Life Cycle Energy and Greenhouse Gas Emissions of Natural Fiber Composites for Automotive Applications: Impacts of Renewable Material Content and Lightweighting

by

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Preface

This thesis is formatted as a journal article and is being submitted for review and publication. It is supported by earlier work published as part of the SAE 2014 World Congress and Exhibition's technical papers and was presented on April 9th, 2014 (Boland 2014). The thesis model described in the SAE technical paper has been refined and expanded to analyze additional vehicles and natural-fiber reinforced composite materials.

Abstract

This study examines the life cycle energy and emissions associated with substituting natural fibers, cellulose and kenaf, for glass fibers in plastic composites used for automotive components. Specifically, a 30wt% glass-fiber composite component weighing 3 kg was compared to a 30wt% cellulose-fiber composite component (2.65 kg) and 40wt% kenaf-fiber composite component (2.79 kg) for seven vehicles. These vehicles ranged from cars, cross-overs and sport utility vehicles. Across these vehicles, it was found that the cellulose composite material on average reduced life cycle energy by 9.4% and reduced greenhouse gas (GHG) emissions by 18.5% while the kenaf composite component reduced energy of 6.1% and GHG by 10.6% compared to the baseline component. The material production of the cellulose-fiber composite is slightly more energy intensive on a part basis (MJ/part) than the glass-fiber baseline composite material, but the non-renewable energy contribution is lower. In the case of both natural fiber components analyzed, a majority of the life cycle energy savings is a result of the use phase lightweighting. Because the use phase dominates over the component's entire life cycle, the fuel consumption parameter (R*) is the single largest determining factor for lightweighting. The R* value for the vehicles examined ranged from 0.33 [L/(100kg 100km)] to 0.38 [L/(100kg 100km)].

Acknowledgements

This research could not have been possible without the guidance and expertise of Prof. Gregory Keoleian and Robb De Kleine from the Center for Sustainable Systems and Dr. Ellen Lee, Dr. Hyung Chul Kim and Dr. Tim Wallington from Ford Motor Company. I gained invaluable experience working as an intern in the Plastics Research group at Ford Motor Company from May 2013 to August 2013. The research was supported by a Ford Motor Company grant to the Center for Sustainable Systems at the University of Michigan as part of the Ford-University of Michigan Innovation Alliance (grant number 12-PAF07634). The author would also like to thank Weyerhaeuser NR Company for providing life cycle inventory data for the cellulose reinforced polypropylene material, Center for Sustainable Systems colleagues Aditi Moorthy and Joe Colett.

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Introduction

Background

Numerous natural-fiber reinforced composite materials have been examined for automotive applications in the literature including hemp, kenaf, and sisal fibers due to their advantageous properties (Holbery 2006) (Mohanty 2000). Natural fibers are a low cost alternative to nonrenewable sourced materials (Njuguna 2011). As they are highly renewable, natural fibers are able to lower the environmental burden of the fiber portion of the composite material. Natural-fiber composites' densities are low compared to other composite materials with the same mechanical properties. This allows the natural-fiber composite components to lightweight vehicles without compromising functional performance (Njuguna 2011). Because the traditional techniques for composites processing, such as resin transfer molding, compression molding, extrusion and injection molding, need to be modified to account for differences in thermal and structural properties of natural fibers, there is an additional learning curve compared to glass fiber and minerals. Techniques to better understand the fibers' water absorption qualities as well as the possibility of breaking fibers within their matrices are being developed (Ho 2012). Overall, given their lightweighting potential, natural-fiber composites are a promising alternative to current nonrenewable composites for automotive components.

In addition to being a key strategy for meeting increasing CAFE standards through 2025, lightweight materials can also have the potential to reduce the total life cycle burdens of an automobile (National Highway Traffic and Safety Administration 2012). Substituting natural fibers for glass fiber in traditional composites allows for lighter components while simultaneously increasing the proportion of renewably sourced content within a vehicle.

Life Cycle Assessment (LCA) provides a framework to understand the environmental impact that the application of natural-fiber composites might have on the vehicle life cycle by increasing renewable material content within a vehicle combined with lightweighting the vehicle for better fuel consumption. It is an established impact comparison method and is supported by the International Standards Organization to evaluate "the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (International Standards Organization 2013).

Since Corbiere-Nicollier et al.'s (2001) study of China reed fiber as a replacement for glass fiber, the area of natural-fiber reinforced composites, and the life cycle assessments evaluating them, has expanded to many technical applications (Corbiere-Nicollier 2001). The automotive industry has pursued the use of natural composite materials in both external components and internal components (Alves 2010) (Munoz 2006) (Kim 2008). In both instances, the natural-fiber composite has a reduced environmental burden when compared to its baseline counterpart. Alves compared natural jute fiber composites with glass-fiber reinforced unsaturated polyester for an exterior component and found the glass-fiber composite component to have an average of 9% increase in total life cycle emissions damage (defined as the damage of the component divided by the annual environmental damage caused by one exterior component) when compared to both treated and untreated jute composite components (Alves 2010). They cite the higher component weight as well as the increased vehicle fuel consumption as the cause for the increased environmental burden of the baseline material. Kim et al (2008) analyzed a one-kilogram interior automotive part, comparing 50% kenaf-fiber reinforced polyhydroxybutyrate and 37% glass-fiber reinforced polypropylene. They discovered that with this material substitution, the system would save 23 MJ/kg (megajoules per kilogram) of nonrenewable energy as well as 0.3 kilograms of CO_2eq (carbon dioxide equivalent). Although the total life cycle emissions were reduced, the kenaf-fiber composite did see an increase in nitrogen and phosphorus-related emissions due to fertilizer use (Kim 2008). Regardless of the automotive component used as a functional unit, both bio-based material life cycle assessments conclude that natural-fiber reinforced composite materials have reduced energy and greenhouse gas emission impacts compared to their nonrenewable counterpart.

In automotive LCAs, the use phase of an automotive component's life cycle accounts for approximately 65-95% of its total life cycle energy demand (Kim & Wallington 2013b). Therefore, any weight that can be shaved off of the vehicle will have a large impact on the total life cycle energy demand. There are two published strategies for allocating fuel consumption to a component on a vehicle: via a (1) mass fraction or (2) fuel-mass correlation (Kim & Wallington 2013b). The first methodology is common in the literature and assumes that the energy used to move the entire vehicle is proportional to the energy associated with one component based on the mass fraction of the component. For example, in Munoz et al. (2006), the use phase is calculated by allocating additional fuel consumption as a ratio of the minor increase in weight (Munoz 2006). The second methodology accounts for the energy used to operate the vehicle, such as the acceleration and rolling forces as well as the energy loss, due to electronics and engine friction (Kim & Wallington 2013a). (Kim & Wallington 2013a). Instead of a "one size fits all" ratio as represented in the former, the fuel-mass correlation model is able to be adapted to each unique vehicle being modelled (Kim & Wallington 2013a). The study found that the use phase burdens were higher than those found using the fuel-mass correlation methodology (Kim & Wallington 2013b). The current study applies the mass-induced fuel consumption methodology outlined in Kim & Wallington (2013) as it can be tailored to different vehicles based on publically available data and, in addition to accounting for acceleration, rolling and aerodynamic forces, it also accounts for mechanical energy losses, which is not considered in current literature (Kim & Wallington 2013a).

Objective

The objective of this study is to better understand, given a fixed component volume, the environmental burdens associated with implementing bio-based composite materials as compared to traditional composite materials on a vehicle. The method is then extended to different vehicles as a means to evaluate how lightweighting with bio-based materials affects the environmental performance of vehicles with respect to different fuel efficiencies. This work compares two natural-fiber reinforced composite components to their baseline material component to better understand the compromises associated with each material. It applies the fuel-mass correlation methodology for the use phase to multiple vehicles and analyzes the automotive component's full life cycle assessment. Looking across vehicles can provide guidance on which applications of bio-based composites can provide the most effective vehicle lightweighting, in terms of improved the life cycle energy and greenhouse gas performance. The study also analyzes which parameters within material production, manufacturing and mass reduction to fuel correlation are most important in order to achieve the greatest life cycle energy and greenhouse gas savings.

Methods

System Boundary

The system boundary extends from the extraction of feedstock materials to the end of life for the component. The system can be sorted into six main phases: fiber production, resin production, material processing, sourcing transportation, use and end of life. The material production phase includes cultivating the natural fiber feedstocks, as well as the extraction of oil and natural gas feedstocks. Three composite materials are included in the system: 30% glass-fiber reinforced polypropylene (PP), 30% cellulose-fiber reinforced polypropylene and 40% kenaf-fiber reinforced polypropylene. The fiber percentages are calculated by weight. Based on material testing, these materials are considered functionally equivalent for this interior automotive component. The boundary excludes any manufacturing equipment for harvesting the natural fiber, material compounding and injection molding as well as any packaging required throughout the supply chain. This study primarily analyzes the life cycle energy and greenhouse gas emissions (CO2eq) associated with the chosen components. The Global Warming Potential (GWP) factors are from International Panel on Climate Change (IPCC) Fourth Assessment Report: Climate Change 2007 (International Panel on Climate Change 2012)

Functional Unit

The functional unit is an interior automotive component with a fixed volume of 2654 cm^3. The component's mass has been estimated based on the material density. The 30% glass-fiber reinforced polypropylene component has a mass of 3kg based on the density supplied by Asahi; the 40% kenaf-fiber reinforced composite component weighs 2.79kg based on laboratory measurement; and the 30% cellulose-fiber reinforced polypropylene component has a mass of 2.65kg, based on the density provided by Weyerhaeuser (Klein 2013), (Lee 2013), (Sonne Hall 2013).

Material Production

Fiber Production

There are three fibers considered in this study: glass fiber, kenaf fiber, and cellulose fiber. The glass fiber data for the production, processing as well as the associated upstream energy and emission factors are from the Gabi 6 LCA database. The dataset is based on US glass fiber production, where the glass raw materials are melted and extruded through a nozzle drawing process, extended into fibers and coated (PE International 2011).

The kenaf fiber life cycle inventory data are adapted from Ardente (2008) which documents the inputs and outputs of cultivating kenaf in Italy (Ardente 2008). The upstream energy and emissions of processing the kenaf fiber have been calculated using Argonne National Laboratory's GREET 1 rev2 2013 (Argonne National Laboratory 2013). The kenaf data assume a 10% scrap rate.

The cellulose fiber energy and emissions data for growing and processing are based on primary data collection by Weyerhaeuser NR Company (Sonne Hall 2013). These data are augmented with upstream energy and emissions data for electricity, natural gas, diesel oil, and biomass from the GREET1 model (Argonne National Laboratory 2013). Using the US Environmental Protection Agency's (EPA) eGrid 2012, the emissions associated with fiber processing (CO_2, CH_4, and N_2O) are calculated based on the MROW grid (Environmental Protection Agency 2013). The embodied energy in the cellulose fiber was assumed to be the same as wood (18.6 MJ/kg) (National Council for Air and Stream Improvement 2011). The processing of the cellulose fiber uses energy from black liquor, the spent cooking liquor from the kraft pulp processing, for a majority of its manufacturing (American Forest & Paper Association 2012). Black liquor is created after the wood chips are cooked in an aqueous solution of sodium hydroxide and sodium sulfide, causing the cellulose fibers and lignin to separate (National Council for Air and Stream Improvement 2011). These spent organics are used as the combustion energy for the production of the fibers. The data provided assume a 13% scrap rate. The carbon emissions associated with the burning of biomass to produce the cellulose fibers was not included, as recommended in the EPA's TRACI (Tool for the Reduction and Assessment of Environmental Impacts) method (Environmental Protection Agency 2013).

The biogenic carbon storage for both natural fibers is based on the carbon content of cellulose. Cellulose is 41% carbon, which stoichiometrically translates to 1.5 kilograms of CO_2 stored for every 1 kilogram of fiber (Cagnon 2009). This methodology is in line with that of the GHG Protocol Initiative developed by the World Resources Institute and the World Business Council for Sustainable Development (Pawelzik 2013).

Resin Production

The polypropylene inventory results were based on Franklin Associates' study of plastic resins for the Plastics Division of the American Chemistry Council (Franklin Associates 2011). It assumes a 10% scrap rate. The inventory represents the average North American production technology in 2011. The data was compiled from 17 resin/precursor manufacturers, representing over 80 plants in North America.

Part Manufacturing

To manufacture the automotive components, the fibers and resin must be compounded together into pellets. These pellets are the input into the injection molder to create the injection-molded component. The compounding energy and emissions for the glass-fiber and kenaf-fiber composites are based on Thiriez and Gutowski's average-energy-consuming extruder (Thiriez A. & Gutowski T. 2006). This data assume a 10% scrap rate and includes the upstream burdens. The compounding for the cellulose fiber was included in the data provided by Weyerhaeuser

(Sonne Hall 2013). The injection molding process was characterized using data from a life cycle inventory study of plastic fabrication processes (Franklin Associates 2011). It assumes a 4.5% scrap rate.

Sourcing Transportation

The resin and fiber extraction as well as component transportation were modeled based on current supplier locations. The land-based transportation was based on Ecoinvent's fleet average data for a 3.5-16t truck (Swiss Centre for Life Cycle Inventories 2012). The shipping transportation is based on Ecoinvent's transoceanic freight ship (Swiss Centre for Life Cycle Inventories 2012). The glass fiber is assumed to be sourced and manufactured nearFowlerville, MI. The kenaf fiber is harvested near Dhaka, Bangladesh whereas the cellulose fiber is sourced in the Southeastern United States and compounded in manufactured in Wisconsin (Lee 2013).

Use

For this life cycle assessment, the use phase is based on the methodology published by Kim and Wallington (2013) (Kim & Wallington 2013a). It is a physics-based model that calculates the mass-induced fuel consumption of a component using the target coefficients from the annual EPA test data (Kim & Wallington 2013a). The fuel consumption of each vehicle is based on the EPA label, using the combined city and highway fuel consumption (Department of Energy 2014). The combustion energy of fuel as well as the upstream factors are taken from Argonne National Laboratory's GREET1 (Argonne National Laboratory 2013). A vehicle's lifetime is assumed to be 180,000 miles.

To determine the carbon dioxide emitted during the combustion phase, we replicated the GREET1 model's methodology by using the criteria pollutants (grams per mile) reported in the

2013 EPA test data, except for the Ford Flex which uses the 2014 data set, as a means for characterizing the CO_2 emission factor (Environmental Protection Agency 2014). The EPA label's combined fuel consumption as well as the criteria pollutants were input into GREET1 as static values for each vehicle in order to calculate the grams per mile emission factor for CO_2 for each specific vehicle modelled (Argonne National Laboratory 2013). GREET1 uses the carbon content of the fuel and subtracts out the carbon-containing criteria pollutants in order to calculate the 8606 grams of CO_2 per gallon of gasoline used in this study (Argonne National Laboratory 2013). The criteria pollutants were used to quantify the carbon dioxide emissions associated with each vehicle but are not reported here due to the inability to associate the reduction of criteria pollutants with lightweighting. The methane and N_2O greenhouse gas factors from the International Panel on Climate Change (IPCC) Fourth Assessment Report: Climate Change 2007 (International Panel on Climate Change 2012). The majority of criteria pollutant emissions occur before the catalyst has reached its operating temperature, during a cold start. There is no evidence that reducing the weight of a vehicle will impact the tailpipe emissions of criteria pollutants and in the present work, we assume that such emissions are independent of vehicle mass (Kim & Wallington 2013a).

Automobile manufacturers often consider powertrain resizing with lightweighting by reducing engine size or gear ratio to maintain equal performance, which could affect the mass induced fuel consumption. However, such effect is negligible for a small range of lightweighting (Kim & Wallington 2013a). Since the differences in the component mass evaluated in this study are very small (~0.3 kg) compared with the total vehicle mass 1304 kg, an analysis on powertrain resizing has not been attempted.

The first portion of the study examines the use phase of the 2013 Ford Fiesta. The methodology that is applied is then used to investigate a range of vehicles. These factors are included in Table 1 as well as the mass induced fuel consumption R^* value from Kim & Wallington (Department of Energy 2014) (Kim & Wallington 2013a).

Table 1: Fuel economy of vehicles in life cycle assessment

	2013 Lincoln MKX FWD	2013 Ford Mustang Coupe	2013 Ford Fiesta S Sedan	2013 Ford Flex	2013 Ford Focus S	2013 Ford Fusion	2013 Ford Explorer FWD
Combined Mileage (mpg)	22.9	24.5	34.5	21.9	31.5	28.6	20.9
R^* [L/(100km 100kg)]	0.33	0.36	0.33	0.33	0.35	0.36	0.38

End of Life

The end of life environmental burden for these components is based on Sawyer-Beaulieu's life cycle inventory of dismantling and shredding plastic automotive components (Sawyer-Beaulieu 2009). All components in this study are dismantled and shredded. The energy and emissions are mass-allocated.

Results

Bio-based components on the 2013 Ford Fiesta

Life Cycle Energy Savings

The life cycle assessment evaluates the substitution of 30% glass-fiber reinforced composite components with either a 30% cellulose-fiber reinforced composite component or a 40% kenaf-fiber reinforced composite component. Both bio-based materials have a lightweighting benefit during the use phase, as seen in Figure 1.

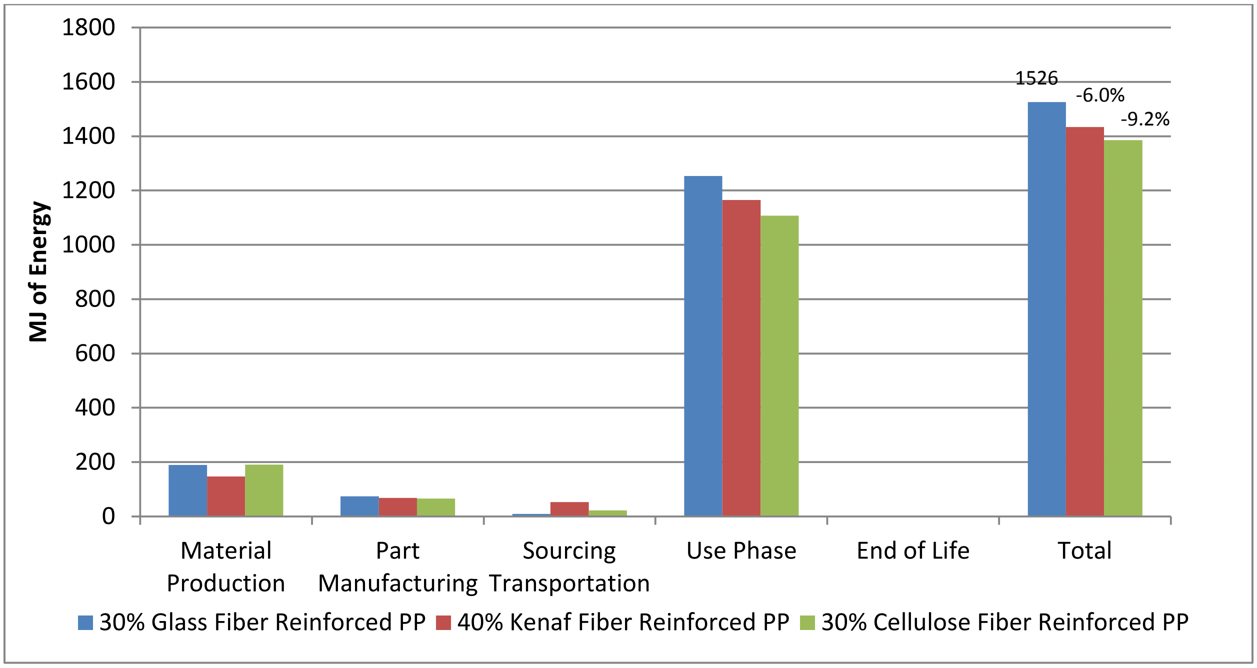

Figure 1: Life cycle energy of a 30% glass-fiber reinforced composite component (3kg) compared to a 30% cellulose-fiber reinforced PP composite (2.65kg) and a 40% kenaf-fiber reinforced PP component (2.79kg) on the 2013 Ford Fiesta

The total life cycle energy of the baseline glass-fiber reinforced component is 1530 MJ whereas the kenaf-fiber component is 1430 MJ (-6.0%) and the cellulose-fiber component is 1380 MJ (-9.2%). The use phase represents 81% of the glass-fiber component's life cycle energy, 85% of the life cycle energy for the kenaf component and 87% for the cellulose component. Of the use phase, 74% of the life cycle energy comes from the combustion, with the rest of the energy burden coming from the associated upstream processes.

The cradle to gate energy demand, including material production and part manufacturing, for the 30% glass composite is 263MJ compared to the kenaf composite's 216 MJ (-18%) cradle to gate energy of 256MJ (-2.6%) for the cellulose composite. When sourcing is included in the cradle to gate analysis, as seen in Figure 2, the kenaf-fiber composite component (267 MJ) is still less than both the cellulose-fiber composite component (278 MJ) and the glass-fiber composite component's life cycle energy (272 MJ).

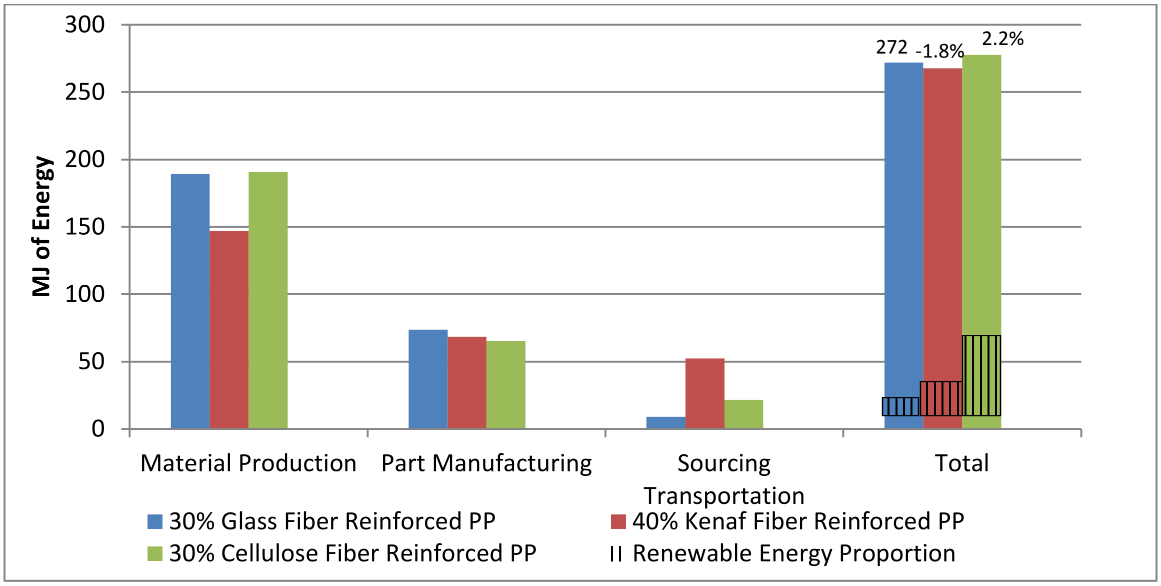

Figure 2: Cradle to gate energy burden associated with a 30% glass-fiber reinforced composite component (3kg) compared to a 30% cellulose-fiber reinforced PP composite (2.65kg) and a 40% kenaf-fiber reinforced PP component (2.79kg) on the 2013 Ford Fiesta. Renewable energy proportion of the cradle to gate energy is identified with striped bars.

The cellulose composite component has higher total life cycle renewable energy content (6.0%) than either kenaf (3.8%) or glass (2.9%) due to the use of renewable processing energy during the fiber production phase. From a cradle to gate perspective (material production to sourcing), the renewable energy proportion for the glass-fiber component is 14 MJ, the kenaf-fiber component is 27 MJ and the cellulose-fiber component is 57 MJ. The renewable energy proportion includes the renewable energy used to process the materials and generate electricity, as well as the renewable embodied energy within the material. Although from a cradle to gate perspective, the cellulose-fiber is the most energy intensive, it has the highest renewable energy proportion and, from a total life cycle perspective, has the highest lightweighting energy savings impact. Uncertainty would indicate that from a cradle to gate life cycle energy perspective, these materials are comparable.

Life Cycle Greenhouse Gas Emissions Savings

As seen with the life cycle energy savings, a majority of the greenhouse gas emissions savings occurs during the use phase, shown in Figure 3.

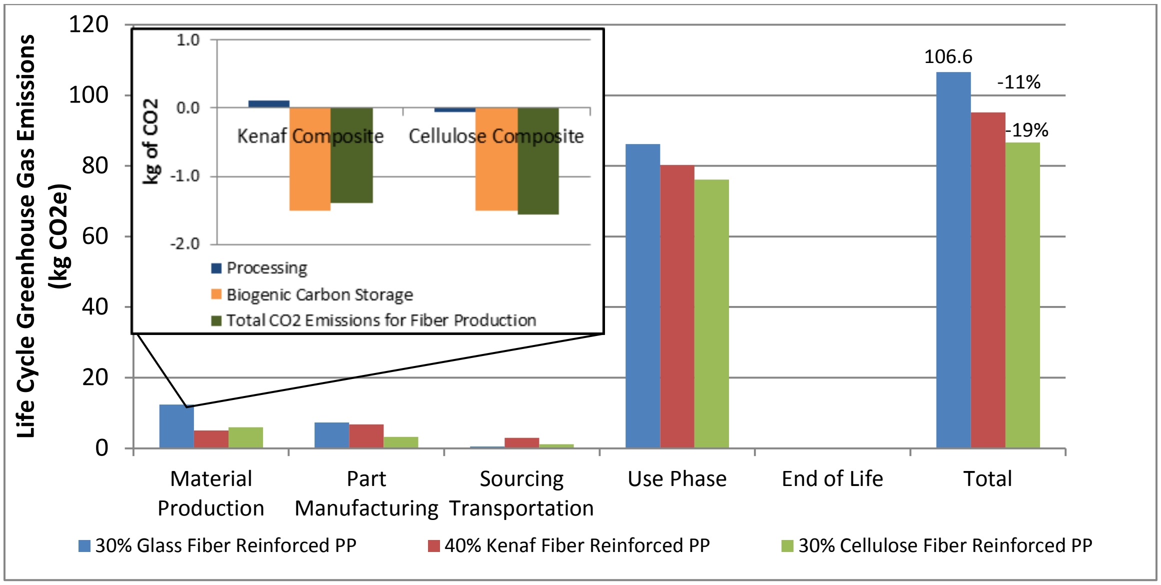

Figure 3: Life cycle Global Warming Potential associated with a 30% glass-fiber reinforced composite component (3kg) compared to a 30% cellulose-fiber reinforced PP composite (2.65kg) and a 40% kenaf-fiber reinforced PP component (2.79kg) on the 2013 Ford Fiesta

The life cycle greenhouse gas emissions for the baseline 30% glass-fiber reinforced composite component is 107 kg CO_2eq. The 40% kenaf-fiber reinforced composite component has a life cycle GHG of 95.2 kg CO_2eq (an 11% reduction from the baseline). The 30% cellulose-fiber reinforced composite component has a life cycle GHG of 86.6 kg CO_2eq (a 19% reduction from the baseline). The cradle to gate (fiber production to sourcing) is 20.2 kg CO_2eq for the glass-fiber component while the kenaf and cellulose components are 14.8 kg CO_2eq and 10.4 kg CO_2eq respectively. Both natural fibers store biogenic carbon during their entire life cycle as is shown in the negative greenhouse gas emissions associated with fiber production. The cellulose fiber is processed using biomass, and thus, the CO_2 associated with burning that biomass is not allocated to the component. The cellulose manufacturing process generates surplus electricity which is sold back to the grid, resulting in a negative GHG for the displacement of emissions from electricity generation. Because the kenaf fiber must travel from Dhaka, Bangladesh, its life cycle GHG emissions for sourcing transportation is 2.93 kg CO_2eq as compared to the glass fiber's 0.493 kg CO_2eq and the cellulose fiber's 1.17 kg CO_2eq.

Scenario Analysis across Multiple Vehicles

Given the lightweighting benefits seen on the 2013 Ford Fiesta, the substitution of a 3kg 30% glass-fiber reinforced polypropylene component with either a 2.65kg 30% cellulose-fiber reinforced composite component or a 2.79kg 40% kenaf-fiber reinforced composite component was modelled across multiple vehicles (See Table 1 for further detail of vehicles modelled).

Life Cycle Energy Savings across Multiple Vehicles

Not surprisingly, in all cases, the bio-based composite components had lower life cycle energy associated with the system than the glass-fiber composite component. The trend across vehicles is shown in Figure 4. Moving from a lower mass induced fuel consumption R^* value [L/(100kg 100km)] to a higher R^* value, the life cycle savings associated with either the substitution of the kenaf composite or cellulose composite increases. The cellulose composite material has consistently higher life cycle energy savings as it is less dense than both the glass and kenaf composites. The cellulose composite substitution saves between 139 MJ to 163 MJ (9.2% to 9.5%) in savings whereas kenaf composite saves between 91.4 MJ to 105 MJ (6.0% and 6.1%). Moving from vehicles with lower R^* values , such as the Lincoln MKX, to vehicles with higher R^* values, such as the Ford Explorer, there is also an increase in percent savings of life cycle energy in relation to the total life cycle energy of that vehicle.

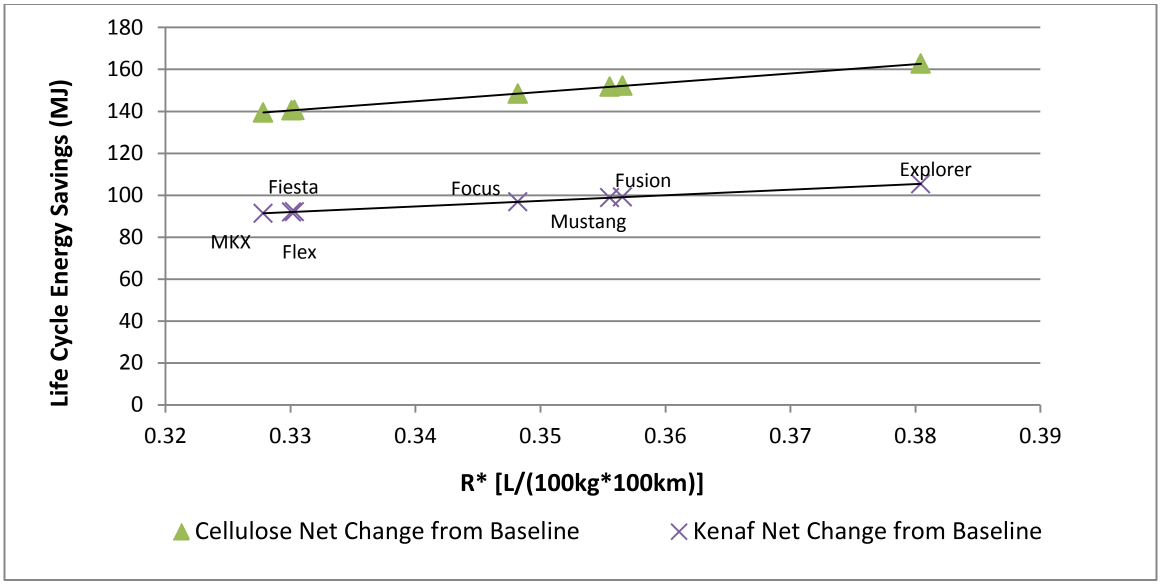

Figure 4: Life cycle energy savings across multiple vehicles when vehicle is lightweighted with kenaf and cellulose composite components

Life Cycle GHG Savings across Multiple Vehicles

When analyzing the GHG savings due to the implementation of bio-based composite components, there is also a net increase in savings, moving from vehicles with lower R^* values to vehicles with higher R^* values. But, shown in Figure 5, there is a decrease in percent savings in life cycle GHG when compared to the baseline material on that vehicle. The percent savings is calculated based on the difference between the life cycle GHG of the glass component and bio-based component divided by the total life cycle GHG of the glass component.

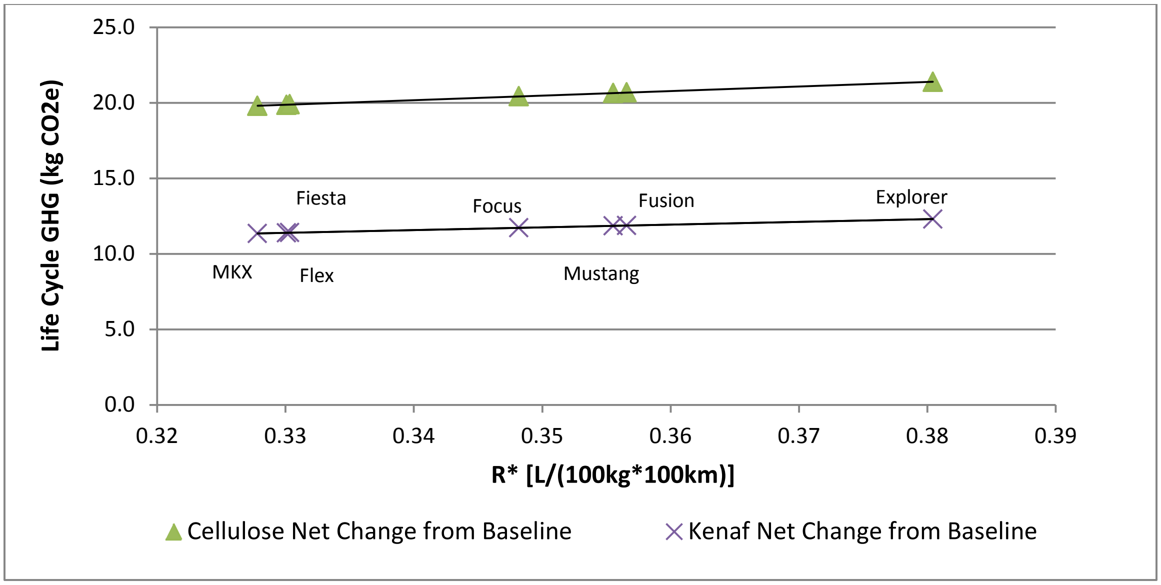

Figure 5: Life cycle GHG savings across multiple vehicles when each vehicle is lightweighted with kenaf and cellulose components

The net life cycle greenhouse gas savings range from 11.3 kg CO_2eq to 12.3 kg CO_2eq (11% to 10%) for the kenaf component and 19.8 kg CO_2eq to 21.4 kg CO_2eq (19% to 18%) for the cellulose composite.

Discussion

Bio-based components on the 2013 Ford Fiesta

Although both natural-fiber composite components are lighter and result in an overall reduction in life cycle energy, there are some tradeoffs. The cellulose fiber production portion of the component is more energy intensive (50.8 MJ) than the glass fiber (30.9 MJ) or kenaf fiber (20.7 MJ). This burden is countered by the fact that there is less mass in the 2.65kg cellulose component and therefore, when analyzed from cradle to gate, the cellulose component is less energy intensive to produce. The kenaf sourcing is more energy intensive than either of the glass or cellulose sourcing. The energy required to transport the materials (52.4 MJ) is in fact over double that to produce the fiber (20.7 MJ).

Both natural fibers store biogenic carbon for their entire life cycle. This quantity is represented in the breakout box within Figure 3. The kenaf fiber has 0.11 kg of CO_2 burden associated with the fiber processing whereas, due to its biomass-based processing energy, the cellulose fiber has -0.059 kg of CO_2. Using the stoichiometric ratios of C to CO_2, it was determined that for every kilogram of fiber, 1.5 kilograms of biogenic carbon dioxide is stored (Cagnon 2009). Because the natural fibers have the same biogenic carbon storage levels, the fiber weight percent in each component becomes the determining factor of which component stores more. The kenaf component, due to its 40wt% of natural fiber, stores 1.55kg of CO_2 whereas the 30wt% cellulose component stores 1.43kg of CO_2.

Due to different upstream parameters for the part manufacturing process, the cellulose fiber component's manufacturing (3.26 kg CO_2eq), which includes compounding and injection molding, is smaller than expected when compared to the kenaf component processing (6.82 kg CO_2eq) and the glass component processing (7.33 kg CO_2eq). The Weyerhaeuser NR Company life cycle inventory data included the compounding of resin and fiber together to make the cellulose composite material and uses the EPA's eGrid to model the emissions based on the Upper Midwest portion of the United States (Environmental Protection Agency 2013). This causes a larger than expected reduction in GHG's due to the regional differences in grid mix compared to the US average grid used in Thirez & Gutowski (Department of Energy 2013). The glass and kenaf composites' compounding stages are based on Thirez & Gutowski (2006) which is based on the US national grid average emissions (Thiriez A. & Gutowski T. 2006). Comparing eGrid from 2004 and 2010, there is a difference of 0.036 kg CO_2/MJ produced. The time difference in the data collection led to the discrepancy (Environmental Protection Agency 2013).

Scenario Analysis across Multiple Vehicles

As the lightweighting is applied to seven vehicles, general trends are able to be identified in terms of life cycle energy savings. Figure 4 shows that the lowest density material that maintains the functional requirements should be used as it saves the most life cycle energy. In this case, the cellulose component, which was 12% lighter than the baseline and had an average life cycle energy savings of 148 MJ as opposed to the kenaf composite, which was 7% lighter than the baseline, had an average life cycle energy savings of 101 MJ. It should also be noted that vehicles with a smaller R^* value had less savings than those vehicles with a higher R^* value. This observation is consistent with the results from Kim & Wallington (2013) which finds that lightweighting vehicles with higher R^* values correlates with higher energy savings during the use phase (Kim & Wallington 2013a). Because the use phase is ~95% of the total life cycle energy savings for these components, the correlation stands.

The cellulose component again has the most life cycle GHG savings when compared to the kenaf component. The cellulose component saves on average 20.4 kg CO_2eq whereas the kenaf component saves on average 11.7 kg CO_2eq. In all cases, the bio-based material substitution led to a positive life cycle GHG savings. Moving from lower R^* to more higher R^* vehicles, there is a slight decrease in percent GHG savings, using the glass component's life cycle GHG as a denominator. This trend is broken down further in Figure 6.

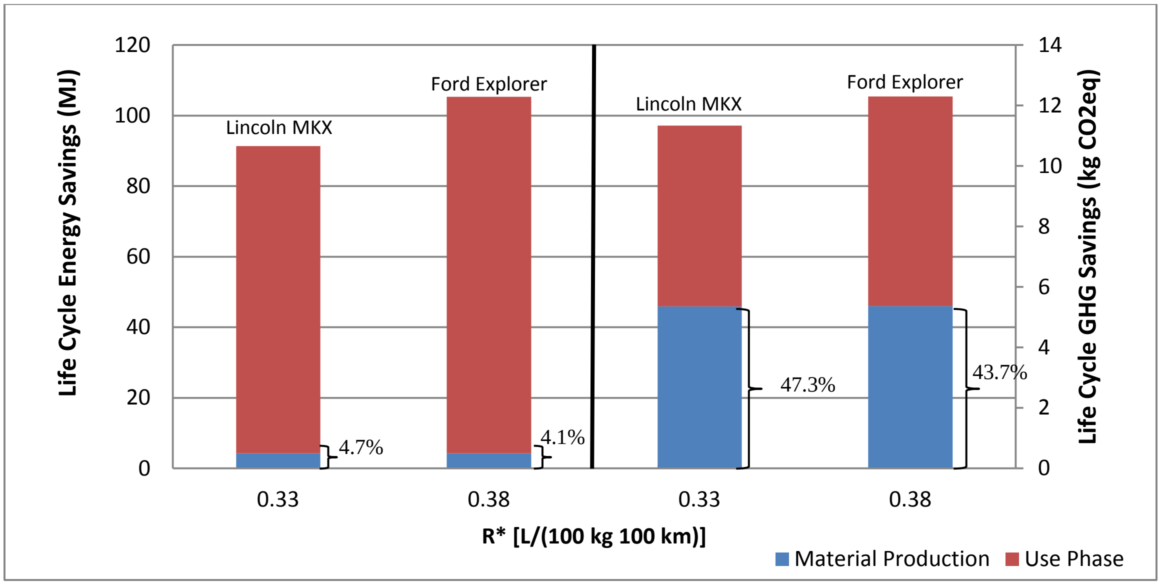

Figure 6: Life cycle energy and GHG savings when substituting glass-fiber component for a kenaf-fiber component on the 2013 Lincoln MKX as well as the 2013 Ford Explorer. The data were broken into material production and use phases across multiple vehicles.

The correlation that as R^* increases, the percent of life cycle GHG savings decreases is due to the fact that the use phase savings represents only 53% of the Lincoln MKX GHG savings as opposed to 95% of the life cycle energy savings. Any additional lightweighting GHG gains that occur as R^* increases are diminished due to the smaller portion of the total savings it represents.

Sensitivity Analysis

Impact of Material Compounding's Electricity Source

One of the sources of variation identified in this study was the electricity used to compound the fiber and resin materials together. Weyerhaeuser NR Company provided a life cycle inventory of the fiber production as well as the compounding energy. For this analysis, the eGrid upstream emissions were used for the Upper Midwest region of the United States. This factor led to the reduced GHG burden for their part manufacturing as seen in Figure 3. Since 2004, when the Thiriez and Gutowski's data was gathered, the percentage of the generation resource mix that is fossil fuels has decreased from 77.4% (2004) to 68.8% (2010) (Environmental Protection Agency 2013).

To understand the impact of this electricity fuel mix for compounding on the results, the Thiriez and Gutowski energy and emissions factors used for the compounding of the glass and kenaf composites was applied to the cellulose processing as well (Thiriez A. & Gutowski T. 2006). This change resulted in a an increase in life cycle GHG of 3.08 kg of CO_2eq. The total life cycle GHG increases by 3.6% for the cellulose component and, from a cradle to gate (fiber production to sourcing) perspective, the change results in a 11% increase in life cycle GHG. Overall, the emissions associated with the compounding electricity have a minimal effect on the total life cycle GHG.

Impact of Biogenic Carbon Storage

To better understand the impact of biogenic carbon storage within the natural fibers, a sensitivity analysis was conducted to understand how the life cycle GHG of each of the natural fibers would change if it was excluded. The life cycle GHG of the cellulose component would increase 1.37 kg of CO_2eq to a total of 88.0 kg of CO_2eq (a 1.6% difference). From a cradle to grave (fiber production to sourcing) perspective, the change has a larger 13% change. The life cycle GHG of the kenaf component would increase 1.79 kg of CO_2eq to a total life cycle GHG of 95.2 kg of CO_2eq (a 1.9% difference) . In terms of cradle to grave impact, the change would cause a 13% increase. Although the biogenic carbon storage has been removed for both natural fibers, the cellulose component still has a negative CO_2 impact during fiber production of -0.041 kg CO_2. During fiber production, Weyerhaeuser NR Company produces more electricity that it requires, allowing it to sell back electricity to the grid (Sonne Hall 2013). This exchange results in a reduction of 83 g of CO_2 for every kilogram of fiber produced.

Conclusions

This study analyzes the substitution of a 30% glass-fiber reinforced polypropylene composite automotive component (3 kg) with either 30% cellulose-fiber reinforced polypropylene (2.65 kg) or 40% kenaf-fiber reinforced polypropylene component (2.79 kg). The substitution was analyzed across seven vehicles, ranging from compact cars to sports utility vehicles. The study fills a gap in the natural-fiber composite LCA literature by investigating cellulose fiber composite materials produced at full scale operations. The LCA energy and emissions savings are in line with other natural-fiber reinforced composite studies.

By understanding how material choices affect the automotive life cycle across multiple vehicles, manufacturers are able to make more informed decisions about which vehicles to target for natural-fiber composite material substitutions in order to achieve the largest life cycle benefits. Because the use phase is dominant, the mass induced fuel consumption value (R^*) from Kim & Wallington (2013) strongly dictates the substitution's environmental impact. The study results indicate that vehicles with higher R^* values should be targeted for lightweight components in order to achieve higher life cycle energy and greenhouse gas emission savings. For cellulose-fiber composite components implemented on a range of vehicles, this substitution results in a life cycle energy savings of 9.2% to 9.5% and a GHG savings of 18% to 19% when compared to the baseline component. Although this study assumes a small interior automotive component, the substitution trends would hold true for larger components, achieving a larger magnitude of savings.

From cradle to factory gate (material production to sourcing), there are compromises from utilizing natural-fiber composite components. The cellulose-fiber component is slightly more energy intensive on a part basis (MJ/part) than the glass fiber component, but uses less nonrenewable energy than either of the composite material options. Transporting the kenaf fiber has a higher burden than either of the other materials since the fibers are shipped a greater distance, indicating that materials should be sourced as close as possible to the manufacturing locations whenever possible. The resin and manufacturing energy savings achieved here would vary if the manufacturer redesigned components and their molds specifically for natural fiber composites. As natural-fiber composites are implemented in higher volume, the life cycle gains from component redesign as well as increased local natural-fiber supply chains should be quantified.

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