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Life cycle impact assessment of different manufacturing technologies for automotive CFRP components

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Abstract

A comparative life cycle assessment analysis among pressure bag molding and bag molding with autoclave for the manufacturing of car components in carbon fiber reinforced plastic (CFRP) was carried out. Four scenarios were analysed: i) autoclave bag molding with aluminum mold, ii) autoclave bag molding with CFRP mold and plastic master, iii) autoclave bag molding with CFRP mold and medium density fiberboard master, and iv) pressure bag molding with aluminum mold. The collected data for life cycle inventory derives from an Italian manufacturer of CFRP car components, scientific references and Ecoinvent database. Cumulative energy demand, global warming potential, ReCiPe midpoint and endpoint methods were used as impact and damage categories for quantifying the environmental impacts of the different manufacturing processes investigated. The results showed that the pre-impregnated composite fibers with thermoset polymer matrix, used as input material for the four investigated scenarios, represents the main source of total environmental impact, due to the use of polyacrylonitrile as a precursor for carbon fibers. The comparison among the environmental assessments of the different scenarios demonstrated that the most impacting process is the autoclave bag molding with composite mold and polyurethane master, whilst the most sustainable process is the autoclave bag molding with aluminum mold.

Keywords: autoclave process, pressure bag molding, life cycle assessment, carbon fiber reinforced plastics.

1. Introduction

The growing awareness of global warming and environmental pollution problems due to the massive use of fossil fuels is pushing car manufacturers to convert their production towards sustainable mobility, such as electro- and hydrogen-mobility. An approach that is gaining interest in mass savings and, at the same time, performance improvements consists in replacing metals with lighter materials, such as Carbon Fiber Reinforced Plastics (CFRPs), to manufacture both structural and non-structural parts (European Environment Agency, 2018; Kabashi et al., 2020; Khorramshahi and Mokhtari, 2017). CFRPs are multifunctional composites characterized by relevant stiffness-to-weight and strength-to-weight ratios (Akbarpour and Akbarpour, 2016; Wilson, 2017); furthermore, they exhibit other important characteristics as corrosion resistance, thermal and electrical insulation, and chemical resistance (Ebrahimpour Komleh and Maghsoudi, 2018).

In the last years, the use of composite materials was limited to high-end applications, in which very high performances were required, despite the high costs. Nowadays, the cost of components fabricated in composite materials are becoming more competitive and more attractive for the consumer' market owing to the growing demand and the development of new manufacturing processes (Holmes, 2017). For this reason, a massive use of these materials is expected also for high production volumes, contributing to the reduction in the use-phase energy consumption of vehicles. However, the replacement of metals, such as steel or aluminum alloys, with carbon fiber reinforced thermoset composites can entail several drawbacks in terms of higher energy consumption, greater environmental impacts during the manufacturing phase, and lower recyclability of the materials at the product end of life (Delogu et al., 2017; Egede, 2017; Kim and Wallington, 2013). Furthermore, an amount of composite waste is generated, as manufacturing cut-offs, out-of-date laminates, testing materials and end-of-life components (Nunes et al., 2018). Therefore, an accurate investigation to evaluate the environmental aspects associated with the raw material production and fabrication processes to obtain CFRP components is a fundamental requirement (Kyono, 2016). A well-established method to evaluate the environmental impacts of products and/or processes is the Life Cycle Assessment (LCA) that, in accordance with the ISO 14040 and ISO 14044 international standards, consists in "the compiling and evaluation of the inputs and outputs and the potential environmental impacts of a product system during a product's lifetime" (ISO-International Organization for Standardization, 2006a, 2006b). As far as the environmental analysis of manufacturing processes of composite materials is concerned, some studies based on the LCA approach are available in literature. Song et al. investigated the energy emissions of the pultrusion process of composite materials in order to compare the environmental impact of pultruded composite materials with respect to those of forming processes to obtain steel and aluminum alloy profiles for automotive applications. The results in the application to trucks and buses showed that pultruded composite parts allow to save energy with respect to steels whilst more energy is consumed as compared to aluminum alloys (Song et al., 2009). Raugei et al. carried out a complete LCA with the aim to compare environmental aspects associated to the components in aluminum alloys, magnesium alloys and carbon fiber composites used in a passenger vehicle. Their analysis showed that the maximum reduction of the full life cycle impacts using composite materials was about 7% (Raugei et al., 2015). Duflou et al. analyzed the environmental impacts of a car component produced in CFRP, showing that the most impactful phase of the entire lifespan is the manufacturing of carbon fibers, by far heavier than the injection molding process (Duflou et al., 2009). Das compared the energy required for producing a component with carbon fibers obtained using two precursors, lignin and polyacrylonitrile (PAN). It was demonstrated a strong reduction in the environmental loads as the natural precursor was used (Das, 2011). However, in order to produce more eco-friendly carbon fibers, different solutions from the PAN are under investigation by researchers and industries (Hermansson et al., 2019; Mainka et al., 2015). Other authors (Das, 2011; Vita et al., 2019a) demonstrated that a further area to realize more sustainable CFRP components consists in the reduction of environmental impacts generated during their manufacturing processes.

Processes based on pre-impregnated materials (commonly called prepreg), such as bag molding, pressure bag molding or compression molding are typically associated to the best mechanical properties of the components, obtained through high compaction pressure and long curing time which allow resin flow and void avoidance. Methods based on dry fibers, such as resin transfer molding or its high-pressure variants, are preferred as process performances, such as manufacturing time, is predominant with respect to product performances (Kim et al., 2019). The bag molding process is the appropriate method as high-performances and low production volumes are required (Advani and Hsiao, 2012). In this process, a carbon fiber fabric or tape, pre-impregnated with a thermoset matrix, is stacked in a sequence over an aluminum or plastic mold. Then, a vacuum bag is realized by using different consumables (peel ply, release film, plastic bag, etc.), and the curing phase occurs in an oven or in an autoclave. The autoclave is used as the highest performances must be reached since it allows to apply high pressure values to the laminate during the curing phase. This manufacturing process typically requires long lay-up and curing times, associated with high production costs. As far as the environmental aspects are concerned, the bag molding process with the autoclave curing is related to high environmental impact as compared to other curing systems, as reported by Witik et al. (Robert A. Witik et al., 2011). Similar results were obtained by Song et al., who demonstrated that pre-impregnated materials, cured in an autoclave, can result in an energy intensity up to 5 times higher than a similar component produced by resin transfer molding (Song et al., 2009).

In order to overcome such drawbacks, several Out-Of-Autoclave (OOA) processes have been investigated by industrial and academic researchers in order to find methods able to provide the high performances achieved from autoclave processes, but reducing time, costs and minimizing environmental impacts (Advani and Hsiao, 2012). A very promising method is the pressure bag molding (PBM), in which pressure is applied through the inflation of a silicone bag over a prepreg preform placed in a metallic mold which is heated to cure the resin (Crivelli Visconti and Langella, 1992; Mitchell and Society of Manufacturing Engineers., 1996). The silicone bag used in the counter-side is designed to resist very high pressures, higher than 10 bar, and ensure a hydrostatic compaction of the preform, thus simulating the autoclave process (Drozda et al., 1983). Consumables (perforated release film, breather fabric and plastic film) are used to allow air and volatile extraction and to protect silicone rubber from the acid environment of the epoxy matrix. The curing of the preform typically occurs in a hydraulic press with hot platens which provide heat necessary for the curing (Vita et al., 2019b). This heating system is more efficient than the autoclave because the heating of laminate occurs by conduction from hot platens instead of convection taking place in autoclave curing. It allows to decrease the curing time of the resin and, thus, to increase productivity. Unfortunately, the analysis of the state of the art shows a lack of data about the environmental impacts of the pressure bag molding process, and, as a consequence, the lack of knowledge of the environmental sustainability of PBM process as compared to bag molding and autoclave processes. Moreover, due to the scarcity of information about transportation, different scientific researches tend to neglect the contribution of this aspect.

In this framework, the present work aims at assessing the environmental impacts of the pressure bag molding process, in order to compare the environmental sustainability of PBM and bag molding processes in a life cycle perspective, from the raw materials extraction until the end of the manufacturing processes, considering also the transportation. To this purpose, the standard LCA methodology was used to assess the environmental aspects associated to the manufacturing of an automotive component, chosen as a reference case study. In particular, four different scenarios were compared, in order to evaluate the contribution of such process alternatives and identify the potential improvement opportunities. The environmental impacts were quantified in terms of the most appropriate and widespread impact and damage categories in the sector of composite materials, such as Cumulative Energy Demand, Global Warming, Potential, ReCiPe Midpoint and Endpoint. The comparison between the environmental aspects obtained by the different scenarios demonstrated that the most impactful process is autoclave bag molding with polyurethane master, whilst the scenario with autoclave bag molding with aluminum mold leads to the lowest environmental impact.

The current study is organized as follows: after the section concerning the Introduction, in which the authors frame the present study within the state of art, the section 2 “Material and Methods” explains the goal of the study and the functional unit, according to the ISO standards; furthermore, the four scenarios for manufacturing the automotive component chosen as case study are described in details, as well as the system boundaries, the full details about the life cycle inventory and the chosen impact assessment methods. The section 3 “Results and discussion” shows the results of the comparison between life cycle impact assessments of the PBM and bag molding manufacturing processes for the production of CFRP components, calculated by using the life cycle inventory data and the chosen environmental impact categories. Finally, the section 4 “Conclusions” reports a summary of outcomes and some proposal for future developments.

2. Material and Methods

The LCA has been used as analysis methodology to quantify and compare the environmental impacts of the considered CFRP component production processes. LCA is an ISO standard methodology (ISO 14040-14044) largely used in the context of environmental engineering to assess the environmental load of products, processes, services and activities in a life cycle perspective (from cradle to grave). Each ISO-compliant LCA analysis must include four different but strictly correlated phases. Firstly, the objectives of the analysis, the functional unit and the system boundaries (spatial and temporal) need to be defined (*1. Goal and Scope definition*). Secondly, according to the chosen goal and scope, all the relevant data (primary and secondary) need to be collected to build a product/process lifecycle model. More specifically, this phase envisages to subdivide the system under analysis in unitary processes and to realize an input-output analysis to classify and quantify all the relevant flows included within the system boundaries (*2. Life Cycle Inventory – LCI*). Thirdly, the input-output flows are "translated" in impact categories (midpoint and endpoint) by means of different impact assessment methodologies that use specific factors for the characterization and weighing of flows (*3. Life Cycle Impact Assessment – LCIA*). Finally, the obtained results must be analyzed and interpreted against the objectives set at the beginning of the LCA study. Moreover, the standards encourage the continuous review of the different choices with the aim to optimize the entire analysis (*4. Results Interpretation*).

This section details the first two phases, while results and related interpretations and discussions are presented in the following section 3.

2.1 Goal of the study and Functional unit

The goal of this research is to measure and compare the environmental impacts of two manufacturing process for CFRP: PBM and bag molding with autoclave curing. More in detail, the LCA study aims to compare different scenarios and establish which is the greener in a life cycle perspective. The results should be principally of interest for the composite industries in order to reduce the environmental loads of their process always keeping performance unchanged. In addition, this comparative study can be the base for a reconsideration of the composites from an environmental point of view.

The component analyzed in this study is a CFRP hood of a luxury car. This part is made of high-strength carbon fiber fabric and epoxy resin and it is composed of two main parts, one aesthetic and another structural. The latter, called rib, is aimed at reinforcing the thinner layer of the aesthetic part and accounts for 7,5 kg. The final total weight of the part is around 11 kg, while the surface of the hood is around 1,8 m^2. The component is realized by laminating together different prepreg templates during the lay-up phase. The templates are realized by means of a computer numerical controlled (CNC) cutting machine but the stacking sequence cannot be showed in detail due to the confidentiality of some project data. However, the total perimeter of the cut templates is 19 linear meters.

The Functional Unit (FU), in accordance to the ISO standards, has been defined as *the manufacturing of a CFRP car hood which presents the characteristics above reported, by using different manufacturing scenarios.* The following scenarios were considered in this research, namely:

- Scenario 1: autoclave processing with aluminum mold
- Scenario 2: autoclave processing with composite mold, plastic master
- Scenario 3: autoclave processing with composite mold, medium density fiberboard master
- Scenario 4: PBM processing with aluminum mold

2.2 System boundaries and scenario description

The life cycle assessment conducted in this research can be classified as “cradle to gate”. Raw materials and manufacturing phases are considered whereas the use and end of life of the product (i.e. car hood) is neglected. The hood disposal has not been considered because the different scenarios lead to very similar products with small weight variations which means identical impacts in the use and disposal phases. The manufacturing of carbon fibers and of epoxy resin is considered including the transport from the manufacturer (Japan and Germany respectively) to central Italy where the prepregging operation is done. This step of the process, reported in green in Figure 1, is common for all the 4 aforementioned scenarios. The industry where the hood is realized is also placed in central Italy. Intercontinental routes are done by ship while continental routes by trucks with different gross tonnages depending on the distance to be covered. Consumables impacts are included only for what regard manufacturing phase; their transports, instead, are neglected due to the limited quantities and thus the irrelevant environmental contribution.

2.2.1 Scenario 1: autoclave processing with aluminum mold

The scenario 1 concerns the production of the CFRP hood through the vacuum bag process with an aluminum mold. Such molds are preferred when the durability of the tools is predominant with respect to the quality of the parts. Indeed, aluminum molds typically present different thermal distortions from the prepreg preform and, thus, it can result in low geometrical quality of the parts. However, they are widely used in the composite industry due to their high wear resistance which guarantees the use for, at least, 100 times.

In Figure 1, this scenario is represented by the blue boxes. The raw aluminum is extracted and then machined through a 5-axis CNC machine. The lay-up, curing and the demolding phases are considered identical for the three autoclave scenarios (i.e. scenario 1, 2 and 3) due to the slight differences which can be found in using CFRP or aluminum molds.

2.2.2 Scenario 2: autoclave processing with composite mold, plastic master

The second scenario regards the vacuum bag process with CFRP molds, manufactured by laminating over a plastic master. The latter is realized using a polyurethane foam, commonly called Ureol®, which allows the manufacturing of high quality CFRP molds. The use of CFRP molds is suggested when the performances of the component are more relevant than the costs. Indeed, plastic masters are suitable for obtaining molds with high surface, dimensions and geometrical properties but their cost is higher than other kind of masters.

In Figure 1, this scenario is pictured in light blue. After plastic boards production, they are glued together and machined a by a 5-axis CNC machine. The useful life of a plastic master is typically defined as 10 uses and after that, it is disposed in landfill. The composite mold is then manufactured exploiting a typical vacuum bag process. This mold is used for the production of the hood and it can be used, before the degradation of the surface quality, for 150 times.

2.2.3 Scenario 3: autoclave processing with composite mold, medium density fiberboard master

The scenario 3 is very similar to the scenario 2 and it is depicted in pink in Figure 1. The difference is represented by the use of a medium density fiberboard (MDF) master boards and its machining. The cost of the two master typologies (Ureol vs MDF) is considerably different. Indeed, the cost of the MDF is 8/10 times lower than the plastic foam but the quality of the CFRP molds obtainable is significantly lower.

2.2.4 Scenario 4: PBM processing with aluminum mold

The scenario 4 is totally different from the others (yellow boxes in Figure 1). There is the presence of a silicone counter-mold, manufactured by a curing reaction in an oven. In addition, the aluminum quantity required for the production of the mold is higher with respect to the vacuum bag process due to the high pressure it needs to withstand in the press. Moreover, the consumables required for the lay-up of the composite part are different both in term of types and quantities. Indeed, for the PBM process, only a plastic film, a breather and a perforated film are used to protect the counter-mold, to allow air extraction and to absorb resin excess. The curing phase is very different from the vacuum bag autoclave process because the press exploits heat conduction instead of convection and the mass (thermal inertia) of the mold for PBM is sensibly higher. For what concern the demolding phase, it requires an energy intensive cooling system, typically based on a specific fluid (ethylene glycol).

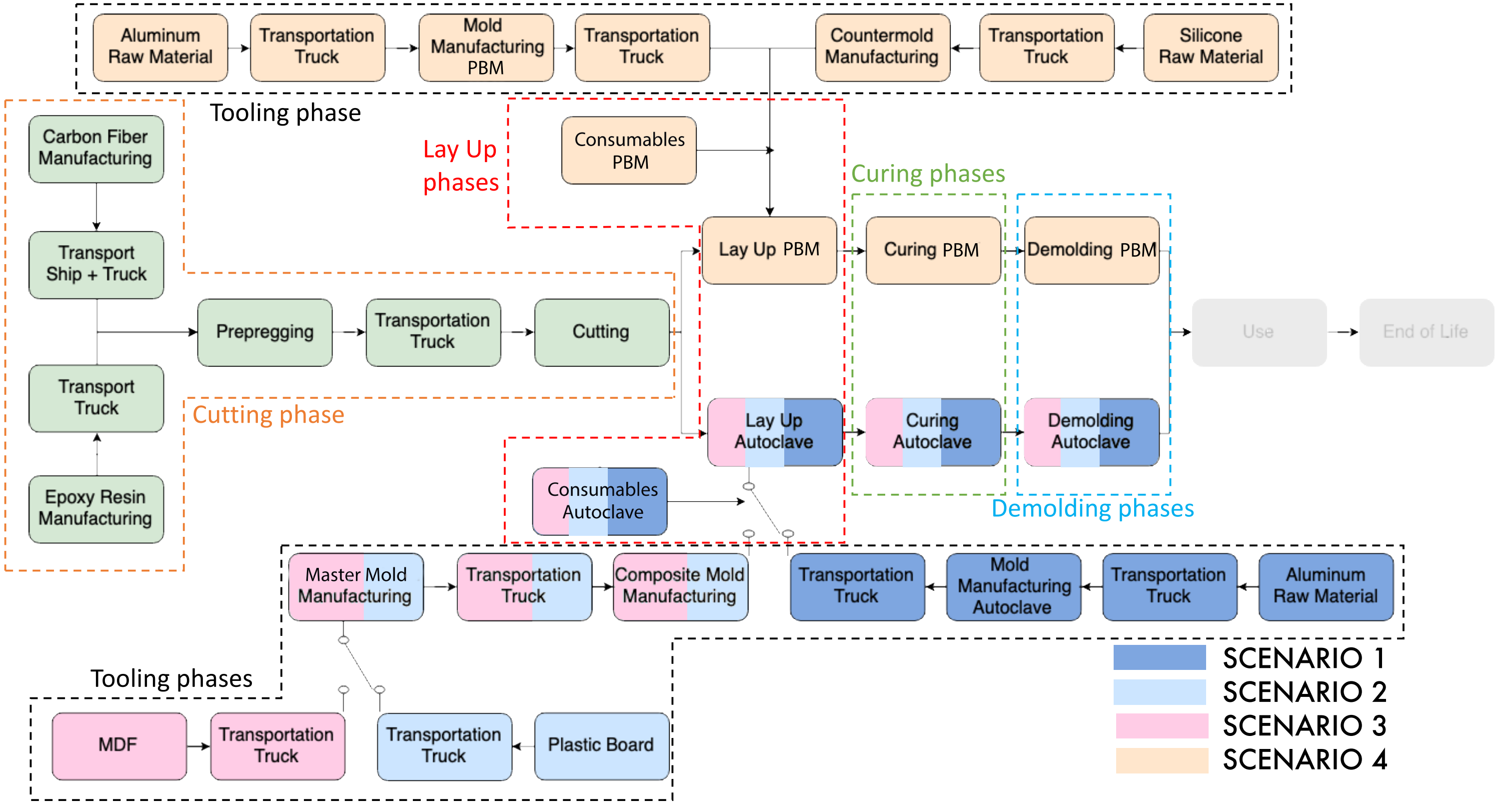


Figure 1: The four scenarios investigated in the LCA analysis.

2.3 Life cycle inventory (LCI)

The LCI considered in this study has been realized by conducting an input-output analysis of all the processes included within the chosen system boundaries. Both primary data, collected by measuring processes of the involved company, and secondary data, retrieved from a commercial LCI database has been used for the analysis. In particular, the Ecoinvent 3.1 has been used as source of secondary LCI data. The chosen database version is the system model "allocation, default" that is based on the following methodological choices: i) it uses the average supply of products, ii) it uses allocation to convert multi-product datasets to single-product datasets, and iii) the flows are allocated relative to their economic revenue corrected for some market imperfections and fluctuations (Wernet et al., 2016).

Regarding assumptions, the following ones have been used for the collection of relevant inventory data:

- Data related to input materials (except prepreg) and consumables have been collected by measuring the quantity involved in the production of the analyzed car hood;
- Due to unavailability of both primary and secondary LCI data from Ecoinvent, the production of precursors, carbon fibers, and prepreg has been modelled on the basis of relevant literature studies (see the dedicated sub-section);
- Data related to equipment (i.e. molds, counter-molds, masters) have been calculated on the basis of the component and equipment 3D models;
- Data related to energy and other resources consumed during all the different phases of the CFRP component manufacturing have been collected by measuring the actual consumption of equipment or estimating a value from aggregated data (e.g. nominal power);
- Inventory data related to input materials have been derived from the Ecoinvent 3.1 database;
- Inventory data related to electric energy generation and other resources (e.g. thermal energy, compressed air) have been derived from the Ecoinvent 3.1 database;
- Distances for all the considered transportation phases have been estimated by considering locations of partners involved in the analyzed production chain;
- Inventory data related to transportation have been derived from the Ecoinvent 3.1 database;
- Impacts related to the manufacturing of machines used during the CFRP component manufacturing processes (e.g. autoclave), are considered negligible, since their service lives are much larger than the temporal boundaries of the analysis (i.e. production of one CFRP car hood);
- According to the system boundaries, car hood use and end of life are not considered in the present study.

All the scenarios have been divided in four main phases. The first one is cutting phases which comprises raw materials (CF and resin), prepregging operation and cutting of the prepreg. The second one is the tooling phase which regards raw materials and manufacturing of masters and molds. The third one is the lay-up phase in which the manufacturing of consumables for all the scenarios is considered. The fourth one is the curing phase, namely the phase where the component is placed in the autoclave or in the press for the polymerization by providing heat and pressure. The last one is de-molding phase which is associated to energy consumption for the Scenario 4 due to the use of a refrigerating system.

The following sub-sections detail the inventory for the input materials, prepreg, equipment, energy and other resources, transportation.

Input materials

The main input material used during the manufacturing of CFRP car hoods is the prepreg, whose modelling is detailed in the next dedicated sub-section. A rib (made of CFRP) is also included in the structure to improve the mechanical performance of the part. In addition, some consumable materials are used during the different manufacturing phases of the four considered scenarios. All the quantities and typologies of input materials have been derived by weighing the materials effectively used during the CFRP car hood manufacturing and consulting the technical sheets of components. Comparing the four alternative scenarios, the differences are essentially related to the use of a vacuum bag for autoclave processing (Scenario 1-3), and the use of a film and a smaller breather for the PBM (Scenario 4).

The following Table 1 reports all the details about the inventory data related to input materials.

Table 1: Input materials used in the four alternative scenarios.

Item (manufacturing phase)	**Material typology**	**Quantity**				**Data Source**
		Scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 4**	
Input prepreg (Cutting phase)	Prepreg	15,7 kg	15,7 kg	15,7 kg	15,7 kg	Measured
Prepreg scrap (Cutting phase)	Prepreg	4,7 kg	4,7 kg	4,7 kg	4,7 kg	Measured
Vacuum bag (Lay-up phase)	Polyamide 66 (PA66)	0,5 kg	0,5 kg	0,5 kg	-	Measured
Film (Lay-up phase)	Polytetrafluoroethylene (PTFE)	-	-	-	0,097 kg	Measured
Breather (Lay-up phase)	Polyethylene terephthalate (PET)	0,375 kg	0,375 kg	0,375 kg	0,25 kg	Measured
Release film (Lay-up phase)	Polytetrafluoroethylene (PTFE)	0,055 kg	0,055 kg	0,055 kg	0,055 kg	Measured
Release agent (Lay-up phase)	Organic solvent	0,03 kg	0,03 kg	0,03 kg	0,03 kg	Measured

Prepreg modelling

Currently, no inventory data related to the manufacturing of CFRP and carbon fibers are available within the Ecoinvent database. For this reason, a dedicated model for prepreg manufacturing has been built on the basis of relevant literature studies about this topic.

The first step for the manufacturing of prepreg consists in the production of the precursor polyacrylonitrile (PAN), obtained through the polymerization of the basic monomer acrylonitrile (AN). This phase has been modelled according to the study of Duflou et al., and the inventory is reported in the following Table 2 (Duflou et al., 2009).

Table 2: Inventory data for the production of 1 kg of PAN (Duflou et al., 2009).

Item	**Material typology**	**Quantity**
Input	Acrylonitrile (AN)	1 kg

	Dimethylformamide solvent	0,00335 kg
	Polydimethylsiloxane	0,1 kg
Energy and other resources	Electric energy	60 MJ
	Steam	18 kg

After the first step, the production of carbon fibers (CF) from the precursor PAN has been modelled according to a literature (Khalil, 2017). Inventory data extracted from this study has been used for the analysis and are reported in the following Table 3.

Table 3: Inventory data for the production of 1 kg of CF (Khalil, 2017).

Item	**Material typology**	**Quantity**
Input	Polyacrylonitrile (PAN)	1,82 kg
	Air	6,95 kg
	Nitrogen (N_2)	0,94 kg
Energy and other resources	Thermal energy for PAN fibers oxidative stabilization	0,48 MJ
	Thermal energy for Carbonization of stabilized PAN fibers	7,56 MJ
	Electric energy for CF surface treatment	0,05 MJ
	Electric energy for CF sizing	0,15 MJ
Output	Water vapor	0,673 kg
	Carbon dioxide (CO_2)	0,407 kg
	Hydrogen cyanide (HCN)	0,255 kg
	Carbon monoxide (CO)	0,038 kg
	Nitrous oxide (N_2O)	0,0007 kg
	Air	6,07 kg
	Hydrogen (H_2)	0,00023 kg
	Ammonia (NH_3)	0,023 kg
	Nitrogen (N_2)	1,183 kg
	Ethane (C_2H_6)	0,0078 kg
	Ethene (C_2H_4)	0,0073 kg
	Methane (CH_4)	0,042 kg

The last operation is prepregging. In this phase, fibers are impregnated with pre-polymerized resin in order to obtain a single composite layer. It presents uniform thickness and constant fiber volume fraction; furthermore, it can be easily handled and processed. For the purpose of this study, the manufacturing of both CF and epoxy resin have been considered and the quantity necessary to produce prepreg has been calculated from the technical datasheet provided by the involved company. Prepregging process has been modelled according to literature (Song et al., 2009). The following Table 4 reports the details of the inventory data used to model the prepreg.

Table 4: Inventory data for the production of 1 kg of prepreg (Song et al., 2009).

Item	**Material typology**	**Quantity**
Input	Carbon fiber (CF)	0,64 kg
	Epoxy resin	0,36 kg
Energy and other resources	Electric energy	40 MJ

Equipment

The four alternative scenarios use three different equipment:

- Master, which is the model used to successively realize CFRP molds in case of autoclave processing. This study considers two typologies of masters: (i) made of a plastic material (i.e. Ureol), (ii) made of wooden material (i.e. MDF);
- Mold, which is used to shape the CFRP component. This study considers two typologies of molds: (i) made of aluminum, (ii) made of CFRP by using an autoclave process;
- Counter-mold, which is the upper part of the mold needed in case of PBM.

Concerning equipment, the differences among the alternative scenarios are related to the use of different typologies of masters/molds, the use of a lighter aluminum mold in case of autoclave in comparison with PBM, and the use of a counter-mold in case of PBM. In addition, the equipment service lives, needed for the purpose of impact allocation, are different. According to indication of the involved company, the following estimated service lives have been set:

- Each plastic or MDF master can be used for producing 10 CFRP molds;
- Each CFRP mold can be used for producing 150 CFRP parts;
- Each aluminum mold can be used for producing 750 CFRP parts;
- Each counter-mold can be used for producing 70 CFRP parts.

The following Table 5 reports a summary of the inventory data related to equipment.

Table 5: Inventory data related to equipment in the four alternative scenarios.

Equipment (manufacturing phase)	**Item**	**Quantity**				**Data Source**
		Scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 4**	
Master mold (Tooling phase)	Input Ureol	-	305 kg	-	-	Estimated from the master 3D model
	Ureol scrap	-	95 kg	-	-	Estimated from the master 3D model
	Input MDF	-	-	0,6 m^3	-	Estimated from the master 3D model
	MDF scrap	-	-	0,2 m^3	-	Estimated from the master 3D model
Mold (Tooling phase)	Input Aluminum	135 kg	-	-	950 kg	Estimated from the mold 3D model
	Aluminum scrap	50 kg	-	-	350 kg	Estimated from the mold 3D model

	CFRP	-	19 kg	19 kg	-	Estimated from the mold 3D model
Counter-mold (Tooling phase)	Silicone rubber	-	-	-	15 kg	Measured
	Counter-mold curing (electric energy)	-	-	-	0,5 kWh	Measured

Energy and resource consumption

The production of CFRP components include the four sequential phases described above and illustrated in Figure 1: (i) cutting of prepreg, (ii) lay-up, (iii) curing and (iv) de-molding. During the first phase, common to all the four alternative scenarios, only electric energy is consumed by the CNC cutting machine. The second phase is considered completely manual, thus no energy/resource flows are included in the present study. The third phase is common for the three alternative autoclave processes (scenario 1-3), while the PBM process foresees different operations and different flows (electric energy and compressed air). The fourth phase is manual in case of autoclave, while a cooling phase is required in case of PBM.

The following Table 6 shows the inventory data related to energy and resources consumed during the different CFRP manufacturing phases. It is worth noticing that the electric energy consumed during the cutting and all the operations of the PBM process have been measured through a power meter. The compressed air needed for the inflation of the counter-mold, instead, has been estimated on the basis of the counter-mold volume. Finally, the electric energy consumed by the autoclave curing phase has been estimated on the basis of a relevant literature study (Song et al., 2009).

Table 6: Inventory data related to energy and resource consumed in the four alternative scenarios.

Manufacturing phase	**Flow**	**Quantity**				**Data Source**
		Scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 4**	
Cutting phase	Electric energy	0,074 kWh	0,074 kWh	0,074 kWh	0,074 kWh	Estimated on the basis of part perimeter, cutting machine speed and nominal power
Lay-up phase	-	-	-	-	-	-
Curing phase	Electric energy (Autoclave)	17 kWh	17 kWh	17 kWh	-	Estimated on the basis of Song et al. (2009)
	Electric energy (Heating)	-	-	-	61,1 kWh	Measured
	Electric energy (Clamp)	-	-	-	3,9 kWh	Measured
	Compressed air at 6 bar (Inflation)	-	-	-	0,7 m^3	Estimated on the basis of counter-mold volume
De-molding phase	Electric energy (Chilling)	-	-	-	16 kWh	Measured

Transportation

Data about transportation of input materials and equipment have been estimated on the basis of indications provided by key managers of the involved company and considering average distances among supplier and customer sites. More specifically, the different companies of the production chain are located in the following geographical locations:

- Carbon fiber producer: Japan;
- Epoxy resin producer: Germany;
- Prepreg producer: Central Italy;
- Polyurethane producer: Germany;
- Polyurethane master producer: Central Italy;
- MDF producer: Northern Italy;
- MDF master producer: Central Italy;
- Aluminum producer: Germany;
- Aluminum mold producer: Central Italy;
- Silicon rubber producer: Germany;
- CFRP car hood producer: Central Italy.

The following Table 7 reports the full details about the inventory data related to transportation.

Table 7: Inventory data related to transportation.

Transportation	**Freight weight [kg]**	**Distance [km]**	**Transportation typology**
Carbon fibers for car hood manufacturing (Scenario 1-4; cutting phase)	9,42	150	Truck 16-32 ton
		16800	Transoceanic ship
Carbon fibers for autoclave CFRP mold manufacturing (Scenario 2&3; tooling phase)	11,4		
		150	Truck 16-32 ton
Epoxy resin for car hood manufacturing (Scenario 1-4; cutting phase)	6,28	1200	Truck 16-32 ton
Epoxy resin for autoclave CFRP mold manufacturing (Scenario 2&3; tooling phase)	7,6		
Prepreg for car hood manufacturing (Scenario 1-4; cutting phase)	15,7	30	Truck 3,5-7,5 ton
Prepreg for autoclave CFRP mold manufacturing (Scenario 2&3; tooling phase)	19		
Polyurethane for master manufacturing (Scenario 2; tooling phase)	305	1200	Truck 16-32 ton
Polyurethane master (Scenario 2; tooling phase)	210	30	Truck 3,5-7,5 ton
MDF for master manufacturing (Scenario 3; tooling phase)	510	600	Truck 16-32 ton
MDF master (Scenario 3; tooling phase)	340	30	Truck 3,5-7,5 ton
Aluminum for autoclave mold manufacturing (Scenario 1; tooling phase)	135	1200	Truck 16-32 ton
Aluminum for PBM mold manufacturing (Scenario 4; tooling phase)	950		
Aluminum autoclave mold (Scenario 1; tooling phase)	85	12	Truck 3,5-7,5 ton
Aluminum PBM mold (Scenario 4; tooling phase)	600		
Silicone rubber for counter-mold manufacturing (Scenario 4; tooling phase)	15	1200	Truck 16-32 ton

2.4 Life cycle impact assessment (LCIA) methods

Currently, a large set of impact assessment methods and impact categories exist and can be used as key performance indicators (KPIs) to quantify results of LCA studies. Each of them is more appropriate to represent a specific typology of impacts. In order to have a comprehensive view of environmental damages potentially caused by the production of CFRP components for the automotive sector, the present study considered different environmental indicators:

- Since the production technologies for CFRP components consume large quantities of energy, the first considered indicator is the Cumulative Energy Demand (CED), as suggested by several relevant literature studies (Das, 2011; Duflou et al., 2012; Raugei et al., 2015). Through the use of specific characterization factors, this metric quantifies the direct and indirect energy resources (i.e. renewable fossil and nuclear energy resources) consumed by a process in a lifecycle perspective. In particular, the chosen energy harvested approach (Frischknecht et al., 2015) can be considered a "standard" CED indicator, which focuses on how much a product/process contributes to the safeguard of energy resources made available for human use.

- The second chosen indicator is the Global Warming Potential (GWP), which is mainly focused on the quantification of greenhouse gases (GHG) emitted in the atmosphere and their contribution to global warming and climate changes. This metric is currently the most used and widespread environmental indicator in many different fields, including the assessment of CFRP components (Das, 2011; Duflou et al., 2012; Khalil, 2017; Raugei et al., 2015; Umair, 2006; R A Witik et al., 2011; Witik et al., 2013, 2012). The present study considers the impact assessment methodology described in 2013 by the Intergovernmental Panel on Climate Change (IPCC) (Stocker et al., 2013). This methodology expresses the greenhouse contribution of each emitted flow in a predefined time horizon (100 years in case of the chosen IPCC 2013 GWP 100a indicator), in comparison with the carbon dioxide, whose greenhouse potential is taken as reference (i.e. characterization factor = 1).

- A comprehensive overview of environmental loads can be only obtained by jointly considering a sufficiently large set of different and heterogeneous indicators. This is the reason why the ReCiPe 2008 impact assessment methodology has been selected and used in this study, as well as in many other similar researches (Duflou et al., 2012; Khalil, 2017; Raugei et al., 2015; Umair, 2006; Robert A. Witik et al., 2011; Witik et al., 2013, 2012). Considering the midpoint level, the ReCiPe methodology with Hierarchist (H) perspective (Goedkoop et al., 2008) allows to consider different typologies of impacts (e.g. eutrophication of water, human toxicity, acidification of soils) by grouping them in 18 impact categories, all of them considered in the present study.

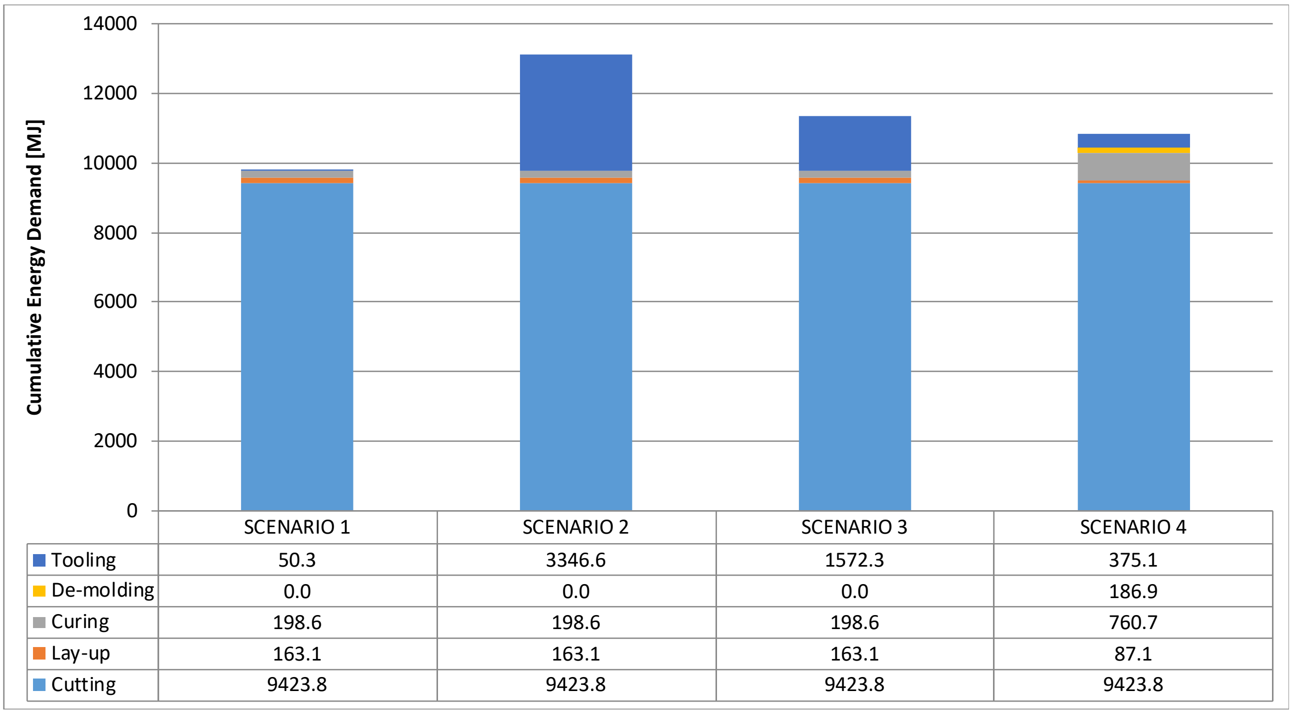
- Finally, as foreseen by the ISO 14044 standard, a normalization and weighting could be applied to calculate damage categories and a single score. According to state of the art studies (Duflou et al., 2012, 2009; Nielsen and Borgen Dam, 2013; Scelsi et al., 2011; Robert A. Witik et al., 2011; Witik et al., 2013, 2012), endpoint categories have been finally considered in this comparative LCA. More specifically, the ReCiPe endpoint with Average (A) weighting set and European normalization factor has been used (Goedkoop et al., 2008).

3. Results and Discussion

In this section, the results of the life cycle impact assessment calculated by using the life cycle inventory data and the chosen environmental impact categories are shown. The analysis of these results provides several outcomes about the environmental impacts associated to different scenarios of CFRP manufacturing processes, confirming the necessity of developing and verifying new “green” techniques and materials to drastically reduce the environmental loads related to composite materials.

3.1 Cumulative Energy Demand

Figure 2 illustrates the results of the environmental evaluation of each scenario in terms of CED. A general outcome is that scenario 1 (autoclave with aluminum mold) presents the lowest environmental load whilst the scenario 2 (autoclave with CFRP mold and plastic master) is associated to the highest impacts, confirming what is reported in literature (Vita et al., 2019b). As it is evident, the main contribution is attributable to the cutting phase which is exactly the same for all the different manufacturing processes (see Figure 1). In most of the cases, the cutting phase (containing the impacts due to input materials, especially prepreg) accounts for more than 90% of the total impact (the exception is scenario 2, in which however the cutting is responsible of about 70% of the total). For this reason, this part of the process is analyzed in detail in the successive section 3.4. De-molding is null for the scenario 1, 2 and 3 whilst it is present for scenario 4, where the aluminum mold is subjected to forced cooling which requires the use of an important amount of energy.

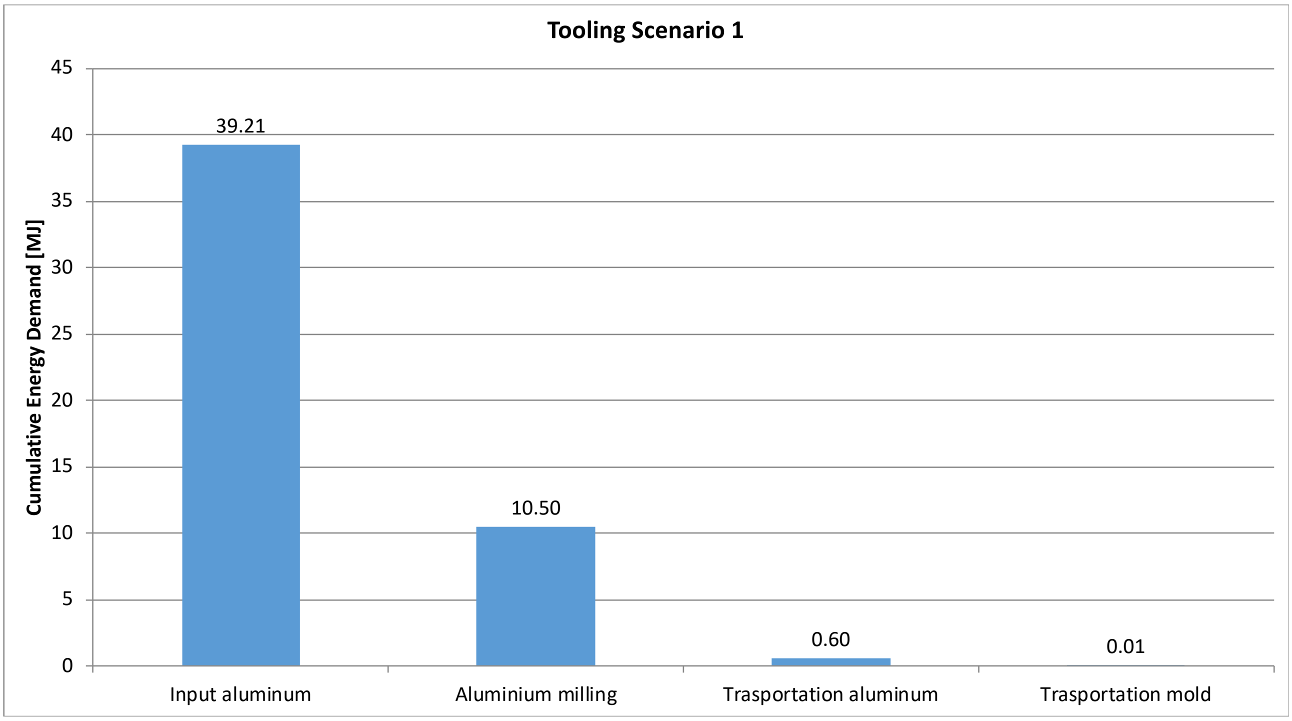


	SCENARIO 1	SCENARIO 2	SCENARIO 3	SCENARIO 4
■ Tooling	50.3	3346.6	1572.3	375.1
■ De-molding	0.0	0.0	0.0	186.9
■ Curing	198.6	198.6	198.6	760.7
■ Lay-up	163.1	163.1	163.1	87.1
■ Cutting	9423.8	9423.8	9423.8	9423.8

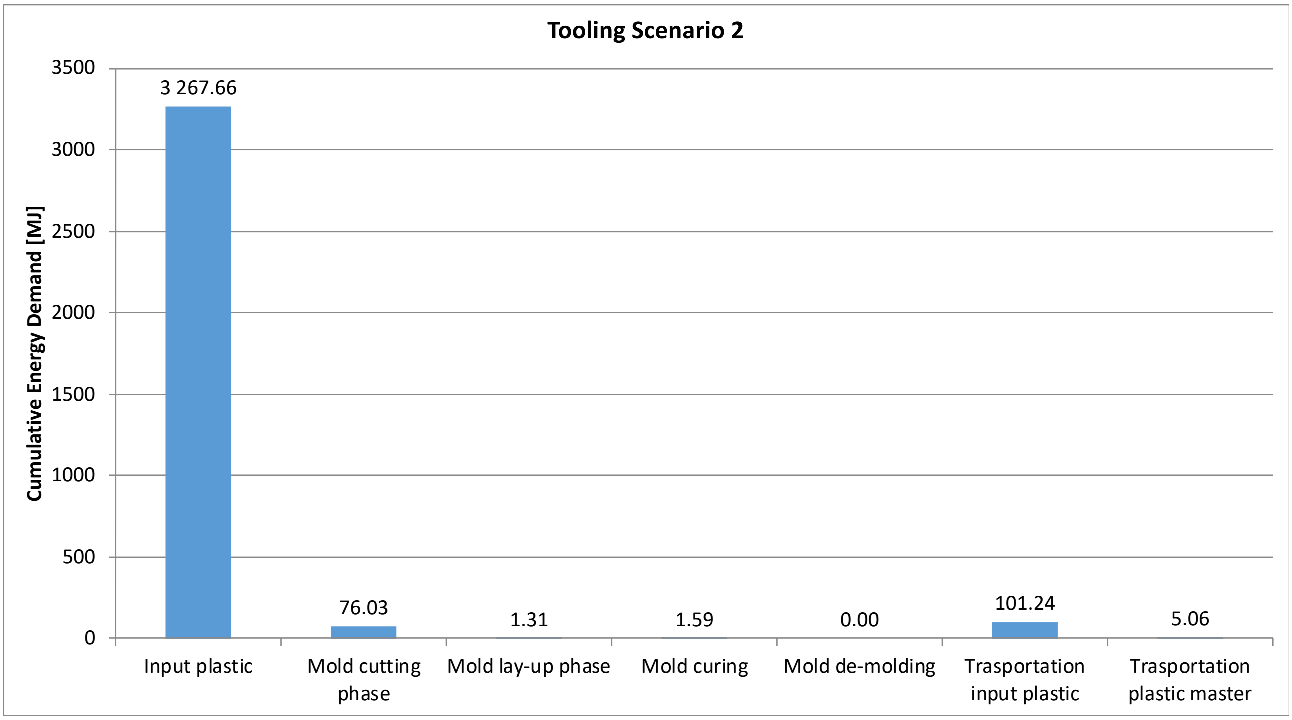
Figure 2: LCIA in terms Cumulative Energy Demand (CED) for each scenario.

The main difference between all the scenarios is represented by the tooling, namely the masters and the molds used. In fact, it accounts for 3346,6 MJ for the scenario 2 (which represents about 25% of the total), whilst only 50,3 MJ for the scenario 1 (0,015%). For a better understanding of this difference, the tooling contributions have been investigated for each scenario (Figure 3). As can be seen in Figure 3a, for scenario 1, the majority of the contribution is imputable to the raw aluminum (39 MJ, 79,5%), followed by the milling process necessary to realize the mold (10,5 MJ, 20%).

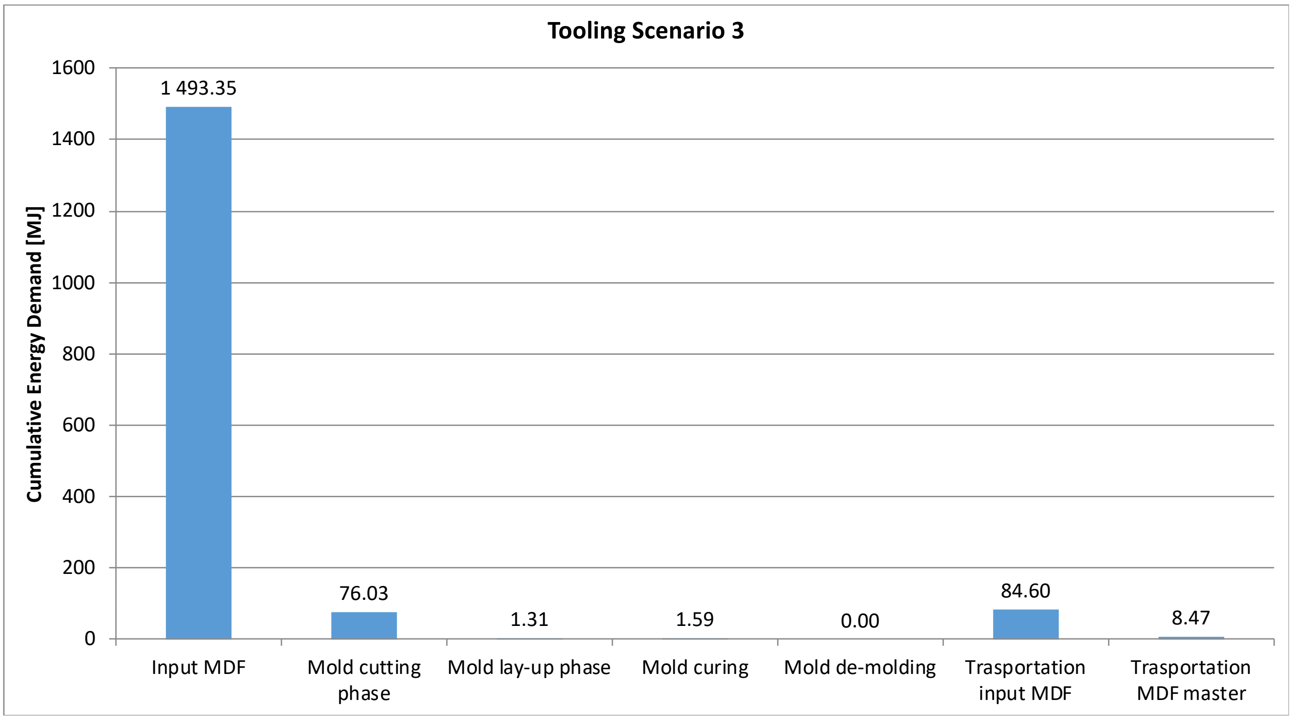
Transportation of the raw aluminum and of the mold lead to negligible environmental impacts. Differently, Figure 3b shows that the high impacts of the scenario 2 are relative to the polyurethane master used to shape the CFRP mold (3267 MJ, 97%). Indeed, this kind of material presents important environmental loads which also overshadow the contribution of the CFRP (76 MJ, 2,5%) and of the process for the realization of the mold (0,5%), which is composed by the same step of the scenario 2. Similarly, same conclusions can be drawn also for the scenario 3 (Figure 3c), where the material of the model (MDF, 1493 MJ, 95%) accounts 20 times the environmental load of the CFRP. However, the lower unitary environmental impact due to the MDF in comparison with the polyurethane (29,2 vs 104 MJ per kg of material, according to Ecoinvent data), drastically reduces the contribution of the master, and, as a consequence, of the entire tooling for the scenario 3. The contributions of the consumables and of the energy required by the autoclave to manufacture the CFRP mold are instead negligible. The environmental impacts of the pressure bag molding (scenario 4, Figure 3d) present a behavior similar to the scenario 1, with the largest part of the contribution attributable to the raw aluminum (275 MJ, 74%). The absolute value is higher than that of the scenario 1 due to the heavier mass of the mold used for the PBM process, necessary to withstand the higher compaction pressure. In addition, also a small load imputable to the synthetic rubber (20 MJ, 5%) used to realize the inflatable counter-mold is present.



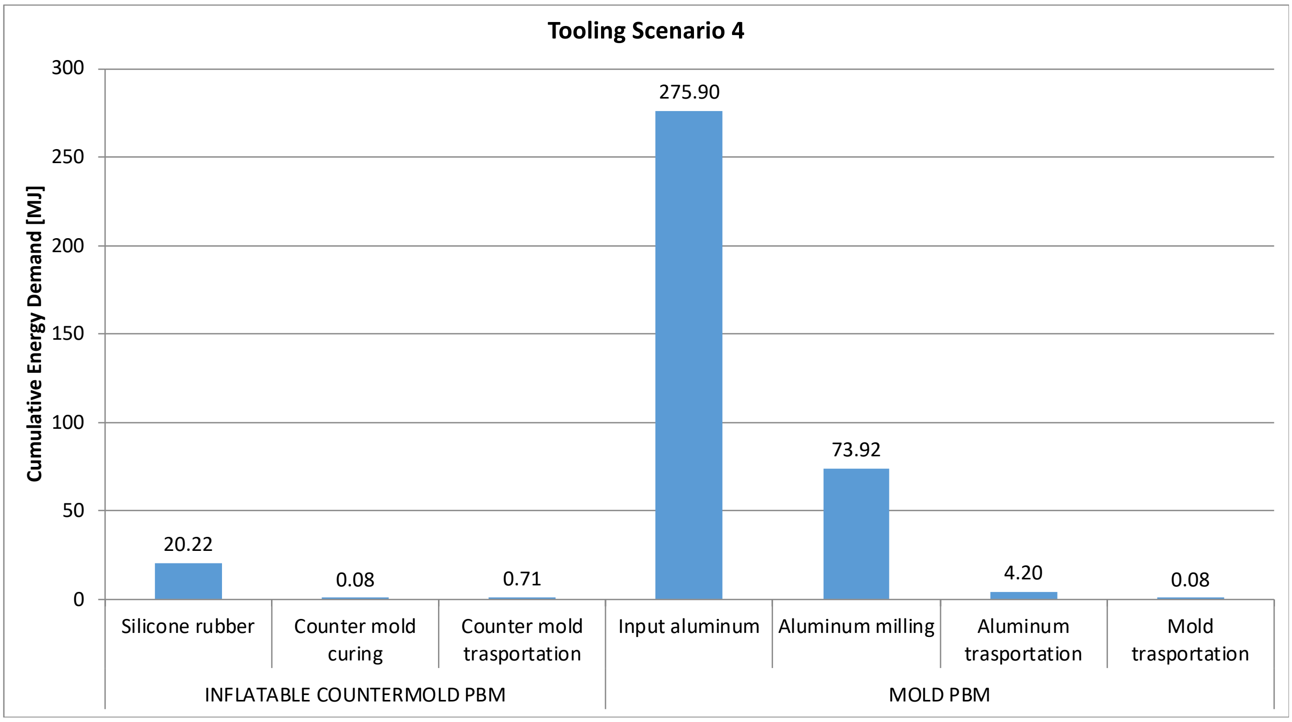
a)


Tooling Scenario 2
Cumulative Energy Demand [MJ]
3500
3000
2500
2000
1500
1000
500
0
3 267.66
76.03
1.31
1.59
0.00
101.24
5.06
Input plastic
Mold cutting phase
Mold lay-up phase
Mold curing
Mold de-molding
Trasportation input plastic
Trasportation plastic master

b)


Tooling Scenario 3
Cumulative Energy Demand [MJ]
1600
1400
1200
1000
800
600
400
200
0
1 493.35
76.03
1.31
1.59
0.00
84.60
8.47
Input MDF
Mold cutting phase
Mold lay-up phase
Mold curing
Mold de-molding
Trasportation input MDF
Trasportation MDF master

c)



d)

Figure 3: Detailed analysis of tooling, in terms of CED, for a) scenario 1, b) scenario 2, c) scenario 3, d) scenario 4.

For what concerns the curing phase, scenario 1, 2 and 3 present identical value (198,6 MJ) due to the same autoclave process used to realize the CFRP component. This environmental load is completely associated to the electricity necessary to power pumps and heaters of the autoclave. In the PBM process, as visible in Figure 4, the curing phase leads to a value of the impact equal to 760,7 MJ, namely 3,8 times that of the autoclave curing. This behavior can be attributable, once again, to the high mass of the mold which must be heated to allow the curing of the matrix (via conduction). In addition, even though in lower quantity, the contribution of the energy necessary to maintain the mold closed (45 MJ, 6%) is present. The compressed air necessary to inflate the counter-mold can be instead considered negligible.

Since previous similar literature studies in the field of LCA of CFRP parts considered different functional units, it is not possible to carry out a detailed comparison of the obtained results. For example, Das (Das, 2011) analyzed a floor pan for a large rear wheel drive vehicle evaluating the possibility of substituting the original material (i.e. steel) with CFRP. His results shows that the impacts in terms of primary energy (i.e. CED indicator) for the manufacturing of a CFRP part is in the order of 10000 MJ, as observed in the present analyses. In addition, most of the impacts related to part manufacturing, as can be derived from the previous Figure 2. Also in the study developed by Raugei et al. (Raugei et al., 2015), where they considered lightweight strategies for a C segment car through the substitution of steel parts with aluminum and composite parts, the impacts related to CFRP parts manufacturing in terms of CED are mainly due input materials. As a conclusion, it is worth highlightins that despite the differences in functional unit, system boundary, input materials, process alternatives and assumptions, the outcomes of the present study can be considered fully aligned with the state of the art: the great majority of the environmental load is due to materials, while the process is responsible of 10-30% of the total.

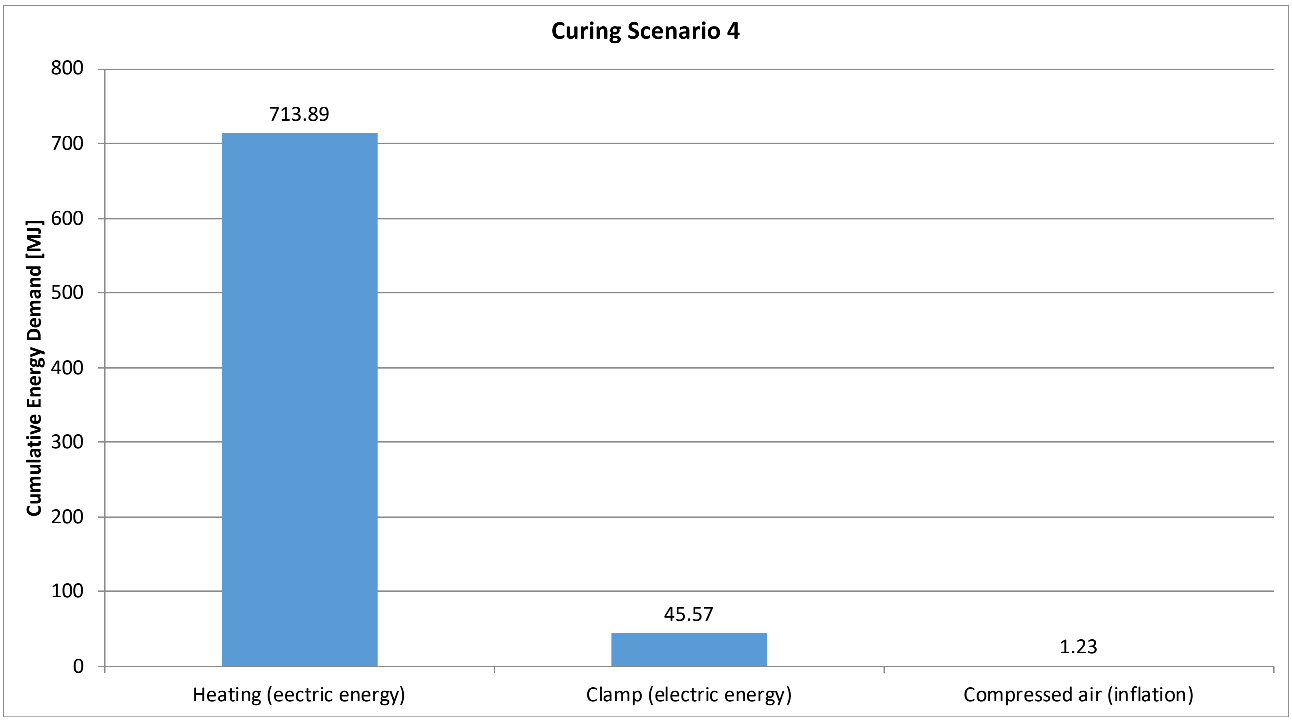
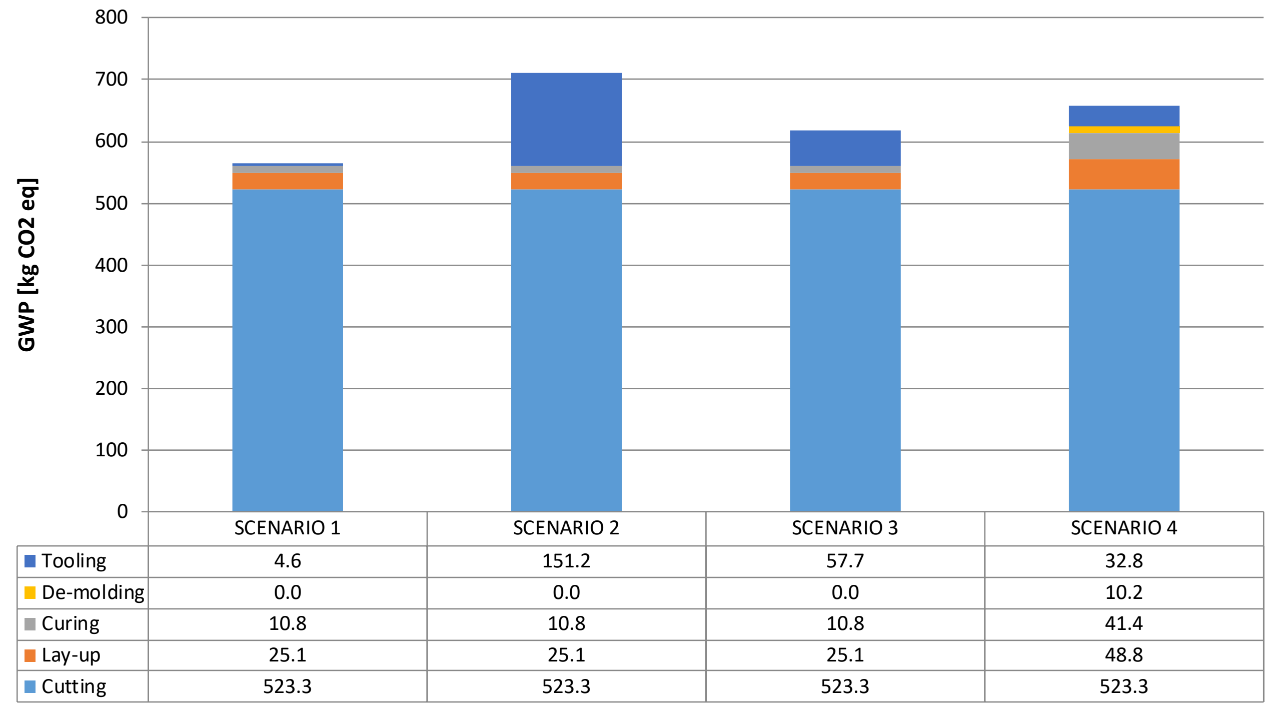


Figure 4: Curing phase, in terms of CED, for scenario 4

3.2 Global Warming Potential

The results calculated for the Global Warming Potential (GWP) are presented in the following figures. In general, the comparison among the four analyzed scenarios leads to the same outcomes observed for CED indicator (Figure 5). In fact, also calculating the GWP, scenario 2 results the most impactful for the considered FU. Its impact is 710,4 kg CO_2 eq, +8% with respect to the scenario 4 (656,5 kg CO_2 eq), +15% with respect to the scenario 3 (616,9 kg CO_2 eq) and +26% with respect to the scenario 1 (563,8 kg CO_2 eq). In addition, the split of contributions demonstrates that, similarly to the CED analysis, the most critical phase is the cutting (due to input materials), whilst the main difference among the four scenarios is represented by the tooling.



	SCENARIO 1	SCENARIO 2	SCENARIO 3	SCENARIO 4
■ Tooling	4.6	151.2	57.7	32.8
■ De-molding	0.0	0.0	0.0	10.2
■ Curing	10.8	10.8	10.8	41.4
■ Lay-up	25.1	25.1	25.1	48.8
■ Cutting	523.3	523.3	523.3	523.3

Figure 5: LCIA in terms Global Warming Potential (GWP) for each scenario.

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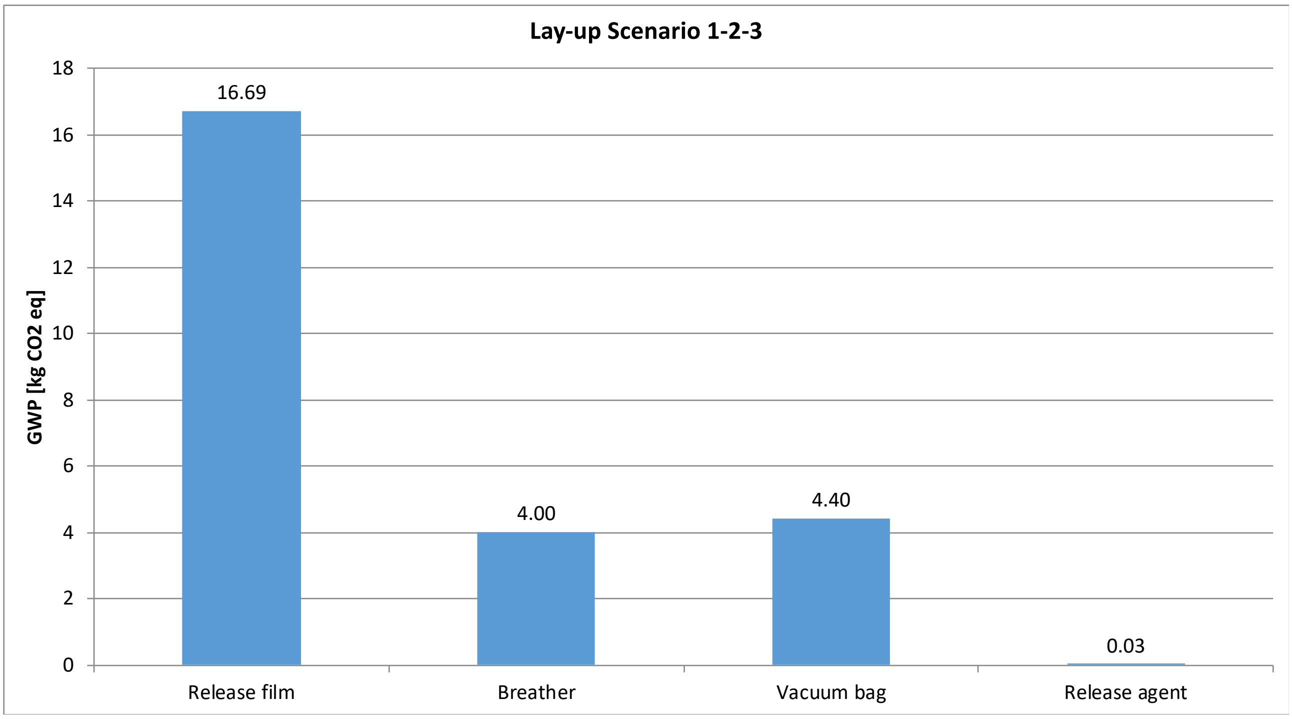
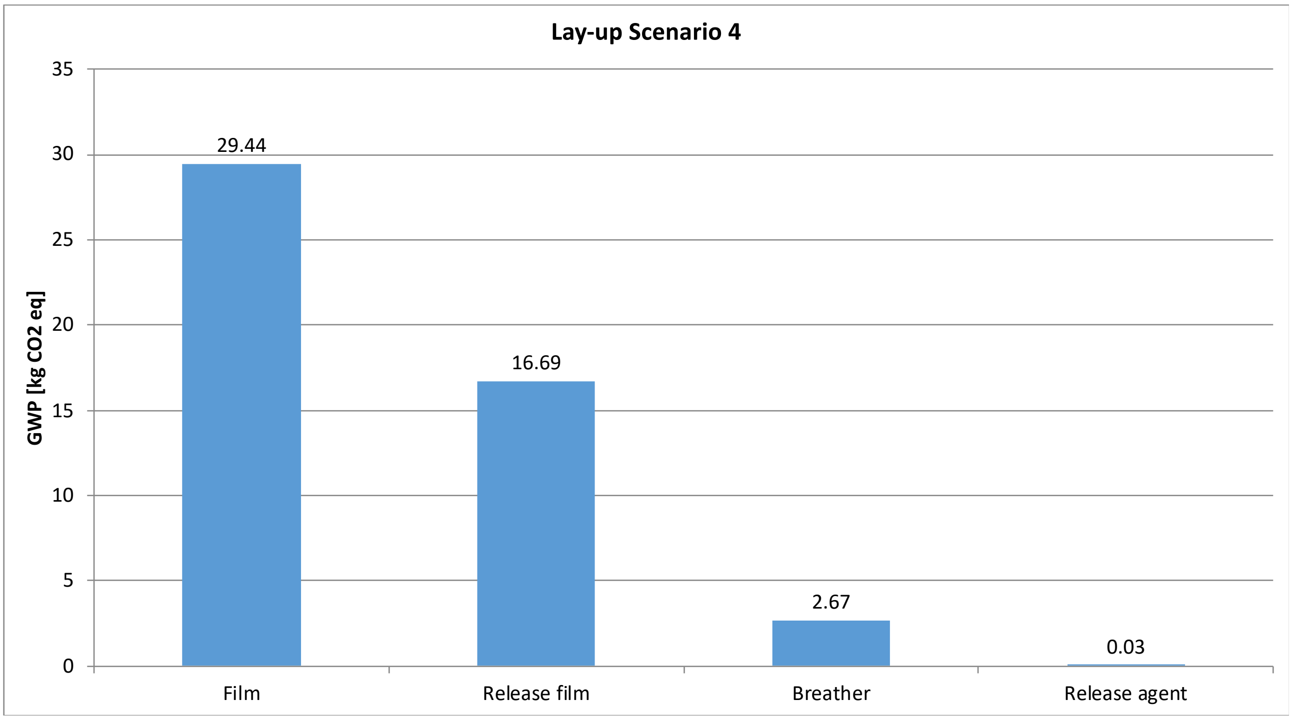
Differently from CED indicator, in the analysis of GWP impacts, the lay-up phase presents a reverse trend. In fact, the impacts related to the lay-up for scenario 1, 2 and 3 are equal to 25,1 kg CO_2 eq, whilst for the scenario 4 are about twice, 48,8 kg CO_2 eq (+94%). Therefore, consumables used in all the scenarios lead to significant environmental loads which cannot be neglected in case of eco-design activities focused on the reduction of emissions associated to the manufacturing processes of composites. The observed difference can be attributed to the film used in the PBM process to protect the inflatable counter-mold from chemical attacks of the resin (Figure 6a and Figure 6b). As reported in Table 1, the film has a low mass (0,097 kg) but causes a high contribution due to the very high unitary GWP of the PTFE (about 303 kg CO_2 eq per kg of PTFE). It is worth noticing that such material is synthetized from the chemical intermediate chlorodifluoromethane (also known as HCFC-22 or R-22) that has a quite low ozone depletion potential (in comparison with other chlorofluorocarbons used in the past in the refrigeration sector), but it is a greenhouse gas 1810 times as powerful as carbon dioxide, determining a very high value in terms of GWP (Ozone Secretariat United Nations Environment Programme, 2000).

Analyzing results obtained in recent literature studies by (Robert A. Witik et al., 2011; Witik et al., 2012), in which climate change indicators have been used to assess lightweight materials for automotive and aircraft applications, 55 kgCO_2eq on a total of about 75 kgCO_2eq for the manufacturing of a CFRP part by using an autoclave process are due to input materials (about 75% of the total). This means that most of the impacts are due to carbon fibers and resin used to produce the prepreg, as observed in the present LCA study. This trend is also confirmed by Raugei et al., (Raugei et al., 2015) where they used the GWP impact category for the assessment of a car and car parts lifecycles.



a)



b)

Figure 6: Lay-up phase, in terms of GWP, for a) scenario 1, 2 and 3 and b) scenario 4.

3.3 ReCiPe Midpoint and Endpoint

In this section, the results of the ReCiPe method, at both the midpoint and endpoint levels, are reported. In particular, the following Table 8 shows the results obtained for each of the 18 midpoint impact categories included in the ReCiPe method, while a “normalized” comparison among the four considered scenarios is illustrated in Figure 7. Through this normalization (consisting in dividing each value by the maximum value obtained in each impact category), the most impactful scenario for each category has an impact of 100%, and thus the total percentage benefits of the other scenarios can be easily determined. Moreover, to better understand the main causes of impacts for each scenario and for each impact category, the four graphs of Figure 8 detail the split of percentage contributions in terms of some main common items:

- Main input material (*Prepreg*);
- Process of cutting the main input material (*Cutting*);
- Additional materials used during the lay-up phase (*Consumables*);
- Process of *Curing*;
- Process of *De-molding*;
- *Mold*;
- *Master* (if any)
- *Counter-mold* (if any);

Table 8: Comparison among scenarios in terms of ReCiPe midpoint categories.

ReCiPe midpoint category	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**
Climate change [kg CO2 eq]	5,64E+02	7,10E+02	6,17E+02	6,57E+02
Ozone depletion [kg CFC-11 eq]	5,81E-04	5,91E-04	5,91E-04	1,50E-03
Terrestrial acidification [kg SO2 eq]	3,27E+00	3,83E+00	3,60E+00	3,63E+00
Freshwater eutrophication [kg P eq]	1,13E-01	1,28E-01	1,25E-01	1,28E-01
Marine eutrophication [kg N eq]	1,42E+00	1,53E+00	1,14E+03	1,69E+00
Human toxicity [kg 1,4-DB eq]	3,97E+02	4,18E+02	4,20E+02	4,17E+02
Photochemical oxidant formation [kg NMVOC]	1,81E+00	2,35E+00	2,06E+00	2,00E+00
Particulate matter formation [kg PM10 eq]	1,03E+00	1,28E+00	1,15E+00	1,15E+00
Terrestrial ecotoxicity [kg 1,4-DB eq]	8,40E+00	8,48E+00	8,48E+00	8,40E+00
Freshwater ecotoxicity [kg 1,4-DB eq]	7,43E+00	8,18E+00	9,01E+00	9,10E+00
Marine ecotoxicity [kg 1,4-DB eq]	1,34E+02	1,36E+02	1,36E+02	1,35E+02
Ionising radiation [kBq U235 eq]	6,14E+01	6,58E+01	6,76E+01	6,96E+01
Agricultural land occupation [m2a]	2,40E+01	2,51E+01	1,15E+02	2,61E+01
Urban land occupation [m2a]	2,30E+00	3,07E+00	3,81E+00	2,74E+00
Natural land transformation [m2]	7,36E-02	7,96E-02	8,78E-02	8,40E-02
Water depletion [m3]	6,59E+00	1,03E+01	7,70E+00	6,95E+00
Metal depletion [kg Fe eq]	9,72E+00	1,23E+01	1,42E+01	1,22E+01
Fossil depletion [kg oil eq]	1,84E+02	2,47E+02	2,03E+02	2,01E+02

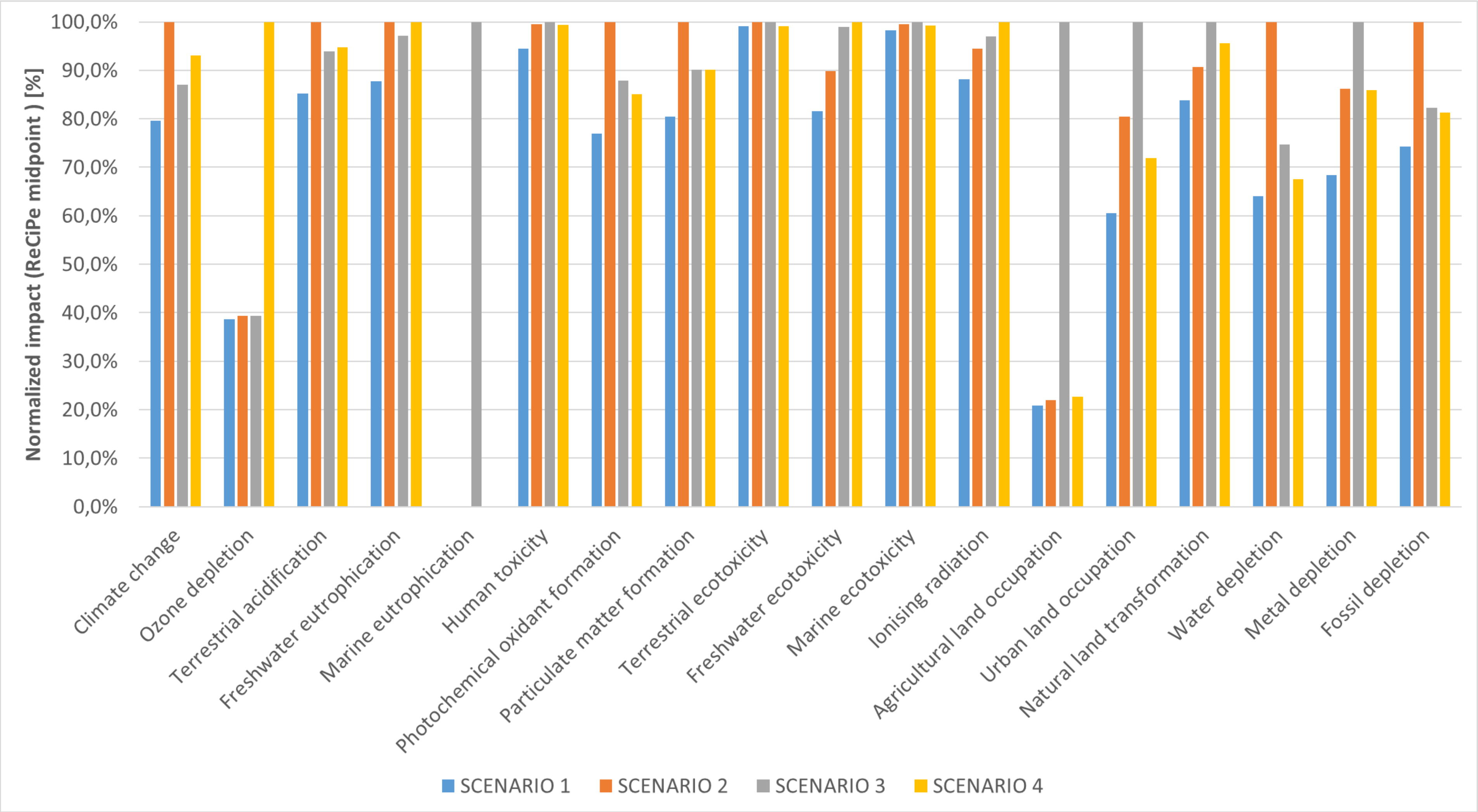
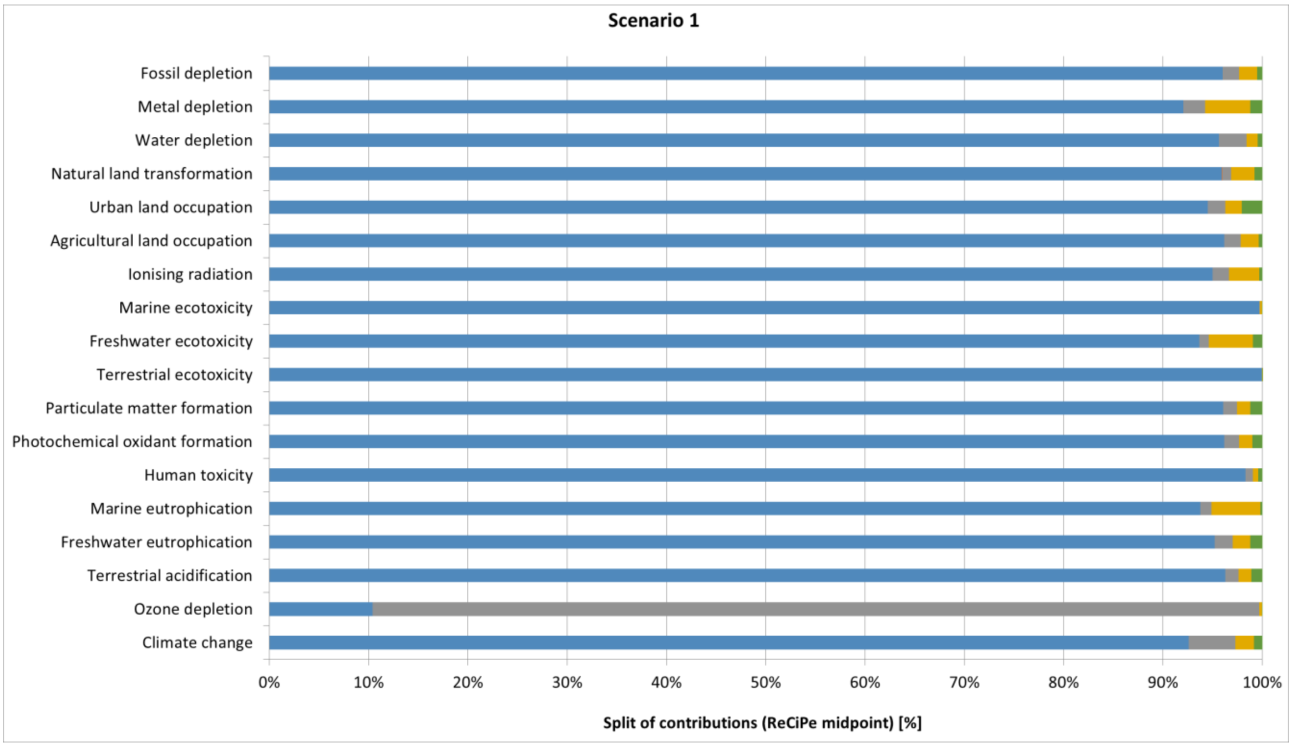
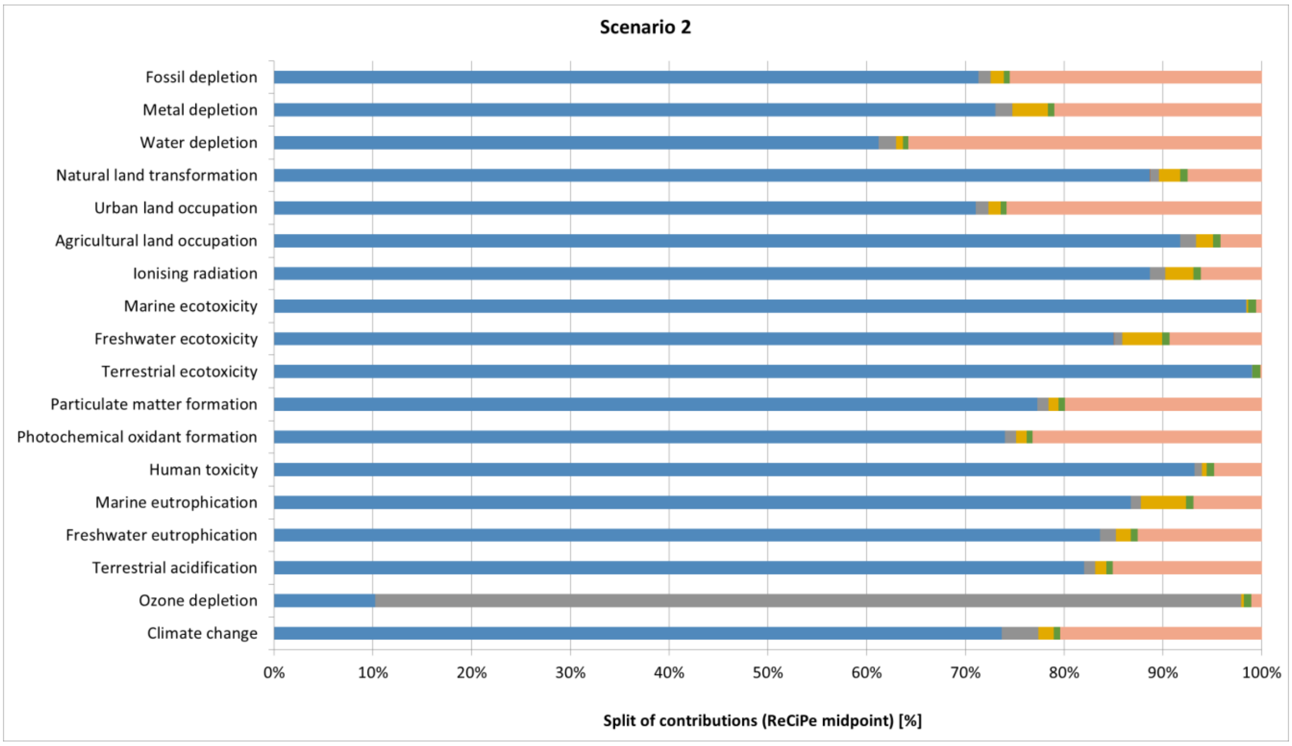


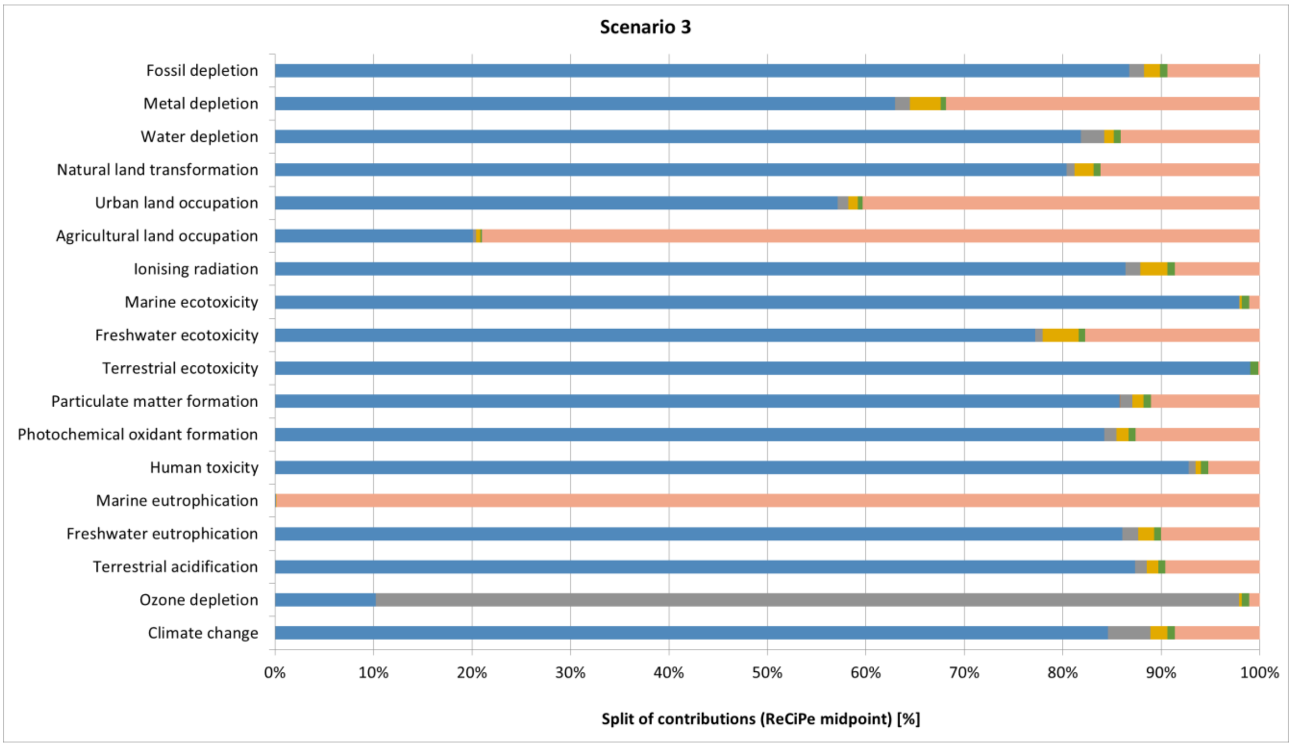
Figure 7: Normalized comparison of the four considered scenarios


Scenario 1
Fossil depletion
Metal depletion
Water depletion
Natural land transformation
Urban land occupation
Agricultural land occupation
Ionising radiation
Marine ecotoxicity
Freshwater ecotoxicity
Terrestrial ecotoxicity
Particulate matter formation
Photochemical oxidant formation
Human toxicity
Marine eutrophication
Freshwater eutrophication
Terrestrial acidification
Ozone depletion
Climate change
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Split of contributions (ReCiPe midpoint) [%]

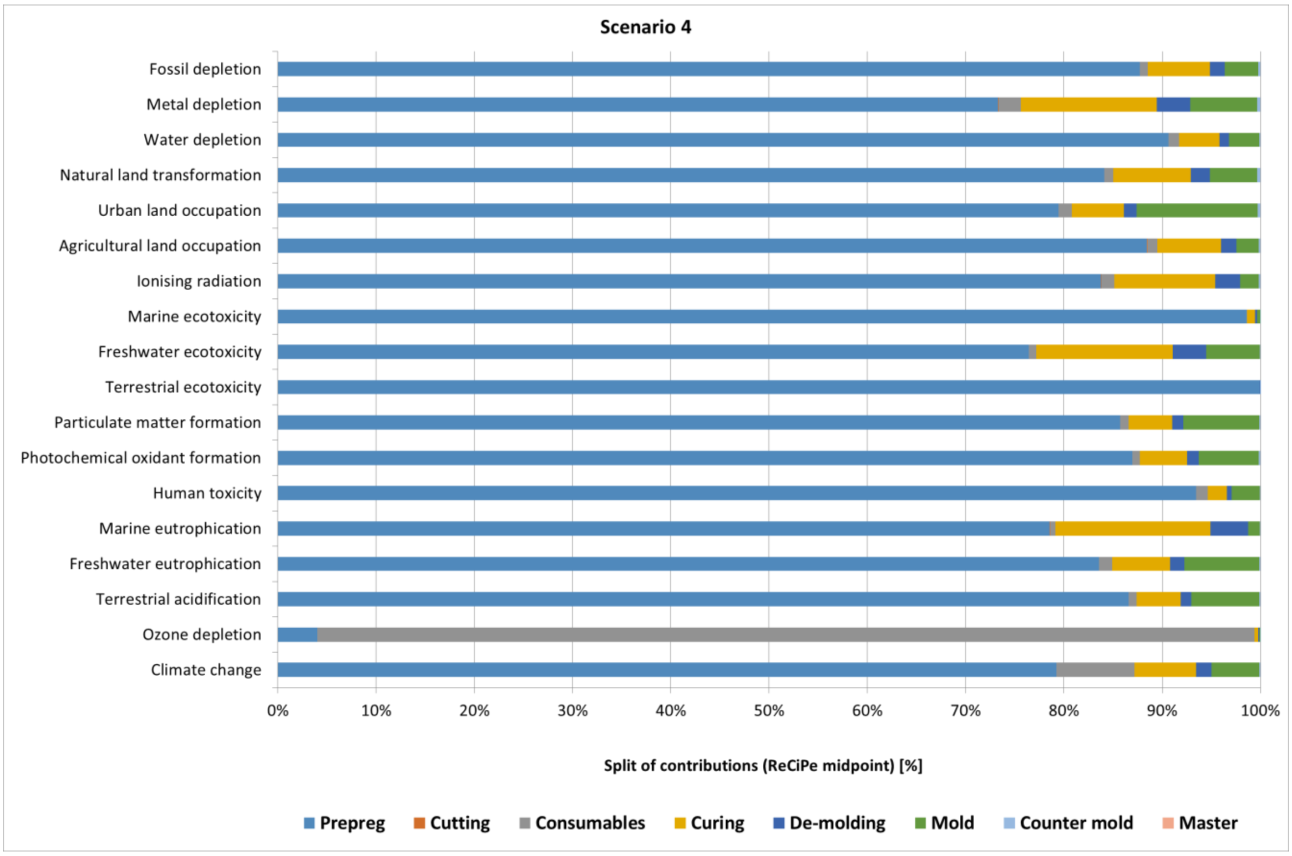
a)


Scenario 2
Fossil depletion
Metal depletion
Water depletion
Natural land transformation
Urban land occupation
Agricultural land occupation
Ionising radiation
Marine ecotoxicity
Freshwater ecotoxicity
Terrestrial ecotoxicity
Particulate matter formation
Photochemical oxidant formation
Human toxicity
Marine eutrophication
Freshwater eutrophication
Terrestrial acidification
Ozone depletion
Climate change
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Split of contributions (ReCiPe midpoint) [%]

b)



c)



d)

Figure 8: Percentage contributions of each input: a) scenario 1, b) scenario 2, c) scenario 3), d) scenario 4

General outcomes of midpoints analysis are:

- The rank of the four considered scenarios is not homogeneous for the different impact categories. However, in all the cases, the scenario 1 resulted the most environmentally sustainable option;
- As observed in the CED and GWP analyses, the impacts related to the pre-impregnated material used for the manufacturing of the component (included in the cutting phase) are predominant with respect all the other phases for almost all the scenarios and impact categories;
- The most evident exception is the ozone depletion for which consumables are predominant in all the scenarios;
- Master is the most impactful flow in terms of agricultural land occupation and marine eutrophication for the scenario 3.

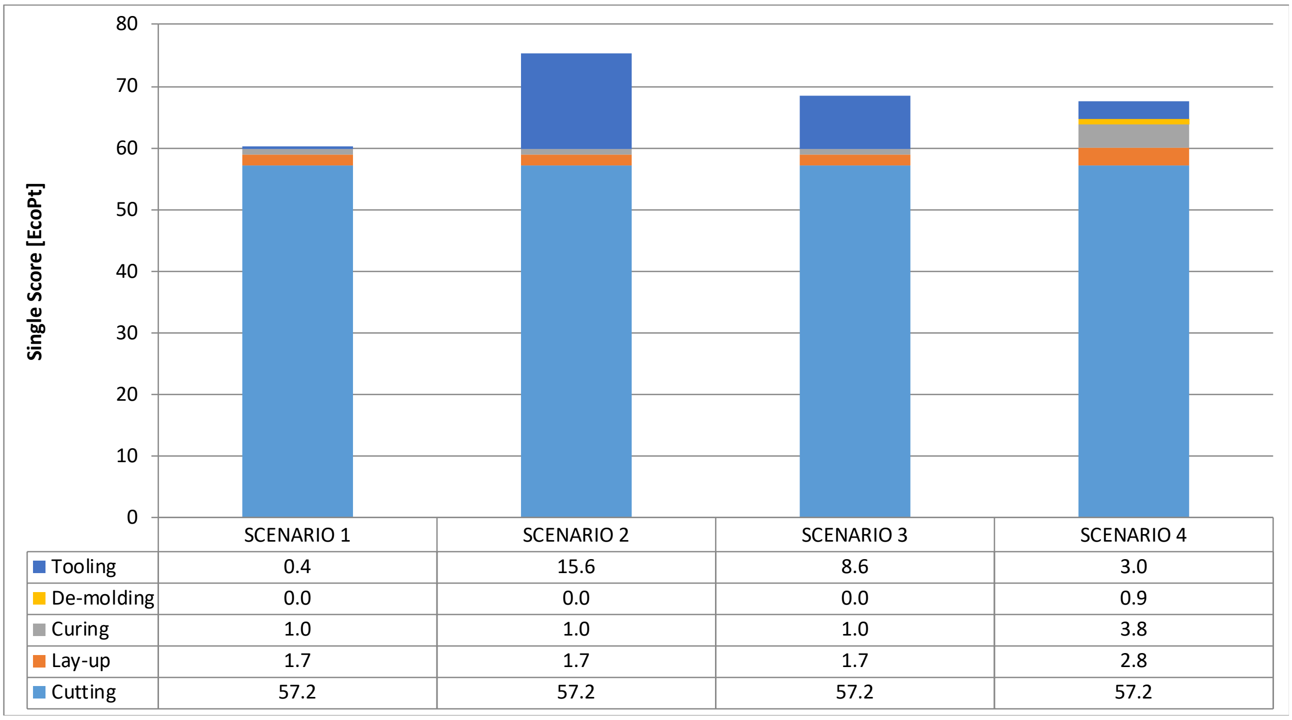
More in details, results obtained in terms of ozone depletion are highly influenced by consumables, particularly film (for all the scenarios) and release film (only for the scenario 4). As in case of the GWP indicator the main cause is due to the use of PTFE, produced starting from the R-22 precursor that, other than a very high global warming potential, has a relevant ozone depletion potential in comparison with other plastic materials (Ozone Secretariat United Nations Environment Programme, 2000).

The main differences among the four scenarios have been observed in case of the marine eutrophication impact category for which the scenario 3 is predominant (three order of magnitude as reported in Table 8). This is completely due to the MDF material used to realize the master (see Figure 8c) that, despite the needed quite low quantity of material (0,6 m^3) and the allocation rule (i.e. each master can be used to realize 10 molds), causes relevant environmental impacts. By deeply analyzing the MDF material included in Ecoinvent, it can be observed that the main issue is related to the wastewater deriving from the MDF production, which generally contains non-biodegradable and refractory compounds difficult to remove with standard water treatment processes (Balcik-Canbolat et al., 2016; Ghorbannezhad et al., 2016).

Concerning the impact categories focused on occupation/transformation of land (particularly agricultural land occupation, but also urban land occupation and natural land transformation), the MDF master is the main contributor for the scenario 3, which resulted the most impactful alternative. In this case the original cause of impact is the production of woodchips and pulpwood, products used for the realization of MDF panels and directly derived from felled trees and forests, not always managed in a sustainable way.

Two are the impact categories for which the scenario 2 can be considered the worst scenario: water depletion and fossil depletion. In both cases, the most impactful flows are the production of polyol and isocyanate, the main petroleum-based precursors used to synthetize the polyurethane needed for the production of the plastic master (Kairytė et al., 2018).

Finally, due to the fact that the different midpoint indicators returned non-homogeneous results, an endpoint analysis has been conducted in order to have a single rank among the four scenarios also in terms of the ReCiPe method (Figure 9). Results essentially confirm the trend found considering CED and GWP indicators: the most impactful process is autoclave curing with polyurethane master, whilst the scenario 1 leads to the lowest environmental load. However, differently from GWP, scenario 3 presents a slightly higher impact (68,5 EcoPt) than scenario 4 (67,7 EcoPt) due to the higher contribution of tooling and, in particular, of the MDF master.



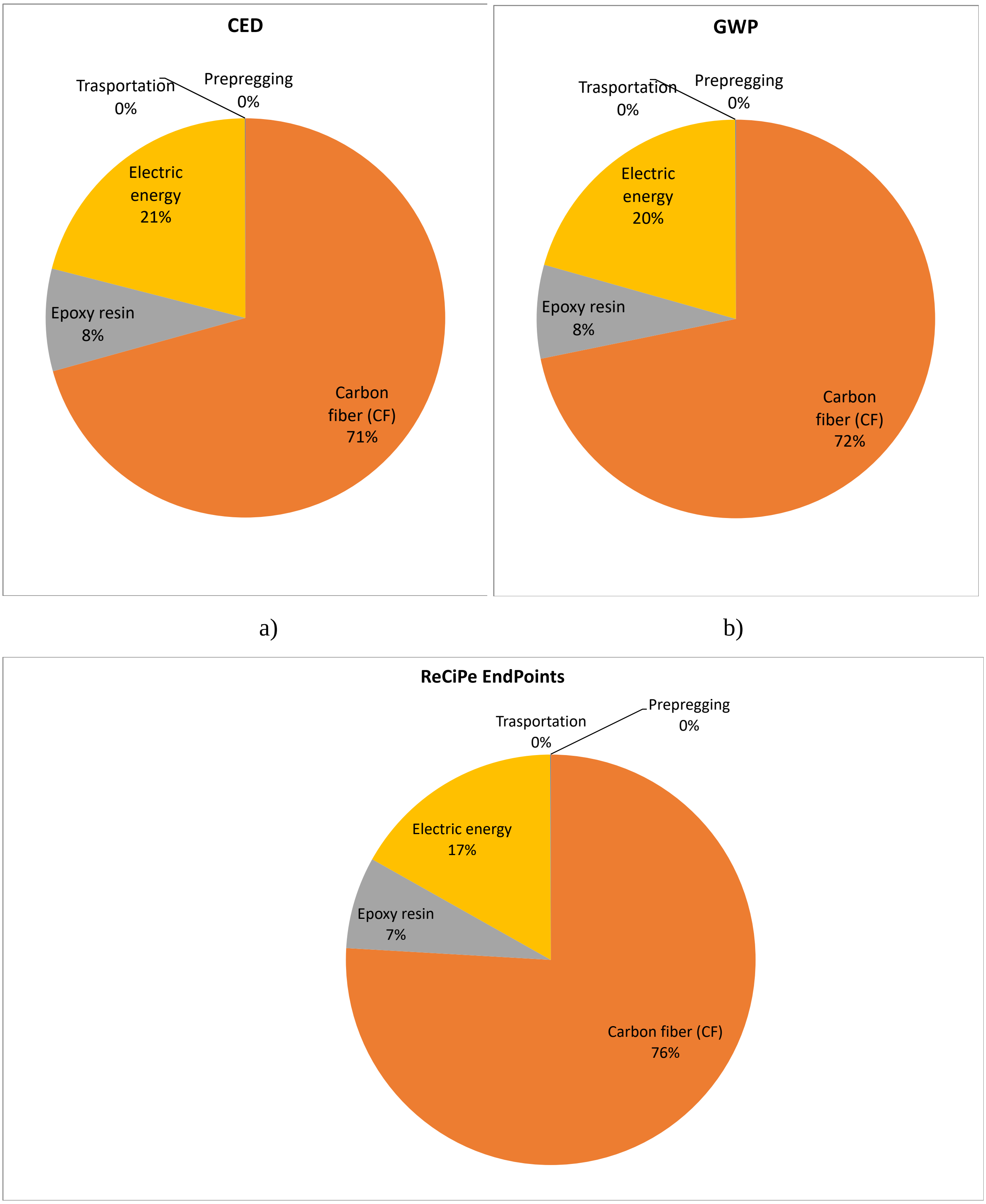
	SCENARIO 1	SCENARIO 2	SCENARIO 3	SCENARIO 4
■ Tooling	0.4	15.6	8.6	3.0
■ De-molding	0.0	0.0	0.0	0.9
■ Curing	1.0	1.0	1.0	3.8
■ Lay-up	1.7	1.7	1.7	2.8
■ Cutting	57.2	57.2	57.2	57.2

Figure 9: LCIA in terms of ReCiPe (EcoPt) for each scenario.

3.4 Detailed analysis of Prepreg

In this section, the detailed analysis of the cutting phase is illustrated. It results the most impacting step for all the scenarios and for all the indicators, indicating that most of the efforts must be focused on the reduction of environmental loads related to this phase.

The cutting phase has been split for the CED, GWP and ReCiPe Endpoint indicators, as reported in Figure 10. It is evident that the largest contribution comes from the production of CF used to prepare the prepreg (always higher than 70% for all the three chosen indicators). Depending on the considered impact category, the production of epoxy resin, prepregging operations and transportations account for a total of 24-29%, with a predominance of the electricity consumed during the prepreg production process that accounts for about three quarters of this contribution (that means about 20% of the total).



a) b)

c)

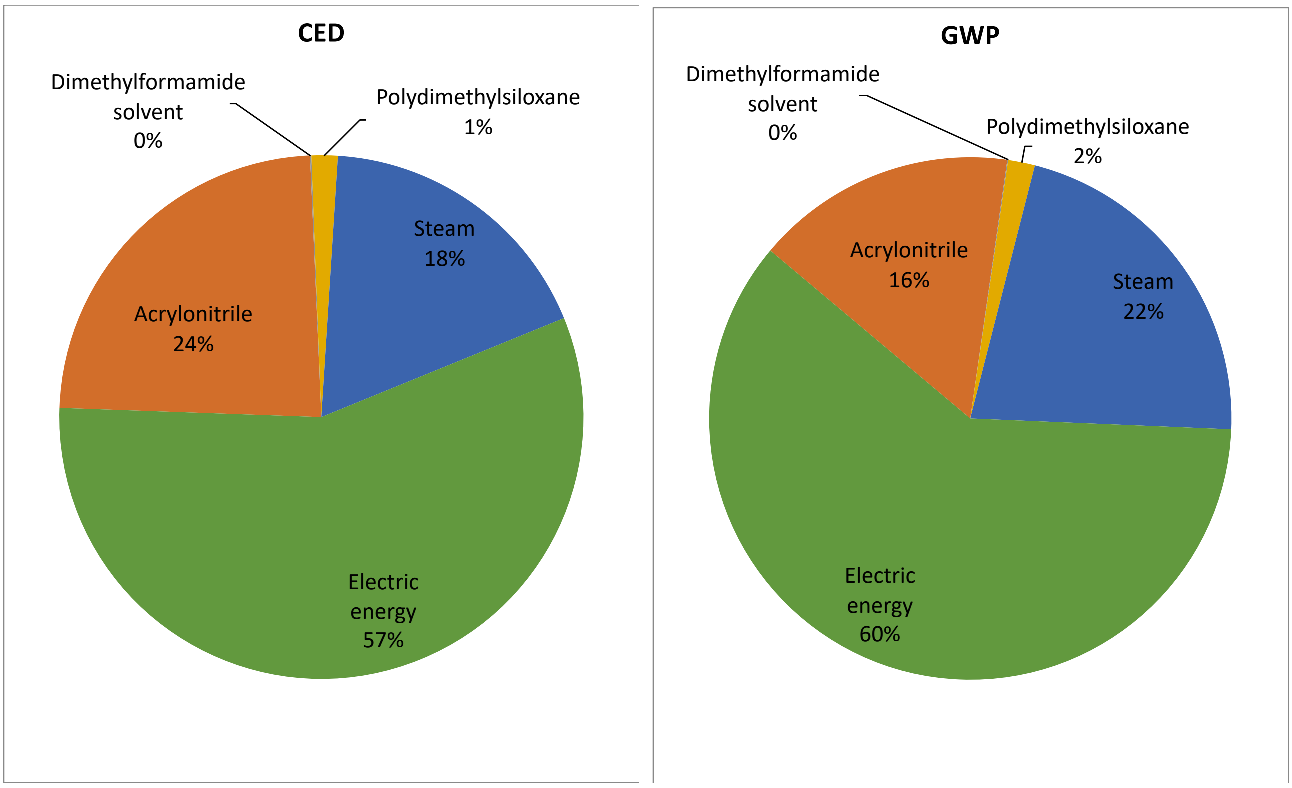
Figure 10: Breakdown of cutting phase impacts in terms of a) CED, b) GWP, c) Endpoints.

Going into more details within the CF (and considering only the net quantity needed to realize the final car hood, excluding prepreg scrap), the following Table 9 reports the split of impacts calculated for the three indicators. From the results it is clear that a very large part of the contribution can be attributed to PAN (about 97% for CED, 93% for GWP and 80% for ReCiPe endpoint), as previously demonstrated in literature (Das, 2011).

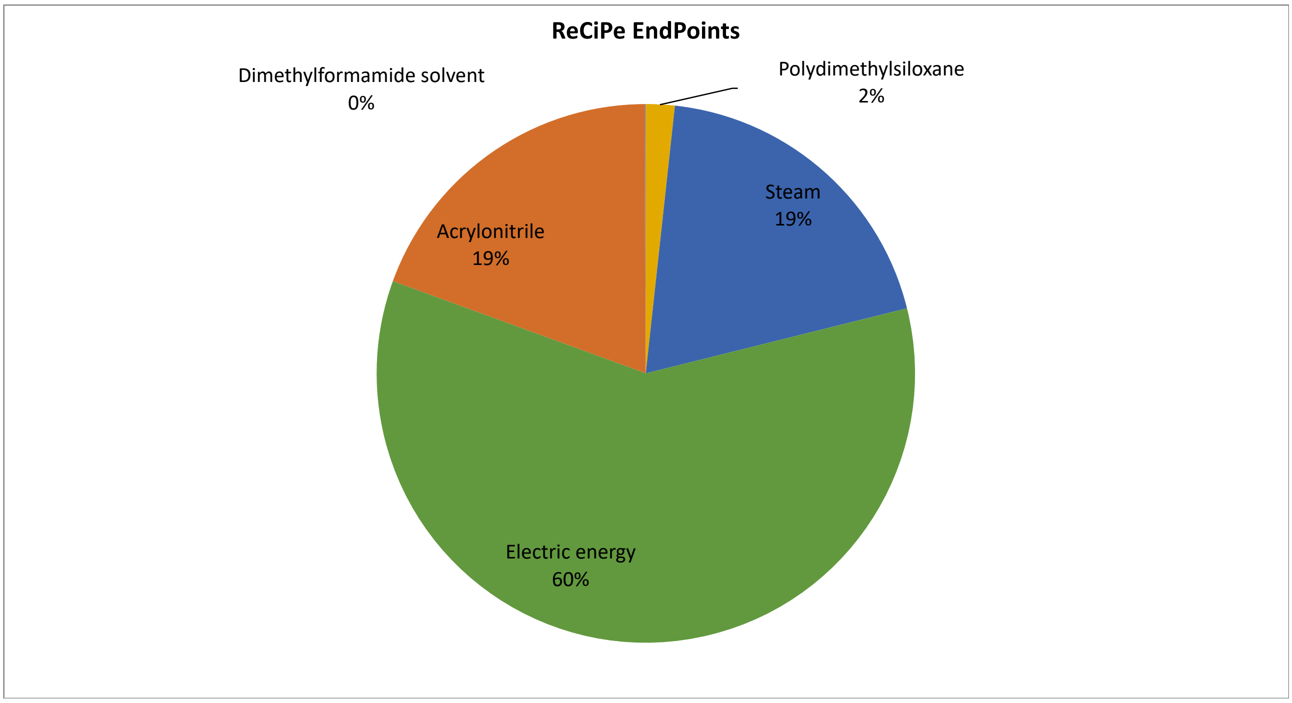
Table 9: Split of contributions of the CF used to produce prepreg used for the final car hood (prepreg scrap excluded) in terms of CED, GWP and ReCiPe endpoint categories.

	CED [MJ]	**GWP [kg CO2 eq]**	**ReCiPe endpoint [EcoPt]**
PAN	4,50E+03	2,43E+02	2,42E+01
Nitrogen	5,92E+01	2,70E+00	2,52E-01
Thermal energy (PAN fibers stabilization and carbonization)	6,70E+01	3,96E+00	3,54E-01
Electricity (CF surface treatment and sizing)	4,68E+00	2,69E-01	2,64E-02
Output emissions	0,00E+00	1,11E+01	5,35E+00
Total	**4,64E+03**	**2,61E+02**	**3,02E+01**

Finally, deepening PAN manufacturing (Figure 11), homogeneous results have been obtained. The electricity required for the polymerization reaction of acrylonitrile represents the first contribution, accounting for about 60% of the total. Both the raw material acrylonitrile and the steam used in the process have comparable impacts in the range 16-24%, while environmental loads caused by other input materials as the dimethylformamide solvent and the polydimethylsiloxane can be considered negligible. As can be expected results are fully in line with the study of (Duflou et al., 2009), confirming the correctness of the built LCA model.



a) b)



d)

Figure 11: Breakdown of PAN manufacturing impacts in terms of a) CED, b) GWP, c) Endpoints.

4. Conclusions

The necessity of developing more eco-friendly processes is also affecting the composites sector. For this reason, assessment of environmental impacts of composite manufacturing techniques is a mandatory task to create awareness and convey engineers' choices to more sustainable processes.

In this study, two manufacturing processes for the production of CFRP components have been assessed from the environmental point of view. One process is bag molding with autoclave curing and the other one is pressure bag molding (PBM). Moreover, for bag molding with autoclave curing, three different scenarios have been investigated, namely the use of aluminum mold, composite mold with polyurethane master or composite mold with MDF master. Both primary and secondary data have been used to calculate loads associated to each process. LCA has been conducted for the four scenarios and different indicators (CED, GWP, ReCiPe mid and endpoint) have been chosen to compare the processes.

The presented LCA study includes the main phases of the processes: raw material extraction, carbon fibers and resin production, prepregging, transportations, molds manufacturing and all the phases related to CFRP component production. The obtained results show that the manufacturing of the pre-impregnated material contributes with the highest impacts in the lifecycle (up to 90%). This is majorly related to the manufacturing of CF and, in particular, to the PAN precursor. This is a well-known issue in the composite sector which is stimulating researchers in developing more ecofriendly precursors such as lignin or bio-based plastics. However, their application is only limited to research laboratories and the mechanical properties of CF produced with these precursors are not still comparable with those of PAN-CF.

The main conclusions of this research are that autoclave curing with aluminum mold is the less impacting process whilst autoclave curing with composite mold and polyurethane master is the worst process from the environmental point of view. These results underlying the importance of avoiding the use of composite mold for the manufacturing of CFRP components. Indeed, the use of masters, in particular based on plastic, and the curing process of the mold lead to a sensible increase in the environmental loads. Moreover, a reduction of aluminum usage in mold production, achievable using innovative processes such as Additive Manufacturing, can lead to a strong reduction of environmental impacts of both autoclave and PBM processes.

In addition, other conclusions can be summarized as follows:

- Considering CED and ReCiPe endpoint, autoclave curing with composite mold and MDF master is more impacting than PBM;
- Considering GWP, PBM is more impacting than autoclave curing with composite mold and MDF;
- The large part of the differences between the scenarios is the tooling phase, namely the impacts related to molds and masters (where needed);
- The curing phase of the PBM presents higher impacts with respect to autoclave curing owing to the high mass of the aluminum mold.

The results of this research represent the starting point for the reduction of environmental loads related to the manufacturing of CFRP components. Indeed, process engineers must take into account, among other product and process specifications (performances, costs, etc.), also the environmental impacts associated to each manufacturing process in order to make informed choices. For this reason, further development will be focused on the investigation of other manufacturing processes (e.g. resin infusion, RTM), in order to guarantee a more comprehensive evaluation of different production methods and to determine the potential environmental benefits deriving from the use of dry fibers technologies.

CRediT author statement

Archimede Forcellese: Funding acquisition, Supervision. **Marco Marconi.**: Data curation, Writing- Original draft preparation, Software, Conceptualization. **Michela Simoncini**: Writing- Reviewing and Editing, Investigation. **Alessio Vita**: Methodology, Investigation, Visualization.

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