Manufacturing Energy Intensity and Opportunity Analysis for Fiber-Reinforced Polymer Composites and Other Lightweight Materials

H. P. H. LIDDELL, S. B. BRUESKE, A. C. CARPENTER and J. W. CRESKO

ABSTRACT

With their high strength-to-weight ratios, fiber-reinforced polymer (FRP) composites are important materials for lightweighting in structural applications; however, manufacturing challenges such as low process throughput and poor quality control can lead to high costs and variable performance, limiting their use in commercial applications. One of the most significant challenges for advanced composite materials is their high manufacturing energy intensity. This study explored the energy intensities of two lightweight FRP composite materials (glass- and carbon-fiber-reinforced polymers), with three lightweight metals (aluminum, magnesium, and titanium) and structural steel (as a reference material) included for comparison. Energy consumption for current typical and state-of-the-art manufacturing processes were estimated for each material, deconstructing manufacturing process energy use by sub-process and manufacturing pathway in order to better understand the most energy intensive steps. Energy saving opportunities were identified and quantified for each production step based on a review of applied R&D technologies currently under development in order to estimate the practical minimum energy intensity. Results demonstrate that while carbon fiber reinforced polymer (CFRP) composites have the highest current manufacturing energy intensity of all materials considered, the large differences between current typical and state-of-the-art energy intensity levels (the "current opportunity") and between state-of-the-art and practical minimum energy intensity levels (the "R&D opportunity") suggest that large-scale energy savings are within reach.

Heather P. H. Liddell*, Energetics Inc., 901 D St. SW, Suite 100, Washington, DC 20024, U.S.A.
Sabine B. Brueske, Energetics Inc., 2950 Newmarket St., Suite 101-156, Bellingham, WA 98226, U.S.A.
Alberta C. Carpenter, Strategic Energy Analysis Center, National Renewable Energy Laboratory, 15013 Denver West Parkway, Golden, CO 80401, U.S.A.
Joseph W. Cresko, Advanced Manufacturing Office, U.S. Department of Energy, 1000 Independence Ave. SW, Washington, DC 20585, U.S.A.

*Corresponding author: hliddell@energetics.com

INTRODUCTION

Lightweighting is a key strategy for reducing fossil energy consumption, particularly in the transportation sector. Composite materials such as carbon fiber reinforced polymer composites offer some of the highest strength-to-weight and stiffness-to-weight ratios amongst all structural materials, and can provide major weight reductions and corresponding energy savings (fuel savings during the use of a vehicle, for example) when used to replace traditional structural materials such as steel. However, it would be short-sighted to accept these fuel savings as benefits without considering the full life-cycle energy impacts of material substitutions. In general, composite materials are extremely energy-intensive to manufacture compared to steel and other structural metals. The net energy impact depends both on this initial energy expenditure—which may be very high—and the fuel savings that accumulate over time during product use. It may take many years of product use for accumulated fuel savings to fully offset the manufacturing energy. In some cases, energy payback may never be reached at all. These complex energy tradeoffs and their effect on the net life cycle impacts of composite products have been analyzed in several recent studies [1–3]. Clearly, to give credence to such analyses it is critical to have a strong understanding of manufacturing energy requirements, both for current typical processes and for the technical potential for improvement.

Energy "bandwidth studies" [4] provide an effective tool to gather and analyze manufacturing energy data, including the current typical (baseline) energy use, the potential for improvement if state-of-the-art technologies were deployed, and the potential for future energy savings if next-generation technologies were realized. In an energy bandwidth study, four measures of energy intensity are quantified: current typical, state of the art, practical minimum, and thermodynamic minimum. The difference between the current typical and state-of-the-art energy intensity represents the *current opportunity*. The difference between the state-of-the-art and practical minimum energy intensity represents the *research and development (R&D) opportunity*. These ranges are termed "energy bandwidths." Energy bandwidth results can be visually compared to determine, at a glance, which manufacturing processes and sub-processes are the most energy intensive and which offer the greatest energy savings opportunities from technology advances. Data can also feed into analytical studies such as those described above to understand the contribution of the manufacturing phase of the product life cycle to the net energy impacts of end-use products.

In this paper, the energy bandwidth methodology is used to assess energy use and energy savings opportunities in the manufacturing of two types of composite materials: carbon-fiber-reinforced polymer (CFRP) and glass fiber-reinforced polymer (GFRP). Energy intensity data are based on preliminary results from a new series of energy bandwidth studies focused on lightweight structural materials (the *Lightweight Materials Energy Bandwidth Studies)* commissioned by the U.S. Department of Energy (DOE) Advanced Manufacturing Office. As of this writing, these studies are available in draft form [5] and are expected to be published in final form in the 2017 fiscal year.

ANALYTICAL METHODOLOGY

An overview of the four energy intensity measures studied are shown in Table I. Energy intensity data reported in this paper reflect onsite energy use (i.e., energy consumed within the manufacturing facility's boundaries), and do not include electricity generation losses. Energy used as feedstocks (i.e., the nonfuel use of fossil energy) are also excluded. If data were reported differently in literature sources, they were adjusted based on the assumed (or reported) energy mix and any feedstock contributions were removed. Complete details of analytical methodologies used can be found in the draft *Lightweight Materials Energy Bandwidth Studies* [5].

RESULTS: CARBON FIBER REINFORCED POLYMER COMPOSITES

Overview of Manufacturing Process

Two general manufacturing methods for carbon fibers have been commercialized to date: the first method involves the production of carbon fibers from a polyacrylonitrile (PAN) precursor, while the second method involves the conversion of a petroleum pitch precursor. The PAN process is by far the most common method used, accounting for approximately 98% of U.S. production capacity by weight [6]. This process was considered as both the current typical and the state-of-the-art manufacturing method for carbon fibers. Alternate, low-energy precursors were included in the practical minimum analysis. The CFRP composites manufacturing process can be divided into six main process steps, assuming the use of the PAN precursor process:

- *Polymerization:* the chemical polymerization of the carbon fiber precursor material (in this case, PAN);
- *Spinning:* the process that produces fibers from the precursor, generally through wet solution spinning;
- *Finishing:* the application of surface treatments and coatings (sizing) to protect the fibers and promote bonding with the polymer matrix material, 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 a polymer matrix and forming a finished composite product (also called consolidation).

The first four process steps (polymerization, spinning, oxidation/carbonization, and finishing) are sub-processes of carbon fiber production. Six different polymer matrix materials were considered, including two thermosetting polymers (epoxy and polyurethane) and four thermoplastic polymers (polypropylene, high-density polyethylene, polyvinyl chloride, and polystyrene). Twelve composite production techniques were considered, including two semi-finished production techniques (pre-impregnated fabric or "pre-preg" and sheet or bulk molding compound), four open forming methods (hand lay-up, spray-up, filament winding, and pultrusion, and six closed forming (mold-based) methods (injection molding, compression molding, resin transfer molding, vacuum-assisted resin infusion, autoclave forming, and cold press).

TABLE I. ENERGY INTENSITY MEASURES

	Current Typical (CT)	**State of the Art (SOA)**	**Practical Minimum (PM)**	**Thermodynamic Minimum (TM)**
Definition	Energy expended during a process (per unit mass) based on current typical manufacturing processes in the United States	Energy expended during a process (per unit mass) assuming adoption of the most energy-efficient technologies and practices available worldwide	Minimum energy required for a process (per unit mass) assuming successful deployment of R&D technologies under development worldwide	Minimum energy theoretically required for a process (per unit mass) under ideal conditions
Methodology	Determined from a literature review and stakeholder outreach, plus data processing to ensure consistency and quality of data	Determined from a literature review and stakeholder outreach, plus data processing to ensure consistency and quality of data	Modeled based on plausible energy savings from identified R&D technologies	Calculated analytically using a Gibbs free energy approach

Data Collection and Analysis

Facility energy data for carbon fiber production from a PAN precursor were provided by Oak Ridge National Laboratory (ORNL), including a detailed energy breakdown by sub-process. The PAN-based process used at ORNL is considered representative of commercial manufacturing processes, and was assumed to reflect the current typical (CT) energy intensity for carbon fiber production. CT energy intensities for the polymer materials considered were drawn from literature sources [7–10], as were the current typical energy intensities for the composite production methods [11,12].

State-of-the-art (SOA) energy intensity data for carbon fiber production were not available from literature sources, but an estimate of the hypothetical SOA energy intensity was made by applying assumed energy savings percentages for applicable SOA technologies to the current typical intensity value using equation (1):

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

where *CT* is the current typical (baseline) energy intensity, and $\{S_1, S_2, \ldots S_n\}$ are the percent savings for each of *n* technologies included in the model. A list of the SOA technologies considered are shown in Table II. A sample calculation is shown in Figure 1. For full details of assumptions, as well as a description of each technology, see Reference 13.

TABLE II. ENERGY SAVING TECHNOLOGIES AND HYPOTHETICAL ENERGY SAVINGS FOR SOA CARBON FIBER MANUFACTURING

SOA Technology	**Assumed energy savings over CT baseline (and sub-process applicability)**	**Note**
Carbon fiber recycling	9% savings (polymerization, spinning, oxidation / carbonization, finishing)	[14]
Motor re-sizing and/or use of variable speed drives	0.5% savings (spinning); 11.5% savings (finishing)	[17]
More efficient furnaces	10% savings (oxidation / carbonization)	[19]
Improved heat transfer / containment	20% savings (oxidation / carbonization)	[20]
Process heating control systems	3% savings (oxidation / carbonization)	[21]
Waste heat recovery systems	13% savings (oxidation / carbonization)	[22]

Sample calculation: Estimated SOA energy intensity of carbon fiber spinning

Current typical energy intensity for spinning (baseline):	CT = 83,740 Btu/lb
9% savings from carbon fiber recycling	$S_1 = 0.09$
0.5% savings from motor re-sizing	$S_2 = 0.01$
State-of-the-art energy intensity calculation (equation (2)):	
SOA = (83,740 Btu/lb)*(1 − 0.09)*(1 − 0.005)	SOA = 75,820 Btu/lb*

* Rounded to the nearest 10 Btu/lb.

Figure 1. Sample calculation for estimating the hypothetical SOA energy intensity of carbon fiber spinning. The hypothetical SOA energy intensities for carbon fiber polymerization, carbonization/oxidation, and finishing were calculated in a similar fashion.

For polymer production, the global SOA energy intensities were estimated by assuming a 20% energy savings over the lowest of the current average energy intensity values reported for U.S. plants (based on American Chemistry Council (ACC) data [7]) and European plants (based on Plastics*Europe* data [8–10, 23–25]). The 20% savings figure is roughly consistent with the ACC report [7], which stated that "individual plant results varied as much as 25 percent on either side of the average total energy." For composites production, the SOA energy intensity was similarly assumed to be 20% lower than the current typical energy intensity, unless a high quality literature source for SOA was available. The 20% savings represents the authors' best judgment as to the difference between typical and state-of-the-art practices.

To estimate the hypothetical practical minimum (PM) energy intensity, a review of applied R&D activities in carbon fiber manufacturing, polymer resin manufacturing, and composites production techniques was conducted. An active area of CFRP composite-related research is precursor development. As mentioned in the previous section, two carbon fiber precursors are used in commercial production today: PAN and petroleum pitch. Several alternative fiber precursors are currently under development. Facility energy data for two alternative precursor processes were provided by ORNL; one of these processes (polyolefin) was selected as the baseline for PM calculations because of its low energy intensity resulting from a higher carbon yield of ~60%. The PM energy intensity was estimated by applying assumed energy savings percentages for applicable R&D technologies to this baseline value, using equation (2):

$$PM = SOA * [(1 - S_1) * (1 - S_2) * \ldots * (1 - S_n)], \quad (2)$$

where *SOA* is the energy intensity baseline (typically the SOA energy intensity, but in in the case of carbon fiber production, the alternative polyolefin process was used as baseline), and $\{S_1, S_2, \ldots S_n\}$ are the percent savings for each of *n* technologies included in the model. The PM technologies considered are shown in Table III. For full details of assumptions, as well as a description of each technology, see Reference 13.

The thermodynamic minimum (TM) energy intensity was calculated for each sub-process by determining the Gibbs free energy associated with the chemical transformations involved under ideal conditions. The TM value is negative when the transformation is net-exergonic (i.e., the reaction is thermodynamically favorable) and positive when the chemical transformation is net-endergonic (i.e., the reaction is not thermodynamically favorable). For some processes, no chemical reactions or phase changes are involved and the TM energy intensity was calculated as zero. Note that the TM bounds the lower limit of energy intensity, but its value is based on ideal conditions and is not practically achievable in real-world environments. Detailed TM results are not included in this paper, but can be found in Reference 13.

TABLE III. ENERGY SAVING TECHNOLOGIES AND HYPOTHETICAL ENERGY SAVINGS FOR CFRP MANUFACTURING AT PRACTICAL MINIMUM ENERGY INTENSITY

PM Technology	**Assumed energy savings over baseline (and sub-process applicability)**	**Note**
Alternative precursor process	n/a (baseline for carbon fiber production)	
Carbon fiber recycling (increased rate compared to SOA recycling)	35% savings (polymerization, spinning, oxidation / carbonization, finishing)	[26]
Recovery and recycling of the polymer matrix	49% savings (resin production: thermoplastic resins); 35% savings (resin production: thermosetting resins)	[27]
Microwave carbonization	45% savings (oxidation / carbonization)	[30]
Improved die design	5% savings (composites production: pultrusion)	[32]
Infrared heating with emissivity matching	50% savings (composites production: pultrusion, autoclave forming)	[33]
Barrel insulation in mold-based processes	10% savings (composites production: injection molding, resin transfer molding, and vacuum-assisted resin infusion)	[34]
Modeling and process control to reduce off-spec material	14% savings (crosscutting)	[35]
Process integration / pinch analysis	4% savings (crosscutting)	[37]

Manufacturing Energy Use Breakdown

A summary of energy intensity values for CFRP composite manufacturing processes and sub-processes are presented in Table IV. To determine the total energy intensity for a given composite product, the contributions of carbon fiber production (all four production steps), resin production (selected matrix material), and composite production (selected technique) can be summed in a "mix-and-match" fashion. The energy intensity values must be weighted to account for the relative quantities of the materials used in the finished product. For example, if the carbon fiber mass fraction in a particular composite is 40%, the energy intensity for carbon fiber production should be multiplied by 0.40 and the energy intensity for resin production should be multiplied by 0.60. The weighting factor for composite production is unity (1.00) because these energy intensities are reported in terms of composite product weight. The total energy intensity for the composite material is given by equation (3),

$$I_{total} = f\left(I_{fiber}\right) + (1 - f)(I_{resin}) + (I_{comp}) \tag{3}$$

where I_{fiber}, I_{resin}, and I_{comp} are the manufacturing energy intensities of the fiber, resin, and composite production respectively, and f is the fiber fraction by weight. Fiber and resin materials lost as manufacturing scrap during composite part production were not considered.

Note that the fiber fraction, resin selection, and composite production technique can have a dramatic impact on the total energy intensity of a given composite product. Table V shows calculations of total energy intensity for several hypothetical CFRP materials, based on current typical energy use, to illustrate this variation. The appropriate choice of these parameters is application dependent. Higher fiber fractions are generally used for high-performance structural components, whereas lower fiber fractions can be used in non-structural or semi-structural parts. In seven automotive case studies identified by the authors (see references [12, 38–41]), fiber fractions ranged from 31% to 69% by weight, with a median value of 49 wt%. A 50% fiber fraction (by weight) is considered generally representative of a typical structural composite. The choice of resin depends on the production method to be used and the properties desired in the end-use product (e.g., strength, stiffness, hardness, heat resistance, or recyclability.) The production method is also selected based on the desired characteristics of the finished product, including its size, shape, and finish requirements.

TABLE IV. ENERGY INTENSITY ESTIMATES FOR CFRP MANUFACTURING

Process Subarea or Sub-Process	**Onsite Energy Intensity***		
	CT (Btu/lb)	**SOA (Btu/lb)**	**PM (Btu/lb)**
Carbon Fiber Production			
Polymerization	85,710	77,990	9,210
Spinning	83,740	75,820	1,430
Oxidation / Carbonization	135,900	75,520	12,620
Finishing	10,740	8,650	3,880
Overall – Fiber Production	**316,080**	**237,980**	**27,140**
Resin Production			
Epoxy resin	31,940	26,880	11,320
Polyurethane resin (PU)	20,140	17,330	7,300
Polypropylene (PP)	5,630	4,510	2,420
High density polyethylene (HDPE)	5,960	4,770	2,560
Polyvinyl chloride (PVC)	9,930	7,180	3,850
Polystyrene (PS)	10,500	8,400	4,510
Composite Production			
*Pre-preg***	17,200	13,760	11,360
*Sheet or bulk molding compound***	1,510	1,200	990
Hand lay-up	8,250	6,600	5,450
Spray-up	6,410	5,120	4,230
Filament winding	1,160	930	770
Pultrusion	1,330	1,070	420
Injection molding	4,830	960	710
Compression molding	4,910	3,920	3,240
Resin transfer molding	5,500	4,400	3,270
Vacuum-assisted resin infusion	4,390	3,510	2,610
Autoclave forming	9,570	7,650	3,160
Cold press	5,070	4,060	3,350

*Energy intensities are reported in terms of Btu/lb of fibers for carbon fiber production (all sub-processes), Btu/lb of resin for resin production, and Btu/lb of composite product (fibers plus resin) for composites production.

** These processes produce *semifinished* products, and would require an additional step (e.g., hand lay-up for a carbon fiber pre-preg or compression molding for a bulk molding compound) to convert the semi-finished product to a finished component, often by a third-party manufacturer that did not produce the carbon fiber pre-preg itself.

TABLE V. CALCULATED MANUFACTURING ENERGY INTENSITIES FOR HYPOTHETICAL CFRP MATERIALS

	Matrix Resin	**Reinforce-ment**	**Fiber Fraction (wt. %)**	**Composite Production Method**	**CT Energy Intensity* (Btu/lb)**
Hypoth. Material #1-C	PU	Carbon fiber	35%	Pultrusion	125,050
Hypoth. Material #2-C	PP	Carbon fiber	40%	Injection molding	134,640
Hypoth. Material #3-C	PVC	Carbon fiber	45%	Resin transfer molding	153,200
Hypoth. Material #4-C	Epoxy	Carbon fiber	50%	Autoclave forming	183,580
Hypoth. Material #5-C	Epoxy	Carbon fiber	55%	Hand lay-up	196,470

*Energy intensity in terms of Btu/lb of composite product (fibers plus resin), calculated by weighting the energy intensities of Table V.

RESULTS: GLASS FIBER REINFORCED POLYMER COMPOSITES

Overview of Manufacturing Process

Glass fibers are produced in two main varieties: glass rovings, which are large-diameter (≥10 μm) filaments that can be used as reinforcements in structural composites; and glass yarns, which are flexible, small-diameter (<10 μm) filaments that are generally woven into fabrics. In this study, glass yarns were not considered as they are not used in structural composites. Glass rovings represent about 81% of global production of glass fibers overall [42]. The GFRP composites manufacturing process, involving the incorporation of glass rovings into a matrix polymer, can be broken 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 (sizing) to protect the fibers and promote bonding with the polymer matrix material, 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 a polymer matrix and forming a finished composite product (also called consolidation).

The first four process steps (batching, melting, fiberization, and finishing) are sub-processes of glass fiber production. As in the CFRP analysis, six different polymer matrix materials and twelve composite production techniques were considered.

Data Collection and Analysis

CT energy intensities for glass fibers were drawn from a 2008 report out of Lawrence Berkeley National Laboratory, *Energy Efficiency Improvement and Cost Savings Opportunities for the Glass Industry* [43], which quantified the average energy intensity of major glassmaking process steps for four different glass industry segments, including glass fibers. SOA energy intensities were also drawn from literature sources [44–46]. CT and SOA energy intensities for the polymer materials and composite production methods were drawn from the same sources as in the CFRP analysis.

To estimate the practical minimum (PM) energy intensity, a review of applied R&D activities was conducted. The PM energy intensity was estimated by applying assumed energy savings percentages for applicable R&D technologies to the SOA baseline using equation (2). The PM technologies considered are shown in Table VI. For full details of assumptions, as well as a description of each technology, see Reference 47. See also the example calculation for carbon fiber composites in Figure 1.

TABLE VI. ENERGY SAVING TECHNOLOGIES AND HYPOTHETICAL ENERGY SAVINGS FOR GFRP MANUFACTURING AT PRACTICAL MINIMUM ENERGY INTENSITY

PM Technology	Assumed energy savings over baseline (and sub-process applicability)	Note
Motor re-sizing and/or use of variable speed drives	11.5% savings (batching)	[17]
Additives to batching solution	4% savings (melting)	[48]
Recycling of cullet	10% savings (melting)	[50]
Reduced batch wetting	0.5% (melting)	[51]
Microwave melting	40% (melting)	[52]
Improved process control in glass melting systems	3% (melting)	[21]
Improved drying systems	30% (finishing)	[53]
Recovery and recycling of the polymer matrix	49% savings (resin production: thermoplastic resins); 35% savings (resin production: thermosetting resins)	[27]
Improved die design	5% savings (composites production: pultrusion)	[32]
Infrared heating with emissivity matching	50% savings (composites production: pultrusion, autoclave forming)	[33]
Barrel insulation in mold-based processes	10% savings (composites production: injection molding, resin transfer molding, and vacuum-assisted resin infusion)	[34]
Modeling and process control to reduce off-spec material	14% savings (crosscutting)	[35]
Process integration / pinch analysis	4% savings (crosscutting)	[37]

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, as in the CFRP analysis. Detailed TM results are not included in this paper, but can be found in Reference 47.

Manufacturing Energy Use Breakdown

A summary of energy intensity values for GFRP composite manufacturing processes and sub-processes are presented in Table VII. To determine the total energy intensity for a given composite product, the contributions of glass fiber production (all four production steps), resin production (selected matrix material), and composite production (selected technique) can be summed in a “mix-and-match” fashion, following the same procedure and formula described above in the CFRP sections. The resin production and composite production energy intensities presented in Table VII are identical to those presented in Table IV because it is assumed that there are no substantial deviations in composite production methods for glass and carbon fiber composites, aside from the incorporation of a different reinforcing fiber material.

Table VIII shows calculations of total current typical energy intensity for several hypothetical GFRP materials to illustrate the variations in energy intensity when key parameters (fiber fraction, resin type, and production method) are varied.

TABLE VII. ENERGY INTENSITY ESTIMATES FOR GFRP MANUFACTURING

Process Subarea or Sub-Process	Onsite Energy Intensity* CT (Btu/lb)	SOA (Btu/lb)	PM (Btu/lb)
Glass Fiber Production			
Batching	550	140	100
Melting	2,800	1,430	590
Fiberization	1,880	750	620
Finishing	1,650	430	430
Overall – Fiber Production	**6,880**	**3,070**	**1,740**
Resin Production			
Epoxy resin	31,940	26,880	11,320
Polyurethane resin (PU)	20,140	17,330	7,300
Polypropylene (PP)	5,630	4,510	2,420
High density polyethylene (HDPE)	5,960	4,770	2,560
Polyvinyl chloride (PVC)	9,930	7,180	3,850
Polystyrene (PS)	10,500	8,400	4,510
Composite Production			
*Pre-preg***	17,200	13,760	11,360
*Sheet or bulk molding compound***	1,510	1,200	990
Hand lay-up	8,250	6,600	5,450
Spray-up	6,410	5,120	4,230
Filament winding	1,160	930	770
Pultrusion	1,330	1,070	420
Injection molding	4,830	960	710
Compression molding	4,910	3,920	3,240
Resin transfer molding	5,500	4,400	3,270
Vacuum-assisted resin infusion	4,390	3,510	2,610
Autoclave forming	9,570	7,650	3,160
Cold press	5,070	4,060	3,350

*Energy intensities are reported in terms of Btu/lb of fibers for glass fiber production (all sub-processes), Btu/lb of resin for resin production, and Btu/lb of composite product (fibers plus resin) for composites production.

** These processes produce *semifinished* products, and would require an additional step (e.g., hand lay-up for a glass fiber pre-preg or compression molding for a bulk molding compound) to convert the semi-finished product to a finished component, often by a third-party manufacturer that did not produce the glass fiber pre-preg itself.

TABLE VIII. CALCULATED MANUFACTURING ENERGY INTENSITIES FOR HYPOTHETICAL GFRP MATERIALS

	Matrix Resin	Reinforce-ment	Fiber Fraction (wt. %)	Composite Production Method	CT Energy Intensity (Btu/lb)
Hypoth. Material #1-G	PU	Glass fiber	35%	Pultrusion	16,830
Hypoth. Material #2-G	PP	Glass fiber	40%	Injection molding	10,960
Hypoth. Material #3-G	PVC	Glass fiber	45%	Resin transfer molding	14,060
Hypoth. Material #4-G	Epoxy	Glass fiber	50%	Autoclave forming	28,980
Hypoth. Material #5-G	Epoxy	Glass fiber	55%	Hand lay-up	26,410

DISCUSSION & CONCLUSIONS

An overview of manufacturing energy intensity results for six materials (two composites and four metals) is shown in Table IX. As noted earlier, the energy intensity of a composite material depends strongly on the fiber ratio and other parameters. The data shown here were calculated based on a 50% fiber weight ratio, and are considered representative of a typical composition.

Figure 2 graphically compares energy intensities for the six materials studied. CFRP composites have by far the highest manufacturing energy intensity of all materials considered—nearly 30 times higher than steel based on current typical manufacturing techniques, and roughly six times higher than GFRP composites. These high energy intensities underscore the importance, from an energy perspective, of carefully considering the product life cycle before deploying CFRP composites in a new product application, as net energy savings are contingent on sufficiently intensive use in the product use phase to offset the initial energy outlay to produce the material. While the CFRP composite was the most energy intensive material, it also had the largest current opportunity band (blue band between CT and SOA) and R&D opportunity band (green band between SOA and PM.) These sizable opportunities, if realized, could play a key role in reducing the energy payback period and increasing life-cycle energy benefits of lightweight composites. The *Lightweight Materials Energy Bandwidth Studies* provide a useful reference for identifying technologies with the greatest potential benefits.

As a next step in the analytical work reported here, an “integrating analysis” is now underway to perform a thorough comparative analysis of the manufacturing energy intensities of the lightweight materials considered, using an application-based case study approach. The data collected in the *Lightweight Materials Energy Bandwidth Studies* will be foundational for this extensional analysis.

TABLE IX. MANUFACTURING ENERGY INTENSITY COMPARISON FOR LIGHTWEIGHT MATERIALS

Process Subarea or Sub-Process	**Onsite Energy Intensity** CT (Btu/lb)	SOA (Btu/lb)	PM (Btu/lb)
CFRP Composite	183,580	136,830	15,490
GFRP Composite	28,980	19,380	2,740
Aluminum*	33,300	24,480	15,090
Titanium*,**	54,950	54,950	19,230
Magnesium*,**	35,270	35,270	29,760
Steel (Baseline)*	6,520	4,040	3,300

* Energy intensities for the metals represent the sum of raw material preparation and primary metal production processes. Secondary metal production (processing of recycled materials) is not shown.
**For titanium and magnesium, the CT energy intensity was estimated to be equal to the SOA energy intensity, representing the sole commercial process used to produce these materials in the U.S.

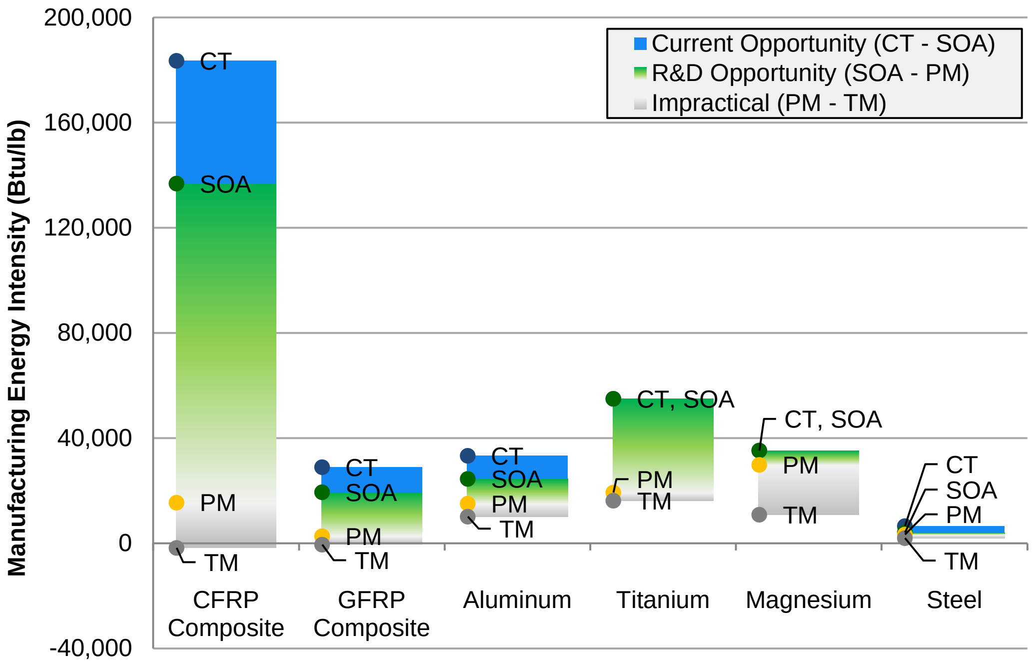

Figure 2. Comparison of onsite manufacturing energy intensities for two composite materials (glass and carbon reinforced polymers) and four metals (aluminum, titanium, magnesium, and steel).

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3. Morrow III, W. R., Das, S., Cresko, J. W., and Liddell, H. P. H., "Net energy consequences of carbon fiber reinforced polymer composites in U.S. light-duty vehicle fleet lightweighting," Proceedings of the 2016 Composites and Advanced Materials Expo (CAMX), Anaheim, CA, September 27–29, 2016. *(in press.)*

4. The concept of an energy bandwidth study, and its use as an analysis tool for identifying energy saving opportunities in manufacturing industries, originated at the U.S. Department of Energy (DOE) in 2002. Since then, DOE has published ten energy bandwidth studies: Steel (2004); Petroleum Refining (2006); Mining (2007); Glass (2007); Pulp and Paper (2006); Chemicals (2006); Aluminum (2007); Iron & Steel (2015 update); Petroleum Refining (2015 update); Pulp & Paper (2015 update); and Chemicals (2015 update). As of this writing, six additional studies focused on lightweight structural materials have been completed in draft form: Advanced High Strength Steel (2016); Carbon Fiber Composites (2016); Glass Fiber Composites (2016); Aluminum (2016 update); Magnesium (2016); and Titanium (2016). These six studies comprise the new *Lightweight Structural Materials Bandwidth Study* series. The DOE energy bandwidth studies can be accessed at the following web address: http://energy.gov/eere/amo/energy-analysis-sector#5.
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7. Franklin Associates. 2011. *Cradle-to-Gate Life Cycle Inventory of Nine Plastic Resins and Four Polyurethane Precursors.* Plastics Division of the American Chemistry Council.
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14. An 88% energy savings was assumed for each pound of carbon fiber replaced by recycled content, based on Kim [15]. The SOA recycling rate was assumed to be 10%, which is the fraction of recycled material in BMW i-series vehicles (see Gardiner [16]), for a total energy savings of 9%.
15. Kim, S. 2014. "Engineering sustainability of mechanical recycling on carbon fiber composite materials." University of Minnesota – Deluth.
16. Gardiner, G. 2014. "Recycled carbon fiber update: closing the CFRP lifecycle loop," *Composites Technology* 20(6): pp. 28–33.
17. Worrell *et al.* [18,43] estimated a typical energy savings of 8-15% from variable speed drives for electric systems used in glass batching. Similar energy savings were assumed for carbon fiber spinning and finishing, applied only to the electricity portion of these processes.
18. Worrell, E., Angelini, T., and Masanet, E. 2010 *Managing Your Energy: An ENERGY STAR Guide for Identifying Energy Savings in Manufacturing Plants.* Lawrence Berkeley National Laboratory (LBNL) and the U.S. Environmental Protection Agency (EPA).
19. The average thermal efficiency of an industrial furnace is estimated at between 75% and 90%, with a theoretical maximum of 92% [18], suggesting a possible savings of 2% to 17% from improved furnace design.
20. Worrell *et al.* [18] reported typical energy savings of 5 to 10% from clean heat transfer surfaces, 4 to 12% for ceramic-coated furnace tubes, 2 to 5% from better insulation, 5 to 10% from controlling furnace pressure, and 0 to 5% from maintaining door and tube seals. In the carbon fiber industry, carbonization ovens are assumed to be carefully pressure-controlled already due to process requirements. Summation of the remaining opportunities gives a range of 11 to 29% energy savings.
21. An energy savings of 2% to 3% from improved sensor and control systems was reported for glass melting furnaces [43]. These savings are assumed to be applicable to carbonization furnaces as well.
22. Typical fuel savings from waste heat recovery, as reported by Worrell *et al.* [18], range from 8% to 18% for waste heat recovery.
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25. Boustead, I. 2005. *Eco-Profiles of the European Plastics Industry: Polyurethane Rigid Foam.* Plastics*Europe*.
26. An 88% energy savings was assumed for each pound of carbon fiber replaced by recycled content, based on Kim [15]. The PM recycling rate was assumed to be 45%, corresponding to an overall savings of 35%.
27. Martin *et al*. [28] reported a 70% energy savings with a 70% applicability for thermoplastic polymer production (49% savings). Thermosets are more difficult to recycle, but technologies exist; see, e.g., Yang *et al.* [29]. A 70% savings with an applicability of 50% was assumed for thermoset polymer production (35% savings).
28. Martin, *et al.* 2000. *Emerging energy-efficient industrial technologies.* Lawrence Berkeley National Laboratory.
29. Yang, Y., *et al*. 2012. "Recycling of composite materials," *Chemical Engineering and Porcessing: Process Intensification* 51: 53–68.
30. Huang [31] reported a 67% reduction in PAN carbonization time for the microwave process. For a polyolefin precursor, carbonization represents approximately 67% of the oxidation / carbonization step. Energy savings were therefore estimated at 45% (67% savings with an applicability of 67%).
31. Huang, X. 2009. "Fabrication and properties of carbon fibers." *Materials* 2: pp. 2369–2403.
32. Schepp *et al.* [11] estimated that rejected product (and the corresponding energy use) could be reduced by 5% through improved die design.
33. Radiant heaters with IR emissivity well-matched to the thermal characteristics of the polymer material could save an estimated 50% in certain thermal consolidation processes. [11]
34. Schepp *et al.* [11] estimated that barrel insulation could reduce heating energy by 7 to 25%.
35. Krause [36] reported that modeling and process analysis could provide 5% and 10% energy savings, respectively, in crosscutting applications. Combining these, a 14% overall savings was assumed.
36. Krause, F. L. 2008. *Energy Efficiency in Manufacturing: the Role of ICT.* The European Commision Smart Manufacturing Consultation Group.
37. Process integration and pinch analysis (i.e., reducing bottlenecks) to increase system synergy could save an estimated 10% with 40% applicability [28], or 4% overall.
38. Rucks, G., Agenbroad, J., and Doig, S. 2013. *Kickstarting the Widespread Adoption of Automotive Carbon Fiber Composites: Key Findings and Next Steps.* Rocky Mountain Institute.
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48. Hains *et al.* reported energy savings of 3% to 10% from lithia additives and 2% to 5% from mixed alkali additives. A 4% energy savings was assumed. Note that the energy savings for this technology occur in the melting stage, although it is implemented during batching.
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50. Worrell *et al.* [43] reported that Owens Corning was able to save 10% in energy costs by using 30% cullet in the glass batch. Note that the energy savings for this technology occur in the melting stage, although it is implemented during batching.
51. Worrell *et al.* [43] estimated that a 1% reduction in the moisture content of the glass batch can provide fuel savings of 0.5% in the glass melting furnace. A total savings of 0.5% was assumed.
52. Worrell *et al.* [43] estimated energy savings in the range of 30% to 50% for microwave glass melting.
53. The Viox Corporation was able to reduce drying time from 58-72 hours per batch to 11 hours per batch [43]. Based on this reduction, a 30% savings was assumed.