Life Cycle Impacts of Natural Fiber Composites for Automotive Applications

Effects of Renewable Energy Content and Lightweighting

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Summary

This study examines the life cycle energy demand and greenhouse gas (GHG) emissions associated with substituting natural cellulose and kenaf in place of glass fibers in automotive components. Specifically, a 30 wt% glass-fiber composite component weighing 3 kilograms (kg) was compared to a 30 wt% cellulose fiber composite component (2.65 kg) and 40 wt% kenaf fiber composite component (2.79 kg) for six cars, crossovers, and sport utility vehicles. The use-phase fuel consumption of the baseline and substitute components, with and without powertrain resizing, were determined using a mass-induced fuel consumption model based on U.S. Environmental Protection Agency test records. For all vehicles, compared to the baseline glass fiber component, using the cellulose composite material reduced life cycle energy demand by 9.2% with powertrain resizing (7.2% without) and reduced life cycle GHG emissions by 18.6% with powertrain resizing (16.3% without), whereas the kenaf composite component reduced energy demand by 6.0% with powertrain resizing (4.8% without) and GHG emissions by 10.7% with powertrain resizing (9.2% without). For both natural fiber components, the majority of the life cycle energy savings is realized in the use-phase fuel consumption as a result of the reduced weight of the component.

Introduction

Background

Numerous natural fiber reinforced plastic materials have been examined for automotive applications in the literature, including composites containing hemp, kenaf, and sisal fibers (Holbery and Houston 2006; Mohanty et al. 2000). Natural fibers can be a low-cost alternative to nonrenewable sourced materials in these composites (Njuguna et al. 2011). Because they are renewable, natural fibers have the potential 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. Using natural fiber composite components can lead to reduced vehicle weight without compromising functional performance (Njuguna et al. 2011). Although these materials have advantages compared to traditional materials, there are also disadvantages to be considered. Traditional techniques for composite processing (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 for processing parts containing natural fibers. Techniques are being developed to better understand the fibers' water absorption qualities and the possibility of breaking fibers within their matrices (Ho et al. 2012). The advantages and disadvantages must be weighed appropriately for each application considered.

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Substituting glass fibers with natural fibers in composites allows for lighter components while simultaneously increasing the proportion of renewably sourced content within a vehicle. It has been used as a strategy for meeting the Corporate Average Fuel Economy (CAFE) Standards through 2025, and its implementation has the potential to reduce the total life cycle burdens of an automobile (NHTSA 2012).

The automotive industry has pursued the use of natural composite materials in both structural components and nonstructural components (Alves et al. 2010; Muñoz et al. 2006; Kim et al. 2008; Joshi et al. 2004; Zah et al. 2007; Corbiere-Nicollier et al. 2001). In both applications, the use of natural fiber composites can lead to lower environmental burdens. Alves and colleagues (2010) compared natural jute fiber composites with glass-fiber reinforced unsaturated polyester for an exterior component and found a lower environmental burden for the jute fiber component. Kim and colleagues (2008) analyzed a 1-kilogram (kg) interior automotive part, comparing 50% kenaf fiber reinforced polyhydroxybutyrate and 37% glass fiber reinforced polypropylene (PP). They discovered that with this material substitution, the system would save 23 MJ/kg (megajoules per kilogram) of nonrenewable energy demand and 0.3 kg CO_2-eq (carbon dioxide equivalent). Although the total life cycle emissions impact was reduced, the kenaf fiber composite had higher nitrogen- and phosphorus-related emissions reflecting fertilizer use (Kim et al. 2008). These bio-based material life cycle assessments (LCAs) conclude that natural fiber reinforced composite materials have the potential to reduce energy demand and greenhouse gas (GHG) emission impacts compared to their nonrenewable counterpart.

In automotive LCAs, the use phase of an automotive component's life cycle accounts for approximately 60% to 90% of its total life cycle energy demand (Kim and Wallington, 2013a). Reducing the component weight will decrease the use-phase energy demand. To determine the use-phase fuel consumption of a component, its fuel consumption is assigned in proportion to mass. As discussed by Kim and Wallington (2013b), published LCAs of vehicle lightweighting have used fuel reduction values (FRVs) in the range 0.2 to 0.5 liters (L)/(100 kilometers [km] 100 kg) to represent the decrease in fuel consumption associated with mass reduction (Kim and Wallington 2013b). FRVs in the range 0.3 to 0.5 L/(100 km 100 kg) are typically used for scenarios where the powertrain is resized to maintain vehicle performance with lightweighting. Smaller FRVs are used for scenarios in which the powertrain is not resized (and hence vehicle performance increases with mass reduction). The FRV-based approach has two drawbacks. First, it is unable to clearly define the fuel consumption of the baseline component given that two distinctive FRVs can be used (depending on powertrain resizing scenario) leading to two different fuel consumption results for the same baseline part (Kim and Wallington 2013b). Second, it is difficult to apply to different vehicle models because FRVs are not readily available for different vehicle models. A novel mass-induced fuel (MIF) consumption model has been developed recently to address these drawbacks (Kim and Wallington 2013b). The MIF approach allocates fuel consumption to mass using a physics-based model and U.S. Environmental Protection Agency (US EPA) fuel economy test records (Kim and Wallington 2013b). The MIF method clearly defines the fuel consumption of the baseline part and allows for the evaluation of the benefits of lightweighting for all vehicles for which US EPA test records are available. The current study used this MIF consumption methodology.

Objective

The objective of this study is to better understand the environmental burdens associated with implementing bio-based composite materials, as compared to traditional composite materials, in a vehicle. The method is then extended to different vehicles as a means to evaluate how the use of lightweight 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 components to better understand the compromises associated with each material. It applies the fuel-mass correlation methodology for the use phase to multiple vehicles and provides a full LCA for the components. Looking across vehicles can provide guidance on which applications of bio-based composites can provide the most effective use of lightweight materials, in terms of improved life cycle energy demand and GHG emission performance. The study provides insight into the relative importance of material production, manufacturing, and mass-induced vehicle fuel consumption for life cycle energy demand and GHG emissions.

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 and extracting oil and natural gas (NG) feedstocks. Three discrete product systems are examined: 30% glass fiber reinforced PP; 30% cellulose fiber reinforced PP; and 40% kenaf fiber reinforced PP. The fiber percentages for each composite material are calculated by weight. The boundary excludes production of manufacturing equipment required for harvesting the natural fiber, material compounding and injection molding, and packaging needed throughout the supply chain. This study primarily analyzes the life cycle energy demand and GHG emissions (CO_2-eq) associated with the chosen components. The global warming potential (GWP) factors needed to convert methane (CH_4) and nitrous oxide (N_2O) into CO_2-eq emissions were taken from the International Panel on Climate Change (IPCC) Fourth Assessment Report: Climate Change 2007 (IPCC 2012).

Functional Unit

The automotive component studied is a semistructural console substrate with a fixed volume. The substrate's mass for each material was calculated based on the material density. The 30% glass fiber reinforced PP component has a mass of 3 kg based on the density supplied by Asahi; the 40% kenaf fiber reinforced PP component mass is 2.79 kg based on laboratory measurement; and the 30% cellulose fiber reinforced PP component has a mass of 2.65 kg, based on the density provided by Weyerhaeuser (Klein and Wiese 2013; Lee 2013; Sonne Hall 2013). Composites were designed to meet the required mechanical properties and performance such that no change was required in part geometry, and are considered functionally equivalent for this interior automotive component over a vehicle service life of 180,000 miles.

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, and the associated upstream energy demand and emission factors are from the Gabi 6 LCA database. The data set is based on U.S. 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 (LCI) data are adapted from a study that documents the inputs and outputs of cultivating kenaf in Italy (Ardente et al. 2008). The upstream energy demand and emissions of processing the kenaf fiber were calculated using Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) 1 rev2 2013 (Argonne National Laboratory 2013). The kenaf data assume a 10% scrap rate.

The cellulose fiber energy demand and emissions data for growing and processing were supplied by Weyerhaeuser NR Company (Sonne Hall 2013). These data are augmented with upstream energy and emissions data for electricity, NG, diesel oil, and biomass from the GREET 1 model (Argonne National Laboratory 2013). Using the U.S. EPA's Emissions & Generation Resource Integrated Database (eGRID) 2012, the emissions associated with fiber processing (CO_2, CH_4, and N_2O) are calculated based on the Midwest Reliability Organization West grid (US EPA 2013a). The embodied energy demand in the cellulose fiber was assumed to be the same as wood (18.6 MJ/kg) (NCASI 2011). The processing of the cellulose fiber uses energy from black liquor, the spent cooking liquor from the Kraft pulp process, for a majority of its manufacturing (AF&PA 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 (NCASI 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 US EPA's Tool for the Reduction and Assessment of Environmental Impacts method (US EPA 2013b).

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

Resin Production

The PP inventory results were based on Franklin Associates' study of plastic resins for the Plastics Division of the American Chemistry Council (Franklin Associates 2011a). The inventory represents the average North American production technology in 2011. The data were 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 for the injection molder to create the injection-molded component. The compounding energy demand and emissions for the glass- and kenaf-fiber composites are based on Thiriez and Gutowski's average-energy-consuming extruder (Thiriez and Gutowski 2006). These data assume a 10% scrap rate and include the upstream burdens. The compounding for the cellulose fiber was included in the data provided by Weyerhaeuser NR Company (Sonne Hall 2013). The injection-molding process was characterized using data from an LCI study of plastic fabrication processes (Franklin Associates 2011b). It assumes a 4.5% scrap rate.

Sourcing Transportation

The resin and fiber extraction and 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- to 16-tonne (t) truck (Swiss Center for Life Cycle Inventories 2012). The shipping transportation is based on ecoinvent's transoceanic freight ship (Swiss Center for Life Cycle Inventories 2012). The glass fiber is assumed to be sourced and manufactured near Fowlerville, Michigan. The kenaf fiber is harvested near Dhaka, Bangladesh, whereas the cellulose fiber is sourced in the Southeastern United States and compounded and manufactured in Wisconsin (Lee 2013).

Use

Fuel consumption during the use phase was calculated based on a methodology that calculates the MIF consumption of a component using coast-down coefficients from US EPA test data (Kim and Wallington 2013b). The fuel consumption of each vehicle is calculated based on the US EPA label values

(US EPA 2013c). The US EPA labels, created from official test cycles, are not necessarily identical to on-road performance, which depends on driver behavior, driving conditions, and vehicle maintenance (Alson 2014). The combustion energy of fuel and the upstream factors are taken from Argonne National Laboratory's GREET 1 model, from which we derive a well-to-wheel energy use for gasoline of 43.6 MJ/L (Argonne National Laboratory 2013). The vehicle lifetime is assumed to be 180,000 miles (290,000 km) based on that used in the US EPA's rule-making analysis for the 2017–2025 Greenhouse Gas Emissions Standards and CAFE Standards (US EPA and NHTSA 2012).

We used a well-to-wheel emission factor of 8,606 grams (g) of CO_2 per U.S. gallon of gasoline (2,277 g/L) from GREET 1 (Argonne National Laboratory 2013) in the analysis. The mass reduction considered in this work would not impact the vehicle's emission control system and hence criteria pollutant emissions.

The first portion of the study focused on the 2013 Ford Fiesta. The same methodology was then used for the other vehicle models. Table 1 lists MIF consumption [L/(100 km 100 kg)] factors from Kim and Wallington for the vehicle models considered in the present work (US DOE 2014; Kim and Wallington 2013b). The calculations consisted of three steps. First, we calculated the use-phase fuel consumption of the baseline 30 wt% glass-fiber composite component based on the MIF values (fuel use = MIF × mass × driving distance). For the Fiesta, this is 0.33 L/(100 km 100 kg) × 3.0 kg × 180,000 × 1.61 km = 28.7 L = 1,250 MJ. Second, we evaluated the use-phase fuel consumption (L) of the weight-reduced components, that is, 30wt% cellulose fiber and 40wt% kenaf composite components without powertrain resizing. We used fuel reduction values (FRVs) without powertrain resizing (FRV ≡ F_w normalized for mass; see figure 1 in Kim and Wallington (2013b) for the different models derived from the US EPA test data and adjusted fuel economy in the US EPA labels (e.g., 0.26 L/[100 km 100 kg] for the Fiesta) and multiplied the mass reduction by the FRV. For the kenaf part in the Fiesta, this is 0.26L/(100 km 100 kg) × (3.00 – 2.79) kg, which over the 180,000-mile vehicle lifetime, is 1.58 L = 69 MJ. Third, we determined the fuel consumption of the lightweighted components with powertrain resizing for a same vehicle performance. The derivation of FRVs with powertrain resizing, FRV^+, based on equivalent acceleration, is documented elsewhere (Kim and Wallington 2014). Fuel consumption based on MIF instead of FRV^+ is a good approximation to simplify the calculation for a small range of lightweighting, such as the current scenarios (i.e., <2% difference). Thus, for the kenaf component, the fuel consumption is 26.7 L (= 28.7 – 0.33 L/(100 km 100 kg) × (3.00 – 2.79) kg × 180,000 × 1.61 km). The MIF consumption approach to estimate fuel savings from lightweighting used in our study (Kim and Wallington 2013b) differs from the FRV approach used by Koffler and Rohde-Brandenburger (2010). In the MIF approach, the fuel consumption measured in the dynamometer test (F) is allocated into the mass-induced component from rolling, acceleration, and rotational resistance (F_M) and the mass-independent component from aerodynamic resistance and accessory power demand (F_A). The power demand profile identified during the coast-down test is translated into the F_M and F_A components by accounting for the thermodynamic, transmission, and mechanical efficiency. Then, the mass-dependent fuel consumption (F_M) is normalized by the vehicle mass (M) to determine the MIF (= F_M/M). The MIF is approximately the mass dependency of fuel consumption with powertrain resizing to hold vehicle performance constant (Kim and Wallington 2013b). MIF does not refer to the mass-dependency of fuel consumption when the powertrain is not resized. Kim and Wallington (2013b) report MIFs of 0.2 to 0.5 L/(100 km 100 kg) based on fuel economy tests by the US EPA for 2013 model year vehicles. The range reflects the range of engine sizes/powers, mechanical efficiencies, and rolling resistances for different vehicle models. Vehicles with larger engines typically have higher engine friction losses, lower mechanical efficiencies, and larger MIFs than vehicles with smaller engines. The fuel reduction value in the study by Koffler and Rohde-Brandenburger (2010) is the mass dependency of fuel consumption with values for the U.S. test cycle of 0.16 and 0.38 L/(100 km 100 kg) without and with powertrain resizing, respectively (Koffler 2014).

The approach of Koffler and Rohde-Brandenburger (2010) is based on the fact that the differential efficiency of engines is similar across vehicle models. This observation enabled Koffler and Rohde-Brandenburger (2010) to propose fuel reduction values for generic gasoline vehicles. The approach of Koffler and Rohde-Brandenburger (2010) has the advantage of simplicity, but does not allow for differentiation between different vehicle models. The vehicle model-specific MIF approach used in the present work captures the effect of such factors and enables us to evaluate the benefits of lightweighting for different vehicle models.

End of Life

The end-of-life environmental burden for these components is based on Sawyer-Beaulieu's LCI of dismantling and shredding plastic automotive components (Sawyer-Beaulieu 2009). All components in our study are assumed to be dismantled and shredded. The energy demand and emissions are allocated on the basis of mass.

Results

Bio-based Components on the 2013 Ford Fiesta

Life Cycle Energy Savings

The LCA 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. The impact of powertrain resizing is also shown.

The total life cycle energy demand of the baseline glass fiber reinforced component is 1,530 MJ, whereas, without powertrain resizing, the kenaf fiber component has an energy demand of

Table 1 Fuel economy of vehicles in life cycle assessment

Fuel economy	*2013 Lincoln MKX FWD*	*2013 Ford Fiesta*	*2014 Ford Flex*	*2013 Ford Focus*	*2013 Ford Fusion*	*2013 Ford Explorer FWD*
Combined mileage (mpg)	21.5	32.8	20.3	30.7	26.2	19.7
MIF [L/(100 km 100 kg)]	0.33	0.33	0.33	0.34	0.37	0.38

Note: mpg = miles per gallon; MIF = mass-induced fuel consumption; L = liters; km = kilometers; kg = kilograms.

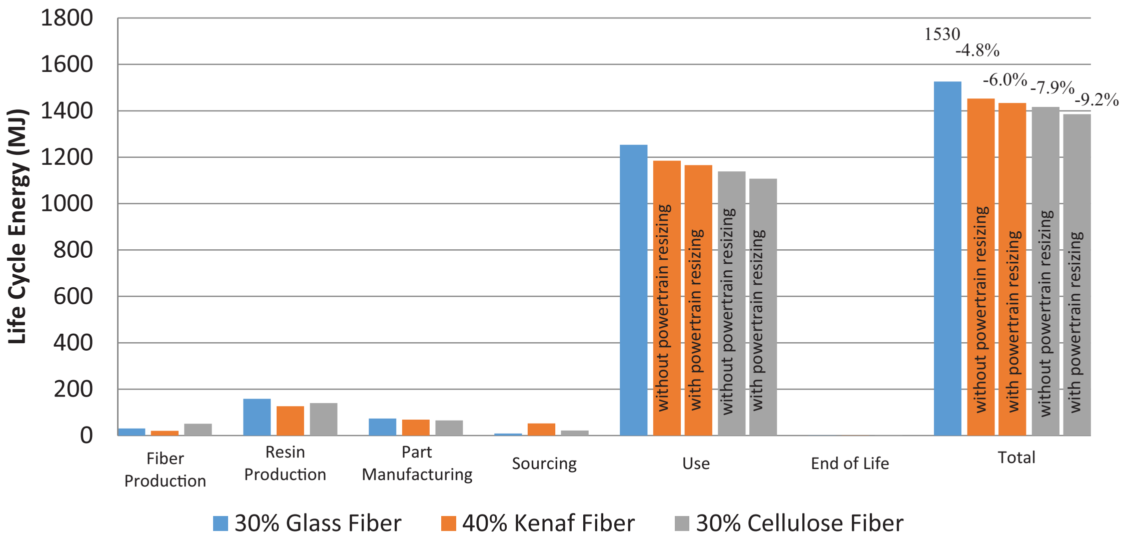

Figure 1 Life cycle energy demand of a 30% glass fiber reinforced composite component (3 kg) compared to a 30% cellulose fiber reinforced PP composite (2.65 kg) and a 40% kenaf fiber reinforced PP component (2.79 kg) on the 2013 Ford Fiesta. Impact of powertrain resizing is also shown. kg = kilograms; PP = *polypropylene*; MJ = megajoules.

1,450 MJ (4.8%) and the cellulose fiber component has an energy demand of 1,420 MJ (–7.2%). With powertrain resizing, the cumulative energy demand is lower for both components, with the kenaf component using 1,440 MJ (–6.0%) and the cellulose component using 1,390 MJ (–9.2%). As seen from figure 2, in all cases, the use phase dominates (approximately 80%) the life cycle energy demand.

The cradle-to-gate energy demand, including material production and part manufacturing, for the 30% glass composite is 263 MJ, compared to the kenaf composite's 216 MJ (–1.8%) cradle-to-gate energy demand of 256 MJ (–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 demand (272 MJ).

The cellulose composite component has a higher total life cycle renewable energy content (6.0%) than either kenaf (3.8%) or glass (2.9%) owing 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. As seen from figure 2, the cradle-to-gate energy demand is very similar (within 2%) for the three components. Within the uncertainties in the analysis, there is no significant difference in the cradle-to-gate energy demand for the components using the three different materials.

Life Cycle Greenhouse Gas Emissions

As seen from figure 3, the majority of the GHG emissions savings occurs during the use phase. The life cycle GHG emissions impact for the baseline 30% glass-fiber reinforced composite component is 107 kg CO_2-eq. The 40% kenaf fiber reinforced composite component (without resizing) has a life cycle GHG of 96.8 kg CO_2-eq (a 9.2% reduction from the baseline); with resizing, it is 95.2 kg CO_2-eq (–10.7%). The 30% cellulose fiber reinforced composite component without resizing has a life cycle GHG of 89.2 kg CO_2-eq (a 16.3% reduction from the baseline); with resizing, it is 86.7 kg CO_2-eq (–18.7%). The cradle-to-gate (fiber production to sourcing burdens) GHG emissions are 20.2, 14.8, and 10.4 kg CO_2-eq for the glass-fiber, kenaf, and cellulose components, respectively.

The natural fibers store carbon during their entire life cycle, as shown in the negative GHG emissions associated with fiber production. The cellulose fiber is processed using biomass, and thus the CO_2 associated with burning that biomass is not

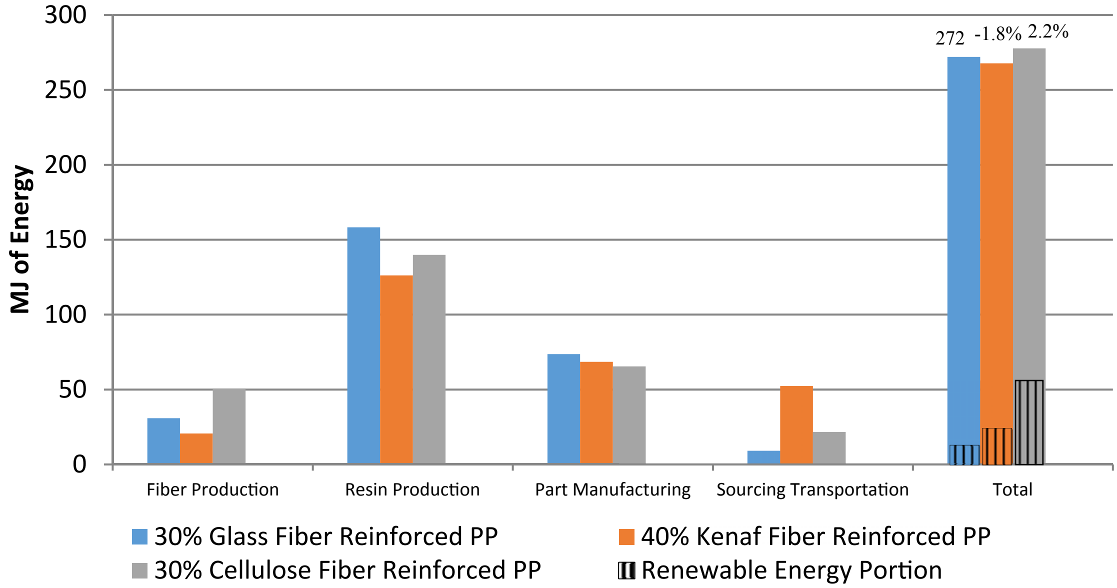

Figure 2 Cradle-to-gate energy demand associated with a 30% glass fiber reinforced composite component (3 kg) compared to a 30% cellulose fiber reinforced PP composite (2.65 kg) and a 40% kenaf fiber reinforced PP component (2.79 kg) on the 2013 Ford Fiesta. Renewable energy proportion of the cradle-to-gate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

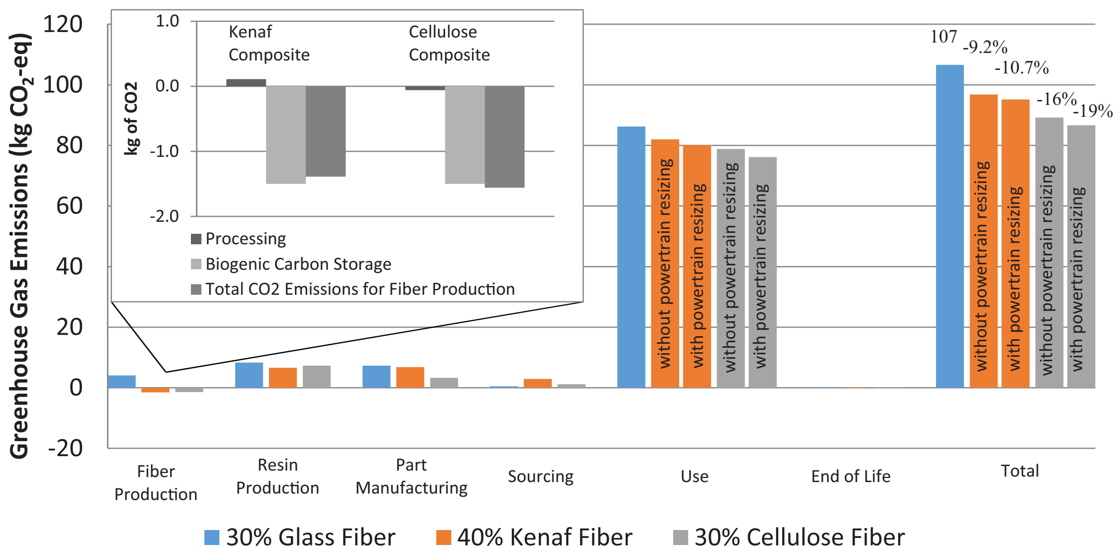

Figure 3 Life cycle greenhouse gas emissions associated with a 30% glass fiber reinforced composite component (3 kg) compared to a 30% cellulose fiber reinforced PP composite (2.65 kg) and a 40% kenaf fiber reinforced PP component (2.79 kg) on the 2013 Ford Fiesta. kg = kilograms; PP = polypropylene; kg CO_2-eq = kilograms carbon dioxide equivalent.

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_2-eq, as compared to the glass fiber's 0.493 kg CO_2-eq and the cellulose fiber's 1.17 kg CO_2-eq.

Scenario Analysis across Multiple Vehicles

Given the lightweight benefits seen on the 2013 Ford Fiesta, the substitution of a 3-kg 30% glass fiber reinforced PP component with either a 2.65-kg 30% cellulose fiber reinforced composite component or a 2.79-kg 40% kenaf fiber reinforced composite component was modeled across multiple vehicles (see table 1 for vehicles modeled).

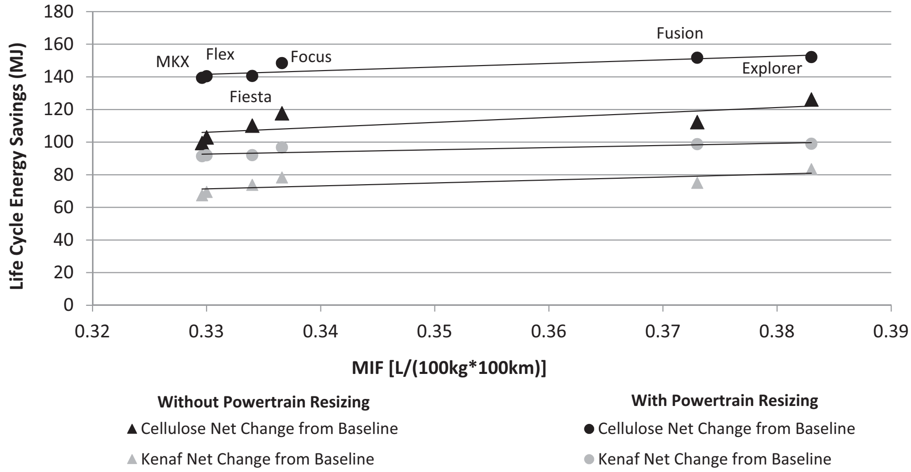

Figure 4 Life cycle energy savings across multiple vehicles when vehicle contains kenaf and cellulose composite components, with and without resizing the powertrain. MJ = megajoules; MIF = mass-induced fuel consumption; L = liters; km = kilometers; kg = kilograms.

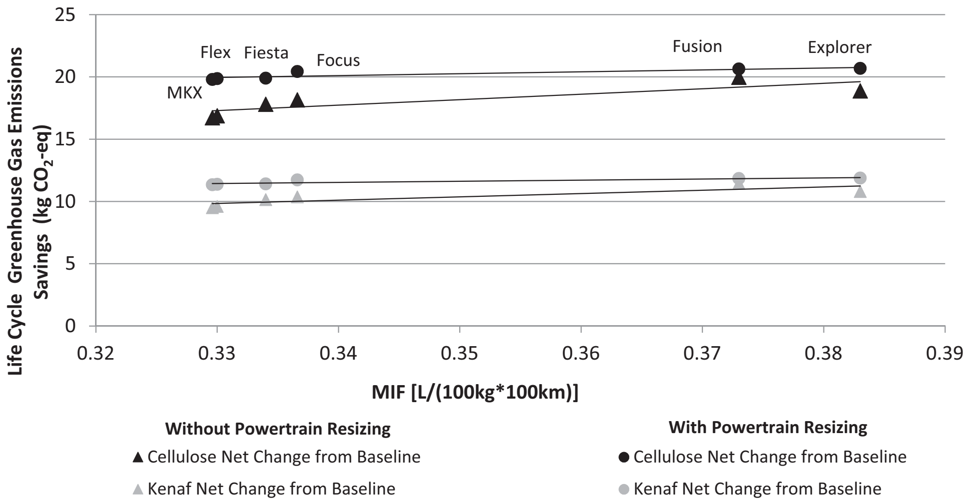

Figure 5 Life cycle greenhouse gas savings across multiple vehicles when each vehicle contains kenaf and cellulose components (with and without powertrain resizing). kg CO_2-eq = kilograms carbon dioxide equivalent; MIF = mass-induced fuel consumption; L = liters; km = kilometers; kg = kilograms.

Life Cycle Energy Savings across Multiple Vehicles

Not surprisingly, in all cases, the bio-based composite components had lower life cycle energy demand than the glass-fiber composite component. The trend across vehicles is shown in figure 4. Resizing the powertrain provides additional life cycle energy savings. Moving from a lower MIF consumption value [L/(100 kg 100 km)] to a higher MIF value increases the life cycle savings associated with the kenaf and cellulose composite. The cellulose composite material has consistently higher life cycle energy savings given that it is less dense than both the glass and kenaf composites. The cellulose composite substitution without resizing the powertrain saves 99.5 to 126 MJ (6.5% to 7.4%), whereas the kenaf composite saves 67.4 to 83.4 MJ (4.4% to 4.9%). The cellulose composite substitution with powertrain resizing saves 139 to 163 MJ (9.2% to 9.5%), whereas the kenaf composite saves 91.4 to 105 MJ (6.0% to 6.1%).

Life Cycle Greenhouse Gas Savings across Multiple Vehicles

The trend in life cycle GHG savings across vehicles is shown in figure 5. Reflecting the trend observed for energy savings, GHG savings from implementation of bio-based composite components are greatest for vehicles with higher MIF values. The net life cycle GHG savings without powertrain resizing are 9.5 to 10.8 kg CO_2-eq (9.1% to 9.3%) for kenaf and 16.7 to 18.8 kg CO_2-eq (16.0% to 16.4%) for the cellulose composite. The net life cycle GHG savings with powertrain resizing are 11.3 to 12.3 kg CO_2-eq (10% to 11%) for kenaf and 19.8 to 21.4 kg CO_2eq (14% to 19%) for the cellulose composite.

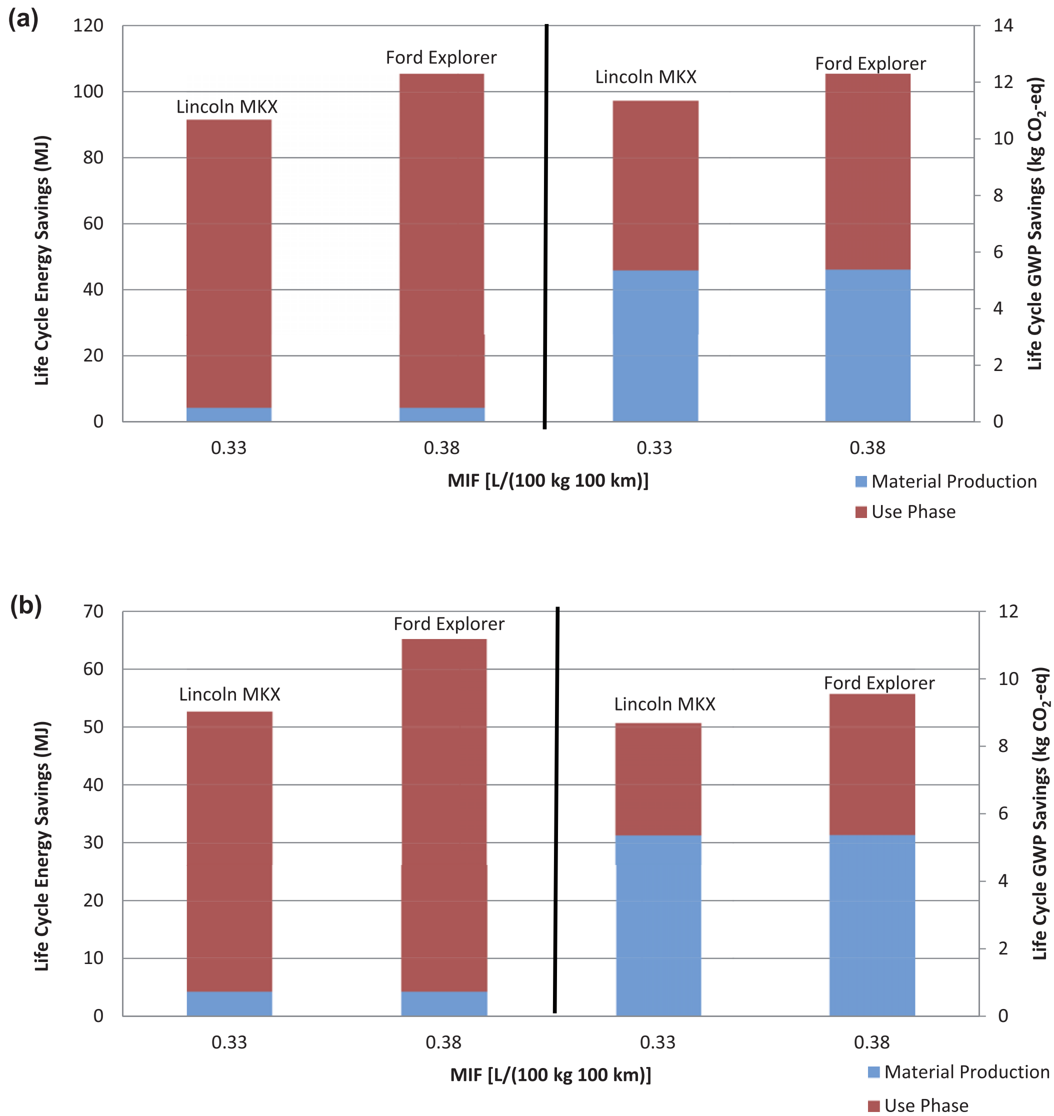

Figure 6 Life cycle energy and greenhouse gas emissions savings when substituting kenaf fiber component for a glass fiber component on the 2013 Lincoln MKX and 2013 Ford Explorer: a) with powertrain resizing; and b) without powertrain resizing. MJ = megajoules; GWP = global warming potential; kg CO_2-eq = kilograms carbon dioxide equivalent; MIF = mass-induced fuel consumption; L = liters; km = kilometers; kg = kilograms.

Discussion

Bio-based Components on the 2013 Ford Fiesta

The cellulose fiber production portion of the component is more energy intensive (50.8 MJ) than glass fiber (30.9 MJ) or kenaf fiber (20.7 MJ). 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, more than double that to produce the fiber (20.7 MJ). Interestingly, as shown in figure 2, despite significant differences in several of the individual elements, the total cradle-to-grave energy demand for the three components is indistinguishable within the uncertainties of the analysis.

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, owing to its biomass-based processing energy, cellulose fiber has –0.059 kg of CO_2. Approximately 1.5 kg of CO_2 is stored for every kg of fiber (Cagnon et al. 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, owing to its 40wt% of natural fiber, stores 1.55 kg of CO_2, whereas the 30wt% cellulose component stores 1.43 kg of CO_2.

Owing to different upstream parameters for the part manufacturing process, the cellulose fiber component's processing emissions (3.26 kg CO_2-eq), which include compounding and injection molding, is smaller than for the kenaf (6.82 kg CO_2-eq) and glass-fiber component processing (7.33 kg CO_2-eq).

The Weyerhaeuser NR Company LCI data included the compounding of resin and fiber together to make the cellulose composite material and uses the US EPA's eGRID to model the emissions based on the Upper Midwest region of the United States (US EPA 2013a). This causes a larger-than-expected reduction in GHGs owing to the regional differences in grid mix, compared to the U.S. average grid used in Thiriez and Gutowski (US DOE 2013). The glass and kenaf composites' compounding stages are based on Thiriez and Gutowski (2006), which is based on the U.S. national grid average emissions.

Scenario Analysis across Multiple Vehicles

As the lighter, natural fiber components are applied to six vehicles, general trends can 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, especially if there is an opportunity to downsize the powertrain of the vehicle. The cellulose component, which was 12% lighter than the baseline, had an average life cycle energy savings of 111 MJ (no resizing), whereas the kenaf composite, which was 7% lighter than the baseline, had an average life cycle energy savings of 74.6 MJ. As illustrated in figure 6, lightweight benefits are greater for vehicles with larger MIF values (Kim and Wallington 2013b).

The cellulose component has greater life cycle GHG savings than the kenaf component. The cellulose component saves, on average, 18.1 kg CO_2-eq, whereas the kenaf component saves, on average, 10.3 kg CO_2-eq. In all cases, the bio-based material substitution led to a positive life cycle GHG savings.

Sensitivity Analysis

Impact of Material Compounding's Electricity Source

One source of variation identified in this study was the electricity used to compound the fiber and resin materials together. Weyerhaeuser NR Company provided an LCI of the fiber production and 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 of manufacturing, as seen in figure 3. Since 2004, when Thiriez and Gutowski's data were gathered, the percentage of the generation resource mix that is fossil fuels has decreased from 77.4% (2004) to 68.8% (2010) (US EPA 2013a).

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 were applied to cellulose processing as well (Thiriez and Gutowski 2006). This change resulted in an increase in life cycle GHG emissions of 3.08 kg CO_2-eq. The total life cycle GHG emissions increase by 3.6% for the cellulose component, and from a cradle-to-gate (fiber production to sourcing) perspective, the change results in an 11% increase in life cycle GHG emissions. Overall, the emissions associated with the compounding electricity have a minimal effect on the total life cycle GHG emissions.

Impact of Biogenic Carbon Storage

To better understand the impact of biogenic carbon storage within 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 by 1.41 kg CO_2-eq to a total of 88.6 kg CO_2-eq (a 1.6% increase). The life cycle GHG of the kenaf component would increase by 1.54 kg CO_2-eq to a total life cycle GHG of 96.3 kg CO_2-eq (a 1.6% increase). Although biogenic carbon storage was excluded for both natural fibers, the cellulose component still has a negative CO_2 impact during fiber production of –0.041 kg of CO_2. During fiber production, Weyerhaeuser NR Company produces more electricity than it requires, allowing it to sell back electricity to the grid (Sonne Hall 2013). This exchange results in a reduction of 83 g CO_2-eq for every kg of fiber produced.

Conclusions

This study analyzes the substitution of a 30% glass fiber reinforced PP composite automotive console component (3 kg) with either 30% cellulose fiber reinforced PP (2.65 kg) or 40% kenaf fiber reinforced PP console component (2.79 kg). The substitution was analyzed across six 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 life cycle 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 to achieve the largest life cycle benefits. The study results indicate that vehicles with higher MIF values should be targeted for lightweight components to achieve higher life cycle energy demand and GHG emission savings. For cellulose fiber composite components implemented on the range of vehicles, the substitution results in a life cycle energy savings of 6.5% to 7.4% and a GHG savings of 16.0% to 16.4%, when compared to the baseline component, without powertrain resizing. Although this study assumes a small semistructural 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 owing to the fact that the fibers are shipped a greater distance, indicating that, all other factors being equal, materials should be sourced as close as possible to the manufacturing locations. The resin and manufacturing energy savings achieved here would change 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 and from increased local natural fiber supply chains should be quantified.

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