THE MANUFACTURING ENERGY INTENSITY OF CARBON FIBER REINFORCED POLYMER COMPOSITES AND ITS EFFECT ON LIFE CYCLE ENERGY USE FOR VEHICLE DOOR LIGHTWEIGTING

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ABSTRACT

The replacement of conventional materials with lightweight materials can improve vehicle fuel economy and associated emissions, but the choice of materials is dependent on complex design requirements. Carbon fiber reinforced polymer (CFRP) composites have high stiffness and tensile strength with relatively low mass, and are increasingly being deployed in light-duty vehicles (LDVs). CFRP composite life cycle energy advantages are a balance between highly energy-intensive production processes and the energy savings and greenhouse gas emissions reductions that mainly occur in the use phase for applications such as transportation. In the production phase, the manufacturing energy intensity of CFRP composites is greater than that of conventional metals. A review of commercially available manufacturing methods estimates the primary energy intensity of CFRP composites with 50% fiber volume fraction to be roughly 800 MJ/kg, whereas that for conventional steel is only 50 MJ/kg [1]. Conventional steel is produced by processes that are well established and have undergone over 150 years of optimization and energy intensity improvements, while CFRP composites are currently produced by relatively new processes that have promising opportunities for optimization and energy intensity improvements. This analysis explores the substitution of a conventional steel LDV door with a carbon fiber reinforced polymer having a 50% fiber volume fraction (50%CFRP). The energy intensity of the 50%CFRP composites is assessed for three scenarios corresponding to the current typical manufacturing techniques, the most energy efficient commercially available techniques, and the practical minimum energy intensity based on applied research technologies with commercial potential identified in an initial investigation. The effect of these variations in manufacturing energy intensity on the life cycle analysis is shown using the LIGHTEnUP Tool (Lifecycle Industry GHgas, Technology and Energy through the Use Phase) developed by the U.S. Department of Energy (DOE) and the Lawrence Berkeley National Laboratory (LBNL). The break-even manufacturing energy intensity threshold for the 50%CFRP composite LDV door to provide a net reduction in life cycle energy and associated carbon dioxide emissions is computed. The paper concludes with a discussion of the practical drivers affecting the design choices, manufacture and use of CFRP composites in LDVs.

1 INTRODUCTION

Lightweighting is an important end-use energy efficiency strategy in transportation. A 10% reduction in vehicle weight can improve fuel efficiency by 6%–8% for conventional internal combustion engines (ICEs), or increase the range of a battery-electric vehicle by up to 10% [2, 3]. A 10% reduction in the weight of all vehicles in the U.S. car and light duty truck fleet could result in approximately 1,060 TBTU (1.12×10^{18} J) annual reduction in energy and a 72 million metric tons (MMT) reduction in carbon dioxide (CO_2) emissions [4]. The DOE Vehicles Technology Office (VTO) estimates savings of more than 5 billion gallons of fuel annually by 2030, if one quarter of the U.S. light duty fleet utilizes lightweight components and high-efficiency engines enabled by advanced materials [5].

In 2012, the U.S. Environmental Protection Agency (EPA) and the National Highway Traffic Safety Administration (NHTSA) set forth new Corporate Average Fuel Economy (CAFE) standards for cars and light-duty trucks that are projected to increase fleet-wide average fuel economy to the equivalent of 54.5 mpg by model year 2025 [6]. Lightweighting has been identified as a technology approach with significant potential to achieve this standard. The U.S. DRIVE (Driving Research and Innovation for Vehicle efficiency and Energy sustainability) Materials Technical Team identified carbon fiber composites as the most impactful material to reduce vehicle mass in their 2013 Roadmap [7]. CRFP composites can offer mass reductions over steel of up to 50–70% [8].

Life cycle energy advantages are a balance between energy-intensive CFRP composites production and energy savings that mainly occur in the use phase. Raw materials are typically derived from energy intensive petroleum processing for the matrix constituent and energy intensive polyacrylonitrile (PAN) for the reinforcement. In the production phase, high temperatures are required in the manufacture of carbon fibers. To reduce the energy intensity of CFRP composites, high quality lower energy raw materials and lower energy production technologies are needed. Das, Masanet and Morrow have investigated the fleet-wide life cycle energy advantages of substituting 100 kg of conventional steel with 50 kg of CFRP having 30 wt. % carbon fiber in a non-structural LDV component using both PAN and polyolefin precursors [9]. This paper expands on their work to explore the effect of reducing manufacturing energy intensity of 50%CFRP composites (having 50 vol. % carbon fiber) on fleet-wide life cycle energy use and carbon dioxide emissions in the application of vehicle lightweighting of a structural component, a door.

2 COMPUTATIONAL ANALYSIS

2.1 Model Description

The LIGHTEnUP Analysis Tool (Lifecycle Industry GHgas, Technology and Energy through the Use Phase) uses a cross-sectoral energy impacts methodology to forecast both the manufacturing sector and product life-cycle energy consumption impacts of manufactured products across the U.S. economy. The LIGHTEnUP tool is based on a prospective life cycle analysis approach to assess and forecast scenarios of anticipated situations or changes in U.S. energy consumption and associated CO_2 emissions. Bounding the inevitable uncertainty of the future with scenarios to describe how technologies and products might be utilized in both the manufacturing and use-phase stages serves as a constructive analysis of plausible future outcomes.

The tool architecture incorporates two publicly available historic and projection datasets of U.S. economy-wide energy use: the Energy Information Agency’s Annual Energy Outlook (AEO) [10] and the U.S. Department of Energy’s Manufacturing Energy Consumption Survey (MECS) [11]. AEO provides data regarding where energy is currently being consumed across the entire U.S. economy, as well as forecasts of anticipated energy consumption. The AEO forecasts utilize the National Energy Modeling System [12], a generalized market equilibrium model. MECS provides detailed data on where (by industrial subsector) and how (by type of energy consuming system) energy is expended in the manufacturing sector. In its current version, LIGHTEnUP is an Excel-based tool that combines these two data sets and calculates prospective energy impacts over a multi-year (2010 – 2050) projection period. For this paper, scenarios of transportation vehicle lightweighting were developed to analyze future manufacturing and use-phase energy impacts.

2.2 Model Limitations

The LIGHTEnUP tool assumes the data and forecasts provided in the Annual Energy Outlook are accurate and valid as a baseline (business as usual), and that the Manufacturing Energy Consumption Survey adequately represents the industrial energy consuming systems under consideration. It does not alter factors outside the explicitly entered technological changes. The tool is not an equilibrium model, as it does not attempt to solve for market equilibria across the economy in response to the developed scenario. The tool assumes that the changes made due to implementation of a given scenario only alter the factors directly modelled by the user. For example, a scenario based on the replacement of a steel vehicle component with a CFRP composite will not consider the effects of the displaced steel re-entering the steel market unless explicitly included in the scenario. The tool is limited to the U.S. economy and the embodied energy of imported products does not appear in the tool's framework. Therefore, the results show impacts on U.S. energy consumption and associated CO_2 emissions and may underestimate impacts of technologies that have a global market. As such, scenarios are best when focused on U.S. domestic manufacturing of products utilized within the U.S. The tool outputs are energy consumption, energy expenditures, and associated CO_2 emissions; not included are non-energy impacts, pollutants other than CO_2, or economic and market effects. For additional details regarding the LIGHTEnUP tool, refer to related publications using this tool [13, 14].

2.3 Assumptions

Conventional Steel Assumptions	**Value**	**Ref.**
1. Mass of steel door being replaced	33 kg	[15]
2. Raw material embodied energy	23 MJ/kg	[16]
3. Energy required to manufacture steel ingot into a coil	6.4 MJ/kg	[16]
4. Energy required to stamp steel	5.1 MJ/kg	[16]
5. Energy required for steel assembly	0.7 MJ/kg	[16]
6. Steel buy-to-fly ratio	1.38	[16]
CFRP Composite Assumptions		
7. Mass of CFRP composite substitution door	10 kg	[15]
8. Carbon fiber volume fraction	50%	[15]
9. Epoxy volume fraction	50%	[15]
10. Manufacturing energy intensity	See Table 2	[1]
11. Required energy mix for epoxy production	90% fuel & 10% electricity	[17]
12. Required energy mix for carbon fibers produced from a PAN precursor ('Current Typical' & 'State-of-the-Art' case studies)	85% fuel & 15% electricity	[18]
13. Required energy mix for carbon fibers produced from a polyolefin precursor ('Practical Minimum' case study)	33% fuel & 67% electricity	[18]
14. Manufacturing technique used for composite production	Resin transfer molding	[15]
15. Required energy mix for RTM composite production	100% electricity	[19]
16. Buy-to-fly ratio for RTM composite production	1.07	[15]
17. Percent of CFRP composite that is recycled	0%	N/A
18. Performance characteristics of substitution part	Same as replaced steel	N/A
Vehicle Lightweighting Assumptions		
19. Average LDV lifetime	16.9 years	[20]
20. Average annual LDV distance traveled	16,100 km/year	[21]
21. 2013 LDV fuel efficiency	12.8 km/liter	[10]
22. Mass induced fuel consumption factor with adaptation	0.38 liter/100km/100kg	[22]
23. ICE LDV sales in 2013 in USA (cars and light trucks)	11,893,800 cars	[23]
24. First year 50%CFRP starts replacing a steel door on new LDVs	2018	[9]
25. Year in which 50%CFRP replaces a steel door on all new LDVs	2034	[9]

Table 1: Key assumptions used in the LIGHTEnUP analysis.

The effects of vehicle lightweighting through partial substitution of CFRP composites for conventional steel in LDVs powered by ICEs in the U.S. through year 2050 are considered. Specifically, this analysis studies the substitution of a conventional steel door with a 50%CFRP composite door. This scenario has been chosen because it was well-documented at the Rocky Mountain Institute workshop in 2012 and conveys the actual experience of one of the workshop participants [15]. Table 1 provides key assumptions for the LIGHTEnUP analysis. Please note that additional assumptions are made in AEO [10] and MECS [11].

The following definitions clarify the terms mentioned in these assumptions. Conventional steel refers to mild steel typically used in automotive manufacturing. The buy-to-fly ratio, a term originating in the aerospace industry, is the weight ratio between the raw material input used for a component and the final weight of the component.

3 MANUFACTURING ENERGY INTENSITY CASE STUDIES

Energetics Inc. has provided initial results from a study under development on the manufacturing energy intensity of CFRP composites for the three case studies under consideration: 'Current Typical', 'State-of-the-Art', and 'Practical Minimum' [1]. These results can be seen in Table 2. The 'Current Typical' is assumed to be the typical U.S. manufacturing energy intensity of CFRP composites deployed today. The 'State-of-the-Art' represents the manufacturing energy intensity of CFRP composites thought achievable through the adoption of global best plant (commercially available) technologies and practices. For carbon fiber production, the 'Current Typical' and 'State-of-the-Art' energy intensities are based on a PAN precursor process, and are assumed to be the same. The 'Practical Minimum' represents the manufacturing energy intensity of CFRP composites conceivably achievable through deployment of applied research technologies currently under development across the globe based on best available knowledge at the time of this publication. The applied research technologies include use of polyolefin precursor, microwave-based carbonization, improved insulation in process heating equipment, process control systems for carbon fiber carbonization, modeling and process analysis to reduce off-specification material, process intensification/pinch analysis strategies to remove process bottlenecks, and plastics recycling and recovery. While these 'Practical Minimum' technologies represent current applied research technologies, additional energy reducing opportunities could emerge as R&D matures. It is important to note that the study considers only technical potential, and does not consider economic feasibility and scale-up potential of the technologies.

Since there are different methods to manufacture CFRP composites, there can be significant variation in the energy intensity values reported. For example, the fiber fraction of the composite can be a significant contributor to the overall manufacturing energy intensity. In all three case studies, it is assumed that the composites comprise 50% carbon fiber and 50% epoxy by volume (58 wt.% fiber), as shown in Table 1. For comparison, the 30 wt.% fiber fraction composite (with different performance characteristics) considered by Das, Masanet and Morrow [9] under 'Current Typical' techniques would result in an overall manufacturing energy intensity of 474 MJ/kg, corresponding to a 40% energy intensity decrease compared to the 50%CFRP composite considered in this paper.

Process	'Current Typical' [MJ/kg]	'State-of-the-Art' [MJ/kg]	'Practical Minimum' [MJ/kg]
Carbon Fiber Production	1134	1134	330
Resin (Epoxy) Production	89.8	8.70	3.63
Composite Production	39.5	39.5	29.3
Subtotal (50%CFRP)	735	701	222
Total (with buy-to-fly-ratio)	786	750	238

Table 2: Preliminary data for the manufacturing primary energy intensity for 50%CFRP composites. It is assumed that composite production is achieved via resin transfer molding (RTM). [1]

These case studies help identify opportunities for life cycle energy savings and associated CO_2 emissions reduction. Figures 1-3 show the life cycle energy consumption from the LIGHTEnUP tool for each case study. The LIGHTEnUP tool has been used in other assessments with different assumptions [9, 24]. Since the LIGHTEnUP output reflects the variability in the assumptions (as was seen in the discussion of the fiber volume fraction), these assessments produced different results.

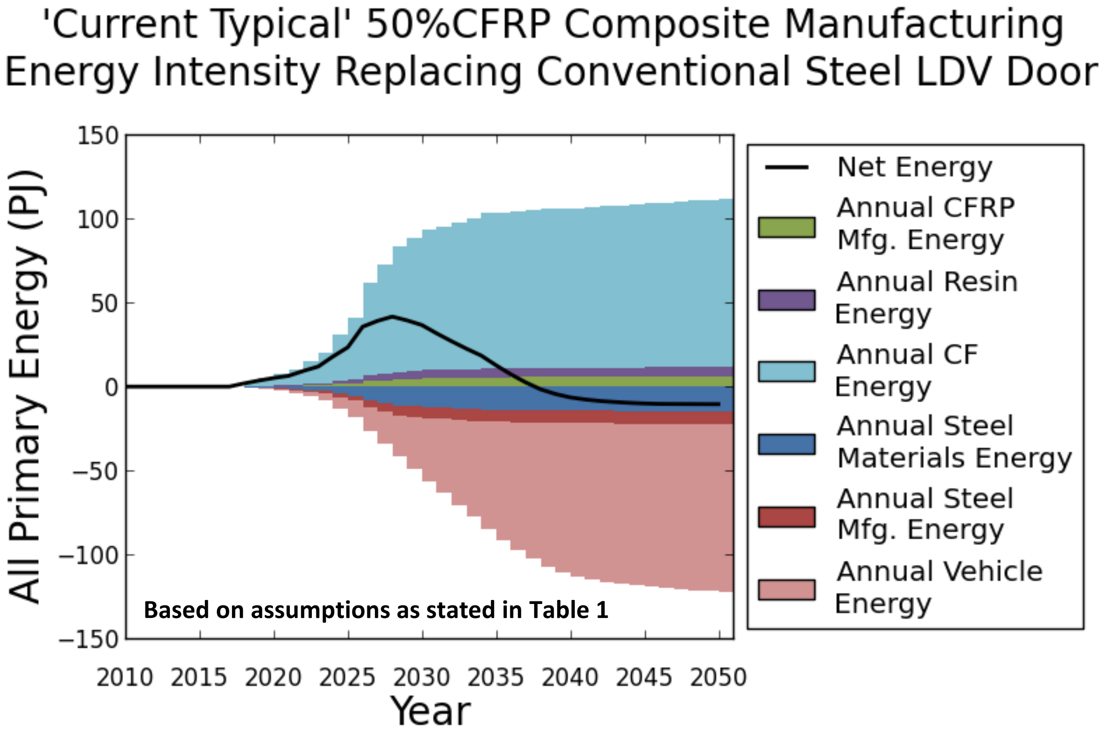

Figure 1: LIGHTEnUP output for the ‘Current Typical’ case study.

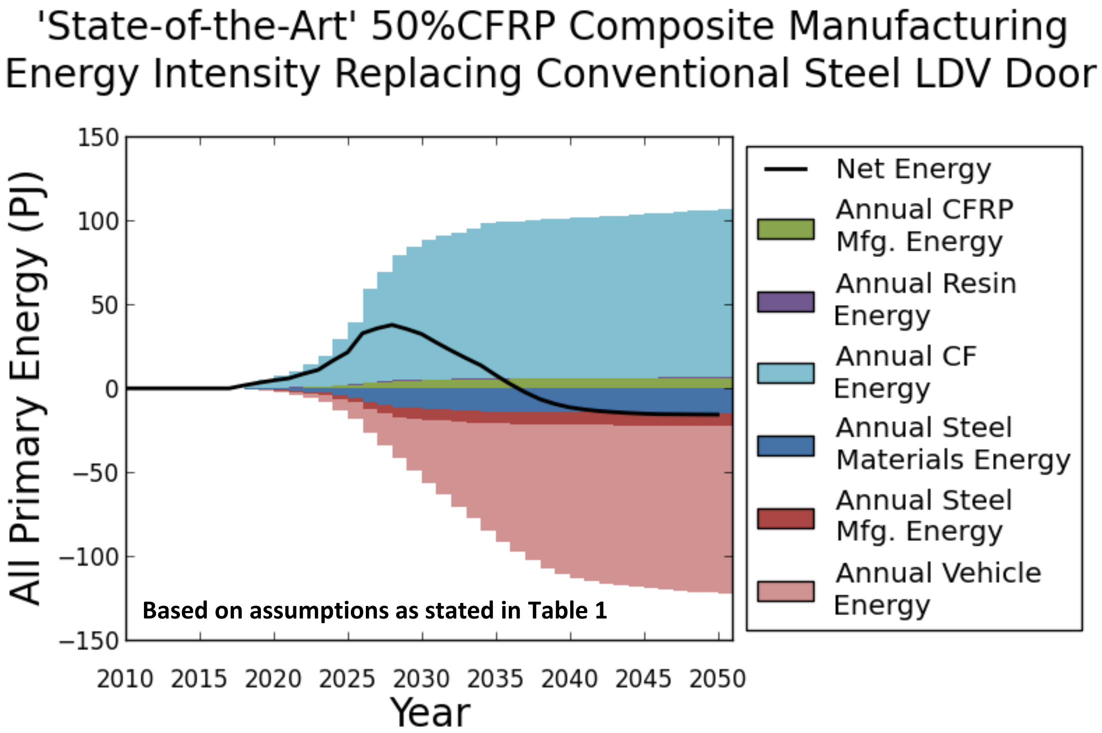

Figure 2: LIGHTEnUP output for the ‘State-of-the-Art’ case study.

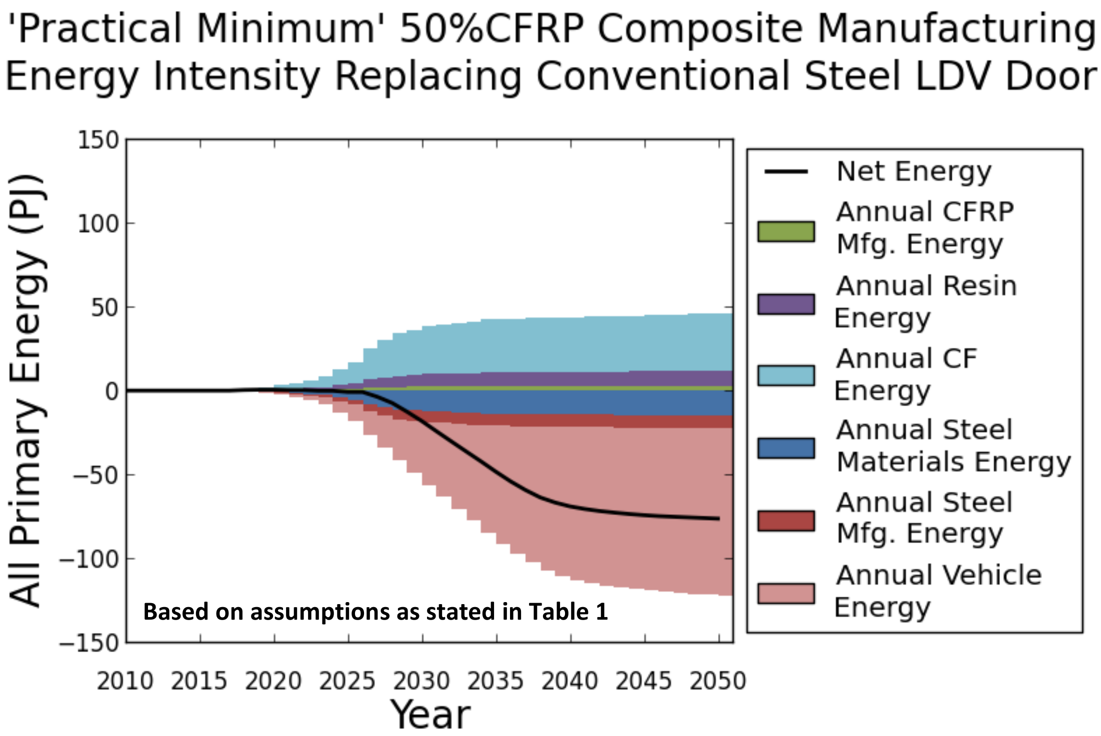

Figure 3: LIGHTEnUP output for the ‘Practical Minimum’ case study.

Several important features should be noted from these figures. As more 50%CFRP composite is substituted for conventional steel LDV doors beginning in 2018, more energy is used to manufacture carbon fiber, epoxy resin, and 50%CFRP composite as indicated by light blue, purple and green shaded areas respectively in Figures 1-3. An equal number of LDV doors are no longer made of conventional steel. The energy savings associated with the avoided use of steel is shown in dark blue (“Annual Steel Materials Energy”) and red (“Annual Steel Mfg. Energy”). Since the 50%CFRP composite LDV door offers a mass reduction of roughly 70% compared to the conventional steel door, use phase energy savings from vehicle lightweighting as seen in pink (“Annual Vehicle Energy’) contributes significantly to overall life cycle energy savings. The sum of all these factors is the net energy expenditure for each year shown by the solid black curve. In both the ‘Current Typical’ and ‘State-of-the-Art’ case studies, the net energy savings in vehicle lightweighting does not offset the energy intensive manufacturing of 50%CFRP composites for roughly 20 years after the LDV door substitution begins. This can be seen by the Net Energy curve passing zero in 2038 for the ‘Current Typical’ case study and in 2037 for the ‘Practical Minimum’ case study. However, in the ‘Practical Minimum’ case study, the vehicle lightweighting energy savings not only offset the manufacturing energy of the 50%CFRP composites but also dramatically reduce cumulative life cycle energy consumption. The cumulative energy consumption and corresponding CO_2 emissions by the end of 2050 can be seen in Table 3. Please note that a negative value implies energy savings and CO_2 reductions.

Case Study	Cumulative Energy Consumption [J]	Cumulative CO_2 Emissions [Million Metric Tons]
‘Current Typical’	2.85×10^{11}	-1
‘State-of-the-Art’	1.63×10^{11}	-9
‘Practical Minimum’	-1.30×10^{12}	-99

Table 3: Cumulative energy consumption and corresponding CO_2 emissions in 2050.

4 MANUFACTURING ENERGY INTENSITY VARIATATION ANALYSIS

The case study analysis in the previous section shows that vehicle lightweighting may offset the high manufacturing energy intensity of 50%CFRP. A sensitivity analysis was performed to determine how much the manufacturing energy intensity of CFRP composites would need to reduce under these conditions so that the cumulative manufacturing energy consumption could be completely offset by cumulative energy savings from vehicle lightweighting by 2050. The results of this analysis are shown in Figure 4. When the line passes zero on this figure, the cumulative effects of vehicle lightweighting evaluated in 2050 have offset the energy required to manufacture the 50%CFRP composite doors, resulting in no net change in energy consumption relative to the baseline of using a conventional steel door. For the cumulative net energy consumption to be zero in 2050, the manufacturing energy intensity would need to reduce to 686 MJ/kg, about a 13% reduction from the 'Current Typical' value. A similar analysis can be seen in Figure 5 for the cumulative net CO_2 emissions. As can be seen in both Table 3 and Figure 5, the cumulative net CO_2 in 2050 is negative for all case studies. Even if energy intensive 'Current Typical' manufacturing techniques are used, there will be a net reduction in CO_2 emissions by 2050 if steel doors are replaced by 50%CFRP doors. The reason for the differences in the results for cumulative net energy consumption and cumulative net CO_2 emissions is that the energy used to manufacture CFRP composites comes from both electricity and fuel, whereas ICE vehicle lightweighting offsets only gasoline use.

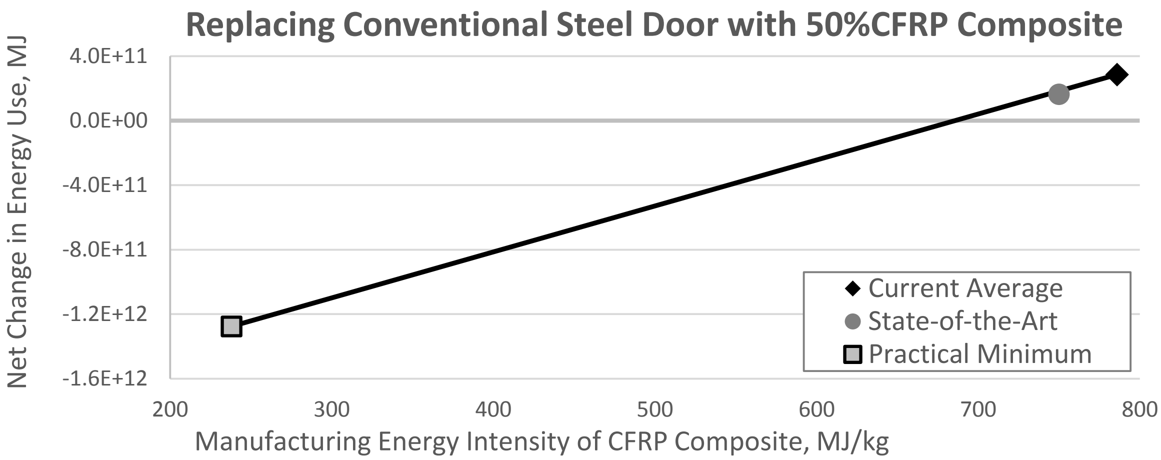

Figure 4: Sensitivity analysis of CFRP composite manufacturing energy intensity on cumulative life cycle energy consumption using LIGHTEnUP tool through 2050.

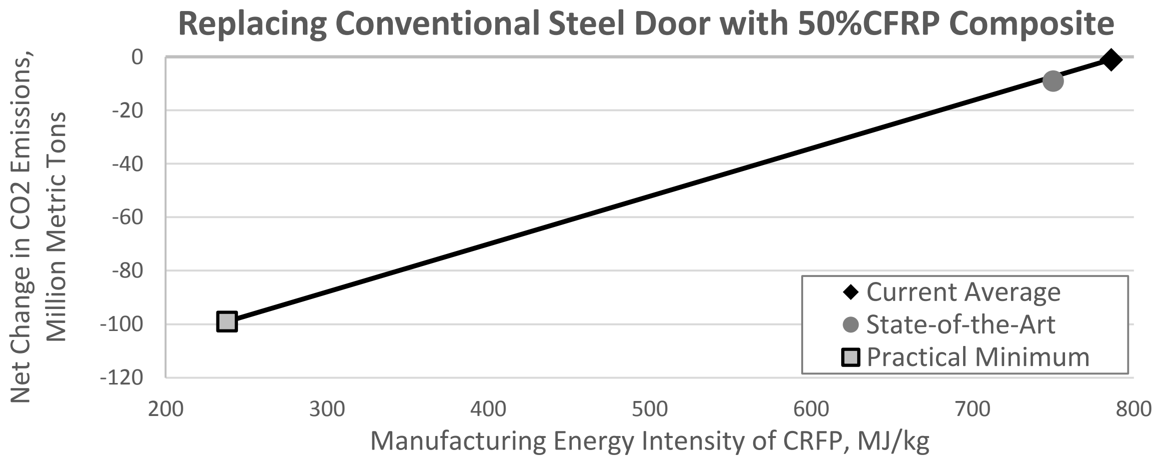

Figure 5: Sensitivity analysis of CFRP composite manufacturing energy intensity on cumulative life cycle CO_2 emissions using LIGHTEnUP tool through 2050.

5 OTHER CONSIDERATIONS

The assumption that CFRP composites manufactured with lower energy intensity will yield fibers and parts with equivalent strength is speculative. The analysis described in this paper is based on a scenario in which a mass of conventional material (steel) is replaced with three variants of 50%CFRP composites equivalent in all properties other than manufacturing energy intensity. From a design perspective, vehicle lightweighting is complex in that material and part functionality dictate property requirements. For example, a low fiber volume fraction, lower strength CFRP composite may suffice for non-structural applications, whereas critical applications may require higher strength parts which could be achieved with a higher fiber volume fraction. There are many practical drivers affecting the design choices, manufacture and use of CF composites in LDVs. These include, but are not limited to, vehicle design, component/subcomponent design, substitution factor, fiber fraction, and energy intensity. As seen in the BMW i-series, CFRP composites can be applied to a system approach for redesign instead of simply a substitution. This allows for additional advantages over vehicle lightweighting, such as improved aerodynamics. A complete sensitivity analysis of the full range of factors in the LCA assessment and a system approach redesign are beyond the scope of this paper.

6 CONCLUSIONS

Based on this case study and assumptions for U.S. fleet wide adoption of carbon fiber composites on new vehicles starting in 2018 with full adoption by 2034, the high manufacturing energy intensity for 50%CFRP composites has the potential for cumulative life cycle energy consumption and CO_2 emissions reductions when conventional steel doors are replaced with 50%CFRP composite doors. To offer cumulative life cycle energy advantages over the forecasted period of 2010-2050, keeping all other design and production variables constant (fiber volume fraction, composite performance, design choices, use of recycled materials, etc.), the manufacturing energy intensity of 50%CFRP composites would need to be reduced by roughly 13% relative to the 'Current Typical' practices. If the 'Practical Minimum' scenario were achieved through deployment of applied research technologies currently under development and all four doors in new ICE LDVs starting in 2018 were made of 50%CFRP, approximately 400 million metric tons of CO_2 cumulatively has the potential to be avoided by 2050. Further research is needed to measure the uncertainty and the criticality of key assumptions in the LIGHTEnUP tool scenarios and to understand the impact of design and production choices for manufacturing, production facility location, use of recycled materials, and other factors.

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