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A life cycle analysis of novel lightweight composite processes: Reducing the environmental footprint of automotive structures

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ABSTRACT

In this study, three novel thermoplastic impregnation processes were analyzed towards automotive applications. The first process is thermoplastic compression resin transfer molding in which a glass fiber mat is impregnated in through thickness by a thermoplastic polymer. The second process is a melt-thermoplastic Resin Transfer Molding (RTM) process in which the glass fibers are impregnated in plane with the help of a spacer. The third process, stamp forming of hybrid bicomponent fibers, coats the fibers individually during the glass fiber production. The coated fibers are used to produce a fabric, which is then further processed by stamp forming. These three processes were compared in a life cycle analysis (LCA) against conventional resin compression resin transfer molding with either glass or carbon fibers and metal processes with either steel or aluminum that can be new, partly or fully recycled using the case study of the production, life and disposal of a car bonnet.

The presented LCA includes the main phases of the process: extraction and preparation of the raw materials, production and preparation of the mold, process, and energy losses. To include the life of the analyzed bonnet, the amount of diesel that is used to drive the weight of the bonnet for 300′000 km is calculated. In this LCA, the disposal of the bonnet is integrated by analyzing the used energy for the recycling and the incineration. The results show the potential of the developed thermoplastic impregnation processes producing automobile parts, as the used energy producing a thermoplastic bonnet is in the same range as the steel production.

1. Introduction

Tackling the climate change is one of the major challenges of the 21st century, which requires a reduction of the emission of greenhouse gases such as carbon dioxide or methane (Schryver et al., 2009). A transition towards a more ecological mobility is key to attain this objective as this sector is responsible for about 15% of emissions (Herzog, 2009; Ritchie and Roser, 2017). Emissions related to mobility are mainly due to the automotive industry and include production, service and decommission.

The longing to reduce carbon dioxide (CO_2) emissions of cars is in direct conflict with the continuous expansion of the automotive sector and in the case of passenger cars, with the increasing comfort and safety standards leading to an increase of weight and thus ecological impact. This is supported by a study investigating the impact on climate change of Volkswagen Gold models over their entire life cycle over the last thirty years (Danilecki et al., 2017). To comply with the reduction of CO_2 emissions imposed in several countries, a more ecological design of the vehicles is therefore necessary.

As additional aspect, the on-road energy demand provided by the suppliers might not be realistic as it does not include effects of traffic, driving styles and topography from each country, with an error up to 30% in Switzerland. That is why a mathematical model is proposed to simulate such effects providing more realistic data for different countries (Küng et al., 2019).

Lightweight design is one of the possibilities to attain this goal since a weight reduction in combustion engine driven automobiles comes with a decrease of fuel consumption. This can be achieved by replacing steel with materials such as aluminum, titanium or composites such as glass

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fiber reinforced plastics (GFRP) and carbon fiber reinforced plastics (CFRP). However, a proper ecological assessment requires consideration of the production and decommissioning in addition to the service (Witik et al., 2011) showed that weight reduction will not always lead to improved environmental performance as some lightweight materials such as carbon fibers or magnesium come with increased environmental burdens associated with their production. Therefore, various guidelines and methods have been proposed for assessing the environmental impacts of cars even at an early stage of design in order to enable designers to make strategic decisions about new products or technology (Arena et al., 2013; Nunes and Bennett, 2010; Orsato, 2006). Additionally, also other aspects such as pedestrian and passive safety could be taken into account (Schulz and Kalay, 2016). propose therefore composite materials that could be used in the car bonnet with the same high energy absorption as aluminum.

Several authors investigated the environmental impact of different lightweight materials (Ferreira et al., 2019). investigated the benefits of strengthening magnesium with submicrometer TiC and demonstrated that the higher environmental burden at production was offset after a mileage of 28′000 km when compared to aluminum (Del Pero et al., 2020). proposed a lightweight rear crash management system based on aluminum and obtained contrasting sustainability effects depending on the impact category (Kim and Wallington, 2013). harmonized the results of 33 studies using a common set of assumptions and found that all studies indicate that using aluminum, GFRP and high strength steel to replace conventional steel decreases the vehicle life cycle energy use and greenhouse gases emissions (Witik et al., 2011). showed that among various composite processes, sheet molding compounds were found to perform significantly better than steel and higher performance materials such as carbon fibers or magnesium from a life cycle perspective despite not being recycled. Lighter vehicle components were found to be always more costly to produce but led to reduced overall costs during their lifetime through lower fuel consumption (Song et al., 2009). investigated the impact of replacing steel with composites or aluminum in trucks and buses. They report that the use of composites will lead to a reduced energy consumption over the whole life cycle of the vehicle, but not aluminum.

Despite their outstanding mechanical properties, composites have a limited penetration into the automotive sector because of the lack cost-effective process technologies. Thermoplastic-based composites are suitable for process automation, a key requirement for implementation into high-volume production segments such as compact cars. In addition, they have a potential for recycling which is a great advantage over the state-of-the art thermoset-based composites from an ecological point of view. However, the current manufacture of structural thermoplastic composites is mostly based on organosheets or tapes, which are rather expensive.

Researchers have been developing new production methods in an attempt to improve the production of thermoplastics composites, which translates into reduced costs or cycle time for example. Three promising methods can be cited among the propositions: thermoplastic resin compression RTM (TP-cRTM) with injection molding as investigated by (Studer et al., 2019), melt thermoplastic RTM (mTP-RTM) with flow-enhancing spacers (Gomez et al., 2021) and stamp forming hybrid bicomponent fibers (st-HBF) proposed by (Aegerter et al., 2018).

This study aims to compare these three processes with the established thermoset compression resin transfer molding (C-RTM) process and metal processes for the case study of the production, use and disposal of a car bonnet driven with diesel. We show which process and material is more ecological from a life cycle perspective. Additionally, replacing glass fibers with carbon fibers is explored as an alternative route for further weight reduction and the impact of these two fibers is analyzed.

This comparative study investigates the potential of thermoplastic composites compared to metal parts from an environmental point of view; the benefits of thermoplastic composites are expected to be further amplified thanks to the simultaneous developments on several fronts including the development of novel thermoplastics with better process ability, and process automation.

2. Material and methods

A life cycle assessment (LCA) is performed following ISO 14040 and ISO 14044 (Jolliet et al., 2003) and the impact 2002+ analysis method for the life cycle inventory. The focus is laid on the weight reduction and its direct impact, as our goal is to evaluate processes, and reserve deeper analysis for a given precise car. Further modelling approaches are described in (Del Pero et al., 2017), Delogu et al. (2016), (Koffler et al., 2010), (Kim and Wallington, 2016). In addition, a sensitivity analysis for the novel thermoplastic composite production processes is carried out such as to unveil the process parameters with the biggest potential for the reduction of energy consumption.

2.1. System boundaries and scenario description

This LCA can be classified as "cradle to grave" since raw materials, manufacturing, use and end of life of the bonnet are considered. The transportation of raw materials, molds and products are however not considered in any of the scenarios. The different steps of the LCA reported in Fig. 1 are common for all the different scenarios. The functional unit is a car bonnet, the external dimensions are 1.6 × 1.5 m^2. The function of the bonnet is to provide an aerodynamically suitable and aesthetic protection for the vehicle engine compartment, which can be easily opened by hinges, to provide access to the engine, but to also provide protection in case of pedestrian impact by absorbing a certain amount of energy without injuries to the pedestrian. As this function requires a full design analysis of the vehicle, we consider in our materials/process screening analysis that this part is designed to ensure a flexural stiffness similar to that of a reference steel bonnet. We assume that the part will travel 300′000 km mounted on a diesel engine vehicle before disposal.

2.2. Scenarios

Seven scenarios are considered, which are then described more in detail below, to produce the car bonnet:

- Scenario 1: thermoplastic compression RTM with polyamide 6 (PA6) and glass fibers
- Scenario 2: melt thermoplastic RTM with PA6 and glass fibers

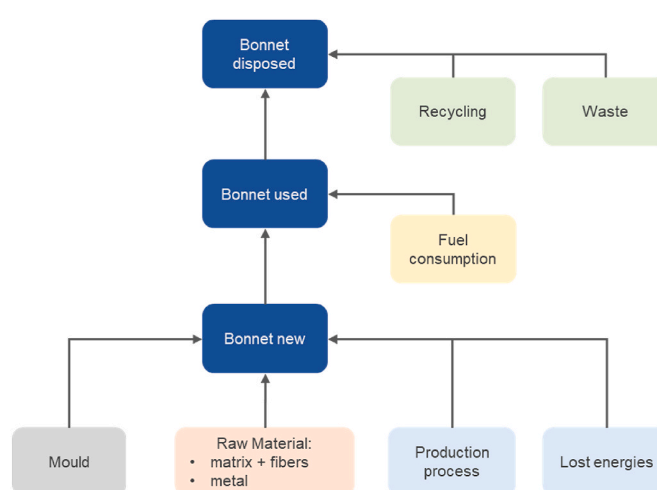

Fig. 1. The different steps of the LCA analyzed in this study.

- Scenario 3: stamp forming hybrid bicomponent fibers with polycarbonate (PC) and glass fibers
- Scenario 4: conventional C-RTM with resin and glass fibers
- Scenario 5: conventional C-RTM with resin and carbon fibers
- Scenario 6: conventional metal bonnet with steel
- Scenario 7: conventional metal bonnet with aluminum

A conventional metal bonnet is produced in two parts and then welded together, as shown in (Aretxabaleta et al., 2019; Masoumi et al., 2011) for typical designs. The RTM processes and the stamp forming hybrid bicomponent process have the advantage of being very flexible in geometry and, unlike sheet metal-based processes, enable parts with different wall thicknesses. In addition, RTM processes allow the composite bonnet to be manufactured in one shot without losing geometry-related features. Thus, in this LCA study we consider that the composite bonnets are produced in one shot while two parts are used in metal bonnets. This does not affect the amount of raw material but only the process itself as only one process cycle is required for the case where the bonnet is produced in one shot. Additionally, on one hand, we analyzed the energy to recycle the thermoplastic and the metal bonnets and on the other hand, we integrated the used energy to incinerate the thermoset resin based bonnets.

2.2.1. Scenario 1: thermoplastic compression RTM (TP-cRTM)

Scenario 1 concerns the production of the bonnet with the TP-cRTM process, using polyamide 6 (PA6) (Evolite® HF XS1480, Solvay) and glass fibers (Tissa Glasweberei AG Switzerland). TP-cRTM is a novel production process combining C-RTM with low-viscosity thermoplastics and conventional injection molding machines as described in (Werlen et al., 2021) and schematically represented in Fig. 2 (Studer et al., 2019). It allows near net-shape part production in one step.

On the one hand, the design of the mold is quite complex and expensive due to varying temperature during the process, and compression process at elevated temperatures that requires taking into account the thermal expansion of mobile mold parts. On other hand, this process allows for relatively short cycle times and high throughput.

2.2.2. Scenario 2: melt-thermoplastic-RTM (mTP-RTM)

Scenario 2 concerns the production of the bonnet with the mTP-RTM process, using PA6 (High Fluidity polyamide 6, Evolite XS1480, Solvay) and woven glass fibers (Chomarat). mTP-RTM is a variant of RTM process where the in-plane impregnation through a spacer is followed by a saturation step to ensure through-thickness impregnation of the reinforcement as described in (Gomez et al., 2021; Salvatori et al., 2019) and represented in Fig. 3. The construction of such a mold is less complex than for TP-cRTM and enables the production of complex geometries. On the other hand, the impregnation along the fibers requires the use of a high permeability spacer channel to distribute flow along the part then through the thickness, otherwise the process would be too slow.

2.2.3. Scenario 3: stamp forming hybrid bicomponent fibers (st-HBF)

Scenario 3 concerns the production of the bonnet with st-HBF using polycarbonate (PC) coated glass fibers. Hybrid bicomponent fibers (HBF) are a novel class of hybrid intermediate material consisting of fibers individually coated with a thermoplastic material intended as the

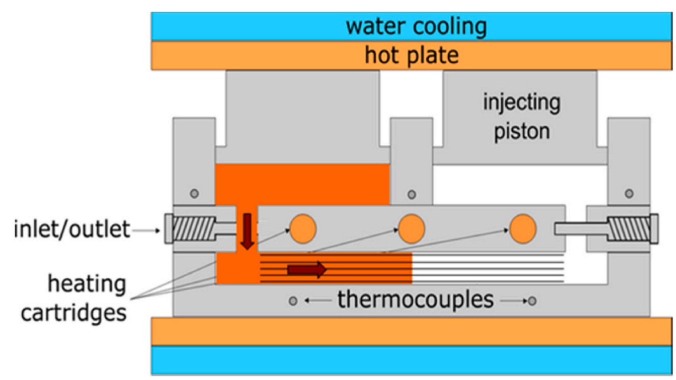

Fig. 3. In thermoplastic resin transfer molding process the fabric and the spacer are heated up and the melt thermoplastic is injected by pressure into the cavity to impregnate the fibers (Gomez et al., 2021).

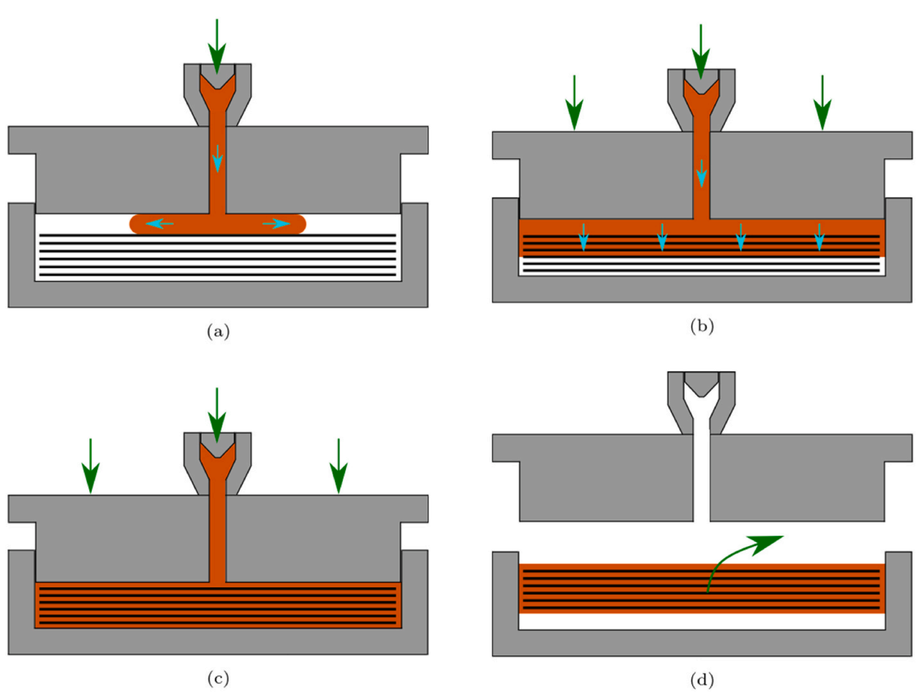

Fig. 2. In the thermoplastic compression resin transfer molding a) the fibers are place into the mold and heated up to the process temperature, when the molten thermoplastic is injected b), c) with the application of pressure the molten plastic impregnates the fibers in the short transverse direction and d) then the demolding is done. Adapted from (Studer et al., 2019).

matrix of the final composite (Aegerter et al., 2018). Textiles made from these coated fibers are easily consolidated into structures by stamp forming as described in (Schneeberger et al., 2017, Schneeberger et al., 2020) and represented in Fig. 4. In the st-HBF, glass beads (SiLibeads Typ SL, Sigmund Lindner) are melted, and glass fibers are drawn out. These fibers are drawn over a so-called kiss roll where they are coated with a thermoplastic solution, here polycarbonate (PC: Makrolon 3108, Covestro). The wetted fibers then pass a hot air drying channel in which the solvent, trichloromethane (ReagentPlus® 132,950, Sigma-Aldrich), is evaporated (Aegerter et al., 2018), recovered and reused.

This concept replaces the bottleneck of impregnation with a high-speed hybridization during fiber production and exhibits the advantage of enabling a stamp forming process that is isothermal and very fast (~30 s cycle time, depending on laminate thickness). On the other hand, the challenge is to apply an exact amount of polymer to coat the fibers while they are spun at high speed.

2.2.4. Scenario 4 and 5: conventional epoxy resin compression RTM (C-RTM)

Scenarios 4 and 5 concern the production of the bonnet with the conventional C-RTM process where an epoxy resin impregnates either glass fiber or carbon fiber-based fabrics, described in detail by (Aretxabaleta et al., 2019). The woven fabric is impregnated during the injection molding with resin. C-RTM process allows short cycle times and high throughput compared to the before described thermoplastic RTM processes (scenario 1 and 2) thanks to the inherently lower viscosity of the thermoset resin. On one hand, the use of a thermoset resin instead of thermoplastic matrix materials enables an isothermal process at a lower temperature (120 °C) and so a lower energy consumption during the process. On the other hand, recycling of the bonnet with a thermoset matrix is rather difficult.

2.2.5. Scenario 6 and 7: conventional deep drawing with metal

In Scenarios 6 and 7 the bonnet is produced conventionally with deep drawing of metal sheets, respectively steel and aluminum. The sheet is formed with a deep drawing process into the shape of a bonnet, which allows short cycle times, and high throughput compared to composite production methods.

At the beginning of production, a metal sheet is cut to the right size, preheated (steel: 200 °C, aluminum: 240 °C) and drawn into the forming die. The mold for the deep drawing is heated isothermally (200 °C). For steel, two scenarios where analyzed: one with virgin materials and the other with fully recycled materials. Aluminum is usually a combination of virgin and recycled materials. For analyzing the impact of the ratios, three different ratio were taken into account: in the first one, virgin materials are used while in the second and the third the materials are partly (70%) and fully recycled. The two extreme scenarios were investigated to explore the range of the impact. The case with 70% recycled aluminum represents a realistic case in current automotive

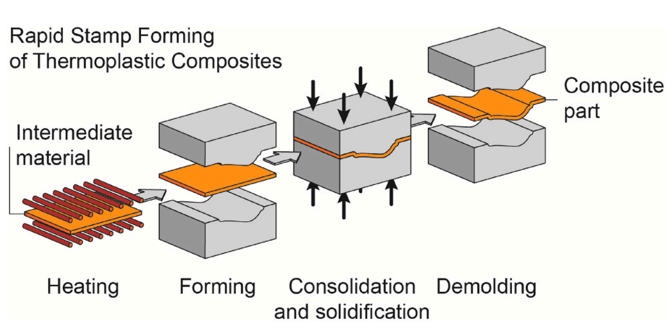

Fig. 4. In stamp forming, a hybrid thermoplastic feedstock material is first heated above forming temperature and then quickly transferred into a press tool which forms, consolidates and cools the material, thereby solidifying the matrix and yielding a fully formed laminate (Schneeberger et al., 2017).

production (Klöpffer and Finkbeiner, 2018).

2.3. Life cycle inventory (LCI)

The LCI in this study was carried out with an input-output-analysis of all the processes within the system boundaries. In this study, data was collected from either experiments, literature or the database Ecoinvent 3.1. We made the following assumptions for the definition of the relevant inventory data:

- Data related to input materials were collected by calculating the mass of used raw materials to produce the respective bonnet.
- Data related to energy and other resources consumed during the production have been calculated mostly considering thermodynamics calculations or directly using the process function (milling, spraying, cutting …) of Ecoinvent 3.1.
- Inventory data for the input materials have been derived from the Ecoinvent 3.1 database.
- Inventory data for the electric energy have been derived from the Ecoinvent 3.1 database where the Swiss country mix was used.
- The Ecoinvent 3.1 database has region-specific data which can be valid for the European market, the global market or the rest of the world. These data are labelled in Ecoinvent as, respectively, {PER}, {GLO} and {RoW}.
- For all the data, the Cut-off System Model was taken. This model is based on the effect that recyclable materials are cut off at the beginning of the treatment processes, becoming available burden-free for following uses.

All scenarios are divided in five main phases. These phases and related assumptions are detailed in the following sections and briefly summarized in what follows. The first one is the tooling phase, which includes the raw materials of the mold and its manufacturing. The second is the raw material phase, which includes all raw materials that end up in the bonnet and their preparation for production. The third one is the manufacturing phase, which includes the energy used in the production process and its energy losses. The fourth one is the life phase, which includes the amount of diesel that is consumed for moving the bonnet over the whole service life. The last one is the disposal phase, which includes the energy for recycling respectively disposal of the bonnet.

2.3.1. Mold

The mold designed to produce a bonnet is assumed to be the same in all scenarios, in the sense that the required amount of raw material and production energy are the same. The stainless-steel mold consists of two parts, an upper and a lower part. The energy input to mill the mold to its shape was taken from Ecoinvent 3.1 based on the amount of steel that is milled away, respectively 4′500 and 2′250 kg for the upper and lower part. The energy used for mold hardening was calculated as the heat quantity that is necessary to heat up the mold once to 1′000 °C and a second time to 500 °C.

We assumed that one mold could be used to produce 100′000 bonnets, which is a typical number for this type of molds in automotive industry, and that an anti-sticking agent followed by the preheating was applied every 2′000 cycles. Table 1 reports all the details about the inventory data related to the mold.

2.3.2. Input materials

The main input materials to produce the composite bonnet are the fibers (glass or carbon) and the matrix material (melt thermoplastic or thermoset resin). For the mTP-RTM process, an additional spacer made of polyphenylene sulfide (PPS) is used between the fiber layers. Steel or aluminum is used for the metal bonnets in Scenarios 6 and 7, respectively. The quantities for the steel and aluminum bonnets were calculated using the volume of the bonnet (2.4×10^{-3} m^3, size of the used

Table 1
The inventory data for the mold used for the calculations.

Item/Material	Upper part	Lower part	Data source
Chromium steel 18/8			
• Amount	108 kg	54 kg	Ecoinvent 3.1[a]
• Milling	14.2 MJ	7.1 MJ	Ecoinvent 3.1[a]
• Hardening	4.2 GJ	2.1 GJ	Calculated
Anti-sticking agent (Polydimethylsiloxane)			
• Amount	1g	1g	Ecoinvent 3.1[a]
• Spraying	14 kJ	14 kJ	Calculated
Preheating:			
• 1 (TP-cRTM)	362 MJ	181 MJ	Calculated
• 2 (mTP-RTM)	391 MJ	196 MJ	Calculated
• 3 (st-HBF)	333 MJ	167 MJ	Calculated
• 4 (C-RTM, glass fibers)	275 MJ	138 MJ	Calculated
• 5 (C-RTM, carbon fibers)	275 MJ	138 MJ	Calculated
• 6 (Deep drawing, steel)	507 MJ	254 MJ	Calculated
• 7 (Deep drawing, aluminum)	507 MJ	254 MJ	Calculated

[a] Ecoinvent data source: GLO.

sheet: 2.4 m^2 with a thickness of 1 mm) and the densities (7860 kg/m^2 and 2699 kg/m^2) of the raw material. The final weights of the calculated bonnets correspond to values found on (Bachem and Opbroek, 2004). Additionally, the ratio of a steel to an aluminum bonnet (19–9.5), including production waste of 2 kg and 0.5 kg respectively, is the same as found in (Masoumi et al., 2011). The amount of steel used for a bonnet was the basis for calculating the amount of matrix and fiber materials used for the composite bonnet to achieve the same mechanical properties, by using the specific weight and Young Modulus of the steel and the composite. The fiber volume content was defined separately for all the processes based on experiments. The environmental impact data for all the raw materials is sourced from the Ecoinvent 3.1 database. Table 2 reports all the details about the inventory data related to the input materials.

The energy required to weave the fibers is calculated according to Koç and Çinçik (2010). The energies for drying the thermoplastic matrix material in the TP-cRTM and mTP-RTM processes were calculated over the temperature of the oven (80 °C) and the used time (4 h) (Eftekhari and Fatemi, 2016). The additional spacer in the mTP-RTM process is produced with injection molding and its production energy was calculated on the basis of the power of the machine (3 kW/kg PPS) and the time used (2 min) (Kaiser and Schlachter, 2019). The energy to roll and cut the steel and aluminum is taken from the Ecoinvent 3.1 database based on the used amount of material (rolling) and the time used (cutting). Table 3 reports all details about the inventory data related to the energy required from input material preparation.

Table 2
The value of the input materials to produce a bonnet.

Scenario	Materials[a]	Quantity
1 (TP-cRTM)	Fiber volume content	55%
	Nylon 6[b]	2.45 kg
	Glass fibers[b]	6.24 kg
2 (mTP-RTM)	Fiber volume content	45%
	Nylon 6[b]	3.14 kg
	Glass fibers[b]	5.35 kg
	Spacer: Polypropylene[c] injection	0.6 kg
3 (st-HBF)	Fiber volume content	50%
	Borosilicate glass fibers	5.82 kg
	Polycarbonate	2.76 kg
	Trichlormethane[b]	0.03 kg
	Activated carbon	0.10 kg
	Electricity, low voltage[d]	205 MJ
4 (C-RTM)	Fiber volume content	45%
	Epoxy resin[b]	2.34 kg
	Glass fibers[b]	6.08 kg
5 (C-RTM)	Fiber volume content	45%
	Epoxy resin[b]	1.83 kg
	Carbon fibers:	
	• Acrylonitrile[e]	6.43 kg
	• Nitrogen, liquid[e]	39.3 kg
	• Epoxy resin, liquid[e]	0.34 kg
	• Electricity, medium voltage[d]	554 MJ
	• Heat, central or small-scale, natural gas[d]	653 MJ
6 (deep drawing)	Steel engineering steel/EU	19 kg
7 (deep drawing)	Aluminum, primary, ingot [f]	9.5 kg

[a] Material data from Ecoinvent 3.1 Database.
[b] Ecoinvent data source: GLO.
[c] Injection molding.
[d] Ecoinvent data source: CH.
[e] Ecoinvent data source: PER.
[f] Ecoinvent data source: RoW.

2.3.3. Process and energy losses

The energies for the injection molding in the TP-cRTM and C-RTM were calculated using the power of the machine and the used time (Kaiser and Schlachter, 2019). The stamp forming in the st-HBF and the deep drawing in the metal processes were taken from the Ecoinvent 3.1 database. The energy for the pressing in the mTP-RTM process was scaled up from the energy used for producing a small plate in the laboratory. In the variothermal processes (TP-cRTM and mTP-RTM) the energy for mold cooling was calculated over the power (Sánchez et al., 2018) and the used time. The energy for preheating the fabric for the stamp forming (200 °C) and the coil for the deep drawing (steel: 200 °C, aluminum: 240 °C) was calculated over the thermodynamics considering the temperature needed for each material (Basril et al., 2017). Table 4 reports all the details about the inventory data related to the different processes.

Thereby the heat radiation of the mold towards the environment and heat convection on the surface or inside the mold were taken into account. Additionally, the energy losses during the preheating of the fabric in the st-HBF and the coil before the deep drawing were calculated using the heat radiation towards the environment. Table 5 reports all the details about the inventory data related to the energy losses.

2.3.4. Life of bonnet

The life of the bonnet is considered over the used diesel over a whole life of a car. The raw material data for diesel was taken from the Ecoinvent 3.1 database. The life of a car is estimated to be 14–15 years. In this time, the car is typically in use for 200,000 to 300,000 km and, annually, from 15,000 to 20,000 km/year (Dun et al., 2015). In this study, a diesel engine car used as the model and its life was defined to be 300′000 km and with a 6 l/100 km diesel consumption on average (International Energy Agency (IEA), 2019). The total weight for the bonnets of the different scenarios is calculated and the used amount of

Table 3
The values of the energy needed to prepare the input materials in each scenario.

Scenario	Process and Quantity				
	Weaving the fibers	Drying the matrix	Injection molding the spacer	Hot rolling metal	Laser cutting metal
	6.8 MJ/kg[a]	1.3 kW/kg[b]	PPS: 3 kg 2 min	Steel: 19 kg Alu: 9.5 kg	10 min[c]
1	42.4 MJ	45.9 MJ	–	–	–
2	36.4 MJ	58.8 MJ	0.22 MJ	–	–
3	59.2 MJ	–	–	–	–
4	41.3 MJ	–	–	–	–
5	23.3 MJ	–	–	–	–
6	–	–	–	105 MJ[d]	217 MJ[d]
7	–	–	–	132 MJ[d]	217 MJ[d]

[a] (Koç and Çinçik, 2010).
[b] (Eftekhari and Fatemi, 2016).
[c] (Gerck and Lima, 1997).
[d] Energy function from Ecoinvent 3.1 Database.

Table 4
The values of the energy needed in the different processes of each scenario.

Scenario	Energy quantity						
	Injection molding	Cooling	Pressing	Heating for spacer	Thermo-forming	Deep drawing	Welding
1	115 MJ	1.1 MJ	–	–	–	–	–
2	–	1.1 MJ	69.0 MJ	45.4 MJ	–	–	–
3	–	–	–	–	105 MJ[a]	–	–
4	61.8 MJ	–	–	–	–	–	–
5	60.9 MJ	–	–	–	–	–	–
6	–	–	–	–	–	101 MJ[a]	21 MJ[a]
7	–	–	–	–	–	50.4 MJ[a]	32 MJ[a]

[a] Energy function from Ecoinvent 3.1 Database.

Table 5
The value of the energy losses in each scenario.

Scenario	Energy quantity			
	Heat radiation	Convection on surface	Convection inside	Heat radiation preheating
1	151.0 MJ	24.6 MJ	15.1 MJ	
2	75.5 MJ	117 MJ	64.3 MJ	33.8 MJ
3	4.0 MJ	0.7 MJ	–	–
4	182.0 MJ	33.8 MJ	–	–
5	182.0 MJ	33.8 MJ	–	
6	159.8 MJ	20.8 MJ	–	
7	159.8 MJ	20.8 MJ	–	

fuel for the specific weight is calculated over the driven kilometers and the density of the diesel (0.83 kg/l). Table 6 reports all the details about the inventory data related to the life of the bonnet.

2.3.5. End of life

At the end of life of the car, the bonnet needs to be disposed or recycled, depending on the scenario. The thermoplastic, steel and aluminum bonnets can be recycled, and the material can be reused. Whereas the thermoplastic is shredded and compounded and can be used for other application with lower requirements since the fiber length is drastically reduced, a so-called down cycling happens, the metals are molten, and the material can be used again, at least with a large fraction, for the same application. The down cycling of the thermoplastic composite was calculated by considering the energy for shredding (2086 kJ for 8.69 kg) and the energy for compounding (8603 kJ for 8.69 kg). No additives for compounding have been considered. For the recycling of the metal shredding was considered by 4080 kJ for 17 kg followed by a melting step at 1500 °C with 11545 kJ for 17 kg.

The composite bonnets made with epoxy resin need to be incinerated and resulting sludge must be disposed of. Table 7 reports all the details about the inventory data related to the end of life of the bonnet.

3. Results and discussion

3.1. Energy consumption

The results of the total energy consumption for all the scenarios are summarized in Fig. 5. The ranking of scenarios in terms of increasing

Table 6
The value of used diesel during the life of the bonnet in each scenario.

Scenario	Total weight of bonnet	Diesel consumption during life
1	8.7 kg	65 kg
2	8.5 kg	63 kg
3	8.7 kg	65 kg
4	8.4 kg	63 kg
5	5.3 kg	39 kg
6	17 kg	127 kg
7	6.0 kg	45 kg

Table 7
The value of the energy used in the end of the life of the bonnet in each scenario.

Scenario	Process and Quantity				
	Shredding	Compounding	Melting	Hot rolling	Incinerating
	50 MJ/kg [a]	110 MJ/kg [b]		Steel: 19 kg Alu: 9.5 kg	12 MJ/kg [c]
1	2.1 MJ	8.6 MJ	–	–	–
2	2.0 MJ	8.4 MJ	–	–	–
3	2.1 MJ	8.6 MJ	–	–	–
4	–	–	–	–	100.8 MJ
5	–	–	–	–	62.4 MJ
6	–	–	11.5 MJ	94.1 MJ[d]	–
7	–	–	6.3 MJ	125.3 MJ[d]	–

[a] (Shuaib and Mativenga, 2016).
[b] (Steer, Omega, technical data sheet, 2011).
[c] (Joshi et al., 2004).
[d] Energy function from Ecoinvent 3.1 Database.

energy needs is: deep drawing recycled aluminum, the thermoplastic composites and C-RTM with glass fibers, C-RTM with carbon fibers and partly recycled aluminum, deep drawing steel (virgin or recycled) and finally virgin aluminum. All the three novel thermoplastic composites production methods and C-RTM with glass fibers require almost the same energy. Use phase dominates clearly the impact for the steel scenarios, due to the part weight. When compared to aluminum, the difference mostly arises from the energy required to produce the raw metal. This latter is very elevated for new aluminum but negligible when recycled. When replacing glass with carbon fibers for the C-RTM process, we find that the reduced fuel consumption does not compensate for the higher energy required to produce carbon fibers.

When comparing the different composite production methods, the main differences between the processes arise from the inherent differences between various raw materials. The processing itself including energy losses makes up only for a small portion of the whole energy balance and is similar for the different processes except for st-HBF, which displays very low energy losses. The total energy for the raw material in the st-HBF process is summarized, as the fibers are coated directly during its production. In the overall, the energy consumption to produce a composite is, for all the composite processes with glass fibers, in the same range independently if the fibers are impregnated during or after their production.

In all the cases, the mold (its raw materials, production and preparation) has a negligible energy impact. The energy used for the mold is only 1–2% of the total energy need for the bonnets.

Fig. 6 analyses the energy required over the use life of a car for the different scenarios considered in this study. The grey area represents the energy of a steel bonnet made with partially recycled materials and is therefore bounded by the completely new and recycled steel respectively on the top and bottom. The value at zero km represents the energy consumed for production, which then changes with the distance

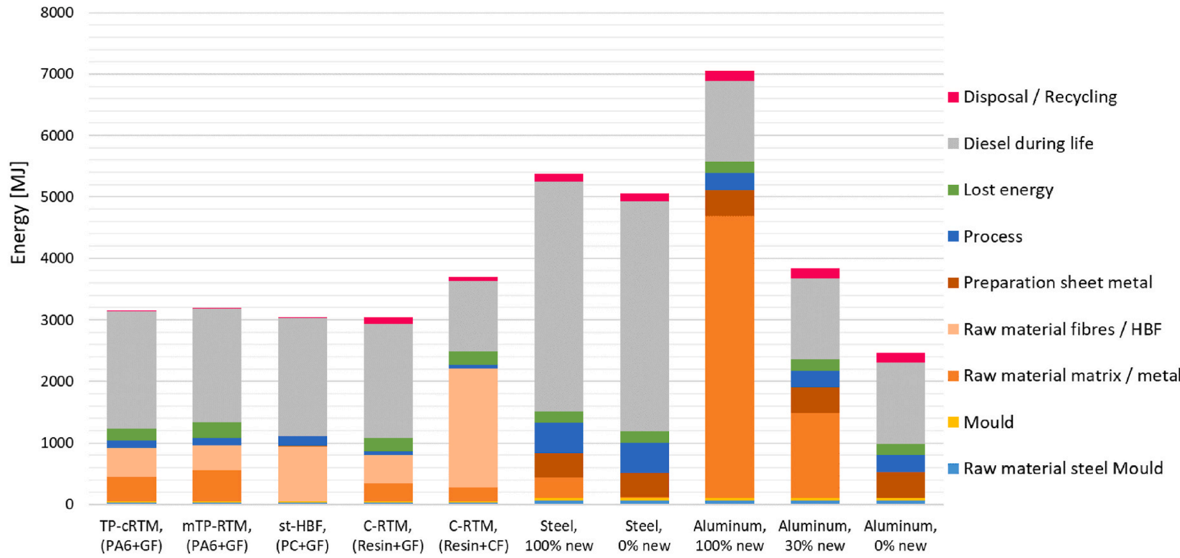

Fig. 5. A comparison of the results of the energy consumption for the different scenarios.

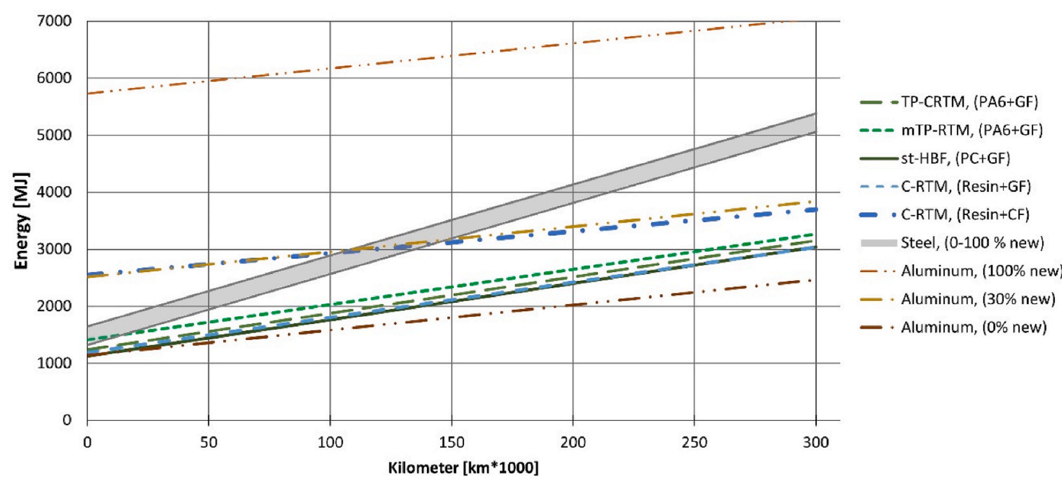

Fig. 6. A comparison of the energy consumption over the lifetime of a car for all the scenarios.

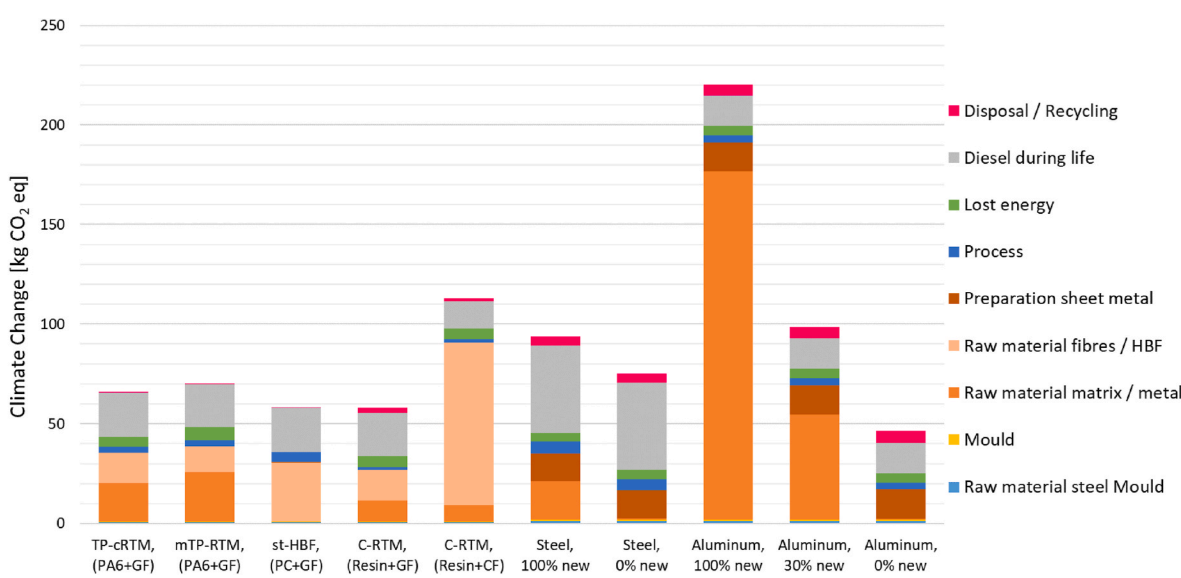

Fig. 7. A comparison of the Impact on the climate change of each scenario.

travelled at different rates depending on the weight of the bonnet. The value at 300′000 km at the end of life of the car corresponds to the final energy consumption.

All composite bonnets with glass fibers show similar energy consumption at the beginning, as mentioned earlier. Regarding the resin C-RTM with carbon fibers and the process with 30% new aluminum, the crossover region with respect to steel occurs after 100′000 to 150′000 driven kilometers depending on the percentage of recycled material. For aluminum, the large difference in energy required for the production depending on the percentage of recycled material makes it so that it can perform either best or worse than any other method considered here. Its low weight also makes it more attractive the longer the lifetime of the vehicle is.

3.2. Environmental impact

Fig. 7 to Fig. 10 show the results for the environmental impact of all the scenarios regarding climate change, ecosystem quality, human health and resources. The classification of the scenarios in increasing order of emitted CO_2 equivalent remains the same, with the exception that C-RTM with carbon fibers is found more polluting than steel, if a Swiss energy mix is considered. The different glass fiber-reinforced composites processes are very similar and offer a very good performance, only topped by the ideal case of fully recycled aluminum, which is not yet common. If a car bonnet was to be produced with coated bicomponent fibers, the best performing process among glass fiber-reinforced composites production methods, 22% of CO_2 emission corresponding to 16.8 kg could be saved over the lifetime of a bonnet considering that the average steel contains 100% recycled steel. The climate change in terms of kg is related to the energy balance and depends on both the amount of the different energy sources and how polluting these are. In this study, the main energy sources are diesel and electricity. The efficiency of the diesel motors influences the amount of CO_2 emissions, which is why this topic is already the subject of many regulations worldwide. The energy mix, however, strongly varies from region to region and mainly depends on the proportion of renewable and nuclear energy. Thus, the results are heavily influenced by the location of production. In this study, the Swiss electricity mix was considered, which shows a similar CO_2 balance as the France electricity mix. If the bonnet is produced in Germany, the CO_2 impact is nearly double in comparison to producing the bonnet in Switzerland or France. This shows the high influence of the different electricity mix of the countries (Densing et al., 2014; Kim et al., 2010).

Regarding the ecosystem quality (Fig. 8) and the human health (Fig. 9), all composite bonnets, regardless of fibers, show a lower impact compared to both metals independently of their amount of recycled materials. The diesel consumed during the lifetime of a bonnet has the greatest impact on ecosystem quality for the composite bonnets with glass fibers, while it remains nonetheless rather large for the metal processes. The largest influence on the ecosystem quality for the metal processes is the forming step, namely the deep drawing due to the high temperatures that are used to shape the steel and aluminum. For the steel bonnet (fully new or recycled), the deep drawing accounts for about 60% of the total impact. The influence of the deep drawing regarding the human health, accounts for around 10% for the steel (new and recycled) and the fully recycled aluminum bonnet. The main impact to human health results from the fully new aluminum to around 80% of the total.

Regarding the used resources (contributing the mineral extraction and non-renewable energy consumption), the diesel consumed during the life of the bonnet has the greatest impact for all the scenarios. The used carbon fibers and the virgin aluminum has the greatest impact on the resources regarding the raw materials. The carbon fibers has a 10 times higher demand for resources as the glass fibers and about 15% more than the virgin aluminum. The production with fully recycled steel and aluminum has the lowest impact to the resources as the raw material has nearly no impact. All the composite bonnets made with glass fibers have more or less the same impact around 1′000 MJ primary.

3.3. Sensitivity analysis

The results of the sensitivity analysis of thermoplastic compression RTM, melt thermoplastic RTM and stamp forming hybrid bicomponent fibers are shown respectively in Fig. 11, Fig. 12 and Fig. 13. For all three methods, the energy balance is most sensitive to the number of used materials, directly related to how efficiently the materials are used and how much waste is generated. Because the base materials make up for most of the energy balance, reducing their amount by a certain percentage almost decreases the energy balance by that same percentage. Efficient use of the raw materials should therefore a main concern when considering the energy balance, and the costs of the final part. For TP-cRTM we observe that the process temperatures and cycle time also exert an influence, these aspects are however linked because the temperature influences the viscosity of the molten thermoplastic and therefore the impregnation time (Studer et al., 2019). The question that should be investigated in further studies is whether the increased energy

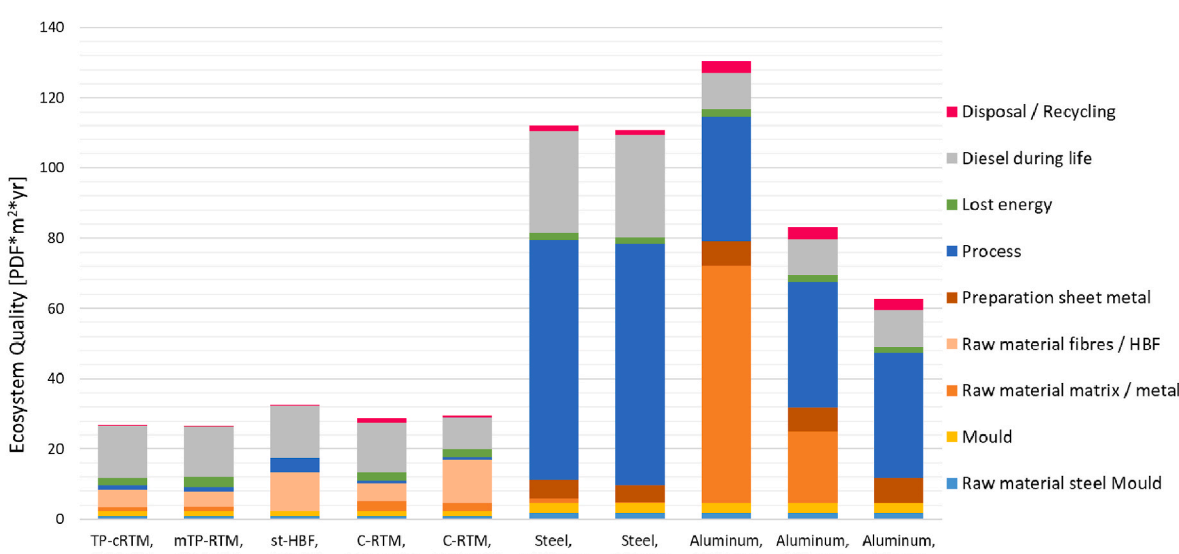

Fig. 8. A comparison of the Impact on the ecosystem quality of each scenario.

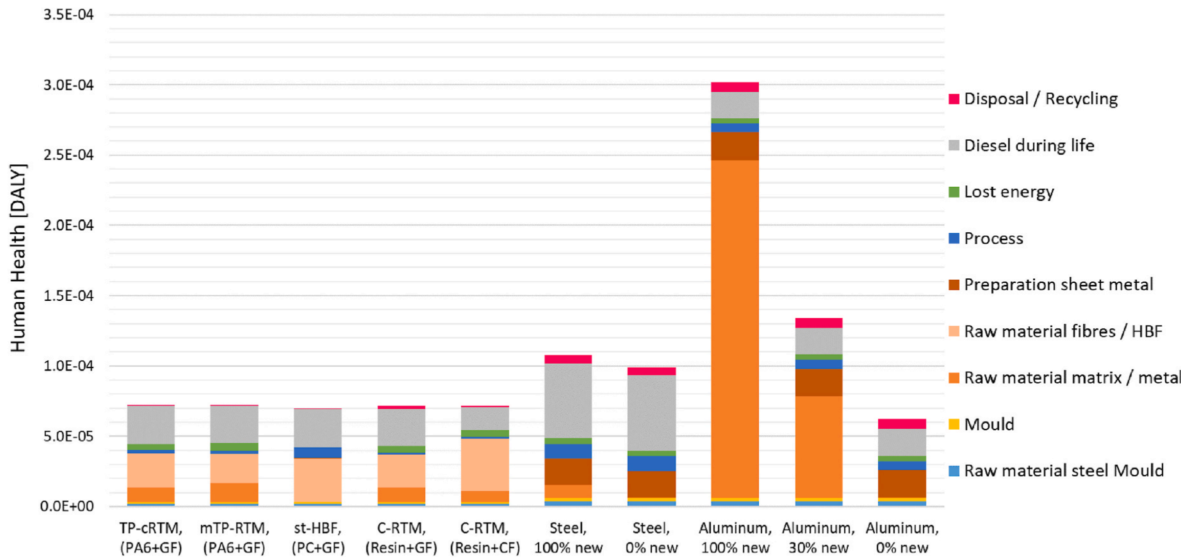

Fig. 9. A comparison of the impact on the human health of each scenario.

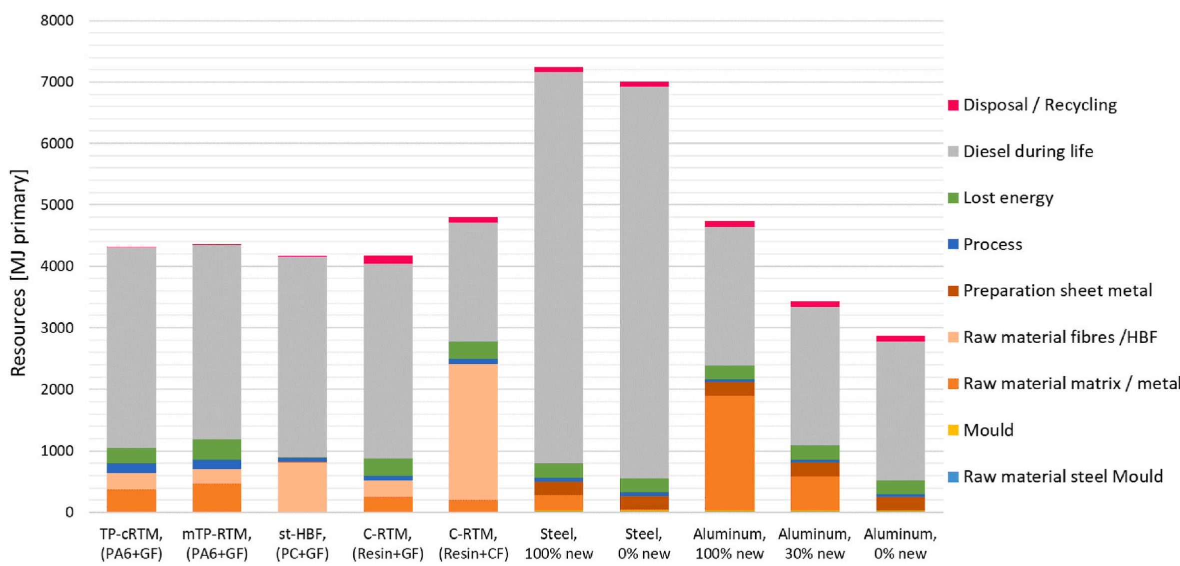

Fig. 10. A comparison of the Impact on the resources of each scenario.

required at higher temperatures is counterbalanced by the reduced process time. For TP-cRTM, the results indicates that the process time has an influence on the energy balance while the process is relatively insensitive to the temperature while st-HBF is influenced neither by the process time nor by the temperature.

4. Conclusion

In this study, we investigated the ecological performance of three novel thermoplastic composites production techniques for the case study of a car bonnet for a vehicle with a diesel combustion engine. These methods were compared against glass or carbon reinforced thermoset composites produced with compression resin transfer molding and state-of-the-art metal bonnets made of either virgin, partly or fully recycled steel or aluminum.

Comparing the different composite production methods revealed that stamp forming hybrid bicomponent fibers has the lowest energy demand mainly because of very efficient fast stamp forming process. The thermoset-based C-RTM process also displays a good performance in the life cycle analysis. However, thermosets are less suitable for cradle-to-cradle processes when compared to thermoplastics which can be recycled. Investigation on C-RTM produced with either glass or carbon fibers shows that the more energy-intensive carbon fiber production is not compensated by its lower weight over the lifetime of the vehicle. In thermoplastic composites the raw materials are the main cause of CO_2 emissions, an efficient process minimizing waste is therefore important to minimize the CO_2 balance. Regarding the RTM-based processes, their optimization through a reduction of the process time or reduction of waste could make these processes even more competitive.

The study shows that all thermoplastic composites bonnets require a lower fuel consumption because of the lower weight and will result in a better energy balance given that the vehicle drives a long enough distance. When considered for the average distance travelled by a car, bonnets made of fully recycled aluminum (ideal case) are found to perform best from a CO_2 emission point of view because of the low energy required for production, followed by the glass fiber reinforced composites produced by C-RTM, then stamp forming hybrid bicomponent fibers and thermoplastic compression resin transfer molding. Steel

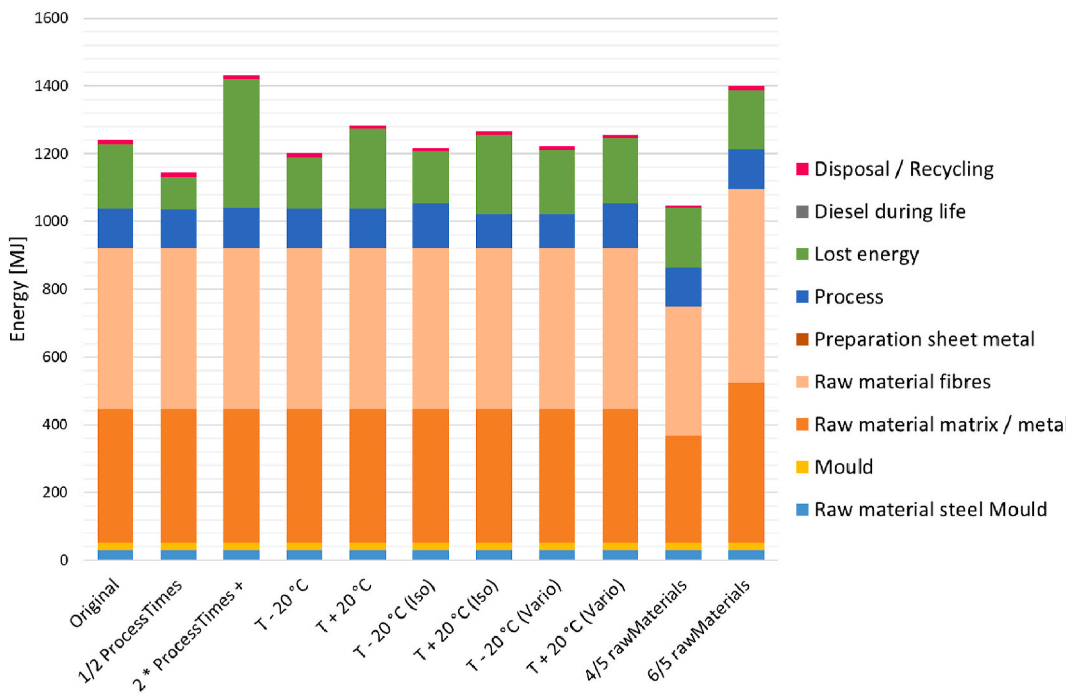

Fig. 11. The results of sensitivity analysis of the thermoplastic compression RTM process (Scenario 1) showing the impact of the variation of the three processes temperatures from 280 °C to 320 °C for the variothermal part during injection, the isothermal mold from 130 °C to 170 °C and the mold heating temperature from 215 °C to 245 °C, the impact of the processing time variation from 8.25min to 33min and the impact of material usage between 7 kg and 10.4 kg on the energy.

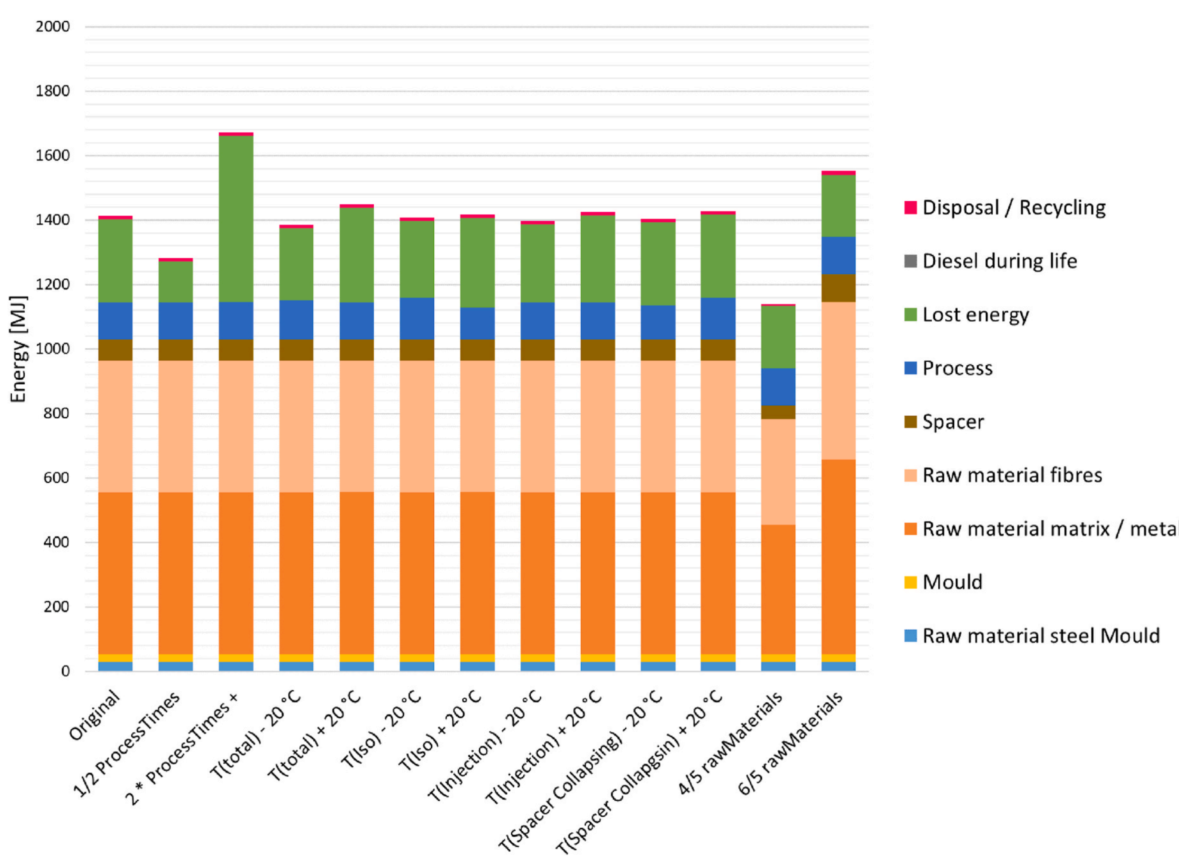

Fig. 12. The results of the sensitivity analysis of the melt thermoplastic RTM process (Scenario 2) showing the impact of the variation of the four processes temperatures from 220 °C to 260 °C for the variothermal part during injection, the isothermal mold from 140 °C to 180 °C and the mold temperature for ejection from 140 °C to 180 °C and the temperature for the spacer collapse from 290 °C to 330 °C, the impact of the processing time variation from 37min to 147min and the impact of material usage between 7.3 kg and 10.9 kg on the energy.

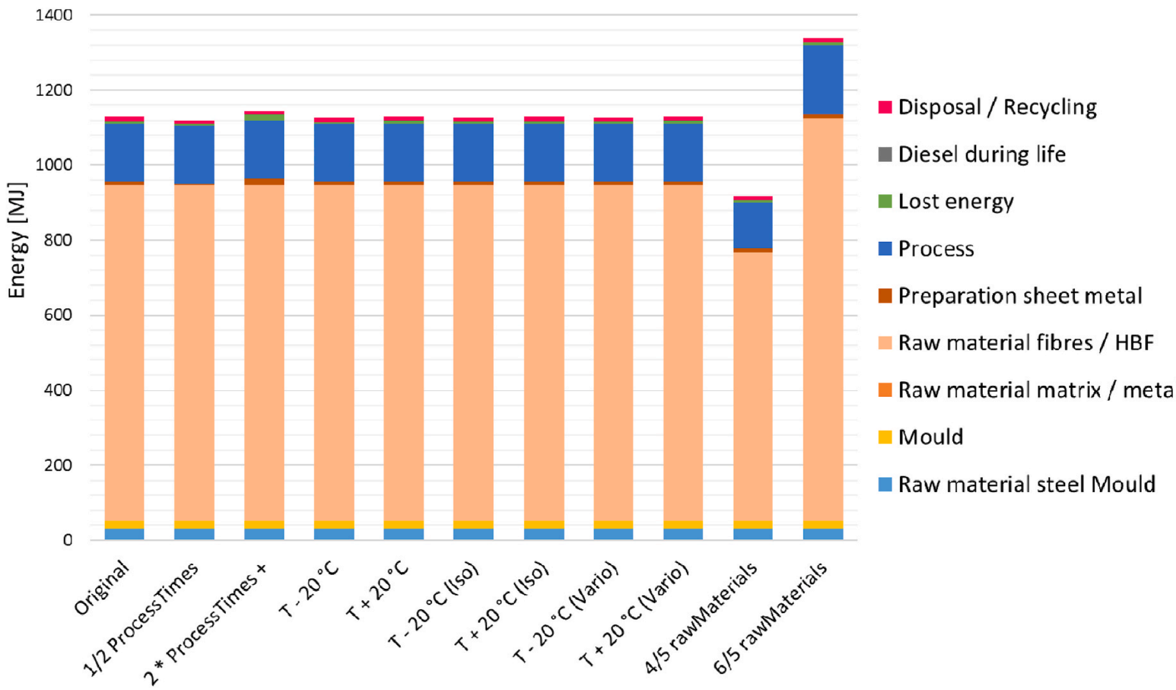

Fig. 13. The results of the sensitivity analysis of the stamp forming hybrid bicomponent fibers process (Scenario 3)) showing the impact of the variation of the three processes temperatures from 180 °C to 220 °C for the preheating of the fabric, the press mold from 120 °C to 160 °C and the combination of both, the impact of the processing time variation from 35s to 140s and the impact of material usage between 7 kg and 10.4 kg on the energy.

bonnets produced either with virgin or recycled steel are found to consume considerably more energy over their lifetime than the other production methods and produce more CO_2 than the before mentioned methods, but less than carbon-fiber reinforced composites produced with C-RTM. Bonnets produced with virgin aluminum were found to perform with distance worse than any other methods.

Regarding the production of metal bonnets, we find that fully recycled aluminum performs best also when compared to composite ones. As a bonnet need to fulfill sufficient mechanical stiffness, fully recycled aluminum is not realistic, thus a more realistic case with 70% recycled aluminum is analyzed. This case shows a higher impact to the energy and CO_2 balance as the composite processes with glass fibers and a comparable impact to the C-RTM process with carbon fibers.

The results of this research show the great potential of these novel thermoplastic composite production methods to reduce environmental impact and shows where potential for optimization lies to become even more efficient and competitive. It was found that fully recycling aluminum (ideal case) leads to an important improvement of the energy and CO_2 balance which led to the best overall performance. Considering that for composites the raw materials are also energy and CO_2 intensive, it is reasonable to anticipate that using recycled materials in composites will lead to a decreasing environmental impact. An option for recycled PA6 old fishing nets and for the glass fibers knitted fibers as a fabric can be taken in account for example. Novel bio-based precursors for carbon fiber production, or the use of renewable resources are also a route currently investigated by automotive users. In the future, we see huge potential of using cradle-to-cradle materials for more sustainable products, which will require further improvements in recycling technology to reach its full potential.

CRediT authorship contribution statement

Stephanie Wegmann: Formal analysis, Data curation, Validation, Investigation, Methodology, Writing – original draft, Writing – review & editing, Software. **Christian Rytka:** Conceptualization, Funding acquisition, Supervision, Writing – original draft, Writing – review & editing, Project administration. **Mariona Diaz-Rodenas:** Investigation, Writing – original draft, Writing – review & editing. **Vincent Werlen:** Investigation, Methodology, Writing – original draft, Writing – review & editing, Validation. **Christoph Schneeberger:** Data curation, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Paolo Ermanni:** Investigation, Methodology, Funding acquisition, Project administration. **Baris Caglar:** Data curation, Investigation, Methodology, Writing – original draft. **Colin Gomez:** Data curation, Investigation, Methodology, Writing – original draft. **Véronique Michaud:** Conceptualization, Methodology, Funding acquisition, Writing – original draft, Writing – review & editing, Project administration, Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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