Environmental impact assessment of zero waste approach for carbon fiber prepreg scraps

(Article begins on next page)

Abstract:

In the present paper, the environmental impact of an innovative technology, based on a zero-waste approach, for reclaiming carbon fiber prepreg scraps is assessed. The innovative process, proposed within the European project CIRCE, aims at reclaiming scraps produced during the cutting operation of virgin prepreg, avoiding the waste materials landfilling or incineration. The prepreg scraps were transformed into a ready-to-use raw secondary material by using two specifically developed automated systems for cutting and peeling of the scraps. By exploiting the prepared scraps in a compression moulding process, recycled composite parts were produced. The evaluation of the environmental impact was carried out by means of the Life Cycle Assessment (LCA) approach, using the different impact assessment methodologies based on the Cumulative Energy Demand, Global Warming Potential and ReCiPe methods. Furthermore, tensile tests were performed at room temperature to investigate the mechanical properties of the recovered scraps products. In order to evaluate the environmental benefits of the innovative compression molding production with recovered prepreg scraps, the LCA analysis was also performed on two different traditional virgin production scenarios, i.e. the compression molding production with virgin prepreg and the autoclave processing with virgin prepregs, both used for the production of CFRP parts. The results show that the reclaim process leads to a strong reduction of the environmental impacts with respect to traditional composite production processes, demonstrating that such process can represent a valid alternative for a more sustainable manufacturing of composite products.

1 INTRODUCTION

In the last years, composite materials market is constantly expanding as a result of the increasing demand for lightweight products characterized by high performances, such as high specific stiffness and high strength as well as low density [1]. These materials are currently used in a wide range of industrial fields, such as automotive, marine, energy (both fossil and renewable), and sporting equipment [2,3] with a global market size estimated for 2021 at USD 82.9 billion [4]. The global demand for carbon fibers reinforced polymers (CFRPs) is expected to reach 194 kt (kilo tonnes) in 2022, while a demand of 117 kt is predicted for the carbon fibers (CF) [5]. The growing demand of CFRPs is associated with some issues related to the relevant environmental impacts of their manufacturing processes; more specifically, the environmental footprint is mainly due to the high energy consumption required for the raw materials production that, according to recent studies, can be quantified as about 90% of the total impacts [6,7]. For example, the production of virgin carbon fibers (vCF) has a Cumulative Energy Demand (CED) between 198 and 595 MJ/kg [8]. Therefore, since the CFRP waste production will increase in next years (it is estimated at 20 kt/year by 2025 [9]), the development of recovery and recycling systems is highly necessary in order to recover the residual end-of-life value of these materials.

The Directive 2008/98/EC of the European Parliament [10] defined the waste management hierarchy which promotes both the prevention of waste production, and reuse and recycling of CFRPs; as a matter of fact, such directive leads the avoidance of solutions with a high impact, i.e. the landfill, and conducts to significant savings due to the reduction in the virgin materials consumption [11]. Even though the EU legislation is currently lacking of specific guidelines for reuse and recycling of CFRPs [12], regulations will become increasingly stringent to push towards complete recycling of composite materials [13]. As far as the automotive field is concerned, EU currently requires the reuse and recycling of at least 85% and the reuse and recover of at least 95% of end-of-life materials [14]. Currently, there are several recycling methods for CFRPs such as the mechanical, thermal (e.g. pyrolysis and fluidised bed process) and chemical recycling processes [15,16] that allow to recover value from the waste materials rather than just sending them to landfill disposal or incinerators. However, for the recovery systems of thermoset matrix based composites, which constitute around 80% of the total reinforced polymers market [17], there are still relevant issues. As a matter of fact, once the cross-linked structure of thermoset matrices is formed, it cannot be melted, reshaped and recycled [18] and, for the most common resins, it is not practical to depolymerise them to recover the matrix original constituents; hence, the matrix, when recovered, is typically used as filler, fuel or chemical feedstock [15]. On the other hand, the recovered carbon fibers (rCF) are reduced in size and usually show a reduction in the mechanical properties with respect to vCF; nevertheless, they could provide a strong reduction of the environmental and economic impacts related to reinforcement fiber production.

Different researches concerning the recovering of prepreg scraps and their use as secondary raw material can be found [19–22]. In these papers, authors aim at demonstrating the feasibility of using prepreg scraps to produce composite components. They compared the mechanical properties of virgin prepreg samples with the ones of those produced by recovered scraps, demonstrating a substantial reduction of resistance and stiffness but leaving an open door to the use of prepreg scraps in some non-structural applications. However, the detailed assessment of the environmental impacts associated with waste recovery processes is lacking.

In this framework, the present paper aims at studying the environmental impacts of an innovative process, based on a zero-waste approach, for reclaiming carbon fiber prepreg scraps. This study was carried out within the European project CIRCE (Circular Economy Model for Carbon Fibre Prepregs) in collaboration with HP Composites s.p.a., a large Italian enterprise that produces CFRP components, mainly for the automotive sector. The innovative process is based on a zero waste approach because it deals with the recovery of scraps produced during the cutting operations of virgin prepreg rolls (off-cuts, trim waste, and end-roll waste), which constitute between 20 and 50%wt of the virgin prepreg used [21]. These wastes typically end up in landfill or incinerator, with negative impacts in terms of environmental impacts and economic costs. The innovative recovery system turns virgin long-fibers fabric prepreg waste into short-fibers small pieces of prepreg that can be used in the production of composite components as a secondary raw material [20,22]. This allows to completely recover the uncured waste. In order to evaluate the mechanical properties of the recovered scraps products, tensile tests were performed at room temperature. The environmental behaviour of the recovery process was evaluated in a life cycle perspective using the Life Cycle Assessment (LCA) methodology. LCA is an analysis technique used to evaluate the environmental impact associated with all the stages of a product (or a process) life. LCA is widely employed to aid decision making for waste management systems [23], new products and process design to optimize the energy and resource consumptions in a life cycle perspective [24–29]. The principles and framework of LCA are described within the ISO 14040-14044 standards [30,31].

To evaluate the environmental advantages of the innovative process for recovering prepreg scraps and compare it with other production scenarios, the LCA analysis was also performed on two different traditional processes commonly adopted to produce CFRP parts using virgin prepregs.

The present paper is organized as follows. After this introduction, Section 2 describes the innovative recovery zero waste approach and presents the mechanical tests and the Life Cycle Assessment methodologies. Furthermore, goal and scope definition, system boundaries and scenario description, Life Cycle Inventory (LCI), and Life Cycle Impact Assessment (LCIA) of the conducted LCA are described. In Section 3, the results of the tensile tests and of the LCIA are presented and discussed. Finally, Section 4 provides the conclusions and the proposals for further developments.

2. Methodologies

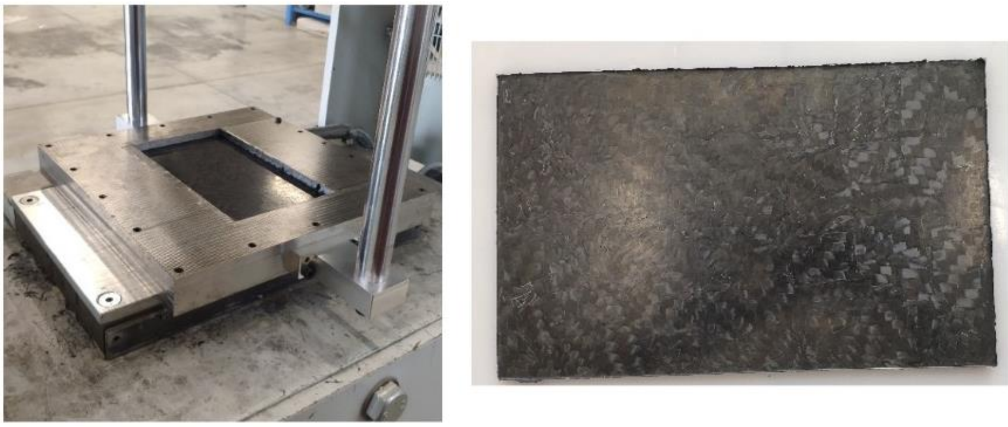
2.1 RECOVERY PROCESS DESCRIPTION

The innovative recovery process developed in the present work is based on two specifically developed automated systems in order to transform the fabric prepreg waste (Figure 1) in ready-to-use secondary material. The former machine in the processing cycle is used for sizing and shredding of scraps (cutting machine), producing small pieces of prepreg characterized by almost uniform size and shape. Specifically, prepreg scraps, still covered with the backing paper, automatically feed rotary cutters that initially cut the pieces into linear strips and subsequently into chips. Prepreg scraps can be oriented before entering the cutting machine in order to modify fiber length and orientation of the resulting chips.

Once prepreg scraps are reduced into chips of the desired dimensions, the polyethylene backing paper is removed by means of the latter automated peeling machine, making the scraps ready for reuse in molding operations. This machine easily removes the film from both the top and bottom surfaces of chips, by exploiting a physical process based on the friction generated on the backing paper surfaces. The backing paper is then collected and treated as a recyclable waste, while chips are conveyed into a dedicated collector. If their use is not immediate, they have to be stored in an industrial refrigerator to avoid the curing of the resin and the adhesion of the chips.

Figure 1: The reclaimed prepreg scraps

The reclaimed scraps are used in a compression molding process to realize laminate panels of planar dimensions equal to 35x45 cm (Figure 2). The prepreg scraps are manually and randomly deposited in the mold cavity in order to guarantee constant in-plane properties. The thickness of the mold cavity can be varied according to the desired thickness of the panel.



a) b)

Figure 2: a) The mold used for the compression molding of prepreg scraps and b) a typical laminated panel produced using the prepreg scraps

2.2 TENSILE TEST

The mechanical properties of the recovered scrap products were evaluated by means of tensile tests performed according to the ASTM D3039 international standard. To this purpose, samples were produced by both recovered material and virgin Sheet Molding Compound (SMC). Specifically, the considered SMC, chosen among the pre-impregnated materials used by HP Composites, is constituted by short discontinuous carbon fibers randomly dispersed in an epoxy resin matrix. The material, a 3K tow, is characterized by fiber length of about 25 mm, nominal fiber content of 60 % in weight, and aerial weight of 1500 g/m^2. A universal testing machine was used to perform the tests; stress vs. strain curves were obtained by measuring load and displacement by means of a load cell and an extensometer.

2.3 LIFE CYCLE ASSESSMENT

The LCA methodology, according to ISO 14040-14044 standards, consists of four different phases [30,31]:

1. Goal and scope definition: The objective of the study, the products or the systems considered, the functional unit, and the spatial and temporal system boundaries have to be clearly defined.
2. Life Cycle Inventory (LCI): it consists in the collection and quantification of all the relevant inputs and outputs of the activities within the system boundaries.
3. Life Cycle Impact Assessment (LCIA): impact categories and impact indicators are chosen to give a complete vision of the environmental load of the products or systems studied. LCI data are translated into possible impacts via characterization and/or weighting factors.
4. Results interpretation: the analysis ends with an interpretation and a critical review of the obtained results. Conclusions, limitations, and recommendation are made to reduce the environmental impact of the system studied.

2.3.1 GOAL AND SCOPE DEFINITION

This paper aims at quantifying and comparing the environmental impact associated with different methods for the production of a CFRP sample, in order to establish if the new scrap recovery system provides environmental benefits in comparison with available standard production systems.

The functional unit (FU) was defined as "the manufacturing of one unit of a CFRP sample with a top surface area of 0.0056 m^2 and a bottom surface area of 0.0057 m^2, that can withstand a tensile load between 5 and 5.7 kN". The considered production processes use raw materials (virgin prepreg and recovered prepreg scraps) characterized by different mechanical properties, as reported in section 3.1. Therefore, to ensure the same tensile strength chosen in the FU, samples with different thickness and weight were considered, depending on the raw material used; in particular, the recovered scrap sample weights 0.07 kg, while the virgin sample weight is 0.06 kg.

Three different scenarios were considered to simulate several industrial cases:

- Scenario 1: compression molding of virgin prepreg (virgin compression molding);
- Scenario 2: compression molding of recovered prepreg scraps (scrap compression molding);
- Scenario 3: autoclave molding of virgin prepreg (virgin autoclave molding).

2.3.2 SYSTEM BOUNDARIES AND SCENARIO DESCRIPTION

The performed Life Cycle Assessment can be classified as a "cradle to grave" analysis, since all the life cycle phases from the raw materials extraction to the final products disposal are considered [28,32,33]. The tools production, transport, and manufacturing phases are considered too. The use phase of the produced samples is not taken into account in this work since the environmental impact associated with their life is negligible and can be considered the same for the three scenarios investigated, notwithstanding the different production systems lead to different product weights [34].

Figure 3 shows the system boundaries of the three considered scenarios. The main phases (tooling, prepregging and cutting, lay up, etc.) are divided in blocks; each block contains the elementary processes colored differently for the three scenarios. Double-colored and white cells indicate that processes are common between two and all the three scenarios, respectively.

The production phase of the virgin prepreg (used in scenario 1 and 3) includes the production and transportation of the CFs, epoxy resin, and PE (polyethylene) release paper as well as the prepregging operations and prepreg roll transport [35]. The virgin prepreg is then stored in an industrial refrigerator and, when needed, it is cut by means of a CNC machine, to obtain the templates used in the lay-up process. The prepreg scraps obtained during the cutting phase are assumed end up in landfill [36].

The production process for scenario 2 is very similar to the one of scenario 1; the difference is that the virgin prepreg production is replaced by the preparation process of the recovered prepreg scraps described in the Section 2. In addition, the different material employed leads to different products weights and consequently to different energy consumptions for the curing phase, different molds weights and different quantity of the consumables used.

After a manual lay-up phase, curing is achieved either by means of a compression molding process (scenario 1 and 2) or in an autoclave process (scenario 3). Aluminium molds were considered for all the scenarios since they have good durability and they are preferred when small tolerances are not required (as is in this case study) [29]. The tooling phase considers the raw aluminium extraction, molds machining, material and tools transport and aluminium EoL (by recycling) [37]. The manufacturing of consumable materials used in the different processes was also considered as well as their EoL (landfill disposal), whilst their transport was not taken into account due to their limited weight and quantity which leads to negligible environmental impacts. At the end of their useful life, the produced components are considered to be sent to landfill [38]. The manufacturing phase of the machines (e.g. the press, the cutting and peeling machines, the autoclave, etc.) is considered out of the system boundaries since, as proved in previous studies [39], their impacts would be negligible due to their long service life.

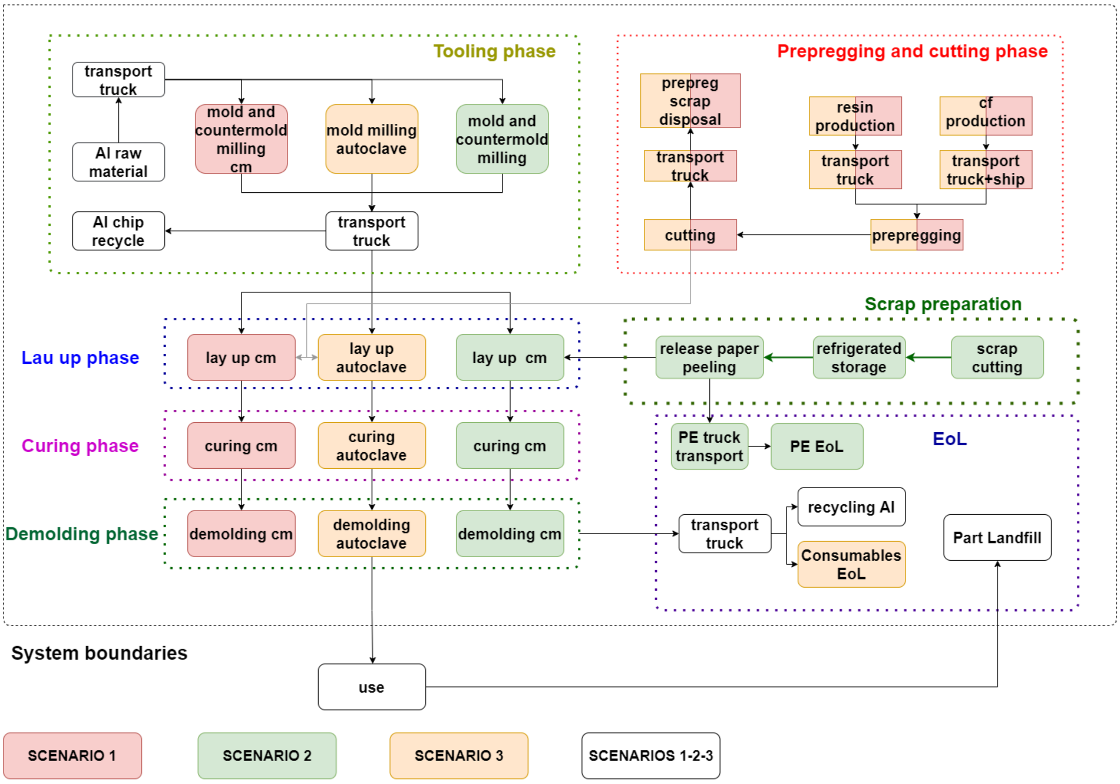


Figure 3: System boundaries of the three considered scenarios

2.3.4 LIFE CYCLE INVENTORY

The LCI considers the inputs and outputs of all the processes included within the previously defined system boundaries. Primary data were collected by direct measurements of the involved company, while secondary data were retrieved from the literature and from the Ecoinvent 3.1 commercial database (the system model "allocation default" version was used [40]).

The main input material for the production of the sample is the prepreg. For the scrap compression molding process, the quantity of recovered scraps needed was measured by weighting the effectively used material, whilst, for the virgin productions, the weight of the sample was estimated considering that the final products obtained in the three scenarios must have the same tensile resistance. Since no inventory data about the prepreg production are currently available within the used Ecoinvent database, the model proposed by Forcellese et al [29], which is, in turn, based on the work of [41], [42], and [28], was used to evaluate the environmental impacts for the production of the prepreg. The prepreg was considered to be composed of 36%wt epoxy resin and 64%wt PAN (Polyacrilonitrile) based carbon fibers; moreover, in this study, the PE release paper production was added to the previous model. The environmental impact of the prepreg waste input is considered negative because the reuse of the waste prevents them from being sent to landfill.

Concerning the recovered scraps preparation process, the energy consumption of the cutting and peeling machines was calculated considering their rated power, their productivity, and the weight of the scraps used [43]. Similarly, the virgin prepreg cutting machine energy consumption was estimated from aggregated data (part perimeter, number of prepreg layers, nominal power of the machine, and cutting speed) and a nesting efficiency of 0.7 was assumed. The quantity of consumables used for the three scenarios was estimated by comparing the present case study to previous literature data [29] and by considering the dimensions of the manufactured products.

The energy consumptions related to the lay-up phase, e.g. these associated to the use of automated cutting tools and the clean room, have not been considered due to their negligible impacts with respect to the other phases.

The quantities of material needed, and the scraps generated during the manufacturing of the mold and countermold used in scenario 2 were calculated considering the tools 3D models. As far as the virgin productions are concerned, since they were not actually realized, the equipment data were estimated on the basis of comparisons of the product weight with the second scenario. The input materials data (for the aluminium and the consumables used) and the energy consumption for the milling phase of the tools have been derived from the Ecoinvent database.

According to the technical data based on the industrial practice of the involved company, the service life of molds is equal to 750 molding cycles. Therefore, to associate the tooling phase with the functional unit, the environmental impacts of the molds production were divided by 750. The recycling rate for the aluminium tools has been set to 80%; the standard rate is about 70% but, since molds are monolithic structure composed by a single material, they are expected to be recycled with high efficiency [44].

The electric energy consumptions for the curing phase of the compression molding processes were obtained by calculating the thermal energy needed to heat molds at 120°C and to keep them at such temperature until complete curing. In this evaluation, a coefficient equal to 1.2 to take into account the heat loss, was considered. For the scenario 3, the autoclave energy consumption was estimated on the basis of the results obtained by Song et al [28].

Most of the transport data were taken from [29], in which the same company of the analysis of the present work was involved. Such data were estimated on the basis of indication provided by key managers of the company and by considering average distances among supplier and customer sites.

Table 1 summarizes the inventory data related to materials, energy consumptions, and transports considered in the present LCA study.

Table 1: LCI data

	Item		**Quantity**		
			Scenario 1	**Scenario 2**	**Scenario 3**
Input materials		Material		Weight	
Prepreg	Virgin prepreg used	prepreg	0.06 kg	-	0.06 kg
	Prepreg waste (cutting phase)	prepreg	0.028 kg	-	0.028 kg
	Prepreg scraps input	prepreg	-	0.07 kg	-
	Prepreg PE release paper	Polyethylene (PE)	0.0067 kg	0.0078 kg	0.0067 kg
Lay-up	Release agent	Organic solvent	0.001 kg	0.0012 kg	0.0005 kg
	Release paper	Polyetrafluoroethylene	-	-	0.0034 kg
	Breather	Polyethylene terephtalate	-	-	0.01 kg
	Vacuum bag	Polyamide 66 (PA66)	-	-	0.035 kg
Equipment		Material		Weight	

Mold	Input Aluminium	Raw aluminium	16.66 kg	19.44 kg	16.66 kg
	Aluminium scraps	Aluminium scraps	1.66 kg	1.94 kg	1.66 kg
	Mold final weight	Aluminium	15 kg	17.5 kg	15 kg
Countermold	Input Aluminium	Raw aluminium	23.14 kg	27 kg	-
	Aluminium scraps	Aluminium scraps	9.43 kg	11 kg	-
	Countermold final weight	Aluminium	13.71 kg	16 kg	-
Electrical energy consumption			Energy consumption		
	Cutting virgin prepreg		0.01 kWh		0.01 kWh
	Cutting prepreg scraps		-	0.0004 kWh	-
	Peeling prepreg scraps		-	0.0065 kWh	-
	Lay-up phase		-	-	-
	Curing autoclave		-	-	0.37 kWh
	Curing compression molding		1 kWh	1.2 kWh	-
	Storage energy consumption		0.082 kWh	0.0672 kWh	0.082 kWh
Transportation		Tranpsortation typology		Distance	
Prepreg	Carbon fibers	Truck 16-32 ton		150 km	
		Transoceanic ship		16800 km	
	Epoxy resin	Truck 16-32 ton		1200 km	
	Virgin prepreg	Truck 3.5-7.5 ton		30 km	
Mold	Raw Aluminium	Truck 16-32 ton		1200 km	
	Aluminium molds and	Truck 3.5-7.5 ton		12 km	
	Aluminium waste	Truck 16-32 ton		200 km	

2.3.5 Life Cycle Impact Assessment

The selection of the impact categories is crucial to obtain clear and relevant LCIA results; different indicators can help to achieve a complete overview of the environmental impacts of the manufacturing processes. This study considers three different impact assessment methodologies that were widely used in relevant studies available in literature to evaluate the environmental performances of CFRP products:

- The Cumulative Energy Demand (CED or primary energy consumption, expressed in MJ) quantifies, by means of characterization factors, all the direct and indirect energy resources (e.g. fossil, nuclear, solar) used by the processes included in the system boundaries. Since the CFRP production technologies are characterized by high energy consumptions, the CED is a meaningful indicator for these processes; for this reason, it was widely used in previous LCA studies [6,45,46].

- The Global Warming Potential (GWP, expressed in kg CO_2 eq) is used to quantify the greenhouse gases (GHG) emissions in the atmosphere and their effects on global warming and climate change. The methodology described by the Intergovernmental Panel on Climate Change (IPCC) was followed. It considers the heat absorbed by any greenhouse gas as a multiple of the heat that would be absorbed by the same mass of carbon dioxide (CO_2) and assess their effects over the years [6,25,42,45–49].
- The ReCiPe method, developed in 2008, provides a comprehensive view of the effect of a product or a process on the environment, considering 18 midpoint impact categories that focus on specific environmental problems (e.g. ozone depletion and terrestrial acidification). Most of the midpoint impact categories can be then aggregated into three endpoint categories: damage to human health (HH), damage to ecosystem diversity (ED), and damage to resource availability (RA) [6,25,42,46–49].

The software Simapro 8.0.5.13 was used to perform the impact assessment.

3 RESULTS AND DISCUSSION

The results of the mechanical tests and Life Cycle Impact Assessment, calculated by using the inventory data in different environmental impact categories, are described and discussed in the following subsections.

3.1 TENSILE TEST

The tensile results of Figure 4 show that the recovered and virgin materials exhibit similar Young's modulus (E); more specifically, it can be observed that the tensile strength of the recovered samples is about 20% lower than that of the virgin alternative. It is expected that the future development of the reclaim technology will improve the performances of the recovered material so that it will be able to achieve the same mechanical properties of the virgin SMC.

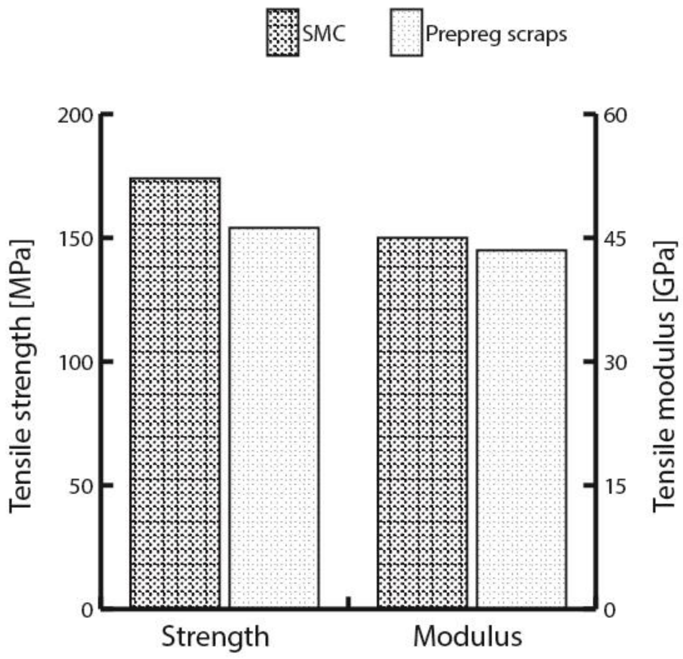


Figure 4: Results of the tensile test on sheet molding compound and reclaimed prepreg scraps

3.2 CUMULATIVE ENERGY DEMAND

Figure 5 and Table 2 show the results of the environmental evaluation of the three production systems in terms of CED. The scenario 2 is characterized by the lowest environmental load (27.7 MJ) whilst scenarios 1 and 3 are associated to much higher impact values, equal to 76.2 and 69.8 MJ, respectively. The choice of scenario 2 leads to a saving of 601 MJ per kg of recovered CFRP if compared with scenario 3. The improved performance is attributed to the utilization of the raw materials; the impacts associated with the scrap recovery system are negligible due to the low electrical energy consumption of the scraps cutting and peeling machines. On the other hand, the main contribution for the scenarios 1 and 3 is attributed to the consumption of virgin prepreg; as reported in a previous study by the authors, the production of carbon fibers/epoxy resin prepreg has a high environmental impact mainly due to the large amount of energy required for producing the carbon fibers. In this analysis, virgin prepreg is about 70% of the CED value; this is confirmed in the study by Forcellese et al. [29] who demonstrated that such value can reach up to 90% for the manufacturing of heavier automotive products (around 15 kg), through production processes similar to those considered in the present work.

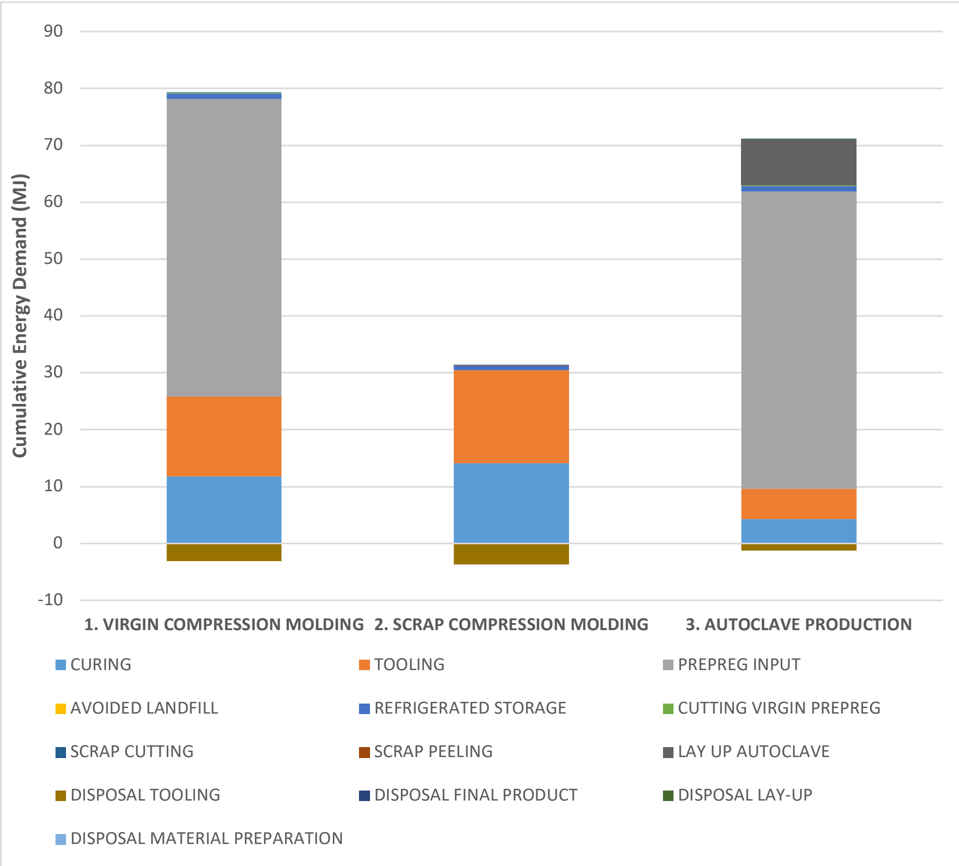


Figure 5: LCIA in terms of CED for the three scenarios

Since virgin prepreg is saved by means of the proposed Zero waste Technology, the environmental savings are expected to increase as the contribution on the total impacts of the raw material used increases. That would be the case of industrial applications of the prepreg recovery process.

Regarding the tooling phase, the energy demand is 14.07 MJ for the scenario 1, and 16.4 MJ for the second scenario. This difference is due to the higher weight of the sample used in the scenario 2, that leads to heavier molds. The autoclave production has the lowest environmental load for the tooling phase (5.3 MJ) because the aluminium mold is the only tool needed while a countermold is not necessary. Since the aluminium tools are considered to be recycled, a negative impact can be observed for their EoL.

Table 2: CED values for all the phases considered in the three scenarios

	Scenario 1 [MJ]	Scenario 2 [MJ]	Scenario 3 [MJ]
Curing	11.739	14.087	4.299
Tooling	14.070	16.393	5.263
Prepreg input	52.349	///	52.349
Avoided landfill	///	-0.022	///
Refrigerated storage	0.961	0.785	0.961
Cutting virgin prepreg	0.159	///	0.159
Scrap cutting	///	0.004	///
Scrap peeling	///	0.068	///
Lay up autoclave	///	///	8.035
Disposal tooling	-3.119	-3.640	-1.305
Disposal final product	0.017	0.020	0.017
Disposal lay-up	///	///	0.014
Disposal material preparation	0.010	0.002	0.010

As far as the curing phase is concerned, the highest energy consumption is associated with the scenario 2 since more thermal energy is required to cure heavier products (with heavier molds). According to the results shown by Vita et al. [37], the impact associated with the curing phase of the autoclave scenario is lower than that of the compression molding ones. In fact, since the CM tools are heavier and have a high thermal inertia, more energy is needed to heat them up, causing relevant environmental impacts. The storage phase has the same impacts for scenarios 1 and 3 while the CED is about 20% lower for the scenario 2. As a matter of fact, all the material stored for the scenario 2 is used in the compression molding process, while, for the virgin productions, 30% of the stored material becomes a waste after the cutting phase (the nesting efficiency is considered to be 70%, so a higher quantity of prepreg must be stored).

Figure 6 shows the effect of the production volume (namely parts produced per year) on the CED results. The analysis considers a range of production volume from 1 to 400 parts per year, values extremely common in the context of composite industries. The impacts related to the manufacturing of the molds are allocated on the number of parts produced in the different scenarios. If the scenario 2 is compared with the scenario 1, a BEP_{1-2} (Break Even Point) is obtained at 27 units whilst the comparison between scenarios 2 and 3 shows a BEP_{2-3} value at 129 units produced. Consequently, as far as low production volumes are concerned, the autoclave scenario has the lowest environmental impact since it is characterized by the lowest contribution of the tooling phase as compared to the compression molding processes.

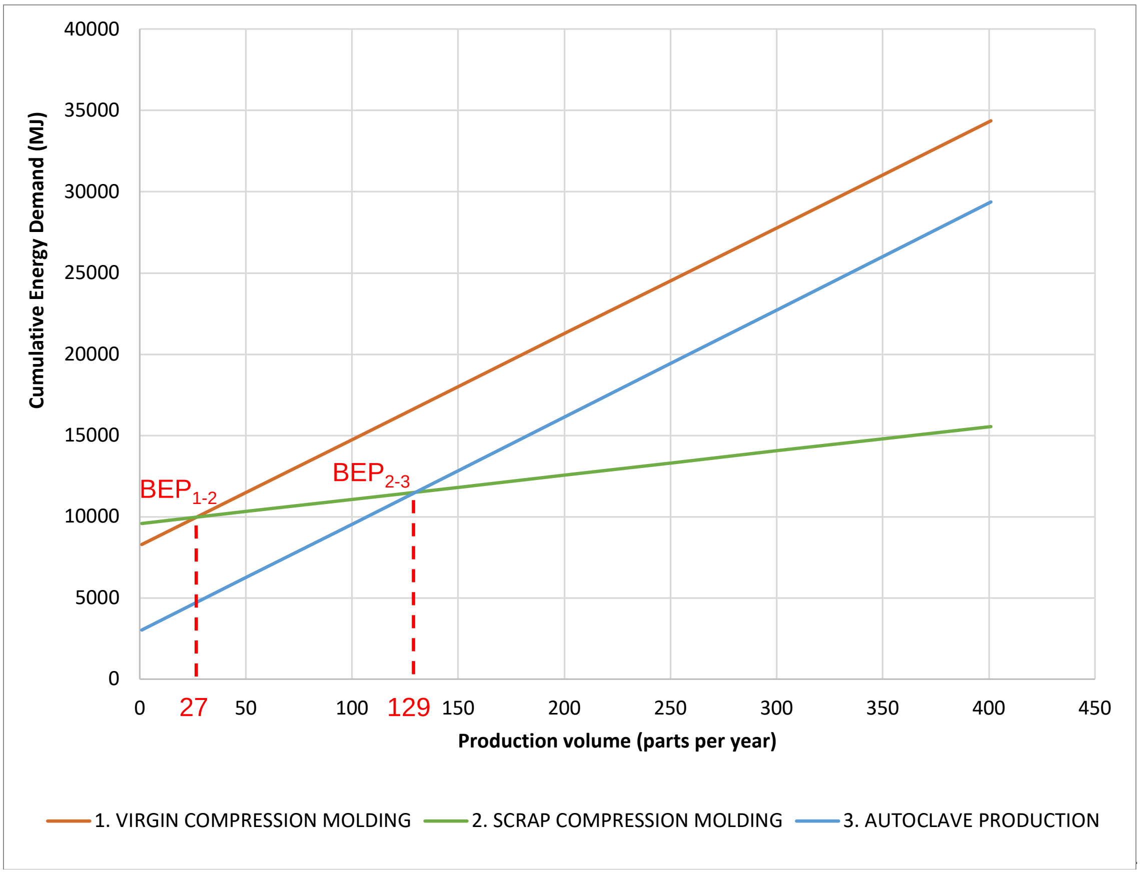


Figure 6: Cumulative Energy Demand vs production volume for the different scenarios

3.3 GLOBAL WARMING POTENTIAL

The LCIA results calculated for the GWP indicator are shown in Figure 7. As for the CED, the recycling process provides a reduction of the environmental load for the considered FU, with a

GWP value of 2.1 kg CO_2 eq, which is less than half the GWP value for the two other considered alternatives (the virgin CM has a GWP value of 4.7 kg CO_2 eq while the autoclave production has a GWP value of 5.0 kg CO_2 eq). The recycling scenario leads to a saving of 37.4 kg CO_2 eq per kg of CFRP recovered. The analysis of the three different scenarios leads to results similar to those provided by CED. The main discrepancy is represented by the highest environmental load associated to autoclave production; this is due to the lay-up phase of the third scenario, in particular to the polytetrafluoroethylene (PTFE) release film. Despite the low mass (0.0034 kg), this film has a high impact due to the very high unitary GWP of the PTFE (about 303 kg CO_2 eq per kg of material).

A comparison among the results of this assessment and other LCA studies carried out on available recycling systems for thermosetting matrix composites has been conducted. Meng et al. [11] analysed the environmental performances of different EoL options for cured CFRP waste (i.e. fluidised bed recycling, mechanical recycling, landfill, incinerator etc), considering a waste composed of 55%wt of fibers and 45%wt of matrix. The fluidised bed recycling process was the best environmental alternative, providing a saving of 25,9 kg CO_2 eq per kg of CFRP recovered, which is still 44% lower than the results obtained in the present study. A rigorous comparison is not possible due to the different FU considered in the two studies (different percentage in weight of fibers and matrix); however, it is safe to think that a higher percentage in weight of fibers (like in the analysis by Meng et al. [11]), would result in an increased environmental saving associated to the scrap recovery process. In fact, the environmental saving of the recovery process depends exclusively on the virgin prepreg saving; in turn, if the load associated to the prepreg production increases, as in the case of higher fiber content, the environmental saving of the recovery process increases too.

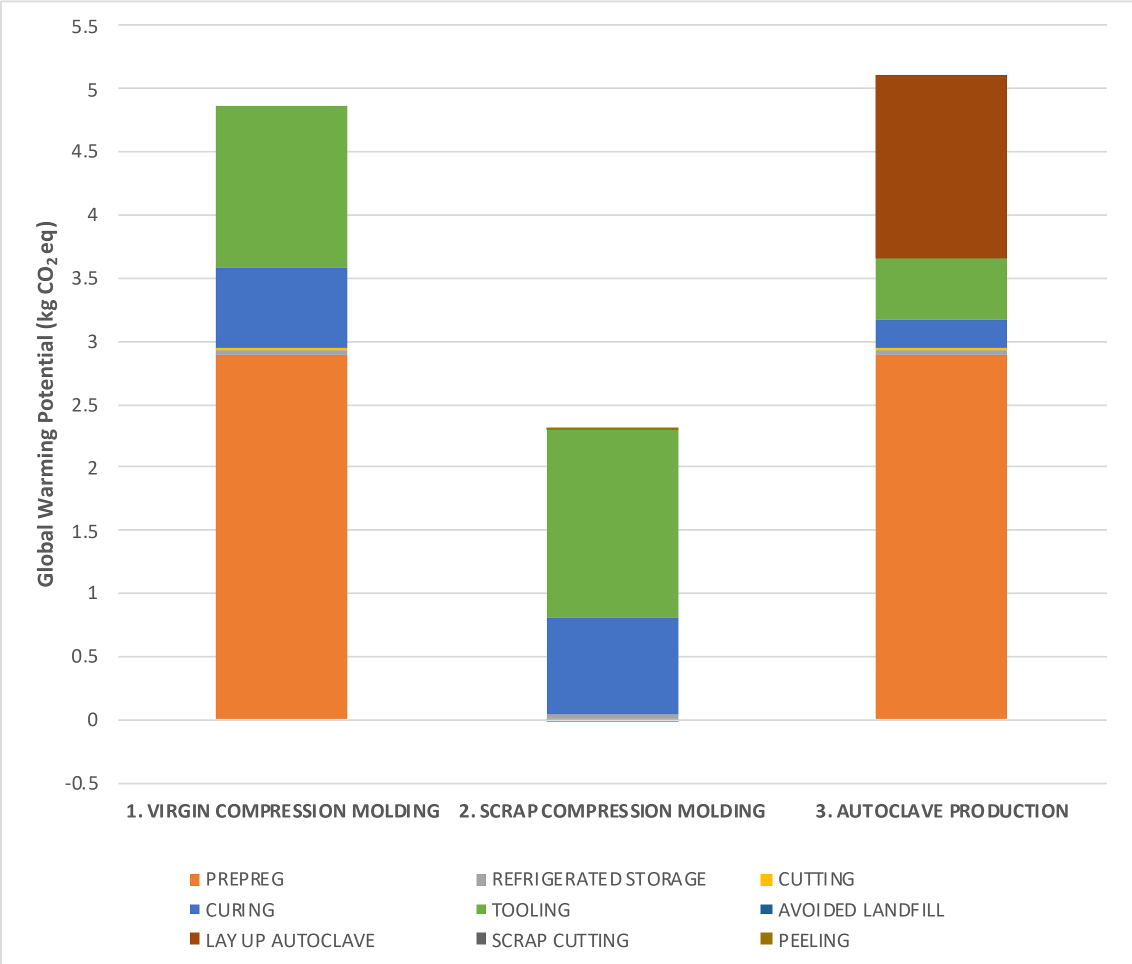


Figure 7: LCIA results in terms of GWP

3.4 ReCiPe

Finally, the results provided by the ReCiPe method, at both the midpoint and endpoint levels, are analyzed. Figure 8 shows the results related to the three production processes for all the 18 midpoint impact categories. Since the impact categories have different units of measurement, the data were normalized in order to make the graphs easier to understand. The applied normalization consists in dividing the results by the maximum value obtained in each impact category, so that the worst scenario has a 100% value. The impacts are mainly caused by four inputs: (i) the energy consumption of the curing phase, (ii) the virgin prepreg used, (iii) the tooling phase, and (iv) the material used for the autoclave lay-up. Even if the rank of the three scenarios is not homogeneous for the different impact categories, it is worth to notice that the

Zero waste Technology shows the best environmental performance for all the considered categories, while the virgin compression molding is characterized by the worst behaviour for most of the ReCiPe midpoint categories. As far as the scenarios 1 and 3 are concerned, the virgin prepreg production represents the major contributor for several indicators; one exception is given by the results in terms of “ozone depletion” for the autoclave production, where the PTFE used in the lay-up phase as release film accounts for almost all the indicator value. As for CED and GWP, the scrap preparation process has a negligible impact.

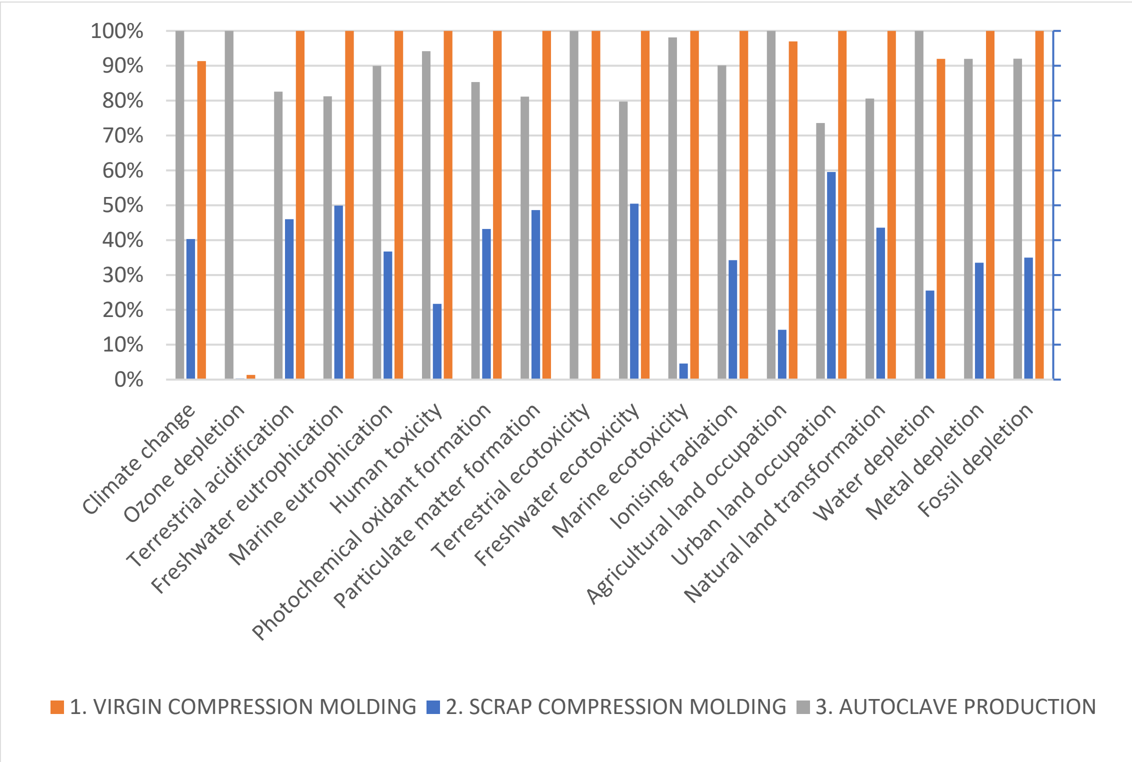


Figure 8: Comparison of the three considered scenarios for all the ReCiPe midpoint categories

Finally, the midpoint categories were aggregated into a single indicator, as shown in Figure 9; the results confirm the same trend observed by considering the CED.

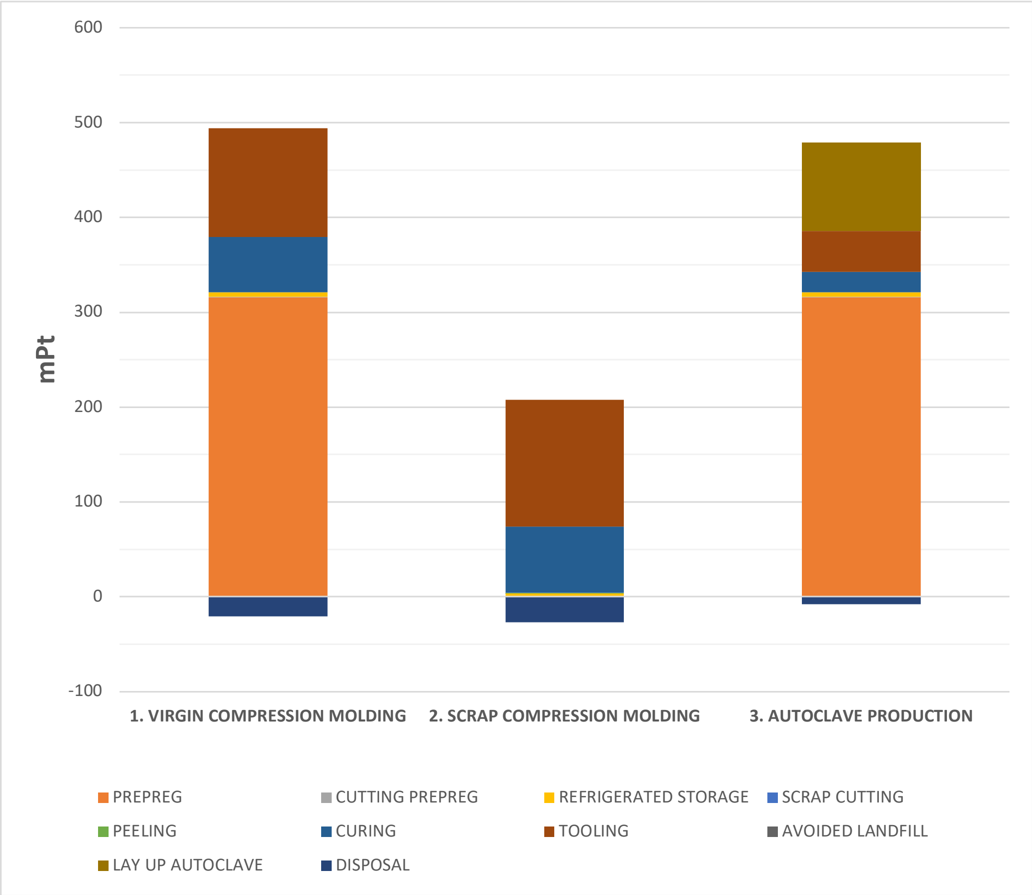


Figure 9: ReCiPe single score results

4. CONCLUSION AND FURTHER DEVELOPMENTS

In the present investigation, a new Zero Waste Technology for the recovery of uncured prepreg scraps, produced during ply cutting operations of virgin prepreg rolls, was developed and assessed from the environmental point of view, against standard production technologies. Usually, waste account from 20%wt to 50%wt of the prepreg produced; since the prepreg production is very expensive and energy intensive, the recovery of these scraps is not only an environmental but also an economic necessity. The proposed recycling process is based on the use of cutting and peeling machines that prepare the scraps for their reuse as a secondary raw material for new production processes.

To evaluate the environmental performance of the recovery process, a Life Cycle Assessment analysis was performed. The production processes of a CFRP sample were investigated considering three different scenarios: compression molding production with virgin prepreg, compression molding production with recovered prepreg scraps and autoclave processing with virgin prepreg. The environmental impacts of the different scenarios were evaluated considering different indicators: CED, GWP, and ReCiPe at both the midpoint and endpoint levels. Impacts from extraction of raw materials to disposal of the final products were evaluated (from cradle to crave analysis), whilst the useful life of the sample was considered out of the system boundaries.

As a general outcome, the innovative compression molding process of prepreg scraps results the most environmentally friendly for all the impact categories considered.

The CED method showed that:

- The use of virgin prepreg, which constitutes the main contribution on the total impacts of the traditional production processes, can be avoided as the prepreg scraps are recovered: in terms of CED results, the compression molding of virgin prepreg and autoclave molding of virgin prepreg are characterized by impact values of 76.2 and 69.8 MJ, respectively, whilst the compression molding of recovered prepreg scraps exhibits an environmental load of 27.7 MJ;
- The innovative compression molding leads to a saving of 601 MJ per kg of recovered CFRP as compared to the autoclave molding of virgin prepreg;
- The virgin compression molding exhibits an energy demand of 14.07 MJ for the tooling phase, whilst the scrap compression molding of 16.4 MJ due to the heavier molds used. The autoclave production has an energy demand of 5.3 MJ since the countermold is not necessary;

- By comparing the Cumulative Energy Demand vs production volume for the different scenarios investigated, two break even points can be detected, at 27 and 129 parts per year;
- For production volumes lower than 27 parts per year, the reclaim process is characterized by the highest environmental load due to the high contribution of the molds, whilst the autoclave molding of virgin prepreg has the lowest environmental impact;
- After 27 units produced, the scraps compression molding shows a lower environmental impact than the compression molding of virgin prepreg whilst, after 129 units produced, the innovative reclaim process of carbon fiber prepreg scraps is the most sustainable alternative among the different manufacturing processes of CFRP parts considered in the present work.

As far as the results obtained by the GWP method is concerned, it was observed that:

- The recycling process provides a decrease in the environmental load for the production of the functional unit, with a value of 2.1 kg CO_2 eq, whilst the virgin CM and the autoclave production are characterized by GWP values of 4.7 kg CO_2 eq and 5.0 kg CO_2 eq, respectively. The recycling scenario leads to a saving of 37.4 kg CO_2 eq per kg of CFRP recovered.

The results given by the ReCiPe method confirmed that the Zero waste Technology is characterized the best environmental performance for all the considered categories, while the virgin compression molding is generally characterized by the worst behaviour.

An investigation of the industrial applications of the recovery process, such as the manufacturing of automotive components, is left as future work. It would be valuable to consider the parts service life too, so that there would be a comprehensive view of the environmental load associated with the recycled products increased weight. In addition, a cost analysis (e. g. through the Life Cycle Cost methodology) and a detailed comparison with other currently available recycling systems can be made.

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