NET ENERGY CONSEQUENCES OF CARBON FIBER REINFORCED POLYMER COMPOSITES IN U.S. LIGHT-DUTY VEHICLE FLEET LIGHTWEIGHTING

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ABSTRACT

Carbon fiber reinforced polymer (CFRP) composites have performance characteristics (specific stiffness and strength) that are advantageous for clean energy products such as lightweight vehicles and efficient wind turbines. In transportation applications, the use of lightweight CFRP composites to replace conventional materials such as steel can provide major fuel energy savings during the use phase. However, carbon fiber (CF)-based composites are highly energy intensive to manufacture compared to conventional materials, and it can take many years for the fuel energy savings accumulated in the use phase to outweigh the increased manufacturing energy consumption. In some cases, it is possible that fuel energy savings will never overcome the embodied energy penalty. As a result, a full accounting of energy impacts based upon a life cycle analysis (LCA) approach is essential to evaluate the balance between increased energy demand to manufacture better performing products, and the downstream energy benefits resulting from their use. This approach can provide insights regarding where improvements in the manufacture and use of CF and CFRP composites are needed to realize timely, economy-wide energy benefits.

This paper presents life cycle assessments for CFRP composites manufactured via two pathways: conventional polyacrylonitrile-based CF, and a hypothetical alternative approach to manufacture lower energy carbon fibers used in CFRP composites. Lawrence Berkeley National Laboratory's "LIGHTEn-UP" LCA tool [1] was used to estimate the net energy consequences of lightweighting the U.S. fleet of light-duty vehicles (LDVs) with CFRP composites in each case. We also examine the energy savings that could be realized through lower-energy precursors and through CFRP recycling. Results demonstrate that cost- and performance-effective CF recycling can play a key role in lowering the net energy consumption and associated emissions of CFRP materials.

1. INTRODUCTION

Life cycle analysis (LCA) is a useful tool for holistically evaluating the net energy impacts of advanced composites and other lightweight materials in the future U.S. light-duty vehicle (LDV) fleet. This paper presents a method to anticipate the future net energy consequences of the use of carbon fiber reinforced polymer composites (CFRP) as the U.S. LDV fleet turns (new vehicles enter the fleet and old vehicles retire). Current and hypothetical future CFRP manufacturing energy requirements are compared to the use-phase energy savings potential of vehicles lightweighted with CFRP parts. Several scenarios explore the effects of shifts in the CFRP manufacturing process and end-of-life treatment for vehicle component production. The estimated current typical and state-of-the-art energy requirements for CFRP production are based on preliminary results from a concurrent effort at the U.S. Department of Energy (U.S. DOE) to assess opportunities for energy savings in lightweight materials manufacturing [2]. This paper also presents a detailed table of relevant parameters necessary to assess the energy impacts of lightweighted LDVs in the U.S. forecast out to the year 2050, and documents the assumptions behind forecast scenarios. Lastly, conclusions and recommendations are provided for interested audience, auto manufactures, and policy makers. It is envisioned that original equipment manufacturers, researchers, and government representatives can utilize this paper and methodology as a reference to understand and explore the net energy consequences of lightweighting LDVs with CFRP composites. The methodology can be extended to evaluate substitutions of other materials, presuming that fundamental embodied and manufacturing energy data are available, and substitutions are supported by rational engineering assumptions.

2. ANALYSIS & RESULTS

2.1 CFRP Lightweighting Case Study — Base Case (No Recycling)

Conventional polyacrylonitrile (PAN)-based carbon fiber composites have a high embodied energy, with a manufacturing energy intensity many orders of magnitude higher than steel, aluminum, and even glass fiber composites [2]. In the 2015 U.S. DOE *Quadrennial Technology Review,* the supporting technology assessments 6E (*Composite Materials*) [3] and 6L (*Sustainable Manufacturing*) [4] each included case studies exploring the energy impacts of CFRP composites in light-duty vehicles. In these case studies (referred to as the "QTR case studies" in this paper), the Lawrence Berkeley National Laboratory's LIGHTEn-UP LCA tool [1] was used to evaluate the life cycle energy impacts of the adoption of a CFRP automotive part produced via two manufacturing pathways in the LDV fleet (both assuming 40% fiber by weight) compared against a business-as-usual baseline of conventional stamped steel. The first CFRP manufacturing pathway was based on a conventional, high-embodied-energy PAN carbon fiber precursor (labeled "Current Typical" in the following tables and figures). The PAN CFRP pathway begins with the polymerization of acrylonitrile and utilizes solution spinning to fiberize the material. The second manufacturing pathway was a hypothetical low-energy CFRP manufactured with an alternate precursor. This low-energy CFRP pathway begins with the polymerization of an alternative high-yield precursor raw material and uses melt spinning to fiberize the material. Both pathways include the high-temperature oxidation and carbonization steps currently required to manufacture high –strength CF.

In the present analysis, the LIGHTEn-UP tool was used along with the same base assumptions as in the QTR case studies to expand upon the initial analysis. In this paper, it was assumed that the low-energy manufacturing pathway can attain a 53% reduction in embodied energy in the CF as compared to conventional, PAN-based CF. In the low-energy pathway, it was also assumed that the energy associated with resin (epoxy) production and part fabrication could be reduced, each by 20%, through the use of state-of-the-art processing technologies. These assumptions are based on preliminary results from the DOE's *Lightweight Materials Bandwidth Studies* [2].

For the use phase, a key assumption is that select CFRP composite parts can substitute for traditional steel parts. Mass substitution factors for automotive parts are application specific, as part design depends on loading conditions, geometry, and other factors. Using a panel structure as a basis for a generic part, a typical mass substitution ratio of 65% was developed based on a theoretical correlation between fiber mass fraction and mass savings for a generic panel configuration (i.e., assuming equivalent properties achieved by a CFRP panel in bending based on CF with 150 GPa fiber modulus) [5]. Typical specific LDV components based on a panel configuration include parts such as trunklids, hoods, roof structures, door skins, etc. Applying a mass reduction of 65% to a nominal 110-kg steel part, it is replaced with a 39-kg CFRP part. To calculate the energy impacts as vehicles with lightweighted parts enter the gasoline internal combustion engine (ICE) LDV fleet, CFRP part deployment was estimated using a bass diffusion adoption curve between 2017 and 2035, scaling to all U.S. light duty vehicle sales. Further key assumptions include a vehicle lifetime driving distance of 250,000 km and a mass reduction induced change in fuel consumption of −0.38 liters/100 km driven per 100 kg of steel replaced by CFRP. Recycling was not considered in the Base Case analysis. Table 1 shows the key assumptions that define the scenario. Figure 1 shows a comparison of the overall energy intensities (reported in MJ per kg of material in the finished part) for the two CFRP manufacturing pathways and conventional stamped steel. Note that for the CFRP materials, these energy intensities represent a summation of the carbon fiber and polymer embodied energies (scaled according to their weight fraction in the composite) plus the process energy of part fabrication.

Table 1. Key Assumptions defining the Base Case scenario

	Value
Conventional Steel Assumptions	
1. Mass of steel door being replaced	110 kg
2. Raw material embodied energy	23.1 MJ/kg
3. Energy required to manufacture steel ingot into a coil	6.4 MJ/kg
4. Energy required to stamp steel	5.1 MJ/kg
5. Energy required for steel assembly	0.7 MJ/kg
6. Steel buy-to-fly ratio	1.39
CFRP Composite Assumptions	
7. Mass of CFRP composite substitution part	38.5 kg
8. Carbon fiber weight fraction of CFRP part	40%
9. Epoxy weight fraction of CFRP part	60%
10. CF manufacturing energy intensity - Current Typical	1150 MJ/kg
11. CF manufacturing energy intensity – Low Energy	388 MJ/kg
12. Matrix resin type used in CFRP	Epoxy resin
13. Resin manufacturing energy intensity - Current Average	94.2 MJ/kg
14. Resin manufacturing energy intensity – Low Energy	75.3 MJ/kg
15. CFRP composite production method	Resin Transfer Molding
16. Composite production energy intensity – Current Typical	38 MJ/kg
17. Composite production energy intensity – Low Energy	31 MJ/kg
18. Buy-to-fly ratio for resin transfer molding (RTM) composite production	1.07
19. Performance characteristics of substitution part	Same as replaced steel
Vehicle Lightweighting Assumptions	

20. Average LDV lifetime	13 years
21. Average vehicle km traveled over vehicle lifetime	250,000 km/vehicle
22. Mass induced fuel consumption factor with adaptation	-0.38 km/vehicle
23. ICE LDV sales in 2013 in U.S. (cars and light trucks)	11,893,776 LDVs
24. First year CFRP part starts replacing an equivalent steel part on new LDVs (first year of bass diffusion)	2018
25. Year in which CFRP replaces an equivalent steel part on all new LDVs (year when bass diffusion reaches 100%)	2034

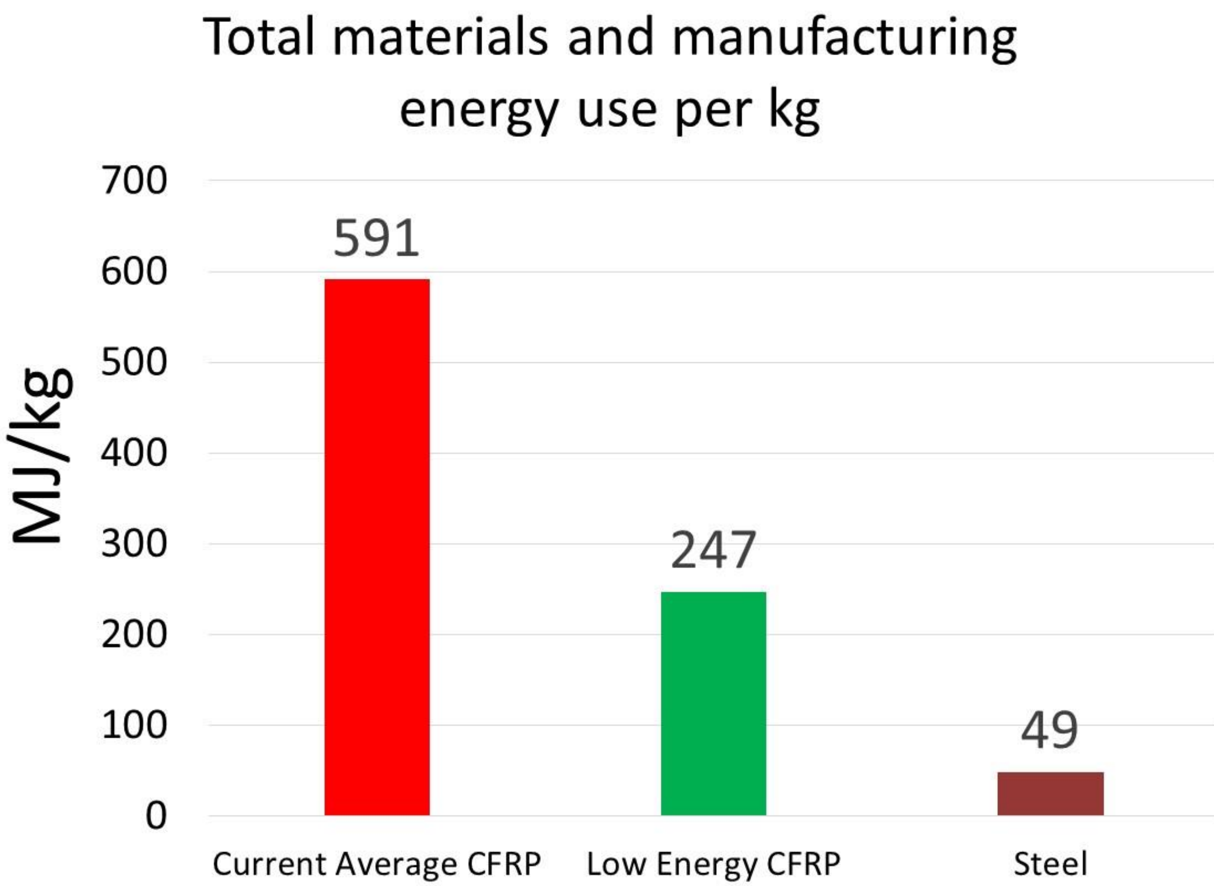

Figure 1 – Comparison of the embodied energy of CFRP to conventional steel

Figure 2 presents LIGHTEn-UP results for the Base Case scenarios, based on assumptions presented in Table 1. The dashed red curve shows the embodied energy for CFRP parts produced via the current typical pathway, while the dashed green curve shows the embodied energy of CFRP parts assuming the low-energy production pathway. The dotted red curve shows the displaced embodied energy associated with steel production and part stamping. The dash-dot green line shows the vehicle fuel savings associated with lightweighting. The net results of the manufacturing and use-phase are shown in the solid curves; the solid red curve represents the current typical (conventional PAN) CFRP scenario, and the solid green curve represents the alternative low-energy CFRP scenario.

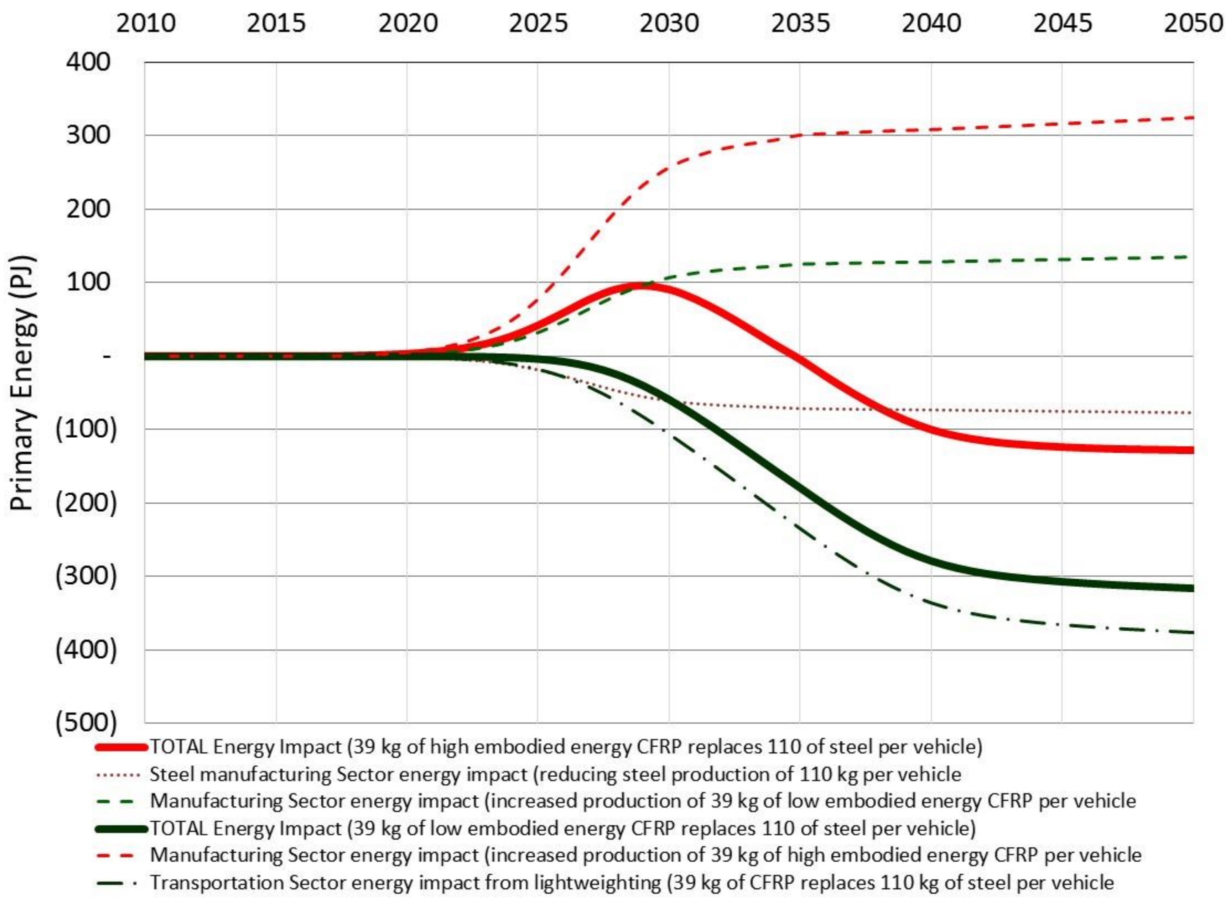

Figure 2 – Estimated net annual life cycle energy impacts of replacing a 110-kg conventional steel part with a 39-kg CFRP part (comprising 40% fiber by weight) throughout the U.S. LDV fleet, comparing two manufacturing pathways (conventional PAN-based CF and an alternative, low-energy CF).

Figure 2 shows that the current typical scenario produces net energy savings by 2037. The average vehicle lifespan in both scenarios is assumed to be 13 years. Although manufacturing energy is expended in the year the vehicles are manufactured, lifetime fuel savings are spread across the lifespan of a lightweighted vehicle. Therefore, there is a net annual energy consumption increase in the earlier years of this scenario, followed by an accumulation of savings that result in net lower energy in the long-run. However, results show that the low-energy CFRP scenario provides net energy savings in all years of the analysis period.

2.2 CFRP Lightweighting Case Study – With Recycling

For consistency, the new recycling scenario applies the same base assumptions as the initial scenario presented (see Table 1), with an additional accounting for recycled CF (recycled CF is assumed to come from retiring LDVs at the end of their lifetime (13 years)).[1] The majority

[1] Recycled CF is assumed to come from retiring LDVs at the end of their lifetime (assumed 13 years). 13-year lifetime is the current average vehicle lifetime. For simplicity, vehicles retiring earlier than 13 years are not included in the figure.

(~60%) of virgin CF's embodied energy intensity is associated with conversion of the precursor into final long filament CF tows [2]. In contrast, recycled CF only requires thermal, mechanical, or chemical processing to separate the resin from the CF in the original CFRP part, which lowers recycled CF's energy intensity to an estimated 80 MJ/kg [6, 7], or 92% lower than current PAN CF (1150 MJ/kg) and 79% lower than the hypothetical low-energy CF (388 MJ/kg). Based on recycling technologies available today [8], most recycled CF is anticipated to be short-length CF with lower mechanical performance properties (e.g., fiber strength and modulus) compared to virgin CF. This might restrict their use to a limited set of applications where the loading conditions, geometry, and other factors are safe and within engineered specifications.

For the recycling scenario, we assume that CFRP parts will be recycled when the vehicles containing them retire. As a result, the model assumes a 13-year delay between when virgin fiber CFRP parts enter the vehicle stock and when they are first harvested and recycled. Furthermore, we assume a 90% harvest rate, and that only the number of parts manufactured in a single year is available for harvesting 13 years later. Table 2 shows the additional assumptions associated with the recycling scenario.

Table 2. Key Additional Assumptions defining the Recycling Case scenario

CFRP Composite Recycling Assumptions	
26. Source of CFRP composites for recycling	Retiring LDVs @ 13 years
27. Recycle rate of CFRP composites from end-of-life vehicles	90%
28. CF re-manufacturing energy intensity	80 MJ/kg

Figure 3 shows the results of the recycling assumption applied to the initial CFRP scenario. The initial solid red and green net energy curves are retained, but for simplicity the manufacturing and use-phase subcomponents of the scenarios are removed. The net effect of CFRP recycling is shown by the shaded areas. The red shaded area shows the effect of recycling on the current typical CFRP scenario and the green shaded area shows the effects of recycling on the low-energy CFRP scenario.

As can be seen in Figure 3, recycling provides significant energy savings in both scenarios. In the current typical scenario, recycling CF doubles the annual energy savings potential in 2050. Even in the low-energy CF scenario, recycling provides an additional 25% savings potential in 2050. In both cases, the 13-year vehicle lifetime assumption delays the availability of recycled CF until 2030.

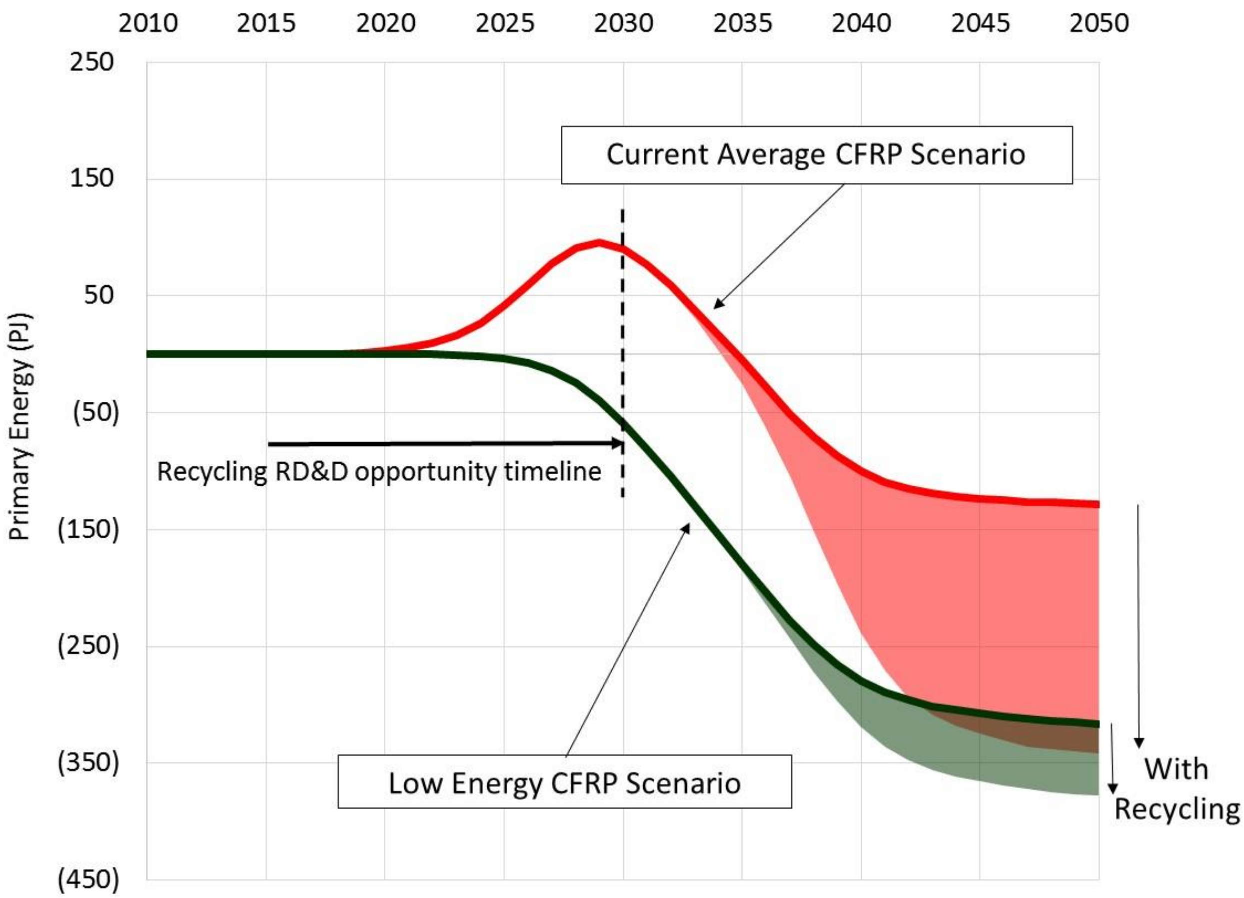

Figure 3 – Estimated net annual life cycle energy impacts of CFRP recycling for a 39-kg CFRP automotive component in the U.S. LDV fleet, based upon the same scenario assumptions depicted in Figure 2.

3. CONCLUSIONS

In this paper, an energy analysis based on an LCA approach was used to evaluate the net energy impacts of the penetration of CFRP composite components into the U.S. LDV fleet, based on high- and low-energy manufacturing pathway scenarios. Despite the greater embodied energy of CFRP when compared to steel, results show that the use-phase energy savings from vehicles lightweighted with current typical CFRP can yield a net energy savings over time as fuel savings accumulate in the LDV stock—but that it can take many years (nearly 20 years in this scenario) to achieve this energy payback. However, energy savings can be realized immediately if a hypothetical, low-energy alternative precursor-based CF is used. Further, CFRP composite recycling can greatly increase the net energy savings associated with CFRP composite lightweighting.

The recycling scenarios presented here are predicated on aggressive recycling assumptions, specifically that:

- the CF will be harvested from 90% of retiring vehicles;

- the recycled CF's embodied energy will be much lower than virgin CF's embodied energy (92-79% lower, as defined above); and
- new parts manufactured from recycled CF meet safety and engineering performance specifications.

Achieving these goals and energy savings will require effective CFRP recycling technologies, a harvesting infrastructure, and new vehicle part designs that utilize recycled fiber. Achieving widespread penetration of recycled composites in vehicles will thus require successful RD&D in the technologies that will enable low-energy, cost-effective CF recycling. The initial scenarios assume that CFRP parts will start showing up in vehicles by 2017, with a gradual accumulation of CFRP parts in the fleet after that introduction year. Based on a historical average vehicle lifetime of 13 years, a typical 2017 lightweighted vehicle would be retired in 2030. This sets a time window for recycling R&D, as shown in Figure 3. However, vehicle parts should always be designed with recycling as an objective, due to the large energy savings benefits from recycled CF. Moreover, anticipating that recycled CF will become abundant, vehicle parts that can utilize recycled CF and still maintain their engineered safety specifications should be a priority for vehicles manufacturers.

It is also important to note that changing consumer choices, vehicle designs, and vehicle ownership paradigms could result in shorter vehicle lifetimes in the future. A reduction in the average vehicle lifetime would increase the energy savings benefit of recycling carbon fiber. Shorter vehicle lifetime, although not specifically shown here, would shift the recycle shaded areas in Figure 3 to the left (earlier in time) and larger in size by 2050.

The authors note that this case study explores a single end-use product scenario (automotive lightweighting), but the energy LCA method can be readily extended to other product categories such as aerospace and renewable energy generation.

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