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ORIGINAL PAPER

The effect of lightweighting on greenhouse gas emissions and life cycle energy for automotive composite parts

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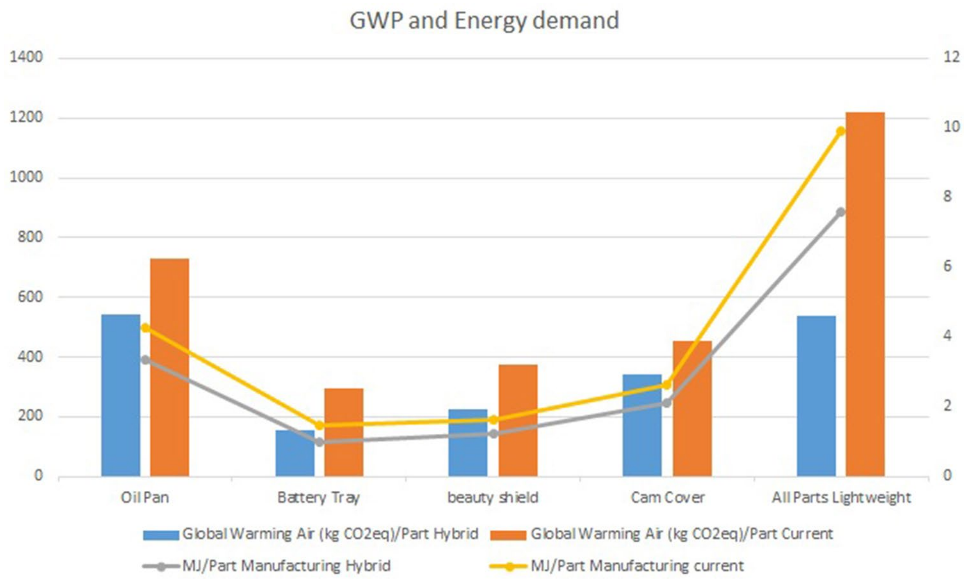
Abstract

Lightweighting is considered as one of the solutions for reducing transportation emissions. Automobile manufacturers and original equipment manufacturers are seeking novel ways to meet this objective. One of the options for emission reduction would be the use of natural and/or recycled fiber-reinforced composites as these materials are lighter and have low energy demand compared to the currently being used materials. In this study, we tried to examine the impact of the use of hybrid bio-based composites as an alternative to the current materials. Four different under-the-hood parts (battery tray, engine beauty shield, cam cover, and oil pan) were manufactured using hybrid bio-based (carbon/cellulose fiber) composites and compared their environmental emission in terms of the greenhouse gas (GHG) emission as well as the cumulative energy demand. The GHG was calculated in accordance with the Intergovernmental Panel on Climate Change, Fifth Assessment Report, whereas cumulative energy demand was calculated based on the International Organization for Standardization life cycle assessment method. The results of this study indicated a noticeable GHG and energy savings and a promising future for these types of hybrid materials.

Graphical abstract



Keywords Recycled carbon fiber · ISO-LCA-based greenhouse emissions · Cumulative energy demand · Biocomposite · Lightweighting

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Extended author information available on the last page of the article

Introduction

Plastics are one of the most important materials that have been developed by humans so far. Despite their bad environmental reputation, they have helped reduce the environmental impacts from the transportation industry by means of lightweighting. An average automotive glass fiber-reinforced plastic (GFRP) has a density of 1.4 g/cm^3, which is almost half that of lightweight aluminum alloy. This means that, in vehicles, replacement of aluminum alloy based parts with glass fiber-reinforced plastics could result in lightweighting and attain the benefits of emission reduction. Aside from lightweighting, high-performance plastics are also well known for flexibility, safety, recyclability, and minimal corrosion (Carlson and Nelson 1996). Extensive amounts of the literature are available with the reports of the benefits of these plastics; however, recently, researchers have been trying to make fiber-reinforced plastics better by replacing the matrices with bio-based ones and/or replacing the energy-intensive fiberglass with a less-intensive natural or recycled fibers (Akhshik et al. 2017; Boland et al. 2014; Kim et al. 2014; Mansor et al. 2014). Though the benefits of lightweighting are a known fact for the driving cycle, its effect on the production phase and end-of-life has not been clear so far. Some literature has promised huge advantages toward GHG and energy savings (Wötzel et al. 1999; Pervaiz and Sain 2003), whereas other researchers have argued these advantages are minimal and in the large scale they are not noticeable (Das 2010).

Transportation industry is one of the major greenhouse gas emissions sources. Reports have indicated that 28% of the total CO_{2eq} emitted comes from the transportation sector (EPA 2018). Lower fuel price causes people to be less concerned about buying a car that is not fuel efficient, and the only working solution for now is the regulation and setting of maximum allowed emissions. This solution dates back to the Kyoto Protocol, in which 140 g CO_2eq/km was initially introduced (1997) as the maximum allowed emissions. This value has been lowered continually, and currently terms like 20 g CO_2eq/km or even zero emissions per km are being discussed (EU and G8+5-states, part of Copenhagen accord 2009). Even in the manufacturing phase, there are regulations that limit greenhouse gas emissions; for example, EU 2014 allows 2.5 g/km per manufacturer per annum (EU 2014), which means if a passenger car will be driven for 250,000 km, regardless of size, it can emit only up to 625 kg CO_2eq during the manufacturing phase.

In the transportation sector, reducing weight can reduce emissions. This lightweighting solution has been used in the industry and forces manufacturers to shift from steels to lightweight options like metal alloys or fiber-reinforced plastics. For an average vehicle during the use phase, reducing 1 kg of weight will save 12.5 g CO_2 per every 100 km driven (European Commission 2016). One important aspect of lightweighting is secondary weight reduction (Lewis et al. 2014), which usually resulted from the replacement of some components to their lightweight versions. For example, if the weight of the engine drops from 500 to 400 kg, the bolts that keep the engine in place and the frame that supports the engine's weight do not need to be as strong as before. The manufacturer can use lighter supports and smaller bolts and can achieve a secondary mass saving due to lightweighting.

Throughout lightweighting research, there have been numerous efforts to replace energy-intensive materials with materials that need less energy. Use of recycled and/or bio-based materials has been indicated as a promising stream. For example, there are studies on replacement of glass fiber-reinforced plastics with natural materials and residues (Akhshik et al. 2017; Pervaiz et al. 2003; Boland et al. 2015; Balaji et al. 2015; Rosa et al. 2014). A 2014 study on the replacement of a glass fiber-reinforced composite with cellulose fiber and kenaf fiber-reinforced composite showed a saving of 39.5 MJ of energy (Boland et al. 2014). For comparison, the energy content for 1 L of crude oil is almost 38.5 MJ. If we replace millions of parts made with current composites with natural fiber-reinforced ones, we could save millions of liters of crude oil. Other studies on this topic estimated even more savings; for example, a research focused on hemp fibers concluded that replacing materials with hemp fiber is better than the glass fiber counterpart in terms of emissions (Wötzel et al. 1999). Though some studies like Luz et al. (2010) have supported replacing materials with sugarcane, which will lead to a 4.5% decrease in the energy required for production, others like Alves et al. (2010) mentioned that replacing glass fiber with jute fiber for parts in an off-road vehicle did not favor jute fiber in the production phase.

The aim of this study is to evaluate energy demand and greenhouse gases based on the ISO-LCA method for four under-the-hood parts—the battery tray, beauty shield, cam cover, and oil pan—in the class of car they represent and replace them with new hybrid composite parts. In an additional scenario, it was assumed that all of these parts had been replaced with new hybrid lightweight materials.

Materials and methods

Evaluation of energy demand and greenhouse gases

This study followed the ISO-LCA and complied with the Canadian Standards Association (CSA). The LCI method used was an updated TRACI-2.1 in which all the greenhouse gas factors were updated and modified from the

Table 1 Updated CF in GHG emission within the TRACI2.1

Flow	AR5-IPCC 2013	AR4-IPCC 2007
CO_2	1	1
CH_4–fossil	28	25
CH_4–biogenic	25.25	22.25
N_2O	265	298
HCFC-141b	782	725
HFC-134a	1300	1430
HCFC-22	1760	18,210
HCFC-142b	1980	2310
CFC-11	4660	4750
CFC-12	10,200	10,900
Sulfur hexafluoride	23,500	22,800

AR4-IPCC-2007 correlation factor to AR5-IPCC-2013, which is more accurate. Table 1 shows the updated values for the TRACI-2.1.

The goal of this study is to compare the life cycle energy and greenhouse gas emissions from the current glass fiber (mineral)-reinforced composite automotive parts with their hybrid biofiber-reinforced counterparts.

System boundaries

The scope of this research is cradle to grave, starting with the material extraction, including energy required for the whole life cycle all the way to the landfill. Figure 1 shows the system boundaries and processes in the life cycle of bio-based and conventional parts. As you can see, the main

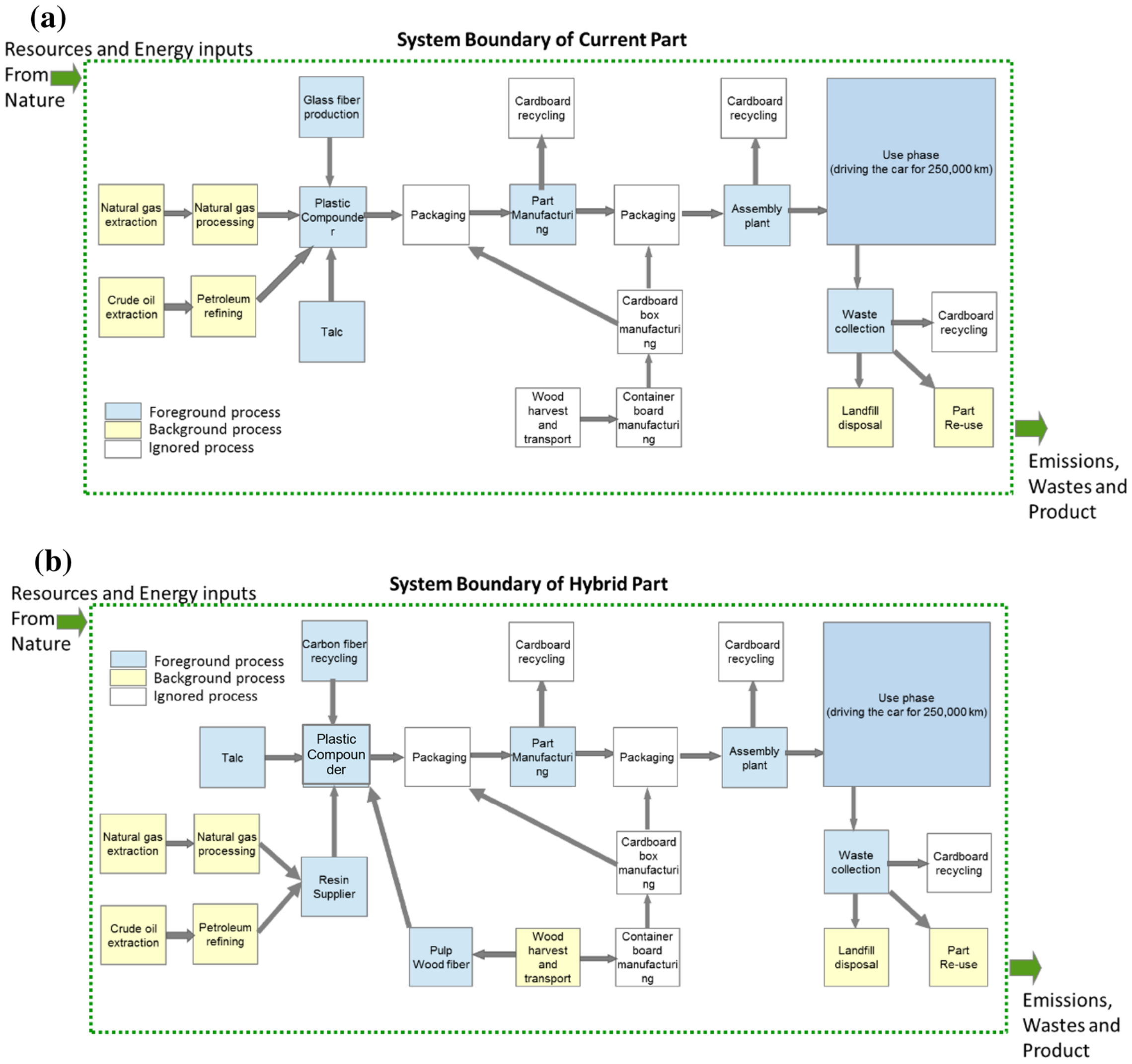

Fig. 1 **a** System boundary and processes in the life cycle of a current automotive part. **b** System boundary and processes in the life cycle of a hybrid automotive part

difference between the two system boundaries is inclusion of natural fibers or glass fiber and related processes.

Functional unit and scope definition

The functional units for this study are an injection-molded automotive part (battery tray, engine beauty shield, cam cover, and oil pan) that will be placed under the hood of an average Ford passenger vehicle and last for 20 years or 250,000 km. The reference flow for the current research is one fiber-reinforced plastic part (for all parts lightweight scenarios, a combination of fiber-reinforced composite auto parts are used) that could be either carbon/cellulose fiber or glass fiber/mineral reinforced. These are injection-molded parts and estimated to have a lifespan of over 250,000 km or 20 years. For the all-part lightweight scenario, we have considered a scenario which we have implemented all of the mentioned lightweight parts in one car. These parts will be shredded and sent to a landfill after their lifespan. The fiber content in the parts was evaluated based on weight. A unit composed of glass fiber (mineral mix in some cases) is assumed to perform similarly to one of recycled carbon/cellulose fiber (and mineral mixed in some cases; see Table 2). Both compounds contain up to 5% proprietary materials (excluded from our calculations), and both compounds meet the manufacturer's minimum standard requirements and passed the necessary tests.

Method, assumptions, and impact limitations

This study focused on the greenhouse gas emissions and life cycle energy consumption of a car with original and lightweighted parts. This study excludes unit processes that contribute < 1% to system total flows of mass, primary energy, and air emissions. In order to comply with ISO14044, section 4.2.3.3, in our analysis, we considered energy and environmental relevance as well. The study considers only the landfill for the end-of-life scenario, which is the current common practice in North America (Stagner and Tam 2012; Miller et al. 2014) for the end-of-life. All parts, regardless of containing hybrid or current materials, contain up to 5% proprietary additives, which we excluded from the model. Part reuse fell into the under 1% category, so we excluded it from the model. We also excluded the impact of cardboard manufacturing, recycling, and packaging because for most OEMs and auto manufacturers, cardboard recycling is very efficient and very similar. We excluded air-conditioning refrigerant leakage (HFC-134a) in the calculations. We assumed the automotive parts will be sent to only one assembly plant (weighted average distance of the actual plants based on the total number of assembled parts) and did not calculate the distances for the assembled car's travel to the dealer and customer. In this study, powertrain adaptation was provided only for comparison, and there were no secondary mass changes for this particular prototyping. All calculations of the fuels

Table 2 Inventory and material composition for this study

Weight in kg	Battery tray	Cam cover	Oil pan	Beauty shield	All parts lightweight scenario
Current					
Polyamide (recycled)	N/A	0.624	1.008	N/A	2.424
Polypropylene	0.333	N/A	N/A	0.382	N/A
Glass fiber	0.095	0.336	0.543	N/A	1.039
Minerals	0.048	N/A	N/A	0.095	N/A
Proprietary[a]	0.025	0.051	0.082	0.025	0.182
Total	0.500	1.010	1.633	0.502	3.645
Hybrid					
Polyamide (recycled)	N/A	0.608	0.940	0.336	2.117
Polypropylene	0.271	N/A	N/A	N/A	N/A
Recycled carbon fiber	0.018	0.107	0.235	N/A	0.529
Wood fiber	0.072	N/A	N/A	0.040	N/A
Minerals	N/A	N/A	N/A	0.019	N/A
Proprietary[a]	0.019	0.038	0.062	0.021	0.139
Total	0.380	0.753	1.237	0.416	2.786
Lightweighting percentage	24	25	24	17	24

[a] These are the additives that companies keep as trade secret and are up to 5% of total weight

are based on the standard gasoline, E10, which is a regular gasoline that contains up to 10% ethanol and emits 2.3 kg CO_2eq for each liter it burns. The simulated car in this model was a non-existing average passenger car that was the weighted average for four actual passenger cars (Fiesta, Focus, Mondeo or Fusion, and Taurus) based on their total number of sales globally. From this weighted average, we calculated the weight of the vehicle and the fuel economy and used these values in this model. The electricity grid mix was based on the average Ontario electricity grid mix during the year 2017. We performed the impact assessment based on an updated TRACI2.1, which, instead of using a standard TRACI2.1, uses updated characterization factors to comply with 2013 IPCC AR5. Data categories were both primary and secondary and were selected based on the impacts, as directed by TRACI (Bare et al. 2012), as well as the availability of data in the databases. We collected all the well-to-pump fuel information from the GREET database (Argonne National Laboratory, US Department of Energy Office of Science). For the landfill, we collected the generic inventory data from Gabi's databases (ThinkStep AG, 2015 Edition); other databases used in this study include US LCI (U.S. Life Cycle Inventory Database 2012) and Ecoinvent3. Where there were no data available for North America, we have used European data from the European Life Cycle Database (ELCD) 3.3.

Logistical data

Due to the business sensitivity of the information, we are not able to reveal the name and exact location of the gates; however, we have tried to keep the data as exact as possible without being too revealing.

For the hybrid materials, fibers were shipped 1935 km via truck and resin was shipped for a total of 2540 km to the compounder gate. (560 km was shipped by trucks and the rest was by train.) Finally, the hybrid materials ready for injection molding were shipped for a total of 377 km (77 km by truck and 300 km by train).

For the current materials, the logistical data were as follows:

Glass fiber was shipped for 1024 km by truck. Precursors were shipped for 2117 km to the compounder gate, and after that, the compound was shipped for 612 km to the part manufacturer.

Both (biohybrid and current) materials were shipped for 669 km to the assembly plant by truck. All the truck shipping was considered long haul except for the hybrid biomaterials, which went through a 77-km short haul. The amount of emissions was calculated based on the weight of the materials for making a single part.

Multifunctionality and allocation

Wood fiber is a by-product of products like construction wood, pulp, and paper; therefore, there is multifunctionality involved. In addition, for plastic production, according to the databases, an allocation for the portions of flow based on the mass exists; therefore, we used system expansion by the substitution approach to avoid cardboard and skid recycling.

Data quality requirements

The geographical coverage of this study is Canada and/or the rest of North America. Data were < 10 years old and most were < 5 years old. This model is based on average North American technology, and the life cycle inventory data were collected in collaboration with the OEM, tier 1 and 2 suppliers, and the researchers. In the cases where no North American data were available, the European data were confirmed by Canadian sources and have been used.

Inventory

The material composition and the inventory for all the parts are given in Table 2. Materials considered consist of the glass-/mineral-filled composites used by the OEM, and our innovative hybrid parts made from recycled carbon-/wood-fiber-reinforced composite were considered equivalent in terms of functionality. Polyamide was recycled from the carpet industry, and carbon fiber was recycled by trimming from the resin transfer molding before the addition of resin (Table 2).

Description of the system and life cycle

Production phase

All parts were made via the injection-molding process and passed the Ford standard requirements. For wood fiber-reinforced composites, all the processes were similar to the current manufacturing methods; however, the injection-molding process used a lower temperature and a higher holding pressure. The parts were then sent to the assembly plant and assembled on the vehicle. They are expected to last for 250,000 km or 20 years on the average passenger car.

Driving cycle calculations

We calculated the fuel economy of a generic Ford passenger car based on the weighted average for advertised fuel economy, city and highway combined, and global number of sales for the 2016 Fiesta, Focus, Fusion/Mondeo, and Taurus. According to the CSA LCA guidelines (CSA SPE-14040-14) and the National Highway Traffic Safety Administration (NHSTA), a passenger car will have a life cycle of 250,000 km, and it will be used in a driving cycle of 45% highways and 55% city, as advised by NHSTA. All the emissions were calculated and compared them based on the fact that burning of 1 L of E10 gasoline in the driving cycle will emit 2.3 kg CO_2eq.

End-of-life

Due to the difficulty in dismantling the vehicle, complexity of the recycling process, lack of cost-worthiness, and unestablished methods for incineration of fiber-reinforced plastics into energy (Khabiri 2014; Stagner et al. 2013; Toth et al. 2014; CELA 2011), and automotive plastics are not considered for recycling. Even though there is sound research on recycling at the end-of-life, fiber-reinforced plastics in North America are considered automotive shredder residue and are sent to the landfill (Stagner et al. 2013). In this study, it was assumed that automotive parts would be sent to the landfill and cause a minor greenhouse gas emission over the 100-year time horizon due to landfill methane emissions and operations (EPA 2014; Al-Salem et al. 2014).

Battery tray, beauty shield, cam cover, oil pan, and combined lightweight scenario

Material composition and the inventory of these parts are given in Table 2. For the all parts lightweight scenario, all the mentioned parts were assumed to be assembled on the average car, and we evaluated the collective effect of the lightweighting by the hybrid materials.

Sensitivity analysis, scenario analysis, and uncertainty analysis

According to ISO and CSA LCA guidelines (CSA 2014), we performed an uncertainty analysis on all the collected data (ISO 14044:2006; CSA SPE-14040-14). The scenario analysis was a comparison of the original car emissions with the lightweighted scenarios. Furthermore, in some cases, an automobile may never reach 250,000 km; therefore, we need to calculate the data based on 200,000 km as well. Then, in a comparison, the results should be considered significant if the difference is more than 10% (CSA SPE-14040-14). Other situations that one should consider in the scenario analysis includes a change in the materials, a change in the processes (designs and manufacturing), and the electric power grid mix (ISO 14044:2006); for example, if our lightweight part was produced in a country or province with a grid mix of 80% nuclear power and hydroelectric as opposed to being produced in a province that was 80% fossil fuel based, the emissions will be different.

Results

Data quality assessment

The method introduced by Weidema and Wesnaes (1996) is still practical for data quality assessment, and we conducted our data quality assessment for collected data based on this method (Weidema and Wesnaes 1996). Table 3 shows the quality assessment indicators and the corresponding scores. In this system, scores are from best (1) to worst (5). Based on the scores given, our data for this study were considered as good.

Driving cycle calculation

For this calculation, data were obtained from the advertised fuel economy, the United States Environmental Protection Agency, and federal test procedure. Since 2016 EPA, uses more aggressive five-cycle test for the fuel economy calculations, and this will not be compatible with the CSA calculations; therefore, the fuel economy for the mentioned make and model wherever the two-cycle test result was not available was calculated based on 2015 vehicle's fuel economy. A weighted average Ford passenger car with the current (conventional) and original parts will burn 20,725 L of E10 gasoline (8.29 L/100 km combined fuel economy) for its total use cycle (250,000 km).

Table 3 Data quality check was done based on the Weidema and Wesnaes (1996)

Data quality indicator	Score	Explanation
Reliability	2	Part of data based on assumptions
Completeness	2	Complete
Temporal correlation	3	The data are < 10 years old
Geographical correlation	3	All data are from North America, except for landfill data which was from Europe, but it was verified by Canadian practices
Technological correlation	2	Data are average recent technology mixed from North America

As a rule of thumb and to check the calculations, based on Stan and Bos's research, every 10% of dropped weight may lead to up to 8% fuel saving (Stans and Bos 2007; Van den Brink and Van Wee 2001). For a weighted average curb weight of 1566 kg (which is the average curb weight of Ford passenger cars weighted by total number of sold cars), the vehicle will be between 0.005 and 0.055% lighter. This lightweighting may yield 0.004–0.044% fuel savings, which, if we consider the total consumed fuel by the original car (20,725 L) for different lightweighting scenarios, will save between 0.829 and 9.119 L of gasoline. The combustion of 1 L gasoline will emit 2.3 kg CO_2eq (2289 g CO_2 + 0.14 g CH_4 + 0.022 N_2O; Environment Canada, 2011). Based on these calculations, savings of 0.829–9.119 L of gasoline result in a reduction of 1.907–20.972 kg CO_2eq. This method provides only a rough estimate and is not accurate; therefore, CSA has suggested different methods to determine the minimum as well as adopted fuel savings.

Assuming no powertrain adaptation, CSA recommend using the following formula:

$$\text{CWA,p} = (\text{mp}-\text{mb}) \times \text{FCO} \times \text{LTDDV} \quad (1)$$

where CWA,p is the minimum total life cycle mass-induced fuel change (L); mp is the mass of the new auto part (kg); mb is the mass of the baseline auto part (kg); FCO is the mass-induced fuel consumption value, without adaptation, [L/(100 km × 100 kg)]; LTDDV is the baseline vehicle lifetime driving distance, here 250,000 km as recommended by (NHTSA 2006).

So for all the scenarios mentioned before, with no powertrain adaptation, total fuel consumption change is calculated:

$$(\text{Lightweighting})\ \text{kg} \ * \ 0.168\ \text{L}/(100\ \text{km} \times 100\ \text{kg}) \times 250,000\ \text{km} = \text{Fuel saved L}.$$

Or, for every kg of lightweighting, we will save up to 4.2 L of fuel.

Additionally, assuming the powertrain adaptation, the mass-induced fuel consumption value (Fco) is 0.40; therefore, the change will be up to 10 L of fuel.

The results of the calculation are presented in Table 4.

Fuel savings with the powertrain adaptation are the maximum possible savings, and it is not the case for real lightweighting; therefore, fuel savings without the powertrain adaptation are used for further calculations. For emissions purposes, every 4.2 L of fuel saved reduces the greenhouse gas emissions by 9.66 kg CO_2eq from the driving cycle. As a car needs less fuel, we need to bring less fuel to the pump, and therefore, the saving of fuel is even bigger; there will be 2.32 kg CO_2eq less emissions (well-to-pump), and in total for every kg of lightweighting in our scenario, the greenhouse gas emissions will be around 12.89 kg CO_2eq less than the original car. The results of the greenhouse gas emissions savings are given in Table 4. The results indicate that both the production and the end-of-life phase of auto parts will have CO_2 savings, and if we take those into account, the emission reduction will be 0.79 kg CO_2eq for replacing the beauty shield; to replace all the mentioned parts, it will be 16.94 kg CO_2eq.

These fuel savings and emissions reductions seem low considering the time horizon of a vehicle lifetime (20 years); however, if we multiply these savings by the total number of cars produced in that year, the number will be significant. For example, a savings of only 0.79 kg greenhouse gases, if multiplied by 1,652,000 (approximate number of sold vehicles), will be over 1305 tons of CO_2eq, which is a significant number. Furthermore, by replacing all the parts, we will have a significant emissions reduction of almost 27,985 tons of CO_2eq, which is only for passenger cars from one auto manufacturer.

The end-of-life

As mentioned in the previous sections, these parts will be landfilled at the end of their life cycles. According to Gabi's database, landfilling of plastics will not emit any greenhouse gases. Other sources have mentioned methane as the main greenhouse gas upon the landfilling of plastics (Bogner et al. 1999; Rinne et al. 2005). However, databases have stated that landfill operations for discarding

Table 4 Fuel saved for the driving cycle under different scenarios. The fuel savings that are bold here are likely the most probable scenarios

	All Parts lightweight	Battery tray	Engine beauty shield	Cam cover	Oil pan
New part weight (kg)	3.645	0.380	0.416	0.753	1.237
Old part weight (kg)	2.786	0.500	0.502	1.010	1.633
Weight difference	− 0.859	− 0.120	− 0.086	− 0.257	− 0.396
Fuel saved without adaptation (L)	**− 3.61**	**− 0.50**	**− 0.36**	**− 1.08**	**− 1.66**
Fuel saved with powertrain adaptation (L)	− 8.59	− 1.20	− 0.86	− 2.57	− 3.96
CO_2eq saved (without adaptation; well-to-wheel included)	11.08	1.55	1.11	3.30	5.11

1 kg of plastic will cause an emission of 0.044–4.310 g CO_2eq. In this study, we have included the landfill of automotive parts and subsequent emission of greenhouse gases. However, we would like to draw the reader's attention to the fact that this landfilling will likely never happen to the actual parts at the end of their lifetimes because these parts will last until 2037, and by then, governments around the world will likely have requested full recycling and zero landfilling for these types of materials.

Sensitivity analysis, scenario analysis, and uncertainty analysis

We performed end-of-life scenario analysis, and the changes in the results were under 1%. We did a sensitivity analysis on emissions with Crystal Ball v11.1.2.4 (ORACLE, USA) and concluded our data are reliable and there might be a variance of < 1% in our data. We also performed an uncertainty analysis for different electricity grid mixes on the production phase, and the changes were below 10%. As required by the standards, a car may never reach 250,000 km and therefore an altered scenario in which the car will last for only 200,000 km was created and analyzed. In this scenario, the car will obviously have a lower total fuel savings (~ 14%) and will burn over 4000 L less gas.

Results of LCA

In this study, ISO-LCA was adopted as described. To have more knowledge of the collected and calculated data, we also performed sensitivity analysis, which will be discussed below. The impact assessments were based on the US EPA TRACI 2.1; however, it was modified to comply with the IPCC-AR5. All energy calculations and water consumptions can be seen in Table 5.

All the indicators are lower for the hybrid materials; however, making the battery tray from the hybrid materials consumes over twice the wood in comparison with the current materials. This consumption leads to an overall increase in the wood consumption for replacing all the parts with hybrid materials.

Table 6 shows the result of the modified TRACI indicators. All indicators are better for the hybrid materials than for the current materials. Among the indicators, the global warming potential will drop by a factor of over 2.2 through replacing all the mentioned parts with the lightweight ones. However, among these indicators, the HH criteria indicator, human health respiratory problems related to particulate matter, was lower than that of current materials for the battery tray and the beauty shield.

We calculated the total life cycle energy consumption for all the parts based on the described methods, and as anticipated, the hybrid materials outperformed the current materials (Table 7). The required energy for making parts with hybrid materials, including biogenic carbon and all the energy sources, was from 19 to 32% lower than making parts from the current materials. These calculations are only for the production phase and include savings on material extraction, transportation, and waste collection (Table 7).

Table 7 also compares the difference in energy demand for the life cycle of the simulated passenger car with new parts as well as the global warming potential for the two scenarios. One of the facts that can be inferred from this table is that even though manufacturing parts is extremely important, the result of the whole life cycle may be different, and a part that is not performing well in the manufacturing phase may outperform other parts considering the life cycle.

Discussion

This study compared the life cycle greenhouse gas emissions and energy demand of current under-the-hood parts (standard glass fiber-reinforced polyamide or glass fiber/

Table 5 Total energy consumption and the energy sources, water, wood, comparison for both the hybrid and current automotive parts

	All parts light.		Battery tray		Beauty shield		Cam cover		Oil pan	
	Current	Hybrid	Current	Hybrid	Current	Hybrid	Current	Hybrid	Current	Hybrid
Coal (kg/part)	1.31	0.50	0.31	0.11	0.45	0.19	0.36	0.25	0.58	0.40
Oil (kg/part)	12.87	9.58	1.94	1.33	2.15	1.63	3.65	2.92	5.90	4.60
Hydro (MJ/part)	1.65	0.59	0.39	0.15	0.54	0.25	0.50	0.34	0.81	0.54
Natural gas (m^3/part)	60.47	22.00	19.35	13.58	21.39	17.13	36.67	30.93	59.29	48.36
Solar (KJ/part)	104.28	25.71	27.38	9.59	38.01	16.47	34.01	22.25	54.99	35.25
Uranium oxide (mg/part)	28.77	15.35	7.00	4.50	8.72	5.84	11.21	9.46	18.13	14.80
Water (M^3/part)	0.11	0.06	0.03	0.02	0.04	0.02	0.02	0.01	0.04	0.01
Wind (MJ/part)	1.07	0.36	0.26	0.10	0.35	0.16	0.34	0.23	0.55	0.36
Wood (kg/part)	80.04	96.87	26.45	56.07	52.39	41.10	1.68	0.92	2.64	1.46
Total energy (MJ/part)	1156.14	885.71	168.54	113.38	190.68	141.22	307.49	247.35	497.42	389.56

mineral-filled polypropylene materials) with alternative materials (natural fiber or recycled carbon fiber-reinforced composites).

Previous studies reported that the natural fibers could be environmentally benign and better in terms of emissions and cumulative energy demand (Luz et al. 2010; Joshi et al. 2004; Boland et al. 2014; Batouli et al. 2014; Akhshik et al. 2017; Xu et al. 2008). Our results are in favor of these reported studies and showed that these new hybrid bio-based composite automotive parts are generally more efficient in terms of greenhouse gas emissions and energy demand. There are studies predicting the use of agricultural waste as a sustainable source of natural fibers (Al-Oqla et al. 2015) and these kinds of replacements are even better for the environment. The carbon fiber that was once considered as an energy-intensive (1800–2000 °C) material is currently, with good-quality recycled carbon fiber, not energy intensive. In fact, if a manufacturer uses recycled carbon fiber that is trimmed from another process and leftovers (which was the case in our study), it could be very beneficial. One of the effective steps in reducing emission is to withdraw the glass fiber that is currently the standard reinforcement in automotive industry because glass fiber production needs a temperature treatment (1550 °C) that is energy intensive and a source of significant greenhouse gas emissions (Kellenberger et al. 2007). Furthermore, by looking at the databases, we can see water consumption is high for this material, which makes it more and more unfavorable for tomorrow's world. As more automotive industries move toward carbon fiber, its cost will decrease; eventually, this material will replace glass fiber. Even though reports have shown that using carbon fiber-reinforced plastic in automotive parts increases the life cycle energy by 3% (Das 2011), this proved to be mitigable by using alternative carbon fiber sources and making natural fiber hybrids.

In addition to the fuel saving benefits of having a slightly lighter car, the production and end-of-life phases of these parts will have between 0.79 kg CO_2eq and 16.94 kg CO_2eq savings in greenhouse emissions. Even though, considering the vehicle life span of 20 years, these are not impressive numbers, the real savings will be in the sales numbers. According to Statista during the year 2017—a total of 96,804,390 passenger cars sold worldwide (Statista 2018)—if they all saved only 0.79 kg CO_2eq, we would have significant emissions reduction of over 76,475 tons of CO_2eq. Alternatively, considering replacing all four parts, we will save over 1.6 million tons of CO_2eq, and this is the savings only for passenger cars, not including commercial cars.

The difference in the materials causes our LCA results to be slightly different in comparison with the results published elsewhere (Boland et al. 2015). Another reason could be the difference in the system boundaries.

Table 6 Modified TRACI2.1 results for replacing current fiber glass part with the hybrid natural fiber ones

	Global warming	Acidification	Human health criteria	Eutrophication air	Eutrophication water	Ozone depletion	Smog	Ecotoxicity	Human health (cancer)	Human health (non-cancer)
All parts lightweight	2.28	2.04	1.56	1.86	1.31	1.30	1.78	1.34	1.47	1.35
Battery tray	1.90	1.42	0.72	1.40	1.41	1.42	1.36	1.41	1.34	1.39
Beauty shield	1.65	1.43	0.94	1.58	1.27	1.27	1.53	1.26	1.22	1.26
Cam cover	1.32	1.17	1.97	1.43	1.20	1.20	1.40	1.19	1.13	1.18
Oil pan	1.35	1.22	2.01	1.45	1.24	1.24	1.42	1.23	1.17	1.22

The results are showing impacts of current materials over hybrid materials

Table 7 Comparison between lightweight and current parts in terms of GHG emissions and energy consumptions (cumulative energy demand) for manufacturing and vehicle lifecycle

	All parts lightweight	Battery tray	Beauty shield	Cam cover	Oil pan
Global warming air (kg CO_2eq)/part					
Hybrid	4.59	1.33	1.94	2.94	4.64
Current	10.45	2.53	3.19	3.88	6.27
Difference	− 5.86	− 1.20	− 1.25	− 0.94	− 1.63
Global warming air (kg CO_2eq)/vehicle lifecycle					
Hybrid	63,636.20	63,628.28	63,628.94	63,632.55	63,636.74
Current	63,619.26	63,625.54	63,628.16	63,628.22	63,629.69
Difference	− 16.94	− 2.74	− 0.79	− 4.33	− 7.06
MJ/part manufacturing					
Hybrid	885.71	113.38	141.22	247.35	389.56
Current	1156.14	168.54	190.68	307.49	497.42
Difference	− 270.43	− 55.16	− 49.46	− 60.14	− 107.86
MJ/vehicle lifecycle					
Hybrid	640,109.03	646,648.61	646,646.77	646,630.00	646,611.26
Current	646,661.45	646,661.45	646,661.45	646,661.45	646,661.45
Difference	− 6552.42	− 12.84	− 14.68	− 31.45	− 50.19

Substitution of the hybrid bio-based materials for the current materials demonstrated a reduction in all the indicators but particulate matter in the beauty shield and battery tray. Hybrid bio-based materials are better than the current materials in terms of water consumption (almost twice better); however, in terms of wood consumption, they are not as good as the current materials (around 1.2 times worse). This is only due to the battery tray, which is over 2.1 times worse than its current material counterpart. This is justifiable because the hybrid composite for this part contains 15% (W/W) cellulose fiber from wood. The new materials are generally better than current materials in terms of environmental emissions; even though some studies have characterized carbon fiber-hybrid composites as energy intensive (Das 2011) or not good in terms of eutrophication (Wötzel et al. 1999), this is not the case in our study. One reason could be because of the fact that these new bio-based hybrids are recycled and not based on agricultural residue.

In terms of the other environmental indicators, the hybrid composites were actually better than the current material with the exception of the human health criteria or particulate matter in the beauty shield and the battery tray. This could be because of the fact that these two parts are lightest and weigh about 0.5 kg each, while the other parts are at least two times heavier.

During this study, we calculated that even if the current materials are 100% recycled, our hybrid materials in the current situation are still slightly better in terms of energy and greenhouse gas emissions.

Conclusions

As we become more environmentally aware, we start changing our consumption materials' profile. Among these materials' profile, two sources have always been considered a go-to solution: recycling and nature. In this study, we combined and utilized both sources as a powerful and effective solution to our emissions problem. We have excluded mass decompounding in this particular prototyping to evaluate the impact of changes in materials for four simple car parts on a feasible and practical scale. There is no doubt that the future belongs to lightweight green materials, and the newly developed hybrid composite performs better in terms of almost all the environmental impact categories. By incorporating these hybrid composite parts, we will have 2.28 times less GHG emission for the lifecycle of those parts in comparison with the current standard method. These lightweighted parts are also great savers in terms of the energy within the manufacturing as well as the use phase and end-of-life.

Composite parts, after replacing the energy-intensive and heavy materials with the lightweight and natural ones, are not as bad as most think for the environment. Moreover, making automotive parts out of composites, especially components around the engine and eventually the engine itself, will pave the way to having commercial 3D-printed cars with significantly less assembly needed which in turn leads to less emission and energy consumption.

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