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: Glass Fiber Reinforced Polymer Composites

March 15, 2016

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DRAFT REPORT

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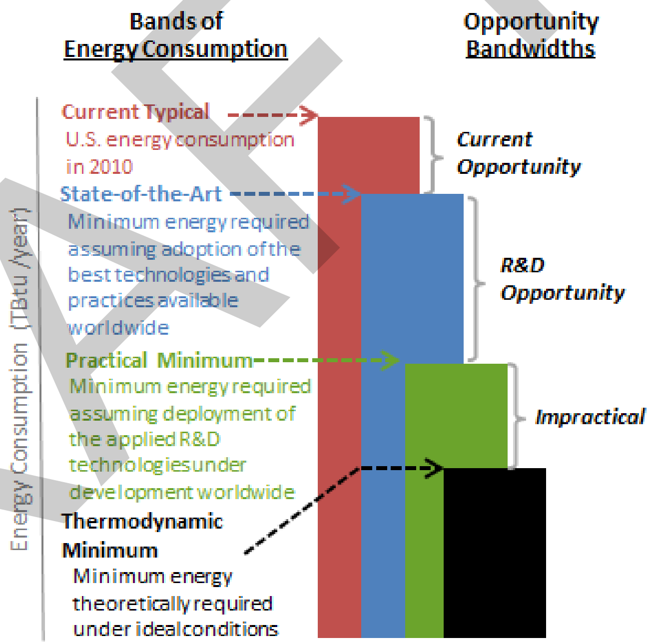
Preface

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

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.

Executive Summary

With their high strength-to-weight ratios, glass fiber reinforced polymer (GFRP) composites have strong technical potential for lightweighting in structural applications. Also known as fiberglass, GFRP composites are used in applications such as pipes and tanks, boat hulls, wind turbine blades, and automobile bodies. However, the use of GFRP composites in many commercial applications continues to be limited by manufacturing challenges such as high costs, variable performance, poor repairability, and low process throughput. 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 GFRP 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 47% of the total glass fiber market.

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

- *Batching:* the preparation of the glass batch, including measuring, grinding and mixing the constituent materials (silica and additives);
- *Melting:* the process of melting the glass mixture and refining the molten glass to remove impurities and air bubbles;
- *Fiberization:* the process of extruding the molten glass through a bushing and attenuating the extruded material into long, thin filaments;
- *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 GFRP 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 GFRP 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 shown 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 GFRP 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 GRFP Composite Manufacturing in the U.S. (Considering Production for Selected Lightweighting Application Areas only)*

Opportunity Bandwidths	Estimated Energy Savings Opportunity for GFRP Composite Manufacturing (per year)
Current Opportunity – energy savings if the best technologies and practices available are used to upgrade production[3,4]	14 TBtu (a 33% savings**)
R&D Opportunity – additional energy savings if applied R&D technologies under development worldwide are successfully deployed[5,6]	25 TBtu (a further 56% savings**)

* Calculated using the production values for lightweight structural application areas considered in this study only (see Section 1.4), and not all glass 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: 43 TBtu – 29 TBtu = 14 TBtu.
[4] Current opportunity savings percentage = [(CT – SOA)/(CT – TM)]x100.
[5] R&D opportunity savings calculation: 29 TBtu – 4 TBtu = 25 TBtu.
[6] R&D opportunity savings percentage = [(SOA – PM)/(CT – TM)]x100

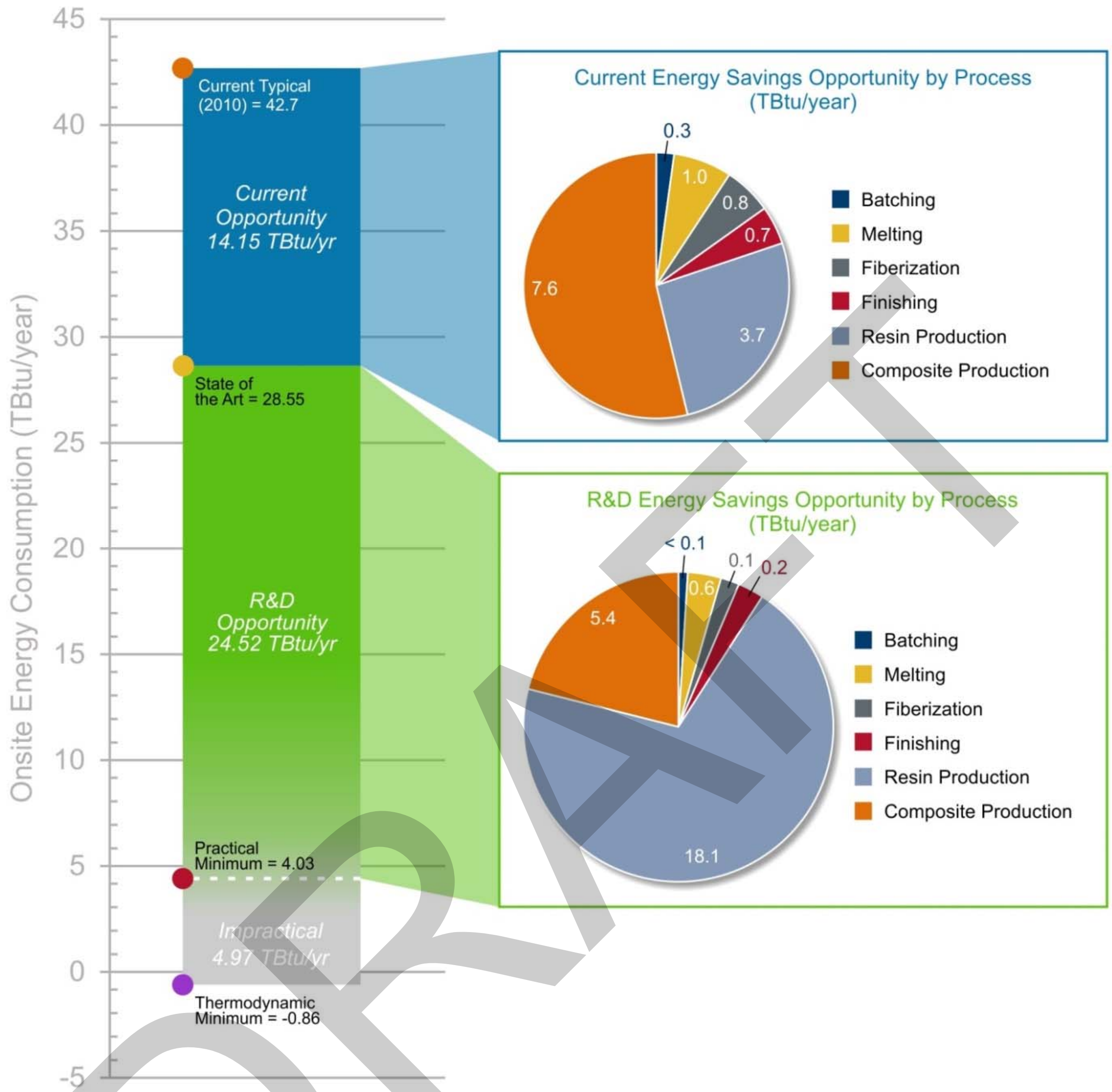


Figure ES-1. Current and R&D Energy Savings Opportunities for GFRP Composite Manufacturing by Process, Based on 2010 Glass Fiber Production for Structural Applications

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

- **Composite Production,** representing 54% of the Current Opportunity (7.61 TBtu/yr);
- **Resin Production,** representing 26% of the Current Opportunity (3.73 TBtu/yr);
- **Glass Melting,** representing 7% of the Current Opportunity (1.01 TBtu/yr).

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

- **Resin Production**, representing 74% of the R&D Opportunity (18.10 TBtu/yr).
- **Composite Production,** representing 22% of the R&D Opportunity (5.44 TBtu/yr);
- **Glass Melting,** representing 3% of the R&D Opportunity (0.62 TBtu/yr).

For both current and R&D energy savings, a large majority of the energy opportunity arises from composite production and resin production. This result reflects the fact that while glass fiber manufacturing techniques are fairly mature, composite production techniques are still undergoing rapid development. Fundamental changes in processes and materials for composite production are being actively pursued by commercial manufacturers and R&D laboratories to drastically reduce processing energy in these steps. For example, a major opportunity to reduce composite production energy is to utilize out-of-autoclave consolidation techniques. A major opportunity to reduce resin production energy in composites is to switch out conventional thermosetting resins such as epoxy with thermoplastic resins such as polypropylene. Not only do thermoplastic resins have low embodied energies compared to thermosetting resins, they also increase recyclability of the composite product and eliminate the need for a curing step. These opportunities are further explored in this report.

List of Acronyms and Abbreviations

ACC	American Chemistry Council
AMO	Advanced Manufacturing Office
Btu	British thermal unit
GF	Glass fiber
GFRP	Glass 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
PM	Practical minimum energy consumption or energy intensity
PP	Polypropylene
PS	Polystyrene
PU	Polyurethane
PVC	Polyvinyl chloride
R&D	Research and development
SOA	State of the art energy consumption or energy intensity
TBtu	Trillion British thermal units
TM	Thermodynamic minimum energy consumption or energy intensity
TP	Thermoplastic (resin)
TS	Thermoset (resin)
VSD	Variable speed drive (motor)

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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 glass fiber-reinforced polymer (GFRP) 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 carbon 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.

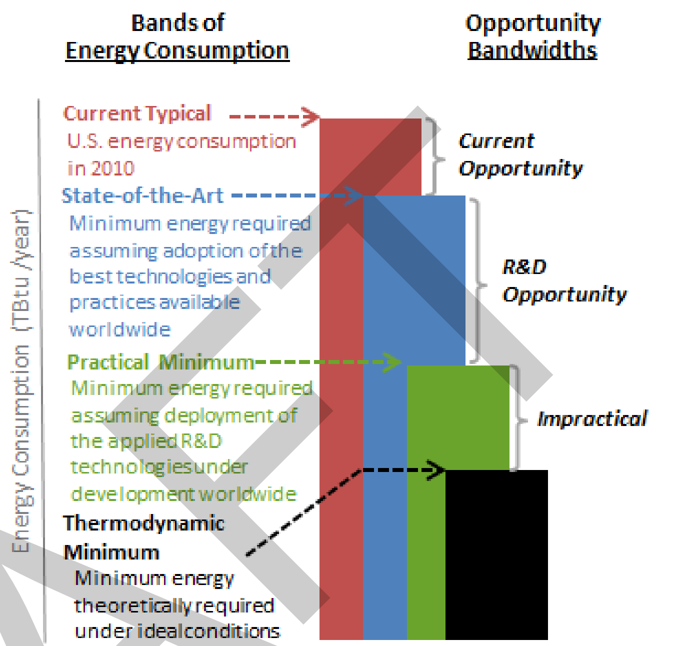
1.2 Definitions of Energy Consumption Bands and Opportunity Bandwidths

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 is 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 GFRP 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 glass 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 GFRP 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.

Glass fibers and fiber-reinforced composites are used in many diverse applications that differ substantially in product use, performance requirements, and relevance to energy use. GFRP 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, glass fibers are used in products such as reinforced cement, insulation, sporting equipment, and electrical devices. 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 47% of overall glass fiber production in the U.S., as shown in Figure 1-1.[8]

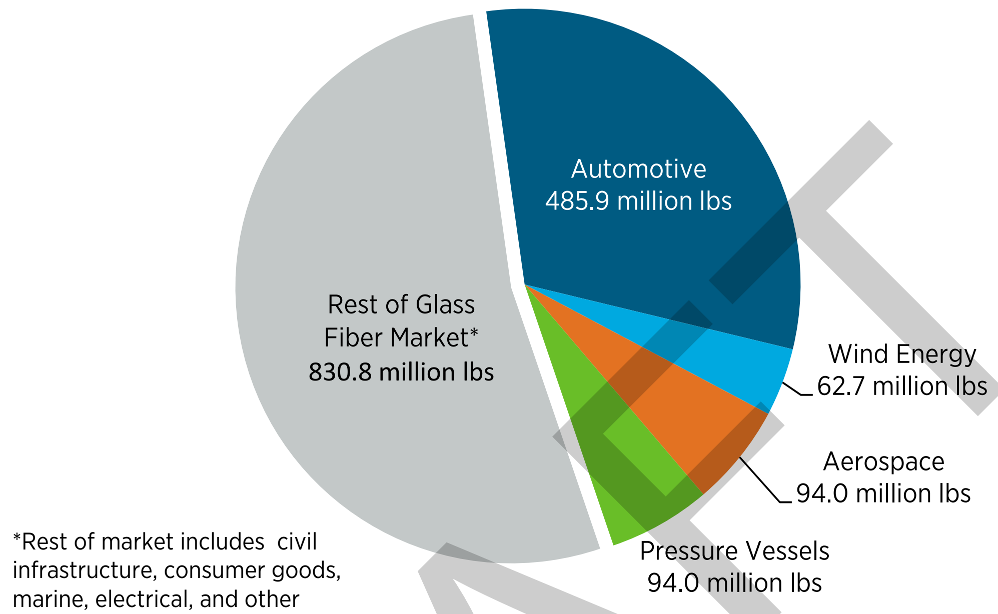


Figure 1-1. Estimated Makeup of the Glass Fiber Market in 2010.

Production of GFRP 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 2011 for production data; JEC 2012 for application breakdown data. Note that Figure 1-1 shows production data for glass rovings only (and excludes glass yarns). Glass yarns are generally woven into fabrics and are not used in structural composites. For further discussion, see Section 2.2.

2. Glass Fiber Reinforced Polymer Composite Production

2.1 Manufacturing Overview

Figure 2-1 shows the GFRP composite manufacturing process schematically. The manufacturing process can be divided into six main process steps:

- *Batching:* the preparation of the glass batch, including measuring, grinding and mixing the constituent materials (silica and additives);
- *Melting:* the process of melting the glass mixture and refining the molten glass to remove impurities and air bubbles;
- *Fiberization:* the process of extruding the molten glass through a bushing and attenuating the extruded material into long, thin filaments;
- *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.

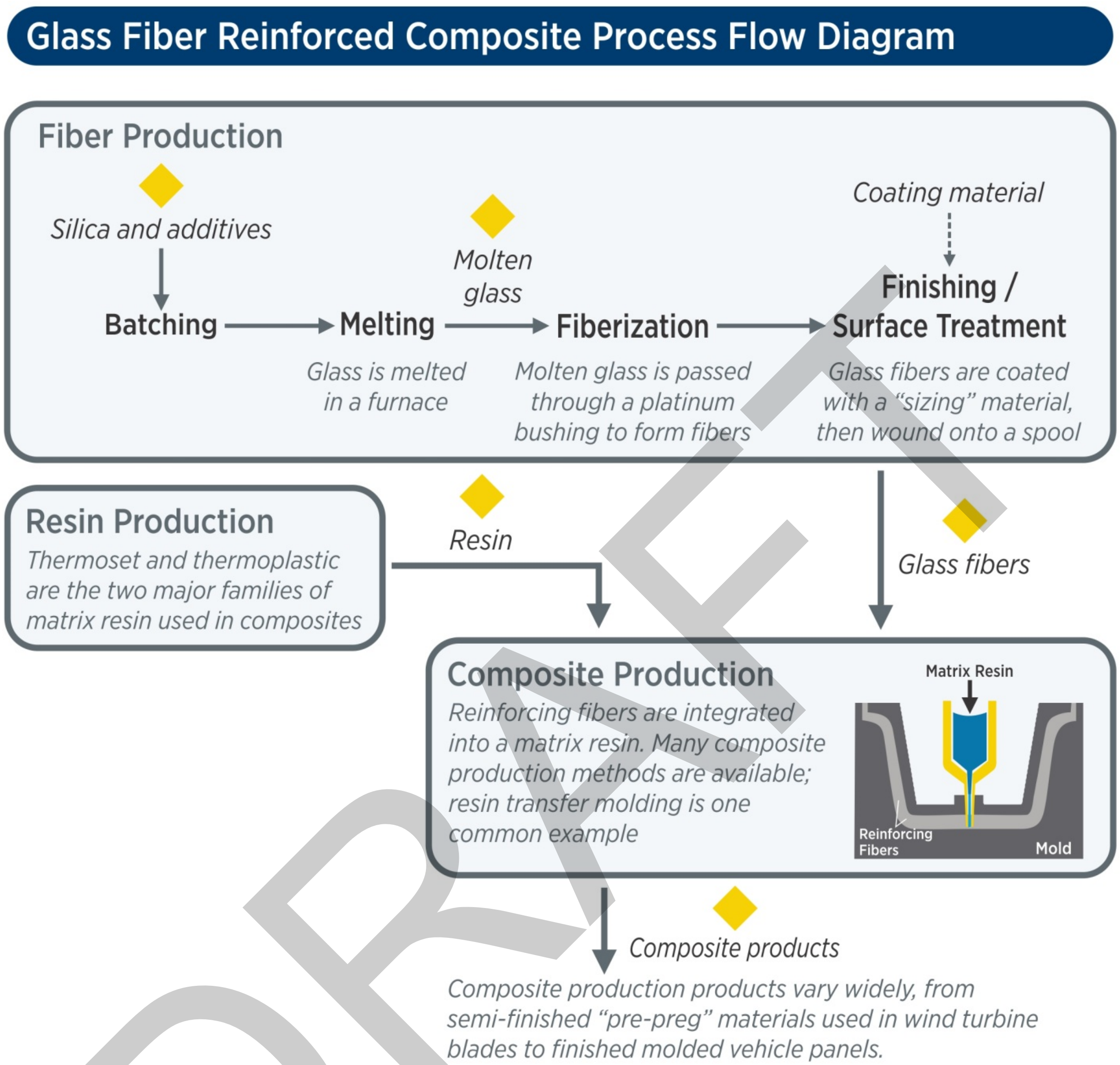


Figure 2-1. Process Flow Diagram for Glass Fiber Reinforced Polymer Composite Manufacturing

These process steps are further identified in **Table 2-1**, noting that the first four process steps listed (batching, melting, fiberization, and finishing) are sub-processes of glass fiber production. Six different polymer matrix materials were considered in this study, including two thermosetting polymers (epoxy[9] and polyurethane[10]) and four thermoplastic polymers

[9] The epoxy system considered was bisphenol-A and epichlorohydrin. Epoxy hardeners were not considered.
[10] The polyurethane material considered was rigid polyurethane foam.

(polypropylene, high-density polyethylene, polyvinyl chloride,[11] and polystyrene[12]). 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. Glass Fiber Reinforced Composites Manufacturing Process Subareas and Sub-Processes Considered in the Bandwidth Analysis

Subareas	Sub-processes / products
Glass Fiber Production ***(four sequential steps)***	- Batching - Melting - Fiberization - 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 glass 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. In 2010, United States

[11] The polyvinyl chloride material considered was produced via bulk polymerization.
[12] The polystyrene material considered was general-purpose polystyrene (GPPS) produced via continuous-mass radical polymerization.

manufacturers produced an estimated total of 1,930 million pounds of glass fibers,[13] representing about 18% of global production (JEC 2011). About 81% of the fibers produced were *glass rovings* (large-diameter [≥10 µm] filaments that can be used as a reinforcement in structural composites), while the remaining 19% were *glass yarns* (flexible, small-diameter [<10 µm] filaments that are generally woven into fabrics). Glass yarns were excluded in this study as they are not used in structural composites. For glass rovings only, estimated production totals were 1,570 million pounds for U.S. manufacturers and 8,470 million pounds globally in 2010. Total fiber production was broken down by application area using data from a market report (JEC 2012) to estimate the quantity of glass fibers produced for the four boundary applications (automotive, wind energy, compressed gas storage, and aerospace). An estimated 740 million pounds of glass fibers were used in these boundary applications, as shown in Figure 1-1.

Resin and composite production values were calculated by assuming a 50:50 weight ratio of fiber reinforcement to polymer matrix.[14] The resin production numbers, therefore, are an estimate of the production of polymer resins for use in glass 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 glass fibers outside of the boundary applications were not used in the production of fiber-reinforced polymer composites. For example, glass fibers are used in the construction industry for cement reinforcement and insulation; 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 Glass Fiber Reinforced Polymer Composites in 2010 (Glass Rovings Only)

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)
Glass Fiber Production	Glass fiber	8,470	1,570	740
Resin Production	Matrix resin	n/a*	n/a*	740
Composite Production**	Composite product	n/a*	n/a*	1,470

* 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 glass 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.

[13] Assumes that 90% of North American production occurs in the U.S. Note that his production total includes fiber production only (not the production of GFRP composites, which would utilize the glass fibers as an input).

[14] It is noted that fiber ratio in a GFRP 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 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 GFRP 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 GFRP 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 glass fibers. Energy intensities for all sub-processes are presented in terms of Btu per pound (Btu/lb) of finished glass fibers. Data were drawn from a 2008 report out of Lawrence Berkeley National Laboratory, *Energy Efficiency Improvement and Cost Savings Opportunities for the Glass Industry* (Worrell 2008), which quantified the average energy intensity of major glassmaking process steps for four different glass industry segments (flat glass, container glass, specialty glass, and glass fibers). 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 Glass Fibers

Glass Fiber Production Sub-Process	Onsite CT Energy Intensity (Btu/lb)	Primary* CT Energy Intensity (Btu/lb)	Data Source
Batching	550	1,020	Worrell (2008)
Melting[15]	2,800	2,860	Worrell (2008)
Fiberization	1,880	2,850	Worrell (2008)
Finishing	1,650	1,820	Worrell (2008)
Total Energy Intensity for Glass Fibers**	6,880	8,550	

Current Typical (CT)
*** 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.**
**** Totals may not sum due to independent rounding.**

[15] Note that for glass melting, the use of an oxy-fuel furnace (rather than a recuperative furnace) was assumed as the current typical process. Oxy-fuel furnaces account for an estimated 75% of production of textile and reinforcement fibers (Rue 2007, Worrell 2008). Recuperative furnaces, while still in use at many facilities, represent older technology and have not been considered in this analysis.

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 excellent 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)

Current Typical (CT)
*** 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* CT 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)

Current Typical (CT)

*** 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 GFRP 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 fiber-reinforced polymer composite 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, as described in Appendix 3. 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 3-4. Calculated Current Typical Energy Consumption for Glass 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)
Glass Fiber Production (glass fibers)						
Batching	550	1,020	740	0.41	0.35	0.75
Melting	2,800	2,860	740	2.06	0.04	2.11
Fiberization	1,880	2,850	740	1.38	0.72	2.10
Finishing	1,650	1,820	740	1.22	0.12	1.34
Resin Production* (matrix polymer)	31,940	40,490	740	23.53	6.30	29.83
Composite Production** (composite product)	9,570	28,730	1,470	14.10	28.24	42.33
Total* **				**42.70**	**35.76**	**78.46**

Current Typical (CT)
*** 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. glass 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

Table 4-1 presents the estimated SOA energy intensities for glass fibers. Energy intensities for all sub-processes are presented in terms of Btu per pound (Btu/lb) of finished glass fibers. Data sources are shown in the rightmost column. Onsite data were converted to primary data using process-specific energy mix assumptions, taking into account the relative use of electricity and fuel in each sub-process. These assumptions are described in Appendix A3.

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

Glass Fiber Production Sub-Process	Onsite SOA Energy Intensity (Btu/lb)	Primary* SOA Energy Intensity (Btu/lb)	Data Source
Batching	140	410	Pellegrino (2002)
Melting	1,430	1,460	Beerkens (2011)
Fiberization	750	1,140	Rue (2007)
Finishing	750	830	Rue (2007)
Total Energy Intensity for Glass Fibers**	**3,070**	**3,840**	

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.**
**** 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. This assumption is in line with the findings of ACC (ACC 2011) and represents 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	Best engineering judgment (20% savings)
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)

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.**

4.2 State of the Art Energy Consumption

Table 4-4 presents the calculated onsite and primary SOA energy consumption for the GFRP 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 composite 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 3. 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 4-4. Calculated State of the Art Energy Consumption for Glass 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)
Glass Fiber Production (glass fibers)						
Batching	140	410	740	0.10	0.20	0.30
Melting	1,430	1,460	740	1.06	0.02	1.08
Fiberization	750	1,140	740	0.55	0.29	0.84
Finishing	750	830	740	0.55	0.06	0.61
Resin Production* (matrix polymer)	26,880	32,390	740	19.80	4.06	23.86
Composite Production** (composite product)	4,400	13,220	1,470	6.49	12.99	19.48
Total* **				**28.55**	**17.62**	**46.17**

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 glass melting at 58.6% energy savings; the greatest *current opportunity* in terms of TBtu savings is composite production at 7.61 TBtu per year savings.

Table 4-5. Calculated State of the Art Energy Savings for Glass Fiber Reinforced Polymer 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)
Glass Fiber Production (glass fibers)				
Batching	0.41	0.10	0.31	75.5%
Melting	2.06	1.06	1.01	58.6%
Fiberization	1.38	0.55	0.83	48.1%
Finishing	1.22	0.55	0.66	54.5%
Resin Production* (matrix polymer)	23.53	19.80	3.73	15.3%
Composite Production** (composite product)	14.10	6.49	7.61	54.0%
Total* **	**42.70**	**28.55**	**14.15**	**32.5%**

Current Typical (CT), State of the Art (SOA), Thermodynamic Minimum (TM)
*** SOA energy savings is also called *Current Opportunity.***
**** SOA energy savings percent is the SOA energy savings opportunity from transforming glass 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, is calculated as follows: SOA Energy Savings Percent = (CT-SOA)/(CT-TM)**
*****Note: totals may not sum due to independent rounding.**

If all U.S. glass fiber, resin, and composites producers (based on the 2010 production level of GFRP composites for application areas considered) were able to attain SOA energy intensities, it is estimated that a total of 14.2 TBtu of onsite energy could be saved annually, corresponding to a 32.5% energy savings overall. 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.

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 GFRP composites in new ways, improving energy efficiency as well as composite performance. Commercialization of these improvements will drive the competitiveness of U.S. GFRP composites manufacturing. In this chapter, the energy savings possible through R&D advancements in GFRP 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 glass 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.

PM energy intensity was estimated for glass fibers by applying assumed energy savings percentages for applicable PM technologies to the baseline SOA energy intensities for each manufacturing sub-process. The PM technologies included in this analysis and assumed energy savings were:

- **Motor re-sizing or VSDs:** 12% savings in the batching process;
- **Additives to batching solution:** 4% savings in the melting process;
- **Recycling of cullet:** 10% savings in the melting process;
- **Reduced batch wetting:** 1% savings in the melting process;
- **Microwave melting:** 40% savings in the melting process;
- **Process heating control systems:** 3% savings in the melting process;
- **Improved drying systems:** 30% savings in the finishing 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 energy savings estimates and sources, see Appendix A4. Appendix A4 also provides details of additional technologies that were considered but not included in the final PM model. The excluded technologies were considered incompatible 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 melting process step. Table 5-1 presents the estimated PM energy intensities for glass fibers.

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

Glass Fiber Production Sub-Process	Onsite PM Energy Intensity (Btu/lb)	Primary* PM Energy Intensity (Btu/lb)	Data Source
Batching	100	300	Calculated; see Appendix A4 for sources
Melting	590	600	Calculated; see Appendix A4 for sources
Fiberization	620	940	Calculated; see Appendix A4 for sources
Finishing	430	480	Calculated; see Appendix A4 for sources
Total Energy Intensity for Glass Fibers	**1,740**	**2,320**	

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, PM energy intensity was again estimated by applying assumed energy savings percentages for applicable PM technologies to the baseline SOA energy intensities for each sub-process. 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 A4. 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 A4 for sources
Polyurethane resin	7,300	9,330	Calculated; see Appendix A4 for sources
Thermoplastic Resins			
Polypropylene (PP)	2,310	5,080	Calculated; see Appendix A4 for sources
High density polyethylene (HDPE)	2,450	5,110	Calculated; see Appendix A4 for sources
Polyvinyl chloride (PVC)	3,850	6,060	Calculated; see Appendix A4 for sources
Polystyrene (PS)	4,510	7,450	Calculated; see Appendix A4 for sources

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 A4 for sources
Sheet or bulk molding compound	990	2,980	Calculated; see Appendix A4 for sources
Open Forming Methods			
Hand lay-up	5,450	16,370	Calculated; see Appendix A4 for sources
Spray up	4,230	12,710	Calculated; see Appendix A4 for sources
Filament winding	770	2,300	Calculated; see Appendix A4 for sources
Pultrusion	420	1,260	Calculated; see Appendix A4 for sources
Closed Molding Methods			
Injection molding	710	2,140	Calculated; see Appendix A4 for sources
Compression molding	3,240	9,730	Calculated; see Appendix A4 for sources
Resin transfer molding	3,270	9,820	Calculated; see Appendix A4 for sources
Vacuum-assisted resin infusion	2,610	7,830	Calculated; see Appendix A4 for sources
Autoclave forming	3,160	9,490	Calculated; see Appendix A4 for sources
Cold press	3,350	10,060	Calculated; see Appendix A4 for sources

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 GFRP 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 GFRP 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 3.

Table 5-4. Calculated Practical Minimum Energy Consumption for Glass Fiber Reinforced Polymer 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)
Glass Fiber Production (glass fibers)						
Batching	100	300	740	0.07	0.15	0.22
Melting	590	600	740	0.44	0.01	0.44
Fiberization	620	940	740	0.46	0.24	0.69
Finishing	430	480	740	0.32	0.03	0.35
Resin Production* (matrix polymer)	2,310	5,080	740	1.70	2.05	3.74
Composite Production** (composite product)	710	2,140	1,470	1.05	2.10	3.15
Total* **				**4.03**	**4. 57**	**8.61**

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:

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

Table 5-5. Calculated Practical Minimum Energy Savings for Glass Fiber Composite Manufacturing

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)
Glass Fiber Production (glass fibers)				
Batching	0.41	0.07	0.33	82.1%
Melting	2.06	0.44	1.63	94.6%
Fiberization	1.38	0.46	0.93	53.7%
Finishing	1.22	0.32	0.90	73.7%
Resin Production* (matrix polymer)	23.53	1.70	21.83	89.5%
Composite Production** (composite product)	14.10	1.05	13.05	92.6%
Total***	**42.70**	**4.03**	**38.67**	**88.8%**

Current Typical (CT), Practical Minimum (PM), Thermodynamic Minimum (TM)
*** PM energy savings is the *Current Opportunity* plus the *R&D Opportunity*.**
**** PM energy savings percent is the PM energy savings opportunity from transforming glass 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, is calculated as follows: PM Energy Savings Percent = (Current-PM)/(Current-TM)**
*****Note: totals may not sum due to independent rounding.**

Among the processes studied, the greatest *R&D opportunity* in terms of percent energy savings is composite production at 92.6% energy savings. The greatest *R&D opportunity* in terms of TBtu savings was resin production at 21.83 TBtu per year savings.

If all U.S. glass fiber, resin, and composites producers (based on the 2010 production level of GFRP composites for application areas considered) were able to attain PM energy intensities, it is estimated that a total of 38.67 TBtu of onsite energy could be saved annually, corresponding to an 88.8% 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 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 GFRP performance could be achieved via the PM processes.

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 GFRP 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.[18] The TM energy intensity is *negative* when the chemical reaction is net-exergonic and *positive* when the chemical reaction is net-endergonic.[19] 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.[20]

TM energy intensity calculations are process 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

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

reactions, the starting material is assumed to be the relevant monomers (not crude petroleum). It is important to note that a negative TM value does not imply that the reaction will occur without being forced by a manufacturing process.

For glass fiber manufacturing, only the melting and fiberization processes had nonzero TM energy intensities. The TM energy for these processes was estimated on the basis of a constant heat capacity.[21] Values are presented in **Table 6-1**. 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 Glass Fibers

Glass Fiber Production Sub-Process	Onsite TM Energy Intensity (Btu/lb)	Data Source
Batching	0	n/a
Melting	470	Calculated*
Fiberization	-470	Calculated*
Finishing	0	n/a
Total Energy Intensity for Glass Fibers	0	

Thermodynamic Minimum (TM)
***See preceding discussion in text for description of methodology.**

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**.

[21] During the melting phase, glass is heated from room temperature to 1370°C; during the fiberization phase, the molten glass is cooled back to room temperature (Wallenberger 2001). Given a heat capacity of 0.345 Btu/lb°C for the glass, the TM energy intensity for melting is 470 Btu/lb and for fiberization is-470 Btu/lb [the opposite].
[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	Onsite 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	Onsite 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 GFRP 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 GFRP cost and energy requirements. Energy consumption values were calculated by multiplying energy intensity (Btu/lb) by the 2010 production volume (lbs).

Table 6-4. Calculated Thermodynamic Minimum Energy Consumption for Glass Fiber Reinforced Polymer Composite Manufacturing – Application Areas Considered

Subarea (product)	TM Energy Intensity (Btu/lb)	Production (million lbs)	TM Energy Consumption (TBtu/yr)
Glass Fiber Production (glass fibers)			
Batching	0	740	0
Melting	470	740	0.34
Fiberization	-470	740	-0.34
Finishing	0	740	0
Resin Production* (matrix polymer)	-1,160	740	0.86
Composite Production** (composite product)	0	1,470	0
Total* **			**-0.86**

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 GFRP composite production in 2010 for the four boundary application areas. Glass fiber production is broken down into its four sub-processes. The 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 GFRP Manufacturing (Onsite Energy Consumption)

Subarea (product)	Current Opportunity (CT – SOA) (TBtu/year)	R&D Opportunity (SOA – PM) (TBtu/year)
Glass Fiber Production (glass fibers)		
Batching	0.31	0.03
Melting	1.01	0.62
Fiberization	0.83	0.10
Finishing	0.66	0.23
Resin Production (matrix polymer)	3.73	18.10
Composite Production (composite product)	7.61	5.44
Total*	**14.15**	**24.52**

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	Polymer Matrix Material	Composite Production Method
Current Typical	Epoxy resin	Autoclave forming
State of the Art	Epoxy resin	Resin transfer molding
Practical Minimum	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* – 14.15 TBtu per year of energy savings could be realized if state of the art technologies and practices are deployed; and
- *R&D Opportunity* – 24.52 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 GFRP manufacturing. The term *impractical* is used because the TM energy consumption is based on ideal conditions that are unattainable in commercial applications.

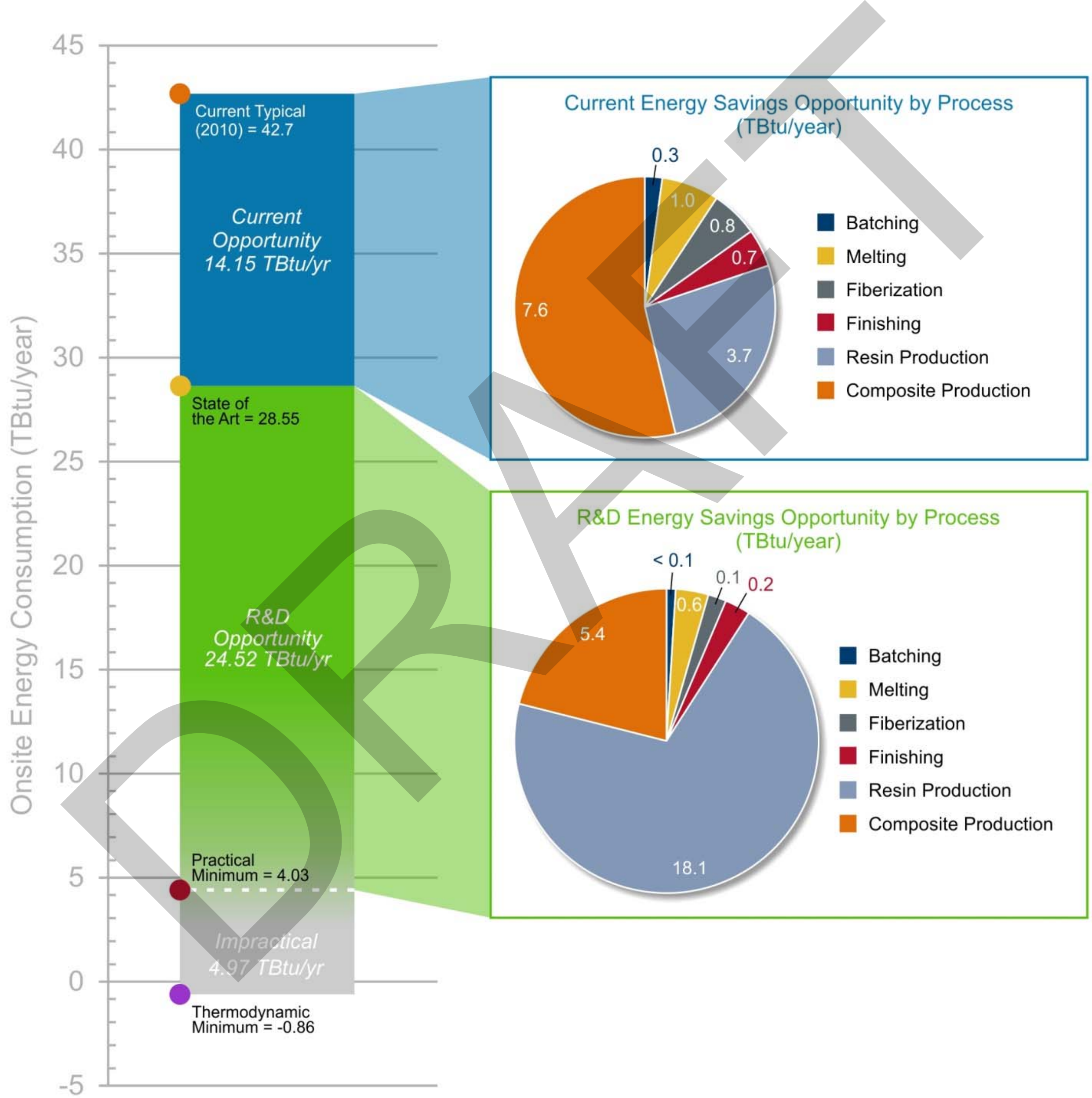


Figure 7-1. Current and R&D Energy Savings Opportunities for GFRP Composite Manufacturing by Process, Based on 2010 Glass Fiber Production for Structural Applications

Based on the bandwidth analysis, the greatest *current* energy savings opportunity for GFRP composites involves upgrading composite production equipment and processes. The greatest *R&D* energy savings opportunities could be achieved through the utilization of advanced matrix polymer materials (in particular, changing from thermosetting polymers to thermoplastic polymers). Examples of technologies that could be deployed to achieve these opportunities were detailed in this report and its appendices.

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Appendix A1. Master GFRP Composite Summary Tables

Table A1-1. Onsite Energy Intensity and Energy Consumption Estimates for GFRP Composite Manufacturing for the Four Bandwidth Measures, Based on 2010 Production of GFRP 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
Glass Fiber Production									
Batching	740	550	140	100	0	0.41	0.10	0.07	0
Melting		2,800	1,430	590	470	2.06	1.06	0.44	0.34
Fiberization		1,880	750	620	-470	1.38	0.55	0.46	-0.34
Finishing		1,650	750	430	0	1.22	0.55	0.32	0
Overall – Fiber Production		**6,880**	**3,070**	**1,740**	**0**	**5.07**	**2.26**	**1.29**	**0**
Resin Production									
Epoxy resin	740	**31,940**	**26,880**	11,320	-120	**23.53**	**19.80**	8.34	-0.09
Polyurethane resin		20,140	17,330	7,300	-190	14.83	12.77	5.38	-0.14
Polypropylene (PP)		5,370	4,290	**2,310**	**-1,160**	3.95	3.16	**1.70**	**-0.86**
High density polyethylene (HDPE)		5,710	4,570	2,450	-1,740	4.20	3.36	1.81	-1.28
Polyvinyl chloride (PVC)		9,710	7,180	3,850	-970	7.15	5.29	2.84	-0.71
Polystyrene (PS)		10,500	8,400	4,510	-470	7.74	6.19	3.32	-0.35
Composite Production									
Prepreg	1,470	17,200	13,760	11,360	0	25.34	20.27	16.73	0
Sheet or bulk molding compound		1,510	1,200	990	0	2.22	1.77	1.46	0
Hand lay-up		8,250	6,600	5,450	0	12.16	9.73	8.03	0
Spray up		6,410	5,120	4,230	0	9.44	7.55	6.23	0
Filament winding		1,160	930	770	0	1.71	1.37	1.13	0
Pultrusion		1,330	1,070	420	0	1.96	1.57	0.62	0
Injection molding		4,830	960	**710**	**0**	7.11	1.41	**1.05**	**0**
Compression molding		4,910	3,920	3,240	0	7.23	5.78	4.77	0
Resin transfer molding		5,500	**4,400**	3,270	0	8.11	**6.49**	4.82	0
Vacuum assisted resin infusion		4,390	3,510	2,610	0	6.46	5.17	3.84	0
Autoclave forming		**9,570**	7,650	3,160	0	**14.10**	11.28	4.66	0
Cold press		5,070	4,060	3,350	0	7.47	5.98	4.94	0
Total for Glass Fiber Reinforced Polymer Manufacturing* **	**1,470**	**28,980**	**19,380**	**2,740**	**-580**	**42.70**	**28.55**	**4.03**	**-0.86**

* Glass 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 GFRP composites in the application areas, assuming 50 wt% glass fibers. Composites production indicates the total production of GFRP composites (all methods) calculated from the above data.

** Energy intensities reported in terms of Btu per pound of fibers for glass 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 GFRP 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% glass 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 GFRP 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 GFRP Composite Manufacturing for the Four Bandwidth Measures, Based on 2010 Production of GFRP 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***
Glass Fiber Production									
Batching	740	1,020	410	300	n/a	0.75	0.30	0.22	n/a
Melting		2,860	1,460	600	n/a	2.11	1.08	0.44	n/a
Fiberization		2,850	1,140	940	n/a	2.10	0.84	0.69	n/a
Finishing		1,820	830	477	n/a	1.34	0.61	0.35	n/a
Overall – Fiber Production		**8,550**	**3,840**	**2,320**	**n/a**	**6.30**	**2.83**	**1.71**	**n/a**
Resin Production									
Epoxy resin	740	**40,490**	**32,390**	13,640	n/a	**29.83**	**23.86**	10.05	n/a
Polyurethane resin		27,690	22,150	9,330	n/a	20.40	16.32	6.87	n/a
Polypropylene (PP)		12,420	9,940	**5,330**	n/a	9.15	7.32	**3.93**	n/a
High density polyethylene (HDPE)		12,420	9,940	5,330	n/a	9.15	7.32	3.93	n/a
Polyvinyl chloride (PVC)		15,610	11,290	6,060	n/a	11.50	8.32	4.46	n/a
Polystyrene (PS)		17,360	13,890	7,450	n/a	12.79	10.23	5.49	n/a
Composite Production									
Prepreg	1,470	51,640	41,310	34,110	n/a	76.09	60.87	50.25	n/a
Sheet or bulk molding compound		4,520	3,620	2,980	n/a	6.66	5.33	4.40	n/a
Hand lay-up		24,790	19,830	16,370	n/a	36.52	29.22	24.12	n/a
Spray up		19,240	15,390	12,710	n/a	28.34	22.67	18.72	n/a
Filament winding		3,490	2,790	2,300	n/a	5.14	4.11	3.39	n/a
Pultrusion		4,000	3,200	1,260	n/a	5.90	4.72	1.85	n/a
Injection molding		14,490	2,880	**2,140**	n/a	21.36	4.24	**3.15**	n/a
Compression molding		14,730	11,780	9,730	n/a	21.70	17.36	14.33	n/a
Resin transfer molding		16,530	**13,220**	9,820	n/a	24.35	**19.48**	14.47	n/a
Vacuum assisted resin infusion		13,170	10,530	7,830	n/a	19.40	15.52	11.53	n/a
Autoclave forming		**28,730**	22,990	9,490	n/a	**42.33**	33.87	13.98	n/a
Cold press		15,230	12,190	10,060	n/a	22.45	17.96	14.82	n/a
Total for Glass Fiber Reinforced Polymer Manufacturing****	**1,470**	**53,250**	**31,330**	**5,970**	**n/a**	**78.46**	**46.17**	**8.79**	**n/a**

* Glass 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 GFRP composites in the application areas, assuming 50 wt% glass fibers. Composites production indicates the total production of GFRP composites (all methods) calculated from the above data.

** Energy intensities reported in terms of Btu per pound of fibers for glass 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 GFRP 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% glass 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 GFRP 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 fiber-to-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 carbon fiber reinforced polymer (CFRP) composite 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. While all of the case studies involved carbon fiber composites (not glass fiber composites), they are referenced in this report to provide continuity with the carbon fiber reinforced composites study in this series. For the sake of comparison, the same fiber fraction was assumed for both fiber-reinforced composite materials (carbon and glass).

Table A2-1. Fiber / Matrix Polymer Ratios: Automotive Case Studies

Case Study	Polymer Type*	Fiber Ratio, by Weight %	Fiber 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 fibers; 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 GFRP Composite Manufacturing Processes

Process Subarea or Sub-Process	Fuel %	Electric %	Data Source
Glass Fiber Production			
Batching	0.0%	100.0%	Rue (2007)
Melting	99.0%	1.0%	Rue (2007)
Fiberization	74.0%	26.0%	Rue (2007)
Finishing	95.0%	5.0%	Rue (2007)
Overall – Fiber Production	88.1%	11.9%	Rue (2007)
Resin Production: Thermosetting Resins			
Epoxy resin	89.8%	10.2%	PlasticsEurope (2006)
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)

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

Process Subarea or Sub-Process	Fuel %	Electric %	Data Source
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**

*All composite production methods were assumed to be 100% electric, which is consistent with several sources (Schepp 2006, Das 2011, Thiriez 2006).

Appendix A4. Practical Minimum (R&D) Technologies Considered

The PM energy intensity for glass fiber composite manufacturing 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. The percent savings over the PM baseline is estimated, along with a brief explanation (Note that the PM baseline energy intensity is considered equal to the SOA energy intensity in this study). Some technologies in Table A4-1 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 A4-1. 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
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.	Batching	Worrell *et al.* estimated a typical energy savings of 8-15% from VSDs for conveyer belt systems used in glass batching. The range was averaged to come up with an overall savings of 12% for batching, which is an all-electric process.	12%	Yes		Worrell (2008); Worrell (2010)
Additives to batching solution	Optimum glass batching compositions (including the addition of lithium or mixed alkali additives) can reduce energy required to melt the glass.	Melting	Hains *et al.* reported energy savings of 3-10% from lithia (Li_2O) additives and 2-5% from mixed alkali additives. A 4% energy savings was assumed. Note that the benefits of this technology occur in the melting stage, although it is implemented during batching.	4%	Yes		Hains (2009)
Recycling of cullet and/or filter dust	Use of cullet and/or filter dust in the glass batch can reduce melting energy.	Melting	A 10% savings was assumed, as Worrell *et al.* reported that Owens Corning was able to save 10% in energy costs by using 30% cullet in the glass batch. Note that the benefits of this technology occur in the melting stage, although it is implemented during batching.	10%	Yes		Worrell (2008)
Reduced batch wetting	A small quantity of water is added to the glass batch to reduce dust and prevent separation and non-homogeneity in the batch during transport, but this water increases energy use because it must be evaporated in the furnace. Reducing water content saves energy.	Melting	Worrell *et al.* indicated that a 1% reduction in the moisture content can provide fuel savings of 0.5% in the glass melting furnace. A 1% total savings was assumed.	1%	Yes		Worrell (2008)

Batch and cullet preheating	Waste heat from the furnace is used to preheat the incoming cullet batch, reducing energy losses.	Melting	Worrell *et al.* estimated energy savings of 12% when installed in an oxy-fuel glass melting furnace.	12%	No	Not compatible with microwave melting	Worrell (2008)
Minimization of excess air in furnace	Non-optimal air/fuel ratios reduce furnace efficiencies. Reduction of excess air in the furnace reduces energy consumption.	Melting	Worrell *et al.* reported that the glass manufacturer Lax & Shaw (U.K.) demonstrated an energy savings of 12% from improved sealing and insulation.	12%	No	Benefit assumed negligible for selective (e.g., microwave) heating	Worrell (2008)
Low-NOx burner	Low-NOx burners can provide increased heat transfer rates and reduced flame temperatures, increasing furnace efficiency.	Melting	Worrell *et al.* reported that Air Liquide (France) had demonstrated a 5% savings from this technology compared to conventional oxy-fuel burners.	5%	No	Not compatible with microwave melting	Worrell (2008)
More efficient furnaces	Furnaces with improved thermal efficiency could save energy during melting.	Melting	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 melting	Worrell (2010)
Improved heat transfer / containment	Energy losses could be minimized through improved furnace technologies, including better insulation, sealing, and pressure control.	Melting	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. SOA glass melting 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 melting	Microwave energy is used to selectively heat and melt the glass.	Melting	Worrell *et al.* estimated savings in the range of 30 to 50%. Averaging this range, a 40% savings was assumed.	40%	Yes		Worrell (2008)
Process heating control systems	Advanced sensors and control systems enable continuous monitoring and optimization of heat inputs for fuel savings.	Melting	Worrell *et al.* reported energy savings of 2 to 3% for glass melting furnaces. 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.	Melting	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 melting.	13%	No	Benefit assumed negligible for selective (e.g., microwave) heating	Worrell (2010)
Improved drying systems	After quenching molten glass during fiberization, water must be removed in a time-consuming drying process. New gravity and filtration technologies can reduce drying time.	Finishing	Worrell *et al.* reported that the Viox Corporation was able to reduce drying time from 58 to 72 hours to 11 hours per batch. Based on this reduction, a 30% savings was assumed.	30%	Yes		Worrell (2008)

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

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DOE/EE-1344 • March 2016