
PlasticsEurope (2005b)	Eco-Profiles of the European Plastics Industry: Polyvinyl Chloride (PVC) (Bulk Polymerization). PlasticsEurope. 2005. http://www.plasticseurope.org/plastics-sustainability-14017/eco-profiles.aspx
PlasticsEurope (2006)	Eco-Profiles of the European Plastics Industry: Liquid Epoxy Resins. PlasticsEurope. 2006. http://www.plasticseurope.org/plastics-sustainability-14017/eco-profiles.aspx
PlasticsEurope (2012)	Eco-Profiles and Environmental Product Declarations of the European Plastics Manufacturers: General-Purpose Polystyrene and High-Impact Polystyrene. PlasticsEurope. 2012. http://www.plasticseurope.org/plastics-sustainability-14017/eco-profiles.aspx

PlasticsEurope (2014a)	Eco-Profiles and Environmental Product Declarations of the European Plastics Manufacturers: Polypropylene (PP). PlasticsEurope. 2014. http://www.plasticseurope.org/plastics-sustainability-14017/eco-profiles.aspx
PlasticsEurope (2014b)	Eco-Profiles and Environmental Product Declarations of the European Plastics Manufacturers: High-Density Polyethylene (HDPE), Low-Density Polyethylene (LDPE), Linear Low-Density Polyethylene (LLDPE). PlasticsEurope. 2014. http://www.plasticseurope.org/plastics-sustainability-14017/eco-profiles.aspx
Rocky Mountain Institute (2013)	Rocky Mountain Institute (2013). Autocomposites Workshop Report. *Kickstarting the Widespread Adoption of Automotive Carbon Fiber Composites: Key Findings & Next Steps*, January 2013.
Schepp (2006)	Schepp, C. et al. (2006), "Plastics Industry Energy Best Practice Guidebook," Focus on Energy.
Shin (2014)	Shin, H. (2014), "CRFP Engine Acoustic Cover: Low Cost Manufacturing Process by Microwave Curing and Carbon Valley Activity in Korea," presented at the 8th International CFK-Valley Stade Convention, 24-25 June 2014, Stade, Germany.
Suzuki & Takahashi (2005)	Suzuki T. and Takahashi J. (2005), "Prediction of Energy Intensity of Carbon Fiber Reinforced Plastics for Mass-Produced Passenger Cars," 9th Japan International SAMPE Symposium, Nov. 29-Dec. 2, 2005.
Thiriez (2006)	Thiriez A. and Gutowski T. (2006), "An environmental analysis of injection molding," Proceedings of the 2006 ISEE International Symposium on Electronics and the Environment
Worrell (2008)	Worrell E., Galitsky C., Masanet E., and Graus W. (2008), "Energy Efficiency Improvement and Cost Saving Opportunities for the Glass Industry," LBNL / EPA
Worrell (2010)	Worrell E., Angelini T., and Masanet E. (2010), Managing Your Energy: An ENERGY STAR Guide for Identifying Energy Savings in Manufacturing Plants, LBNL/EPA, LBNL Report No. 3714E.
Yang (2012)	Yang Y. et al. (2012), "Recycling of composite materials," Chemical Engineering and Processing: Process Intensification 51, pp. 53-68

Appendix A1. Master CFRP Composite Summary Tables

Table A1-1. Onsite 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 Onsite Energy Intensity** (Btu/lb)				Calculated Onsite Energy Consumption (TBtu/yr)			
		CT	SOA	PM	TM	CT	SOA	PM	TM
Carbon Fiber Production									
Polymerization	20.4	85,710	77,990	9,210	-1,560	1.74	1.59	0.19	-0.03
Spinning		83,740	75,820	1,430	0	1.70	1.54	0.03	0
Oxidation/Carbonization		135,900	75,520	12,620	-800	2.77	1.54	0.26	-0.02
Finishing		10,740	8,650	3,880	0	0.22	0.18	0.08	0
Overall – Fiber Production		**316,080**	**237,980**	**27,140**	**-2,370**	**6.43**	**4.84**	**0.55**	**-0.05**
Resin Production									
Epoxy resin	20.4	**31,940**	**26,880**	11,320	-120	**0.65**	**0.55**	0.23	-0.002
Polyurethane resin		20,140	17,330	7,300	-190	0.41	0.35	0.15	-0.004
Polypropylene (PP)		5,630	4,510	**2,420**	**-1,160**	0.11	0.09	**0.05**	**-0.02**
High density polyethylene (HDPE)		5,960	4,770	2,560	-1,744	0.12	0.10	0.05	-0.04
Polyvinyl chloride (PVC)		9,930	7,180	3,850	-970	0.20	0.15	0.08	-0.02
Polystyrene (PS)		10,500	8,400	4,510	-470	0.21	0.17	0.09	-0.01
Composite Production									
Prepreg	40.7	17,200	13,760	11,360	0	0.70	0.56	0.46	0
Sheet or bulk molding compound		1,510	1,200	990	0	0.06	0.05	0.04	0
Hand lay up		8,250	6,600	5,450	0	0.34	0.27	0.22	0
Spray up		6,410	5,120	4,230	0	0.26	0.21	0.17	0
Filament winding		1,160	930	770	0	0.05	0.04	0.03	0
Pultrusion		1,330	1,070	420	0	0.05	0.04	0.02	0
Injection molding		4,830	960	**710**	**0**	0.20	0.04	**0.03**	**0**
Compression molding		4,910	3,920	3,240	0	0.20	0.16	0.13	0
Resin transfer molding		5,500	**4,400**	3,270	0	0.22	**0.18**	0.13	0
Vacuum assisted resin infusion		4,390	3,510	2,610	0	0.18	0.14	0.11	0
Autoclave forming		**9,570**	7,650	3,160	0	**0.39**	0.31	0.13	0
Cold press		5,070	4,060	3,350	0	0.21	0.17	0.14	0
Total for Carbon Fiber Reinforced Polymer Manufacturing* **	40.7	183,580	136,830	15,490	-1,760	7.47	5.57	0.63	-0.07

* 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 assumes 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 (for CT and SOA) and polypropylene (for PM). The composite production method was assumed to be autoclave forming (for CT), resin transfer molding (for SOA), and injection molding (for PM). 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] + Composite Production Energy).

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	20.4	105,760	96,240	21,230	n/a	2.15	1.96	0.43	n/a
Spinning		91,140	82,520	4,290	n/a	1.86	1.68	0.09	n/a
Oxidation/Carbonization		183,570	102,010	26,930	n/a	3.74	2.08	0.55	n/a
Finishing		32,240	25,970	11,640	n/a	0.66	0.53	0.24	n/a
Overall – Fiber Production		**412,700**	**306,730**	**64,100**	**n/a**	**8.40**	**6.24**	**1.30**	**n/a**
Resin Production									
Epoxy resin	20.4	**40,490**	**32,390**	13,640	n/a	**0.82**	**0.66**	0.28	n/a
Polyurethane resin		27,690	22,150	9,330	n/a	0.56	0.45	0.19	n/a
Polypropylene (PP)		12,420	9,940	**5,330**	n/a	0.25	0.20	**0.11**	n/a
High density polyethylene (HDPE)		12,420	9,940	5,330	n/a	0.25	0.20	0.11	n/a
Polyvinyl chloride (PVC)		15,610	11,290	6,060	n/a	0.32	0.23	0.12	n/a
Polystyrene (PS)		17,360	13,890	7,450	n/a	0.35	0.28	0.15	n/a
Composite Production									
Prepreg	40.7	51,640	41,310	34,110	n/a	2.10	1.68	1.39	n/a
Sheet or bulk molding compound		4,520	3,620	2,980	n/a	0.18	0.15	0.12	n/a
Hand lay up		24,790	19,830	16,370	n/a	1.01	0.81	0.67	n/a
Spray up		19,240	15,390	12,710	n/a	0.78	0.63	0.52	n/a
Filament winding		3,490	2,790	2,300	n/a	0.14	0.11	0.09	n/a
Pultrusion		4,000	3,200	1,260	n/a	0.16	0.13	0.05	n/a
Injection molding		14,490	2,880	**2,140**	n/a	0.59	0.12	**0.09**	n/a
Compression molding		14,730	11,780	9,730	n/a	0.60	0.48	0.40	n/a
Resin transfer molding		16,530	**13,220**	9,820	n/a	0.67	**0.54**	0.40	n/a
Vacuum assisted resin infusion		13,170	10,530	7,830	n/a	0.54	0.43	0.32	n/a
Autoclave forming		**28,730**	22,990	9,490	n/a	**1.17**	0.94	0.39	n/a
Cold press		15,230	12,190	10,060	n/a	0.62	0.50	0.41	n/a
Total for Carbon Fiber Reinforced Polymer Manufacturing******	**40.7**	**255,330**	**182,780**	**36,850**	**n/a**	**10.40**	**7.44**	**1.50**	**n/a**

* 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. The conversion from onsite energy intensity to primary was made using process-specific energy mix assumptions (see Appendix A3).

*** Primary energy is not applicable for TM because electric conversion is assumed to be perfect in the theoretical minimum case.

**** Total assumes 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 (for CT and SOA) and polypropylene (for PM). The composite production method was assumed to be autoclave forming (for CT), resin transfer molding (for SOA), and injection molding (for PM). 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] + Composite Production Energy)

.

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 onsite 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 onsite 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. Composite production processes were assumed to be 100% electric, which is consistent with several sources (Schepp 2006, Das 2011, Thiriez 2006).

An electricity generation efficiency of 33.3% was used to calculate offsite electricity generation losses. The formula used to convert between onsite and primary consumption was as follows:

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

where $E_{primary}$ and E_{onsite} are the primary and onsite 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	88.3%	11.7%	*Calculated**
Spinning	95.6%	4.4%	Das (2014)
Oxidation/Carbonization	82.5%	17.5%	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	34.9%	65.1%	*Inferred**
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	89.8%	10.2%	PlasticsEurope (2006)

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

Process Subarea or Sub-Process	Fuel %	Electric %	Data Source
Polyurethane resin	86.1%	13.9%	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)	71.4%	28.6%	PlasticsEurope (2005b)
Polystyrene (PS)	67.4%	32.6%	PlasticsEurope (2012)
Composite Production: Semifinished Products			
Prepreg	0.0%	100.0%	*Best engineering judgment****
Sheet or bulk molding compound	0.0%	100.0%	*Best engineering judgment****
Composite Production: Open Molding Methods			
Hand lay up	0.0%	100.0%	*Best engineering judgment****
Spray up	0.0%	100.0%	*Best engineering judgment****
Filament winding	0.0%	100.0%	*Best engineering judgment****
Pultrusion	0.0%	100.0%	*Best engineering judgment****
Composite Production: Closed Molding Methods			
Injection molding	0.0%	100.0%	*Best engineering judgment****
Compression molding	0.0%	100.0%	*Best engineering judgment****
Resin transfer molding	0.0%	100.0%	*Best engineering judgment****
Vacuum assisted resin infusion	0.0%	100.0%	*Best engineering judgment****
Autoclave forming	0.0%	100.0%	*Best engineering judgment****
Cold press	0.0%	100.0%	*Best engineering judgment****

* Given the known overall energy mix and known energy mixes for all other sub-processes (spinning, oxidation/carbonization, and finishing), the energy mix for polymerization could be calculated.
** Assumed the same energy mix for PAN precursor finishing step as for polyolefin precursor finishing.
***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)
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:

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

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

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; Autoclave Forming	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)
Modeling and process analysis	Computer modeling and process analysis are used to improve process performance, e.g.,to reduce off-spec material.	Cross-Cutting (all subareas and sub-processes)	Krause reported that modeling and process analysis could provide 5% and 10% energy savings, respectively. Combining these, 14% overall savings were assumed for all steps.	14%	Yes	Krause (2008)
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.

U.S. DEPARTMENT OF ENERGY

Energy Efficiency & Renewable Energy

For more information, visit: manufacturing.energy.gov

DOE/EE-1347 • March 2016