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FULL RESEARCH ARTICLE

Cradle-to-gate life cycle assessment: a comparison of polymer and metal-based powder bed fusion for the production of a robot end-effector with internal conformal channels

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Abstract

Different industries are adopting additive manufacturing (AM) technologies to produce complex designs with minimum material wastage. The sustainability assessment of AM technologies is therefore essential to address the current environmental challenges. This research aims to compare the environmental impacts of different raw materials used for the production of a robot end-effector with internal conformal channels via powder bed fusion (PBF) and provide a framework to assess the sustainability of polymer, metal, and composite-based materials selected for this technology. A life cycle assessment (LCA) was performed comparing the production of a robot end-effector using three different raw materials, *i.e.,* Polyamide 12 (PA12), aluminum alloy powder AlSi10Mg, and a composite of PA12 and graphene nanoplatelets (to induce electrostatic-dissipative properties for attaining functionality of picking and placing printed circuit boards) via PBF technology. Selective laser sintering (SLS) and direct metal laser sintering (DMLS) processes were considered to produce the robot end-effector. The scope was cradle-to-gate, including raw material extraction, transportation, transformation during manufacturing, and corresponding energy utilization. Environmental impact assessment categories are divided into air, water, and land emissions. These include global warming (GW), stratospheric ozone depletion (SOD), fine particulate matter formation (FPMF), water consumption (WC), freshwater ecotoxicity (FWT), freshwater eutrophication (FWE), fossil resource scarcity (FRS), land use (LU), terrestrial acidification (TA), and terrestrial ecotoxicity (TE). Three different raw materials used to produce robot end-effectors were compared using the ReCiPe Midpoint (H) impact assessment methodology. According to the results, the production of the robot end-effector using PA12 had the lowest environmental impact. Electricity consumption during the PBF and the production of raw materials were the overall major contributors to the selected environmental impact categories. A generic framework to assess the environmental performance of materials used for PBF is proposed. A detailed cradle-to-gate LCA is performed to highlight the environmental hotspots of PBF technology and ways to improve the environmental performance of AM in general.

Keywords Additive manufacturing · Powder bed fusion · Sustainability assessment · Life cycle assessment

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1 Introduction

Additive manufacturing (AM) refers to a group of technologies that enable the production of objects by the addition of raw material, layer-by-layer, in an exact geometric shape [1, 15]. These have become one of the most disruptive technologies potentially changing the value chain of a product from the design phase to the end of life, providing superiority over conventional manufacturing processes [16–18, 30].

Powder bed fusion (PBF) is a type of AM technology that involves the fusion of fine polymer, metal powders, or ceramics layer-by-layer, using a high-powered laser or electron beam to form complex three-dimensional objects. PBF is considered the most commonly used AM technology due to its capability of producing complex geometries using various materials [23, 36, 38]. There are various types of PBF which include selective laser sintering (SLS), selective laser melting (SLM), direct metal laser sintering (DMLS), selective heat sintering (SHS), and electron beam melting (EBM). PBF systems have been transforming since their development in terms of materials used, speed and precision of printing, and scale of the printed objects. Most AM techniques produce an object using a single material. However multi-material manufacturing using PBF technology is expected to provide an opportunity to produce more complex designed objects with advanced functionalities. Soft robotics, biomedical engineering, and electronics are some of the well-known areas where AM multi-material could be applied [7, 13, 19, 20, 34, 42]. It involves using more than one type of material within a single print. Multi-material additive manufacturing technology can reduce production time with no extra cost for manufacturing parts with complex morphology [29].PBF systems have become advanced with the usage of low-diameter laser beams, multiple lasers, precise laser positioning systems, and the use of automation to provide better quality products. The precision of PBF has been improved, with many systems now managing the production of parts with dimensions as low as 20 microns and as high as 1 m [24]. Overall PBF is becoming a popular technology for manufacturing complex objects and is expected to continue to grow in the coming years.

A historical overview of previous studies performed on sustainability assessment shows different aspects related to PBF and other AM technologies. A sustainability study related to SLS was performed which used Environmental and Resource Management Data (ERMD) and Eco-indicators collected and calculated by Pre-Consultants an environmental consulting company [35]. The study was performed considering only the energy perspective of SLS with Polyamide 12 (PA12). The results showed of the energy was consumed by the chamber heater (37%) whereas only utilized 16% of the total energy was utilized

Table 1 List of abbreviations and acronyms used in paper

Abbreviation	Definition
AM	Additive manufacturing
DMLS	Direct metal laser sintering
EBM	Electronic beam melting
FPMF	Fine particulate matter formation
ERMD	Environmental resource management data
FRS	Fossil resource scarcity
FWE	Freshwater eutrophication
FWT	Freshwater ecotoxicity
GNP	Graphene nanoplatelets
GW	Global warming
LCA	Life cycle assessment
LCI	Life cycle inventory analysis
LCIA	Life cycle impact assessment
LU	Land usage
OAT	One at a time
PA12	Polyamide 12
PA2200	Polyamide 2200
PBF	Powder bed fusion
PCBs	Printed circuit boards
SHM	Selective heat sintering
SLM	Selective laser melting
SLS	Selective laser sintering
SOD	Stratospheric ozone depletion
TA	Terrestrial acidification
TE	Terrestrial ecotoxicity

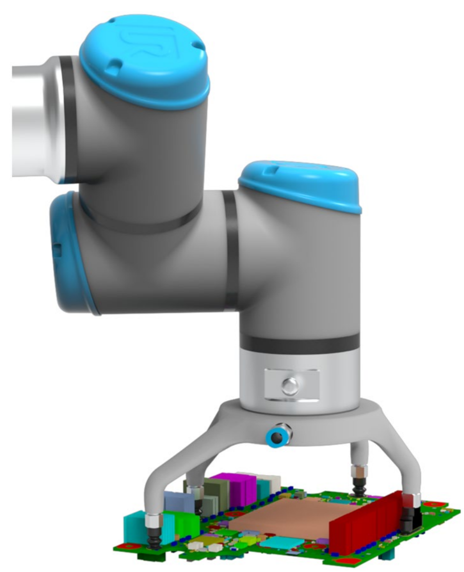

Fig. 1 Robot end-effector connected to the robotic arm

Fig. 2 Robot end-effector produced using PA12 (white), AlSi10Mg (silver) and PA12-GNP(gray)

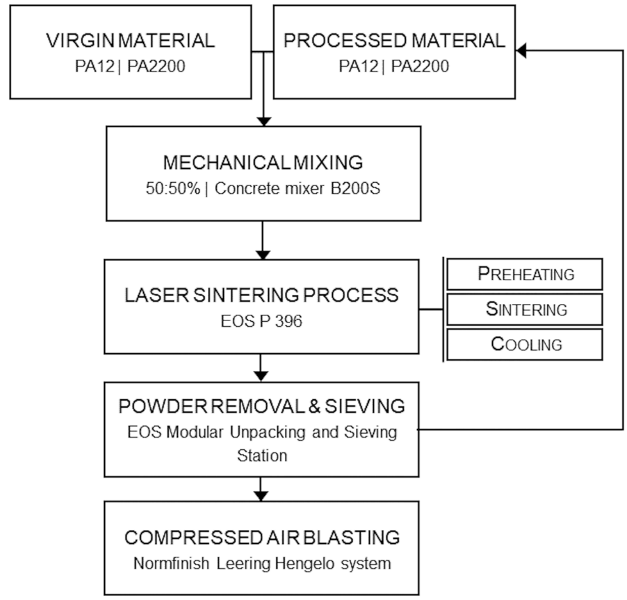

Fig. 3 Workflow of PBF using PA12

by the laser. The study showed that environmental impacts due to electricity consumption are significantly reduced by operating the build process at room temperature although the integrity of the final product will suffer if raw material such as PA12 is used.

A predictive model for environmental assessment in the AM process was developed which assessed the performance of laser AM of a part composed of a pocket of 200 mm square and 80 mm depth. The model predicted environmental impacts by not only electricity consumption but also fluid consumption (powder and gas consumption) during the manufacturing stage. The results showed that the environmental impact of powder utilization was high as compared to the electricity consumption during manufacturing [4].

A cradle-to-gate life cycle assessment of a hydraulic valve body made up of stainless steel produced via SLM was conducted [26]. ReCiPe midpoint and endpoint impact assessment methodology was used to assess the environmental impacts. A life cycle assessment of the same hydraulic valve body with an optimized design was also performed which showed improvement in environmental performance after design optimization. Results showed the process of atomization to produce the powder for laser sintering had 46% of the total impact in most of the categories while

Table 2 LCI of material preparation, processing, and post-processing for PBF using PA12

Material preparation		
Amount of PA12	Virgin material	2500 g
	Processed material	2500 g
Mechanical mixing	Power: 1.10 kW	Time: 30 min
Transportation	Germany - Portugal	2090 km
Processing		
Amount of PA12	Material introduced into the machine	5000 g
	Material used in the process	4215 g
	Material separated for reuse	785 g
Preheating	Power: 2.40 kW	Time: 02h00
Sintering	Power: 2.40 kW	Time: 02h06
Cooling	Power: 1.40 kW	Time: 10h00
Compressed air (8 bar)	Very difficult to quantify	
Coolant		
Post-processing		
Amount of PA12	Material collected for reuse	4035 g
	Material wasted	93 g
	Material used in the part	87 g
Powder removal and sieving	Power: 0.20 kW	10 min
Compressed air blasting	0.85 kW	10 min
Compressed air (7 bar)	Very difficult to quantify	
Coolant		

SLM had 25% of the total impact but after optimization of design the SLM impact increased by 3.65% due to more printing time requirement but impact due to atomization was decreased by 2.25% as it required less amount of raw material to produce the powder required for printing.

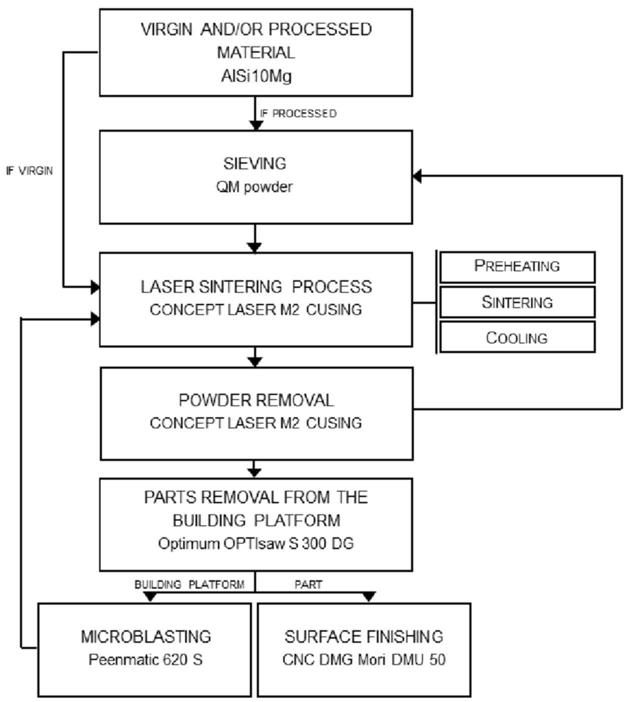

Fig. 4 Workflow of PBF using AlSi10Mg

Another study evaluated pre-, main, and post-process stages during PBF of metals in terms of energy intensity. Pre-process activities included the sieving of metal powder and its loading in the machine followed by the main process of the DLMS stage which included a 400 W laser usage. Post-process activities were cleaning off excess powder and impurities and removal of the part from the building platform. Results demonstrated how the total energy consumption was distributed among the pre-, main, and post-processes. Energy profiles showed that the main metal sintering process and dry-cleaning process during post-processing had a major impact on energy demand. 25% of the entire energy consumption was related to the post-processes. So, in terms of energy saving, the ratio of cleaning to printing should be reduced [25].

This article presents the sustainability assessment of PBF technologies using polymer, metal, and composite-based powders as raw materials to produce a robot end-effector. The main objective of this research is to produce a cradle-to-gate life cycle assessment study of the manufactured robot end-effector and compare the environmental performance of different materials processed by PBF. It also recommends actions for reducing the environmental impact of the selected functional unit by changing process parameters and raw materials. The results of this article may not capture the intricacies associated with the selection of the raw material as metal-based PBF can produce a robot end-effector with a longer lifespan than polymer-based PBF.

Table 3 LCI of material preparation, processing, and post-processing for PBF using AlSi10Mg

Material preparation		
Amount of AlSi10Mg	Material input	15020 g
	Material wasted	70 g
Sieving	Power: 0.50 kW	Time: 60 min
Transportation	Canada - Portugal	3000 km
	Portugal - Guimarães	150 km
Processing		
Amount of AlSi10Mg	Material introduced into the machine	14950 g
	Material separated for reuse	11300 g
	Material unused	3440 g
	Material wasted	210 g
Preheating	Power: 6.80 kW	Time: 00h25
Sintering	Power: 6.80 kW	Time: 13h41
Cooling	Power: 6.80 kW	Time: 01h40
Post-processing		
Amount of AlSi10Mg	Part with supports	250 g
	Material wasted (supports removal)	20 g
	Material used in the part	230 g
Part removal from building platform	Power: 1.50 kW	Time: 5 min

The initial part of the article explains the methodological framework and the PBF process, including the process flow diagram for the production of the robot end-effector via PBF with three different materials. The second part gives details about the process inventory analysis followed by the impact assessment results. The third part discusses the results with a sensitivity analysis of the main parameters. In the end, data details for the production of a robot end-effector using the PBF technology are provided. With this article, the authors hope to contribute to the evaluation of the environmental relevance of material selection for PBF technologies. The detailed abbreviations and their definitions used in the paper are listed in Table 1.

2 Methodology

2.1 Goal and scope

The goal of this LCA is to compare the environmental performance of three different materials processed by PBF (*i.e.,* polymer, metal, composite), based on the processing of a common functional unit, *i.e.,* a robot end-effector required to pick and place printed circuit boards (PCBs). Since the usage phase of the selected functional unit will be the same for all raw materials as the functionality remains the same regardless of the mechanical properties of three raw materials during its lifetime and data related to the end of life of the manufactured part is unknown, the scope of the study is selected to be cradle-to-gate, meaning that the assessment will cover the life cycle phases of raw material extraction, production and transportation, and the production process. The results of this comparative analysis are expected to support the selection of sustainable raw materials for PBF, in terms of energy consumption, emissions and waste generation, and to make producers and consumers aware of the carbon footprint of such AM products.

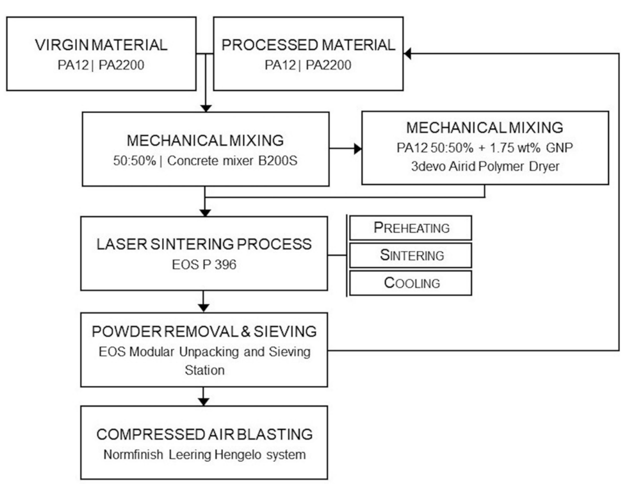

Fig. 5 Workflow of PBF using PA12-GNP

Table 4 LCI of additional material preparation for PBF using PA12-GNP

Addition of GNP	
Material input	3.15 g
Material wasted	0.00 g
Mixing	
Power: 0.85 kW	Time: 36 h

2.2 Functional unit

The functional unit selected for the LCA of PBF technologies is a robot end-effector designed to pick and place printed circuit boards (PCBs) through vacuum suction cups (Fig. 1).

Compared to other manufacturing technologies, PBF has a series of advantages in producing functional products with complex geometry. When parts are well-designed for the technology, supporting structures are nearly not required, which, therefore, allows the manufacturing of parts with complex geometry [22]. This is an advantageous condition for the production of robot end-effectors with internal conformal channels to pick-and-place PCBs through vacuum suction.

The robot end-effector defined for analysis was developed and produced in Guimarães - Portugal based on three approaches considering different raw materials (Fig. 2), namely:

- PBF using Polyamide 12 (PA12) from EOS GmbH (*i.e.,* PA2200) in a mixture ratio of 50% of processed with 50% of virgin powder;
- PBF using aluminum alloy from General Electric Additive (*i.e.,* AlSi10Mg);
- PBF using PA12 with 1.75 wt.% of graphene nanoplatelets (GNP) from Graphenest, S.A.

These materials have different base properties (*e.g.,* electrical conductivity, mechanical strength, thermal conductivity)

Table 5 Eco-attributes of AlSi10Mg [28]

Eco-property	Unit	Average value
Embodied energy, primary production	MJ/kg	189.0
Carbon dioxide footprint, primary production	kg/kg	12.1
Carbon dioxide footprint, recycling	kg/kg	2.6
Energy demand for powder atomization	MJ/kg	8.1
Carbon dioxide footprint for powder atomization	kg/kg	0.5
Embodied energy, recycling	MJ/kg	32.7

Table 6 Overview of selected midpoint impact categories [12]

Emission	Impact category	Unit	Indicator
Air	Global warming (GW)	kg CO_2 eq	Rise in temperatures, shift in snow and rainfall patterns [3]
	Stratospheric ozone depletion (SOD)	kg $CFC-11$ eq	Decrease in stratospheric ozone layer [41]
	Fine particulate matter formation (FPMF)	kg $PM_{2.5}$ eq	$PM_{2.5}$ population intake [37]
Water	Water consumption (WC)	m^3	Increase of water consumption [11]
	Freshwater ecotoxicity (FWT)	kg $1,4-DCB$	Hazard-weighted increase in freshwater [37]
	Freshwater eutrophication (FWE)	kg PO_4 eq	Increase of phosphorus in freshwaters [10]
Land	Fossil resource scarcity (FRS)	kg oil eq	Upper heating value [14]
	Land use (LU)	m^2a crop eq	Occupation and time-integrated land transformation [5]
	Terrestrial acidification (TA)	kg SO_2 eq	Increase of proton in natural soils [32]
	Terrestrial ecotoxicity (TE)	kg $1,4-DCB$	Hazard-weighted increase in natural soils [37]

but the functionality of the the three robot end-effectors is the same which is to lift PCBs and place them at the desired place . However, this was not a critical factor in this study, since its main objective was to understand the environmental impact of processing polymer, metal and composite-based materials by PBF, regardless of the part to be produced.

In this study, it was assumed that the robot end-effector has the same lifetime regardless of the material used, knowing that all of them fulfill the pick and place cycle requirements in terms of number and mechanical stress.

2.3 System boundaries

System boundaries include the raw material acquisition (*i.e.,* PA12, AlSi10Mg, and GNP), the transportation from the raw material producer to the consumer, and its transformation into the robot end-effector through PBF. The process stages of the product system are divided into three fundamental steps of production: (*i*) material preparation that consists of raw material production and transportation, mixing of virgin and processed powder (in the case of polymeric PBF), and sieving (in the case of metallic PBF); (*ii*) processing that consists of preheating the prepared material, sintering, and cooling of the sintered part before taking it out of the machine; and (*iii*) post-processing consisting of the final part removal from the building chamber or platform (if there is any support material required for printing), unused powder removal, mixing or sieving of powder to prepare it for reuse, and surface finishing of the robot end-effector. System boundaries of the model are based on the following assumptions:

1. The manufacturing of the equipment used in all approaches, *i.e.,* mechanical mixer, laser sintering equipment, powder removal, sieving station, and compressed air blasting machine have the same burdens as they are used not only for a single raw material but also for other raw materials included in the comparison. Thus, environmental burdens associated with the manufacturing of the equipment are excluded. Also, the percentage of the environmental impact of manufacturing equipment is negligible in comparison to the overall impact because this equipment is not only used for this case study but for manufacturing other products as well.
2. Transportation of the raw materials uses the same mode to perform a fair analysis for PA12 and PA12-GNP. It is different from aluminum alloy, which is sourced from

Table 7 LCIA results for PBF using the three different raw materials

Impact category	Unit	PA12	AlSi10Mg	PA12-GNP
Global warming (GW)	kg CO_2 eq	14.2442	50.4951	26.3944
Stratospheric ozone depletion (SOD)	kg $CFC-11$ eq	4.32E-05	1.91E-05	4.73E-05
Fine particulate matter formation (FPMF)	kg $PM_{2.5}$ eq	0.0209	0.0917	0.0420
Water consumption (WC)	m^3	0.1198	0.4404	0.2285
Freshwater ecotoxicity (FWT)	kg $1,4-DCB$	0.3644	4.1670	0.7063
Freshwater eutrophication (FWE)	kg PO_4 eq	0.0037	0.0178	0.0080
Fossil resource scarcity (FRS)	kg oil eq	3.8371	13.5264	7.1745
Land use (LU)	m^2a crop eq	0.1927	0.8595	0.4224
Terrestrial acidification (TA)	kg SO_2 eq	0.0637	0.2600	0.1284
Terrestrial ecotoxicity (TE)	kg $1.4-DCB$	20.3755	76.1693	35.6793

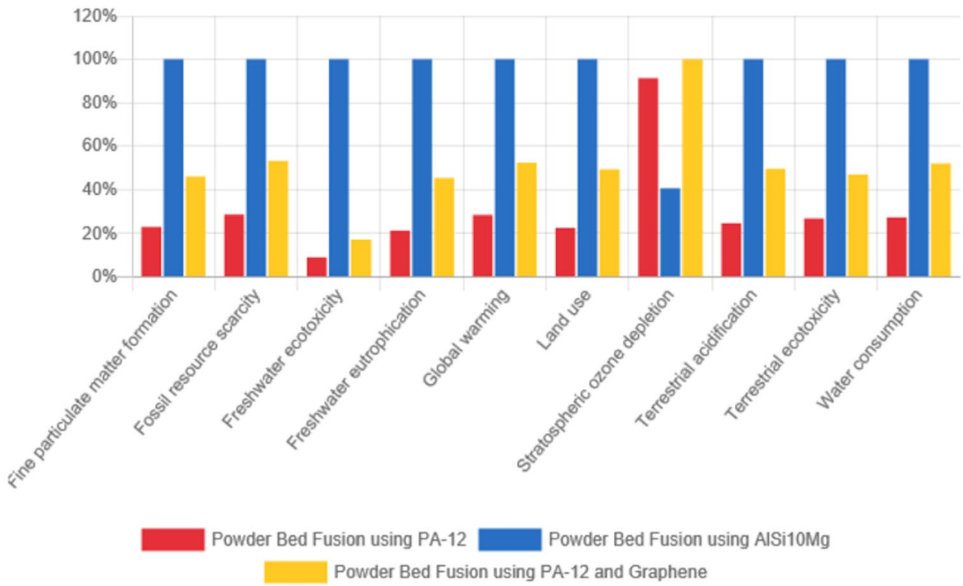

Fig. 6 Relative results for selected environmental impact categories for PBF

outside Europe, so contains flow related to the shipping of raw materials.

3. Since gas atomization data for the raw materials was unavailable, it is also excluded for all three approaches.
4. Emissions due to the construction of laboratory facilities are also excluded as it also performs other operations and burdens.

2.4 Inventory analysis

To collect all data needed for LCA, life cycle inventory analysis (LCI) is performed using both experimental processing data and the Ecoinvent v3.8 cut-off database for background processes. For measuring the material and energy consumption flows during the production of the robot end-effector through all approaches, weighing is performed during each stage of the process. This includes weighing all empty containers of the machines (*e.g.,* feed and supply bins, and removable frame) and powder introduced in each container at every stage of the process. The amount of material introduced in the sintering machines depended on the material that was already prepared for AM productions. In the end, all the waste was accounted for, as well as all the remaining material, which is utilized for new production cycles. Operating and idle time and data related to auxiliary consumables, tools, and equipment are also considered.

2.4.1 PBF using PA12

The production of the robot end-effector with PA12 comprises of the stages shown in Fig. 3. Life cycle inventory data related to the process parameters, material and energy inflows, and outflows were collected in each stage.

PA12 is sourced from EOS GmbH and transported from Germany to Portugal. The supplier did not provide life cycle data related to the production of the powder material. After sourcing the raw material, virgin PA12 is mixed with processed powder in a mixture ratio of 50–50% using a Concrete mixer B200S equipment. After material preparation, 5000 of PA12 is introduced into the laser sintering machine. The sintering stage is divided into three substages including preheating the sintering chamber for 2 hours to make the sintering chamber ready for the stage of sintering which takes place for 2 h and 6 min cooling for 10 h before extracting the robot end-effector and excess powder. This data were provided by the equipment software, according to the defined process parameters. After the sintering process, the post-processing phase begins which consists of removing the excess unsintered powder using brushes and sieving the unsintered powder in a sieving station followed by compressed air blasting to remove powder from the surfaces of the robot end-effector. Table 2 resumes all values obtained for this material in the three stages.

2.4.2 PBF using aluminium alloy

The second approach in producing the robot end-effector used AlSi10Mg aluminum alloy powder, previously processed (Fig. 4). The choice of all peripheral equipment used was plainly due to availability in the field.

The process begins with material preparation. Aluminum alloy powder is supplied by General Electric, Germany which imports the raw material from its subsidiary company

AP &C Powders, located in Canada. After sourcing the raw material, it is used as it is for sintering unless the powder is processed and a leftover from another process. In this case, it is sieved at a sieving station where impurities are removed.

Similarly to the laser-sintering of polymers, PBF of metals also occurs in three stages: preheating, sintering, and cooling. The post-processing operations consist of excess aluminum powder removal followed by the separation of the robot end-effector from the building platform using Optimum OPTIsaw S 300 DG. The building platform goes for micro blasting and the robot end-effector goes through the process of manual surface finishing to remove support structures. Material and energy flow during these three stages are shown in Table 3.

2.4.3 PBF using PA12-GNP

Inventory data for PBF using PA12-GNP is the same as for PBF using PA12, except for the phase of material preparation which includes the addition of GNP sourced from Graphenest, S.A., located in Portugal. PA12 is mixed GNP to obtain a composite material with electrostatic dissipative properties that, sometimes, can be an essential condition for many industrial applications. For mixing purposes, 1.75 wt.% of GNP is added to the 1:1 material of virgin and processed PA12 during the material preparation stage (Fig. 5 and Table 4). The amount of GNP was defined based on a previous study [22]

2.4.4 Background data collection

Ecoinvent v3.8 [6, 40] is used as the database for background reference data. It embraces more than 18000 datasets with reference to different human activities such as the production, storage, and transportation of goods, providing different services. The cut-off modeling approach is selected and imported into openLCA v1.11.0 software. Life cycle inventory data related to PA12 were not available in ecoinvent v3.8 so PA6 was used as a proxy dataset representing life cycle inventory data related to the production of PA12

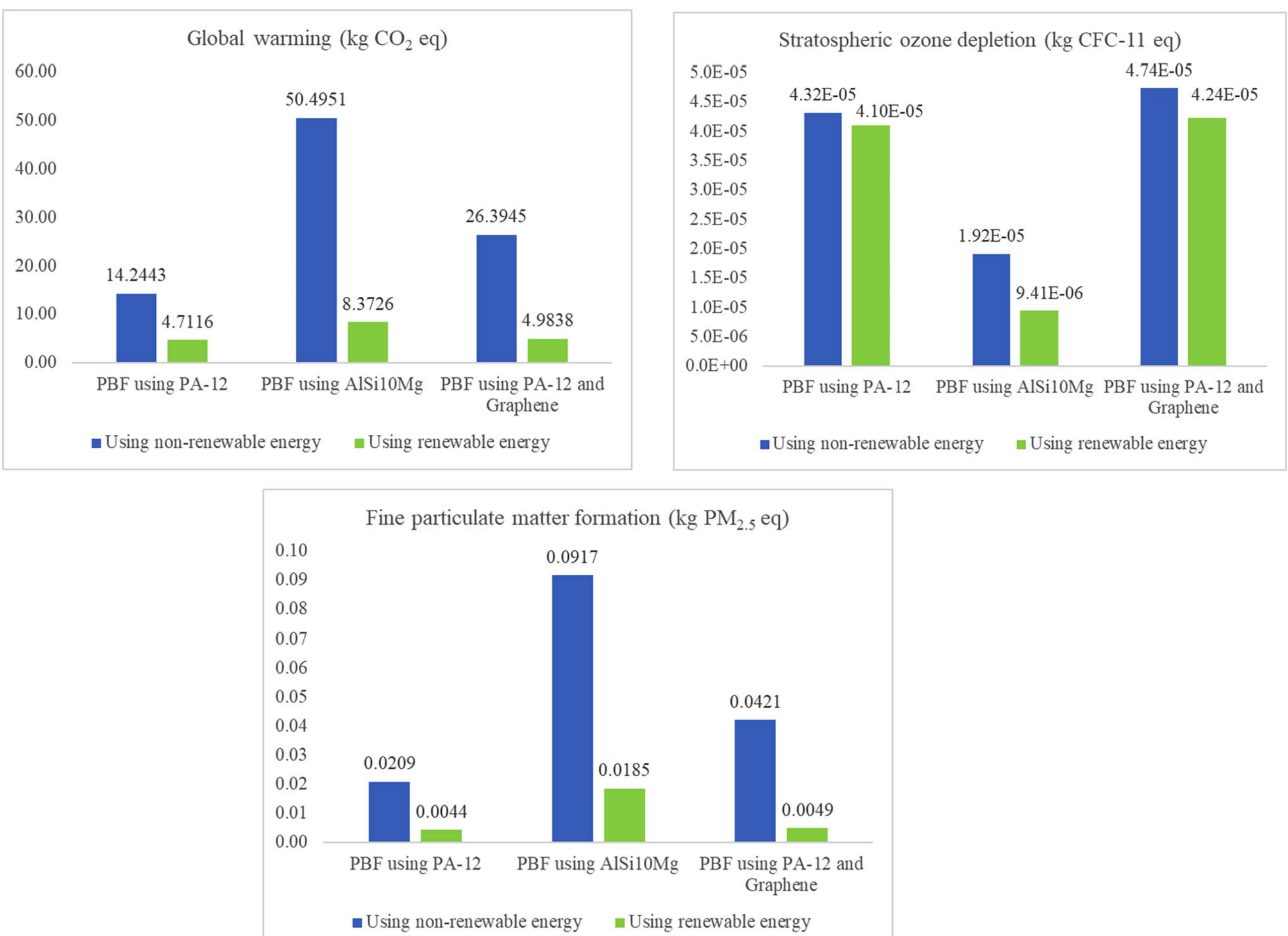

Fig. 7 Air emissions with and without using renewable energy source for PBF

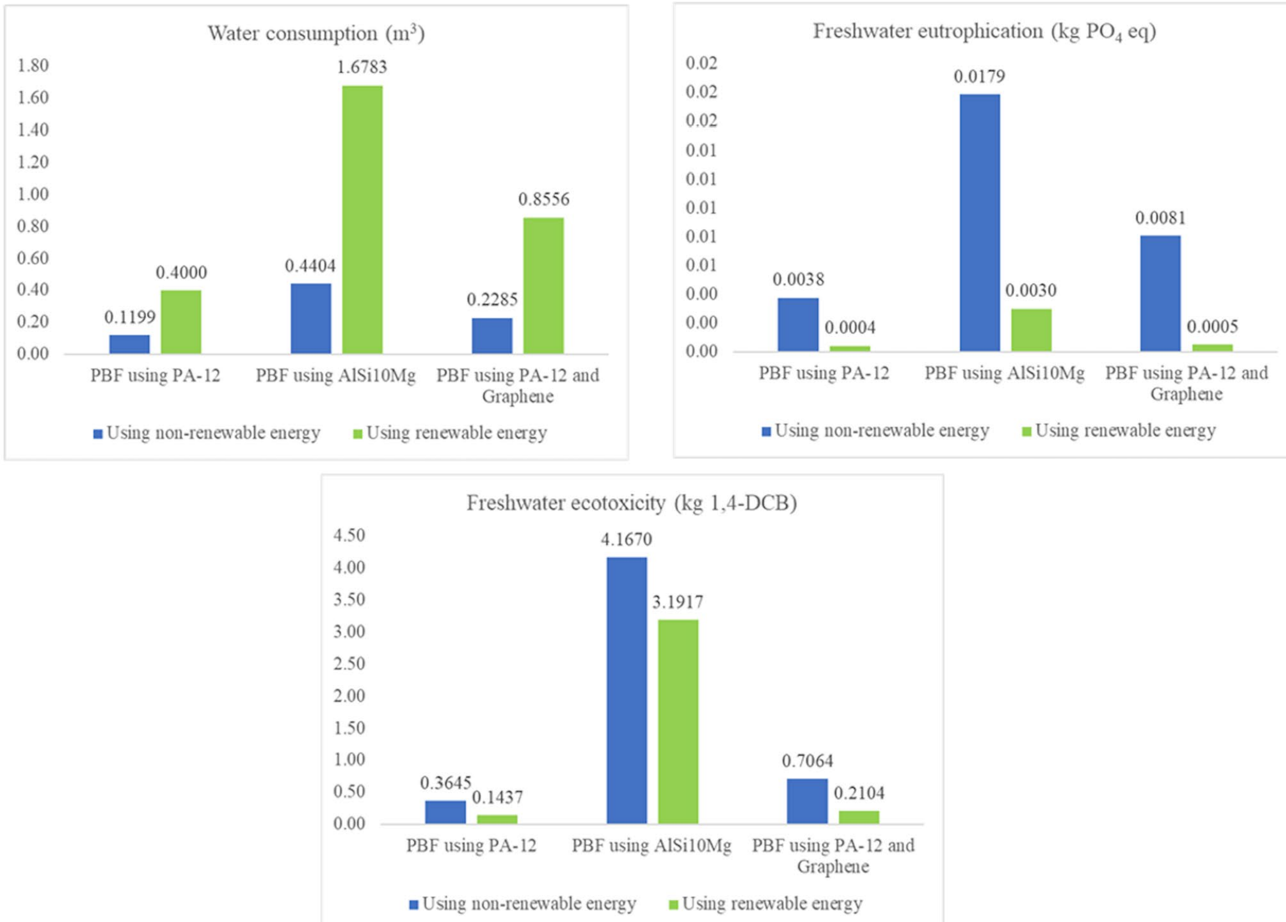

Fig. 8 Water emissions with and without using renewable energy source for PBF

raw material [8, 21]. The eco-attributes shown in Table 5 for the AlSi10Mg material were collected through literature [28]. "AlMg3" is selected as a proxy dataset to represent AlSi10Mg since eco-attributes of AlSi10Mg show some similarity with AlMg3 ecoinvent v3.8 does not have a dataset representing AlSi10Mg powder.

Since the dataset for graphene production was not available, *"market for graphite* | graphite | *Cutoff"* is used for referencing sourcing of graphene, as it is a subatomic layer of graphite. In this work, it is assumed that both have the same ecological properties. The activity for this dataset starts at the gate of the activities that produce 'graphite', within the global geography, from the cradle, *i.e.,* including all upstream activities. This activity ends with the supply of 'graphite', to the consumers of this product. Transportation is included thus separate dataset for the transportation of graphene is not considered. Product losses during transportation are assumed negligible and are, therefore, not included.

Market activity is considered as a background dataset for all the power consumption flows for the equipment used for the production of the robot end-effector with different materials. Each market represents the consumption mix of a product in a given geography and for this market activity *"Market for electricity, medium voltage | electricity, medium voltage | Cutoff"* is selected. For transportation of raw materials from inside Europe, market activity for road transport is selected, having a max load of 7.5 metric tons with a EURO4 emission truck. *"Market for transport, freight, lorry 3.5–7.5 metric ton, EURO4 | transport, freight, lorry 3.5–7.5 metric ton, EURO4 | Cutoff"* is selected as a background database. For transportation of AlSi10Mg powder from Canada to Portugal, *"market for transport, freight, sea, bulk carrier for dry goods | transport, freight, sea, bulk carrier for dry goods | Cutoff"* is used which consists of emissions from the global transportation of dry goods via sea.

2.5 Impact assessment methodology

To convert the life cycle inventory data into environmental impact results, the ReCiPe 2016 Midpoint impact assessment method is selected using the hierarchic perspective.

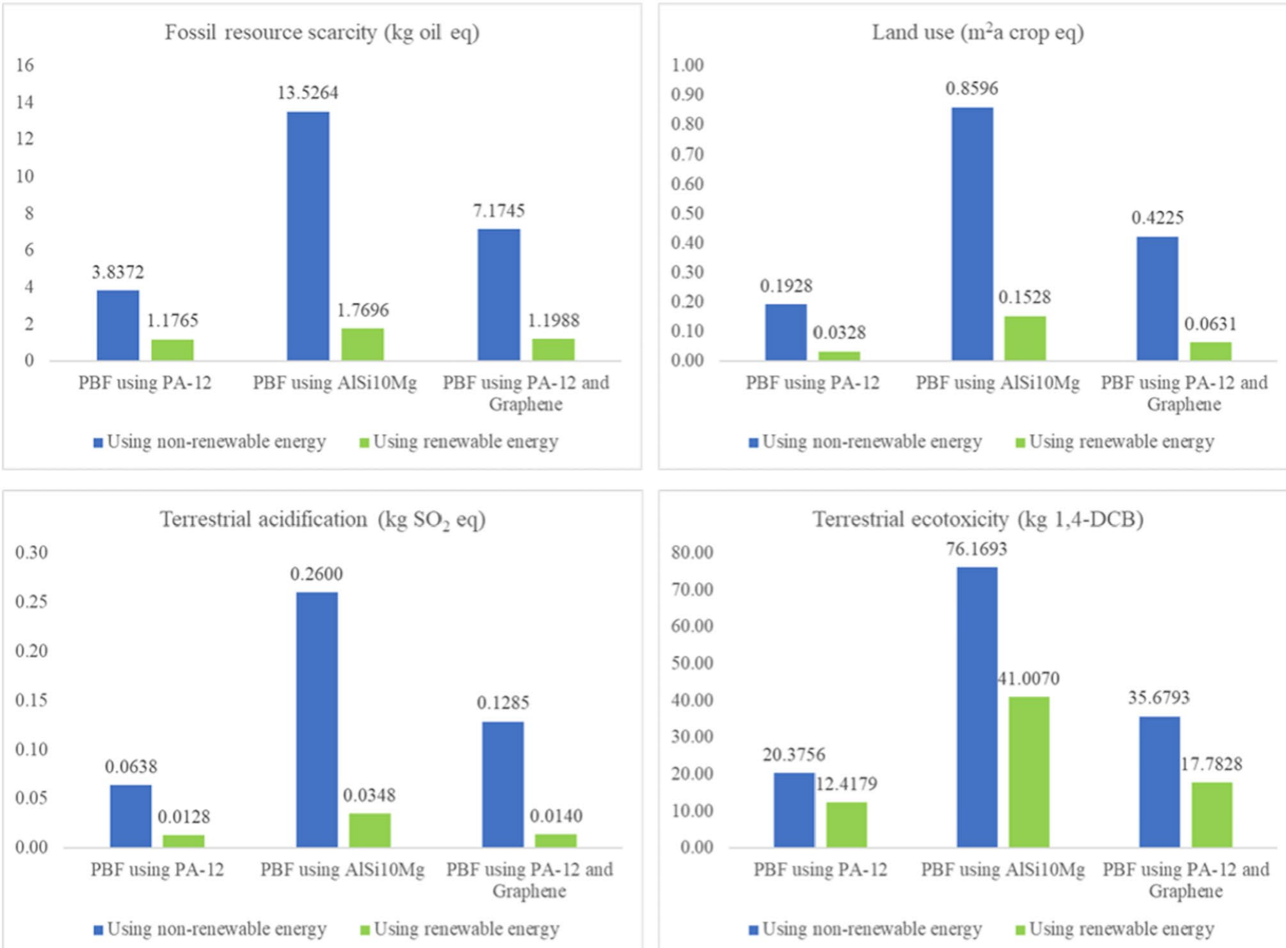

Fig. 9 Land emissions with and without using renewable energy source for PBF

Impact categories for air, water, and land emissions as shown in Table 6 are selected from the available impact categories in the ReCiPe methodology. Global normalization factors indicated in World (2010) H set are used for the normalization step.

3 Results

The leading contributors toward emissions from the production of the robot end-effectors via PBF using three different raw materials found during the life cycle impact assessment are listed below:

- Electricity utilization throughout all the stages of production of the robot end-effector.
- Production of raw material powder used in PBF.
- Transportation of raw material from the production plant site to the facilities where the robot end-effector is produced.
- Compressed air utilization during processing and post-processing stages.

The life cycle impact assessment (LCIA) results produced using life cycle inventory and ReCipe 2016 midpoint (H) impact methodology are shown in Table 7. Process impact contribution results provided in the supplementary information of PBF using PA12 shows the share of the electricity consumption during PBF is higher in emissions of all considered impact categories except SOD where the production of PA12 is the highest contributor. Electricity consumed during the cooling stage of the sintering process is responsible for most of the electricity consumption. Transportation of PA12 powder from its production site (Evonik Industries GmBH, Marl, Germany) to Guimarães (Portugal), and usage of compressed air during processing and post-processing have negligible emissions in comparison to electricity consumption and PA12 production in all impact categories. Whereas for PBF using

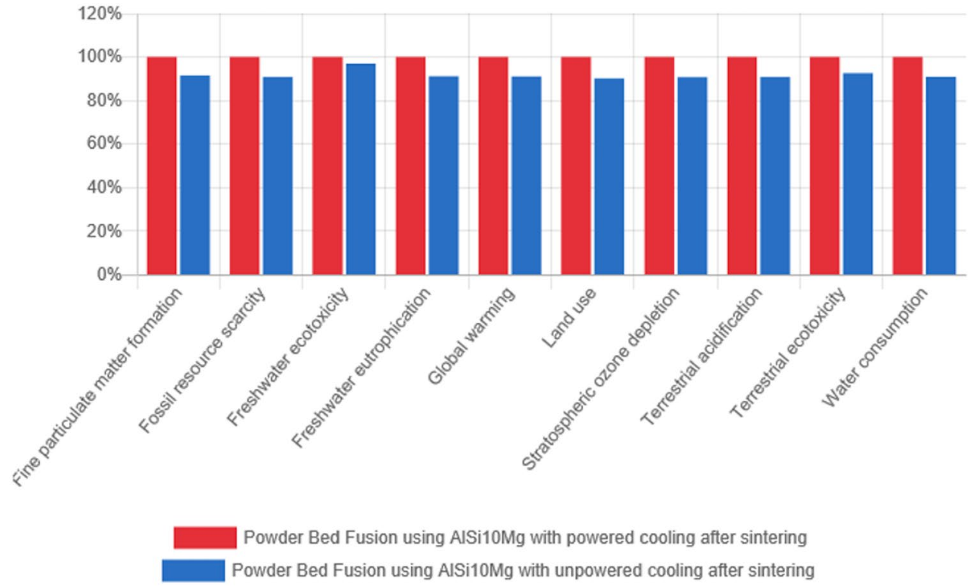

Fig. 10 Life cycle impact result with powered and unpowered cooling after sintering of PA12

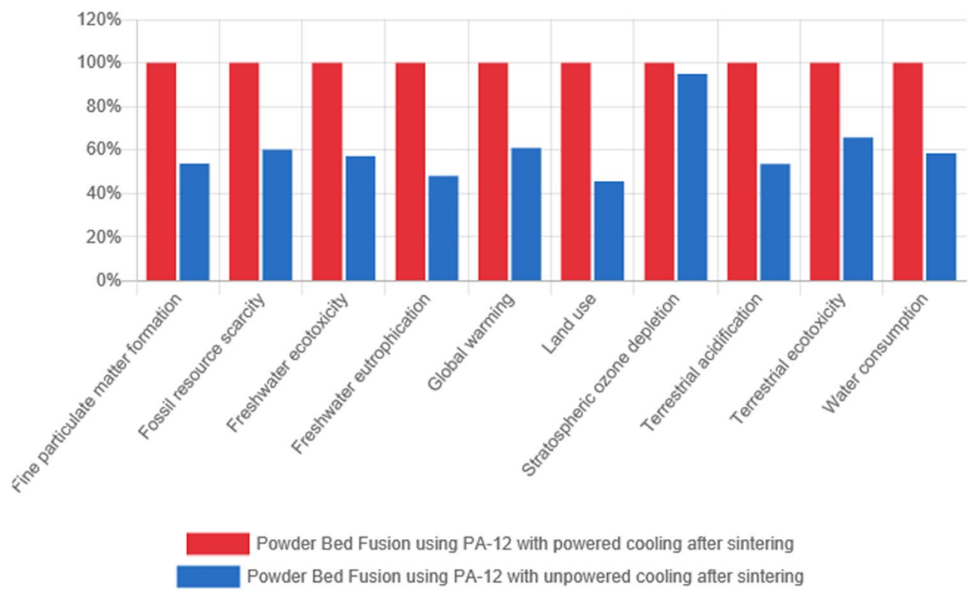

Fig. 11 Life cycle impact result with powered and unpowered cooling after sintering of AlSi10Mg

AlSi10Mg, electricity consumption has the largest share of emissions in all categories except freshwater ecotoxicity which occurred mostly due to AlSi10Mg powder production. PBF using the composite of PA12-GNP shows similar contribution results as when using PA12. Although the additional step of mixing GNP with PA12 during raw material preparation increased the total emission, the division of share among the main contributors remained the same.

3.1 Relative results

Relative results in Fig. 6 show that the production of the robot end-effector via PBF using AlSi10Mg have higher impacts in all impact categories except on stratospheric ozone depletion (SOD). This is because the sintering of AlSi10Mg takes more time in comparison to the sintering of PA12 and the longer time requirement leads to more energy consumption (see Tables 2 and 3). In addition, laser sintering machines use more power during the sintering

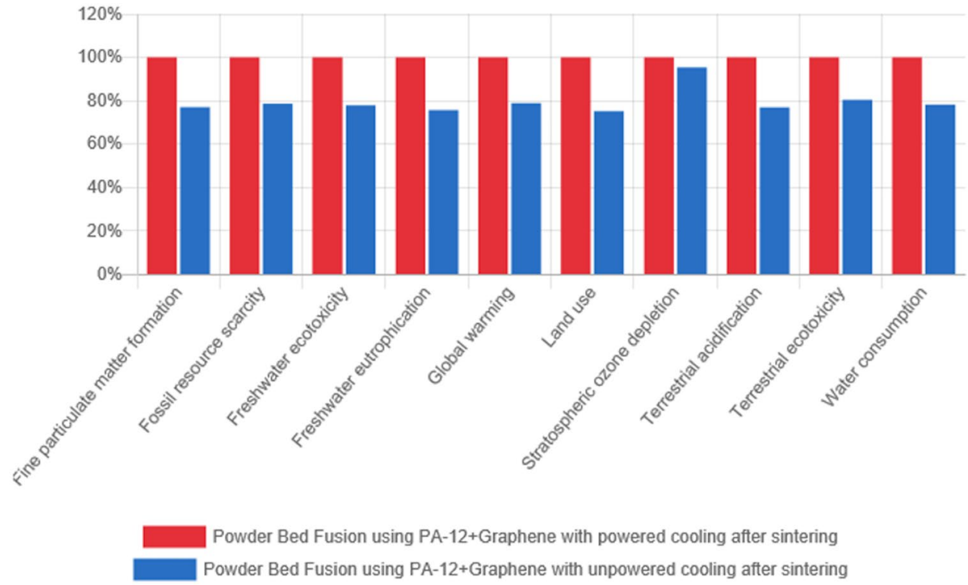

Fig. 12 Life cycle impact result with powered and unpowered cooling after sintering of PA12-GNP

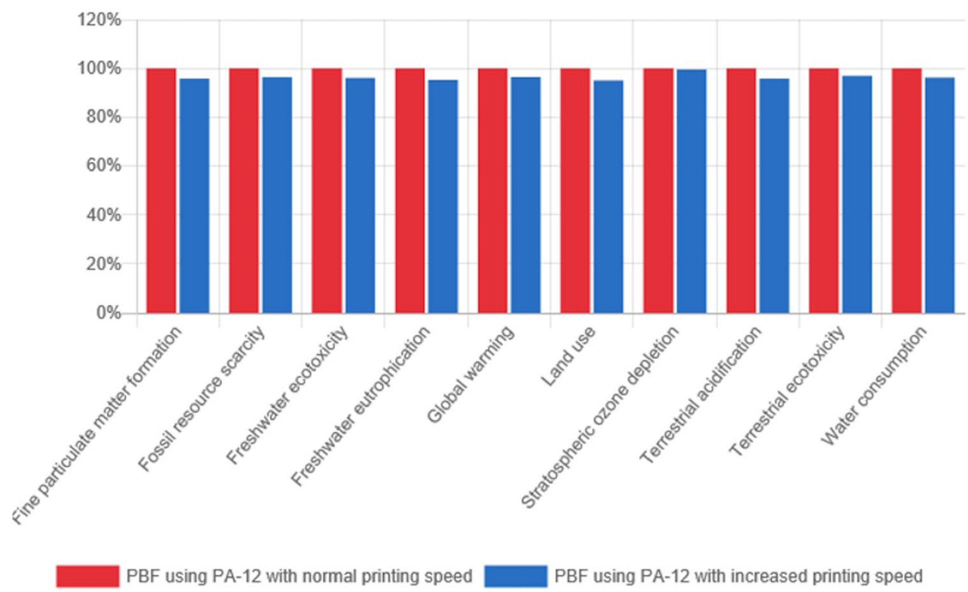

Fig. 13 Life cycle impact result for PBF using PA12 with normal and increased printing speed

process for metals due to the requirement of higher sintering heat in comparison to polymers which contributes more toward power consumption throughout the process. Production of PA12 shares most of the emissions for the SOD impact category so the production of robot end-effectors using PA12 and PA12-GNP is more harmful to the environment in terms of a decrease in the stratospheric ozone layer.

3.2 Environmental hotspots

The results from this study identified environmental hotspots responsible for the environmental emissions during the production of the robot end-effectors.

3.2.1 Electricity consumption during the processing stage

For PBF using all three raw materials, electricity consumption during all stages especially in processing was found to be the major contributor in all environmental impact categories except SOD. For PBF using PA12, the cooling stage during the sintering process consumes the largest

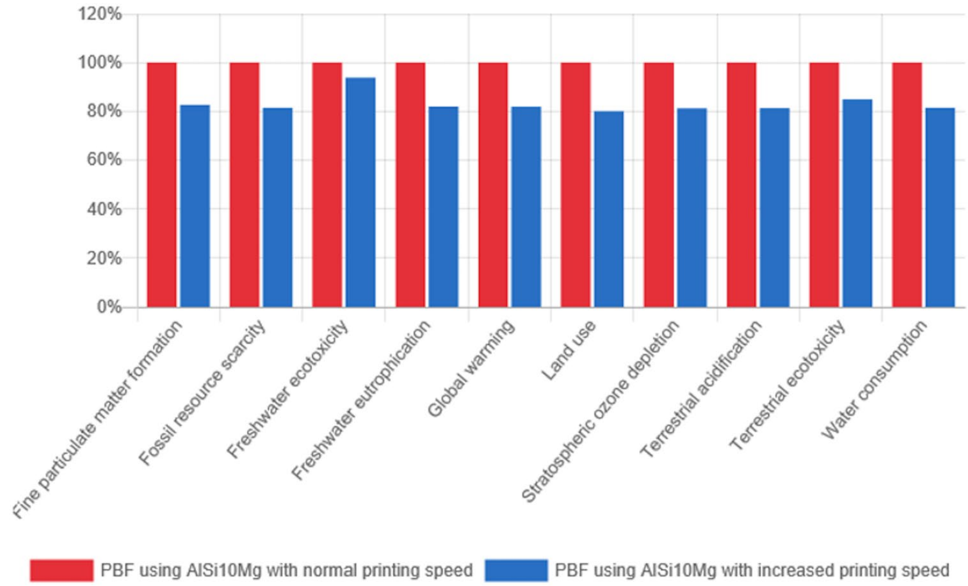

Fig. 14 Life cycle impact result for PBF using AlSi10Mg with normal and increased printing speed

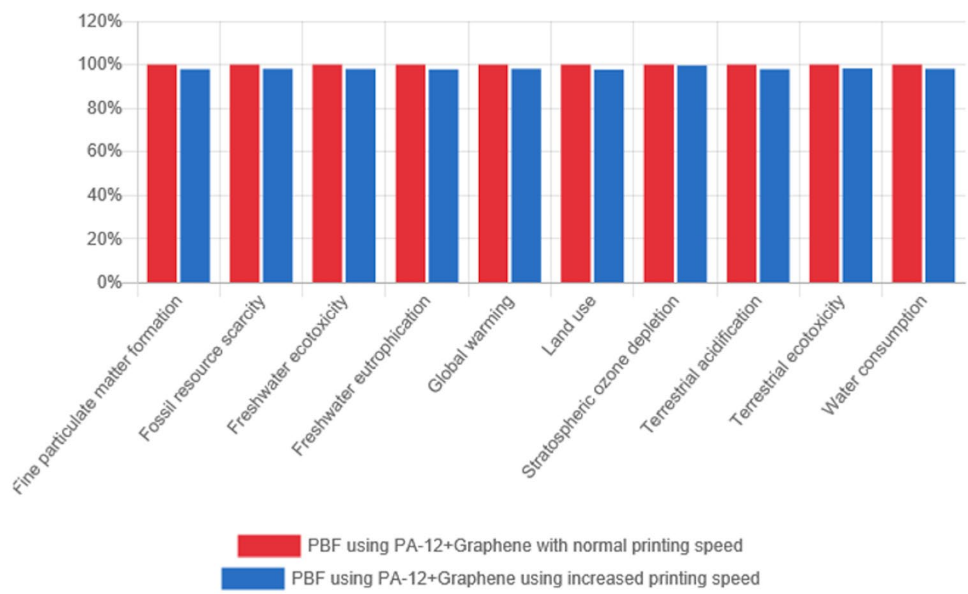

Fig. 15 Life cycle impact result for PBF using PA12-GNP with normal and increased printing speed

amount of electricity (14 kWh). To reduce the emissions, the cooling process has to be minimized or performed naturally by switching off the sintering machine. For PBF using AlSi10Mg, the laser sintering stage requires more than 13 h of laser usage which consumes almost 91 kWh of electricity. Reduction in emissions for PBF using AlSi10Mg can be done by reducing the sintering time. This could be done by either redesigning the robot end-effector or using a higher layer thickness. The additional mixing process in the third approach using PA12-GNP consumes 30 kWh of electricity which increases the emission almost twice as when only PA12 is used.

3.2.2 Production of raw material during material preparation stage

Production of PA12 has the largest share of SOD and the second-largest share of all remaining impact categories during PBF using PA12 which means that the production of this material emits a lot of chlorofluorocarbons which as a result depletes the ozone layer in the stratosphere of the earth. 28%

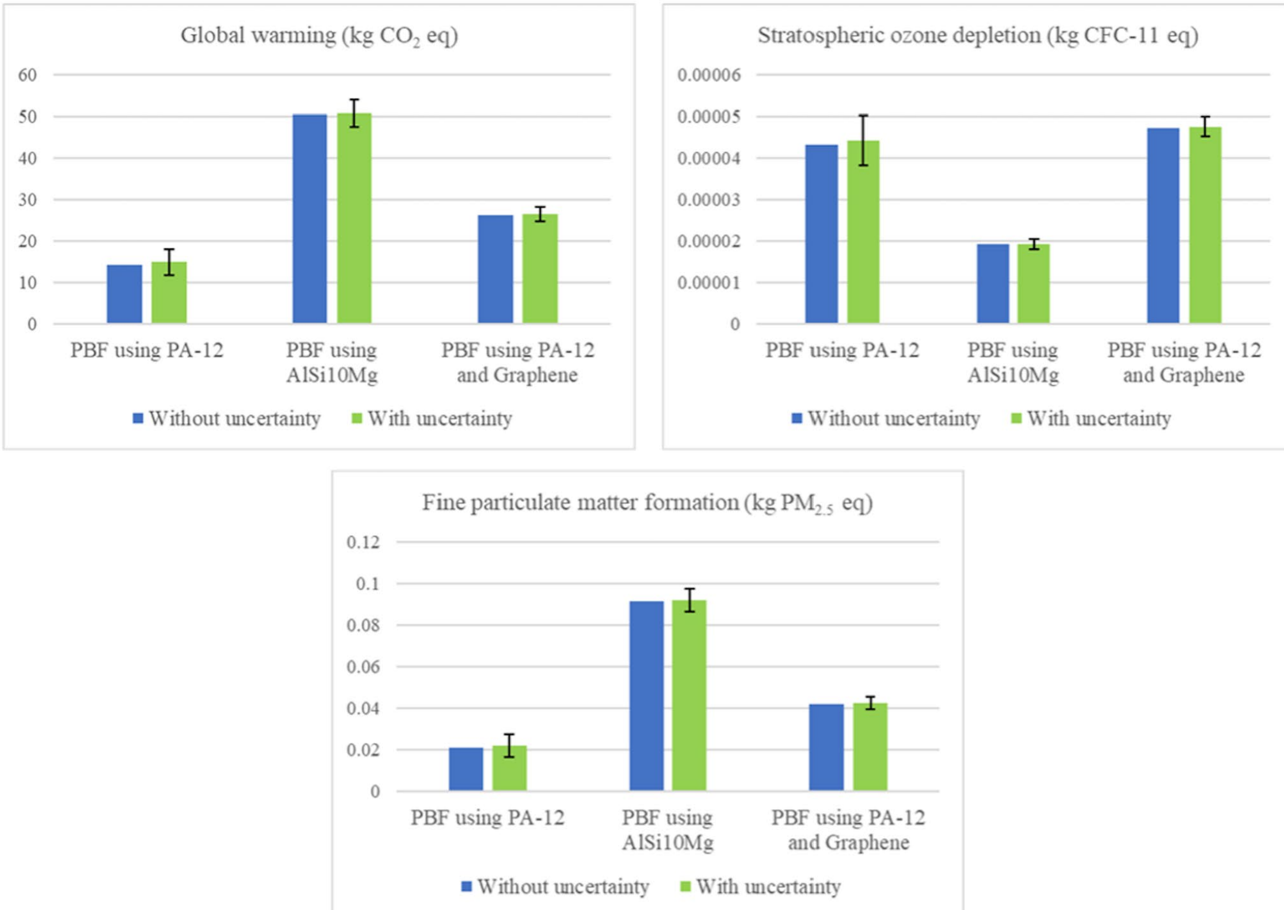

Fig. 16 Air emissions impact result with and without uncertainty range

of the total global warming (GW) emissions coming from the process of PBF using PA12 is also caused by the production of PA12 whereas the production of the AlSi10Mg during the production of robot end-effector via PBF using AlSi10Mg is the highest contributor toward freshwater ecotoxicity (FWT) having caused 70% of the total emissions. In addition, it is the second-highest contributor in the remaining 9 impact categories. The amount of graphene mixed with PA12 to produce a composite of PA12-GNP is too small thus the environmental impact due to the production of GNP is negligible in comparison to the production of PA12 and AlSi10Mg for all impact categories.

4 Discussion

The results of the LCA of the production of robot end-effector by PBF using three different materials have shown that the use of polymeric raw material is relatively less harmful in terms of environmental concerns. In this section, sensitivity analysis and uncertainty of the results are discussed to provide an overview of which parameters could be changed to reduce the overall emissions and which category results are more susceptible to uncertainties due to uncertainties in background data.

4.1 Sensitivity to key parameter

Sensitivity analysis is performed using the one at a time (OAT) approach by taking a subset out of a list of input parameters and changing one at a time (with an arbitrary value or within its range) to check how much change occurs in the overall results. This approach of performing sensitivity analysis is easy to perform but requires a lot of time if the system under study is large and contains a lot of input parameters. Since our product system did not depend on many parameters, OAT is used to keep the analysis simple and easy to understand. Input parameters such as the source of electricity used during the PBF process, printing time, and cooling method during the sintering phase are modified to check the output for each parameter.

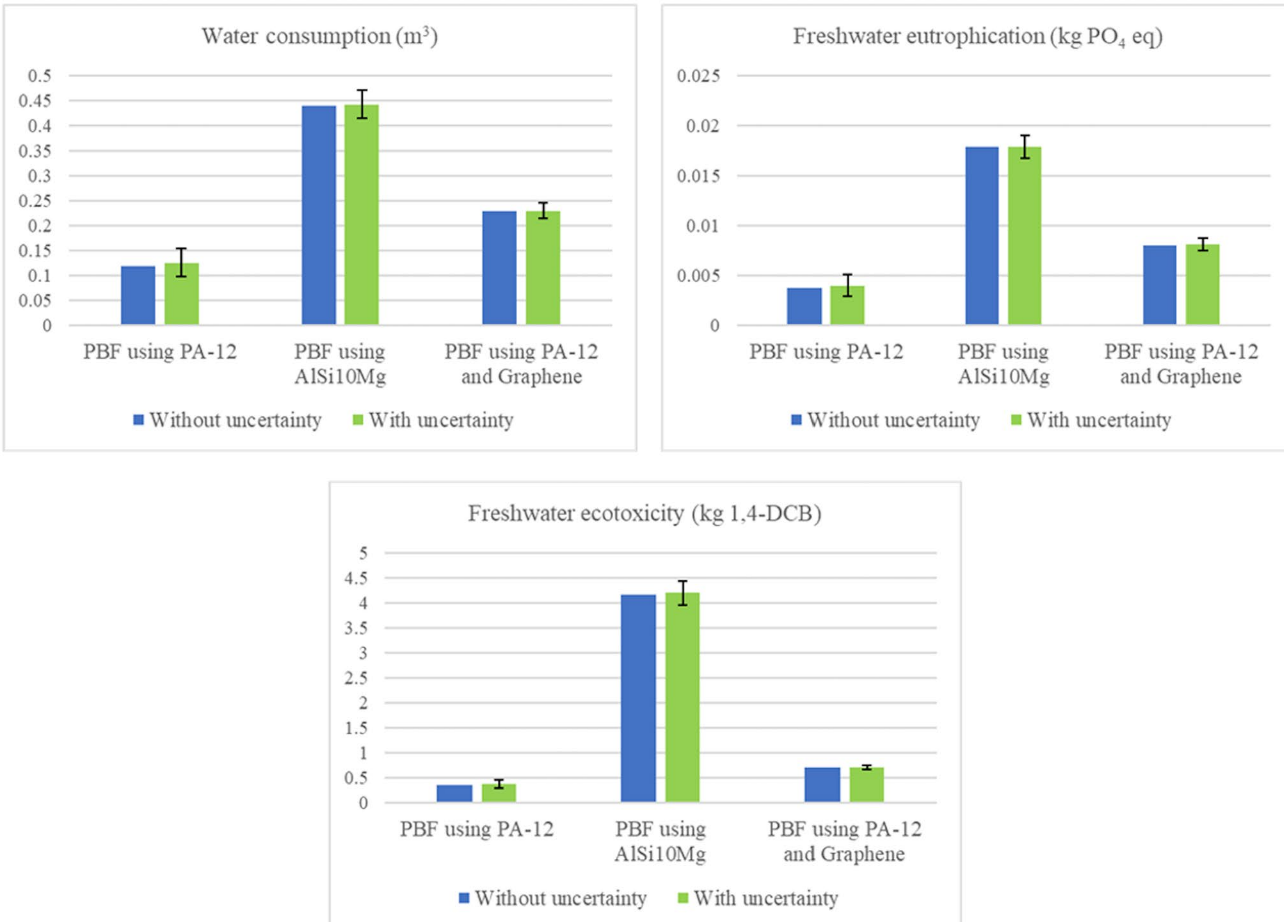

Fig. 17 Water emissions impact result with and without uncertainty range

4.1.1 Renewable energy powered PBF

Based on the results generated and environmental hotspot identification *i.e.*, electricity consumption during the PBF process, this study analysed how a difference in the source of electricity used for this process would change the impact categories result. For this purpose, the dataset used for the flow of electricity of medium voltage was changed from *"Market for electricity, medium voltage, electricity, medium voltage, Cutoff"* to *"market for electricity, medium voltage, renewable energy products, Cutoff"*. This dataset contains life cycle inventory data for the production of electricity from renewable energy sources including its delivery to the end user. Results were generated for all impact categories.

Air emissions result in Fig. 7 show that the emissions related to SOD are not reduced even after using renewable energy for robot end-effector production. This is mainly due to the reason that emissions for this category are dominated by the production of raw materials. So, for GW and FPMF (fine particulate matter formation), emissions are significantly reduced by more than 50% after changing the electricity source from fossil fuel to renewable.

Water emissions results in Fig. 8 show that water consumption increases if a renewable energy source is used to power PBF. The reason is the dataset selected for electricity production using renewable sources also includes emissions from hydroelectric power plants which utilize a large amount of water for producing electricity. Emissions of freshwater ecotoxicity and eutrophication are also decreased after using renewable energy for the production of robot end-effectors.

Emissions in all impact categories related to land are decreased after using renewable energy for producing the robot end-effectors (Fig. 9). Fossil resource scarcity (FRS) emissions are decreased when PBF is performed using renewable energy. The decrease in this category is high in the case of PBF using metals due to more electricity requirements for sintering. Emissions related to terrestrial ecotoxicity and Acidification potential are reduced after performing PBF with renewable energy for all three raw materials.

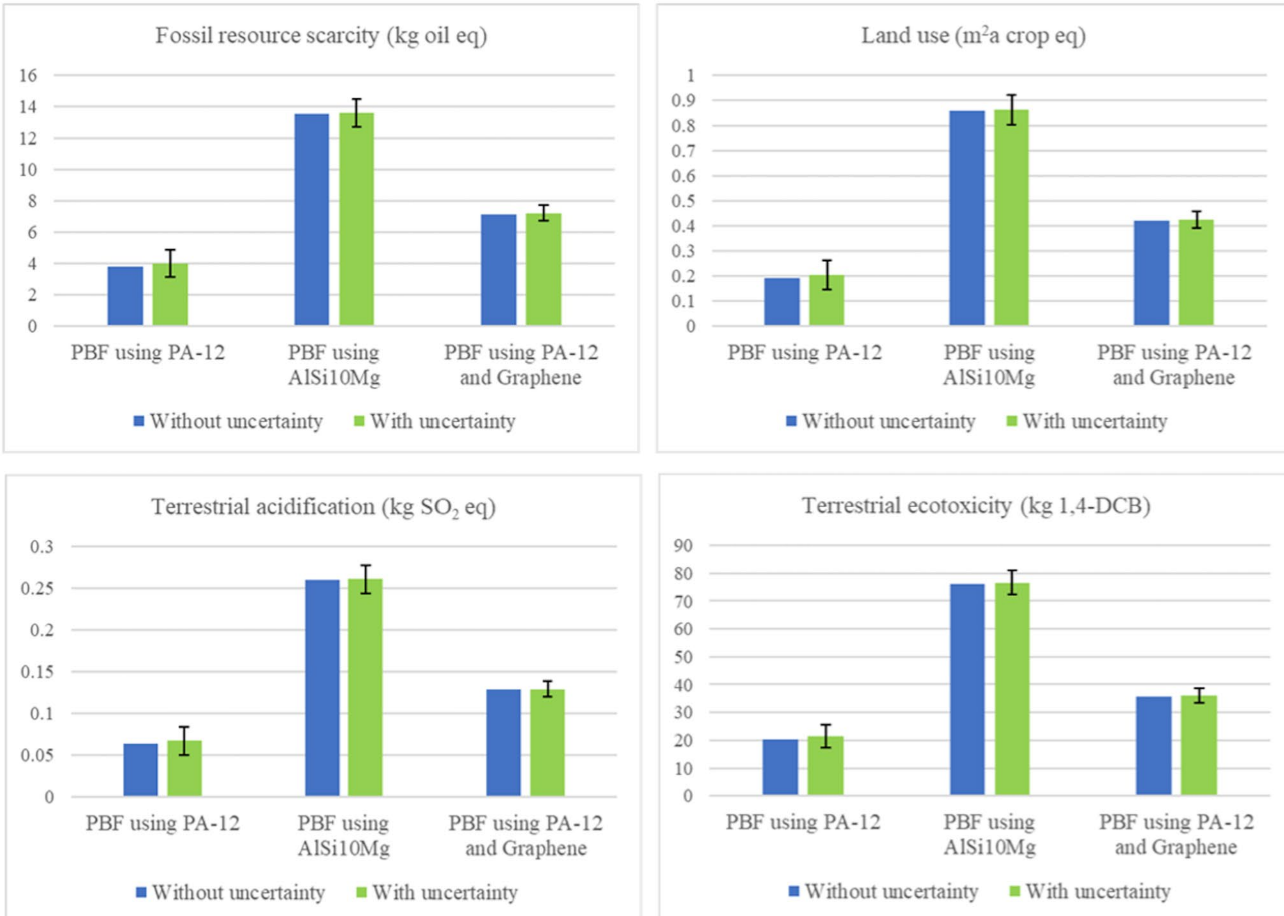

Fig. 18 Land emissions impact result with and without uncertainty range

4.1.2 Powered and unpowered cooling during sintering stage

The cooling stage during sintering is an important stage of PBF. Controlling the cooling rate and sintering time determines the mechanical properties of the sintered end-effector [33]. Cooling must be controlled and kept as uniform as it can be to ensure no distortion takes place [39]. The decision to use powered or unpowered cooling depends on the part geometry, material properties, printing parameters, and desired part quality. Powered cooling is particularly relevant in high-density build jobs containing parts with complex geometries and intricate features that involve high energy density. For sintering of end-effector cooling strategy is useful to ensure uniform cooling rates and prevent warping or distortion of the parts produced. In turn, powered cooling can be omitted without compromising the quality of the parts in low-density builds containing parts with more simple geometry and with thin walls that have a lower tendency for warpage [27][39].

PBF of polymers requires more cooling time as compared to metal. Emissions are simulated with the cooling process occurring while the sintering machine is on idle which consumes more electricity than cooling while the sintering machine is switched off. For PBF using PA12, emissions for all impact categories are decreased to half except SOD (Fig. 10). For PBF using AlSi10Mg with unpowered cooling emissions in impact categories did not reduce because the cooling time of the metal sintered part was less (Fig. 11). Due to the complex geometry of the end-effector, the mitigation of environmental emissions by using unpowered cooling may result in distorted geometry of the end-effector.

PBF using the mixture of PA12-GNP with unpowered cooling shows a decrease in emissions in all impact categories (Fig. 12). The reduction in emissions is greater as compared to AlSi10Mg alloy powder but less in comparison with PA12.

4.1.3 Printing speed

The influence of increasing the printing speed of the sintering machine used for the production of the robot end-effector is evaluated. Increasing the printing speed may require using two laser beams for the sintering process, which consequently implies more power consumption during the sintering stage, or increasing the layer thickness. An LCIA is performed with a change in the printing speed, which is reduced to half of the original required time. Moreover, power consumption during sintering is increased to 1.5 times to generate results to compare how a change in printing time will affect the emissions in impact categories.

After decreasing the sintering time, emissions are decreased by nearly 5% for PBF using PA12 (Fig. 13), and a nearly 20% decrease in emissions is observed for the sintering of AlSi10Mg (Fig. 14). The reason for this difference is the increase in sintering time for metal as compared to the polymer so increasing the printing speed is more beneficial in terms of environmental performance when using AlSi10Mg as compared to PA12 or PA12-GNP.

Decreasing the sintering time by increasing the printing speed did not impact much on the result of emissions during the sintering of the mixture of PA12-GNP (Fig. 15).

4.2 Uncertainty assessment

An uncertainty assessment was performed to understand which impact categories might respond to more variations depending on the data quality or uncertainties in background data used with the EcoInvent database. As explained by [2], embodied energy and emissions data should generally be assumed no more precise than a ± 10% baseline. Thus, a base uncertainty of 10% was selected for this study. In addition to base uncertainty, the pedigree matrix approach was used for data quality assessment using the EcoInvent data quality system. Normally, 1000 or 10000 iterations are performed during Monte Carlo simulation, and with the increasing size of LCA databases, an excessively high number of iterations may be a time-consuming task [9]. Therefore, the number of runs was 10000 to save time. Results in Figs. 16, 17, 18 show that the SOD had the highest standard deviation percentage and was most affected by uncertainty in PBF using PA12. However, it shall not be used to get a confidence interval as the assessment is based on the pedigree matrix approach [9, 31].

5 Conclusion

This research performed comparative LCA analyses on a robot end-effector produced by PBF technologies using three different raw materials, namely PA12, AlSi10Mg, and PA12-GNP. Through comprehensive LCA analyses, it was demonstrated that using PA12 as a raw material for PBF is more environmentally sustainable than the AlSi10Mg and PA12-GNP composite, for the conditions used in this study. It was also verified that the processing stage consisting of preheating, sintering, and cooling processes has the highest environmental impact throughout the life cycle of the robot end-effector. Besides the functionality required from the materials depending on the product application purpose (*e.g.*, insulative, electrostatic-dissipative, or conductive), the different environmental impacts associated with each material must be considered from a sustainability perspective. Since the production of raw material used for the sintering of the end-effector is one of the environmental hotspots found in this study so reduction in raw material usage via redesigning the end-effector without compromising its functionality will subsequently reduce the environmental emission. Optimizing fundamental sintering parameters during its production may also substantially reduce environmental emissions.

It is suggested that in future studies, raw material production data includes the emissions due to atomization and packaging of raw material powder which would result in a more detailed analysis. In addition to this, life cycle inventory data of PA12, AlSi10Mg, and graphene is unavailable in open-access databases available for use. The availability of the life cycle inventory data will lead to more certain results and a more transparent comparison will be possible. Further research on similar materials and technologies using more precise datasets is required to produce more refined results to sketch a more detailed overview of raw material selection criteria for PBF in AM industry.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s40964-024-00640-x.

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Data availability All data generated or analyzed during this study are included in this published article and are also available with the supplementary information files.

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