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Asymptotic pathways to carbon minimization in laser powder bed fusion

Giulia Colombini^{1*} , Silvio Defanti¹, Lucia Denti¹ and Elena Bassoli¹

Abstract

Laser powder bed fusion of metals (PBF-LB/M) is increasingly recognised as a pivotal technology to drive the green transition in manufacturing. While its high material efficiency and minimised resource usage offer sustainability benefits, the energy-intensive nature of the process poses a major environmental challenge. This study explores potential avenues to asymptotically reduce the carbon footprint of the PBF-LB/M process through a multifaceted approach, to realise its full potential as a sustainable manufacturing process. A cradle-to-gate scope is used to identify the key drivers of environmental impact and propose a structured sequence of targeted optimisations of the operating conditions, each quantified using a life cycle approach. Key strategies to reduce environmental impact—including switching to renewable energy, using lower impact gases such as nitrogen, increasing recycled content, on-site nitrogen generation and optimising component design—are progressively implemented and their cumulative impact is quantitatively assessed within the GHG Protocol. The paper provides a clear roadmap through a sequence of scenarios for sustainable PBF-LB/M, to meet the requirements of responsible manufacturing.

Highlights

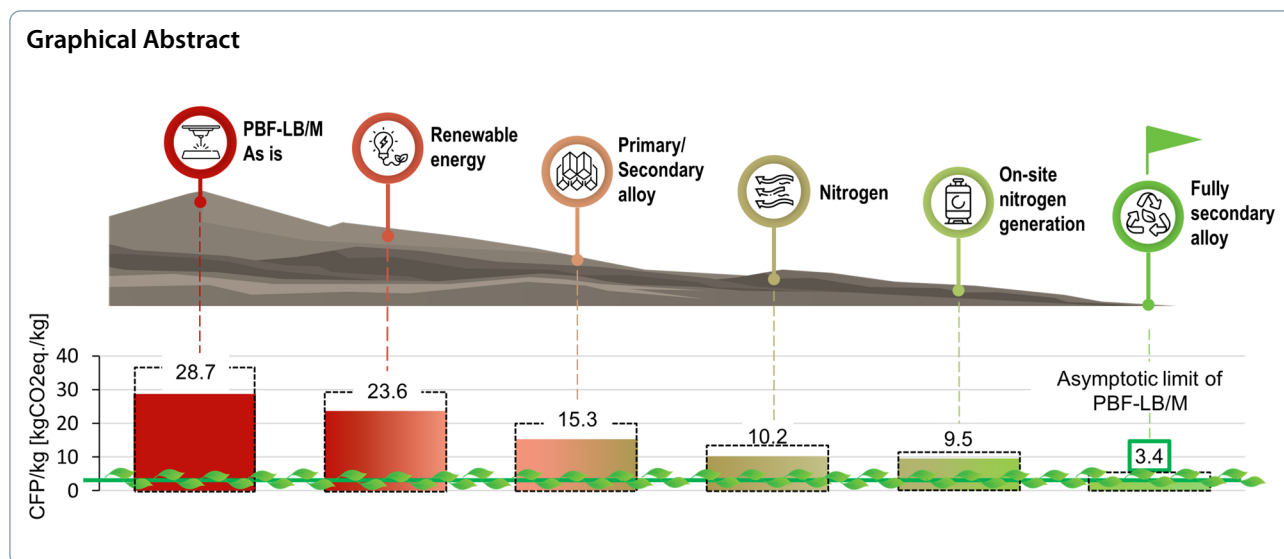
- Critical analysis of the current carbon footprint of PBF-LB/M, identifying the main contributors to its impact.
- Quantitative assessment of strategic improvements related to material, process and part design, leading to an 89% reduction in carbon emissions.
- Definition of a “greening pathway” to support industrial decision-making with a sound scientific framework.

Keywords Sustainable manufacturing, Carbon emissions, Powder Bed Fusion, Asymptotic reduction

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1 Introduction

Laser Powder Bed Fusion of metals (PBF-LB/M) has evolved into a mature production technology, alternative and not preliminary to traditional subtractive processes, at least for the production of high-performance components with complex geometries and high buy-to-fly ratios (Bassoli et al. 2023). Its capacity to fabricate intricate, near-net-shape parts with minimal material waste makes it particularly attractive for the aerospace, automotive, and energy sectors (Buchmayr et al. 2017; Katz-Demyanetz et al. 2019; Scime and Beuth 2018). Recent advances have extended its potential to functional integration and combined thermo-structural applications, which are characterised by shapes that are often unfeasible or economically prohibitive using traditional methods (Defanti et al. 2024; Sufiarov et al. 2020).

However, the broader industrial deployment of PBF-LB/M for end-use parts faces ongoing challenges. These include limitations in scalability, production speed, and cost-effectiveness, as well as growing concerns about its environmental impact (Calignano et al. 2019). As the technology transitions from prototyping to full-scale production, it must also be aligned with global sustainability goals and regulatory frameworks to mitigate climate change (Waddell et al. 2011).

From an environmental standpoint, PBF-LB/M presents a complex picture (Hapuwatte et al. 2016; Kellens et al. 2017). On the one hand, it offers significant advantages in terms of material efficiency, design-driven mass reduction, and reduced post-processing, all of which contribute to lower emissions during the use phase (Campo et al. 2019). The inherent layer-by-layer nature of this process enables the fabrication of near-net-shape parts, minimising material waste and machining operations,

which is in line with the principles of green manufacturing (Santecchia et al. 2020). In addition, the process is characterised by improved resource efficiency compared to subtractive manufacturing methods, as it enables the reduction of material waste (Rahmani et al. 2025; Ramadugu et al. 2024; Yang et al. 2019). In the list of environmental advantages of the technology, the absence of a tooling phase and the resulting saving of resources plays an important role, which also means that a break-even point can usually be determined in terms of emissions compared to conventional technologies, similar to what happens with costs (Liao et al. 2023). On the other hand, the sustainability of PBF-LB/M is not unproblematic. The process is energy-intensive, particularly during powder production and laser operation. Despite the power requirements being typically low, the very low productivity of PBF-LB/M machines takes the overall energy consumption well above that of conventional manufacturing (Faludi et al. 2017). Several comparative analyses point to the relatively high energy consumption and the associated carbon emissions, especially compared to conventional manufacturing processes. Priarone et al. (2023) conducted a cradle-to-grave life cycle assessment of the environmental impact of manufacturing a bracket using two different manufacturing solutions, i.e., traditional iron casting and PBF-LB/M with an optimised design using the aluminium alloy AlSi10Mg. While the component produced with AM showed a weight reduction of 69%, which could lead to lower emissions in the use phase, the energy requirements of the process, especially for powder production and laser operation, resulted in a higher carbon footprint. Similar results were reported by Dalpadulo et al. (2023), who investigated the impact from cradle to use phase of an aluminium rocker arm

bearing in a pull-rod suspension system designed to be manufactured with both PBF-LB/M and CNC machining. Despite the 21.9% weight reduction achieved by AM, the results show that the overall carbon footprint of the process remained higher than that of conventional CNC machining, mainly due to the high energy requirements of metal AM technologies. Although energy consumption is widely recognized as the dominant contributor to the environmental impact of PBF-LB/M, it is also the most straightforward to mitigate, for example, by sourcing electricity from certified renewable providers. In contrast, the environmental burdens associated with inert gas usage and raw powder production are more challenging to address (Liao et al. 2023). Recent studies have demonstrated that optimizing gas flow parameters and adopting closed-loop recirculation systems can significantly reduce inert gas consumption and related emissions without compromising part quality (Emminghaus et al. 2022). While the substitution of argon with nitrogen has been proposed as a lower-impact alternative, its environmental benefits are seldom quantified through sensitivity analyses (Teubler et al. 2019). Parallel efforts are focusing on powder reuse and recycling strategies to enhance resource efficiency. Although powders derived from recycled metal alloys are increasingly available and align with circular economy principles, their net effect on the overall carbon footprint remains underexplored in current literature (Emminghaus et al. 2022). These findings underscore the need for a holistic, data-driven approach to assess and mitigate the environmental impact of metal-based AM processes, which comprehensively analyses the system in its crucial interplay of the resources involved and defines improvement strategies (Ochs et al. 2021).

This study addresses a critical gap in the literature by providing a quantitative, scenario-based life cycle assessment (LCA) of the environmental impact of PBF-LB/M, integrating a set of feasible greening strategies into a cumulative framework. While individual sustainability measures—such as powder recycling, energy-efficient laser strategies, or build orientation optimization—have been explored in isolation, their combined impact has not been systematically quantified. This research develops a structured methodology to assess the environmental benefits of these improvements when implemented collectively, offering a realistic and scientifically grounded basis for industrial decision-making. The novelty of this work lies in the quantitative assessment of a pathway towards an asymptotic state, i.e., a theoretical minimum carbon footprint achievable under current technological constraints. This approach is inspired by the "ideal condition" framework proposed by Madan et al. (2015) for injection moulding processes, where progressive

layers of inefficiency are systematically accounted for to distinguish between ideal, theoretical and actual performance limits (Madan et al. 2015). Similarly, our asymptotic model enables the evaluation of the environmental performance of PBF-LB/M and identifies the residual potential for improvement. It serves as a decision-support tool to quantify how close a given configuration is to the lowest attainable carbon footprint, thereby guiding prioritization of sustainability interventions. By simulating multiple improvement scenarios, the study provides actionable insights for reducing the environmental burden of PBF-LB/M while maintaining its functional and economic viability. The results contribute to the advancement of sustainable manufacturing practices and support the alignment of metal AM with circular economy principles (Dornfeld 2014).

2 Materials and methods

2.1 Inventory Analysis

To systematically assess the carbon footprint (CFP) of the PBF-LB/M process and possible improvements, the study applies an LCA approach with a cradle-to-gate perspective, as shown in Fig. 1. The goal of this preliminary analysis is to provide a comprehensive quantitative assessment of the environmental impacts associated with the current manufacturing process. The scope considers the key stages of the life-cycle, from raw material extraction and powder production to gas atomisation and, an in-depth assessment of the manufacturing phase, broken down into unit actions with a high level of detail to identify the operations, equipment and resources involved. Subsequent post-processing and/or heat treatments are neglected as they are not directly related to the PBF-LB machine and therefore would not provide meaningful insights for the identification of optimisation strategies. The methodology used builds on the approach presented in an earlier study, which also analysed the sustainability aspects of the technology under investigation (Colombini et al. 2024). The focus of the analysis is on the production of components with the aluminium alloy AlSi10Mg using the SLM 500 four-laser system (NIKON SLM Solution GmbH, Lübeck, Germany), whose specifications are listed in Table 1. In detail, the manufacturing procedure consists of three distinct phases through which a job is completed. Firstly, the preliminary set-up steps are completed to achieve the operating conditions. These include sieving the metal powder via the PSV auxiliary unit, installing and heating the build platform to 80 °C and creating an argon atmosphere with an oxygen concentration of less than 0.1%. The main build phase, the duration of which varies depending on the geometry and size of the component, involves recoating and laser melting under controlled conditions. These are ensured by a

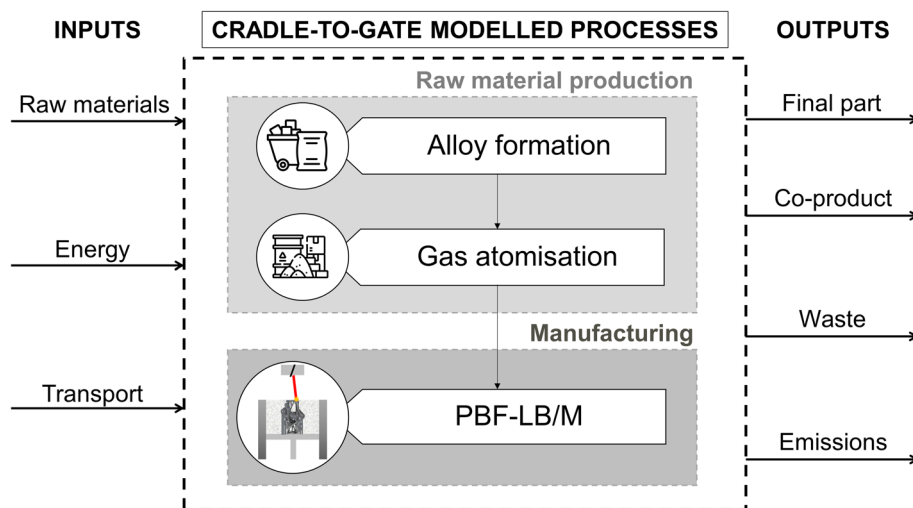


Fig. 1 Cradle-to-gate system boundaries adopted for the analysis, covering and modelling the life cycle phases from raw material production, through the manufacturing phase, to the factory gate

Table 1 Technical specifications of the SLM 500 machine used during the experimental activities to assess the current environmental footprint of the technology

SLM 500	
Maximum build envelope (X x Y x Z)	500 × 280 × 365 mm
Laser power	4 × 700W
Average layer thickness range	20–90 μm
Average argon consumption during construction	16 L/min
Average argon consumption in the purging phase	250 L/min
Power supply	400 Volt 3NPE, 63 A, 50/60 Hz, 8–5.5 kW
Compressed air requirement	ISO 8573–1:2010 [1:4:1] 7 bar

recirculation pump that continuously supplies argon at a constant speed of 36 m/s to reduce defects caused by the formation of metal vapour plumes and the ejection of spatter, and by a chiller to cool the laser and optics. After the build, the part and platform are cooled and transported to the Part Removal Station (PRS) where the unmelted powder is collected in an inert atmosphere, sieved and reused for subsequent builds.

The main input resources used in the evaluated manufacturing process are therefore electrical energy for the operation of the machine and auxiliary equipment, gas atomised metal powder and argon to prevent oxidation and defects. In addition to the manufactured part, the corresponding output resources are the emissions, the recycled powder and the waste resulting from the process. Field studies and experimental measurements are carried out during the production of a selected job in order to precisely quantify these resources across all manufacturing steps. Specifically, the test case is a component designed for automotive applications, which also

serves as the functional unit of the analysis, with box dimensions of 225 × 236 × 303 mm and weight of 1.43 kg. The total number of four parts nested onto the build plate is obtained from the industrialization procedures of positioning and orientation performed with Materialise Magics 25 software (Materialise Software, Leuven, Belgium) to fully utilize the build chamber, as shown in Fig. 2. The result is a job with a total mass of 7.76 kg, with the 5.73 kg of manufactured parts requiring a total mass of 2.03 kg of support structures. The layer thickness is set to 90 μm and a contour-core scanning strategy is selected. Specifically, the core areas are processed with a laser power of 620 W, a scanning speed of 1440 mm/s and a hatching distance of 0.19 mm, while the contours and support structures are scanned with a reduced power and speed of 400 W–1050 mm/s and 500 W–800 mm/s respectively. The recoating time required to apply each new layer of metal powder is set at 9 s, with a minimum scanning time of 8 s. To quantify the electrical energy consumption of the PSV sieve system, SLM machine

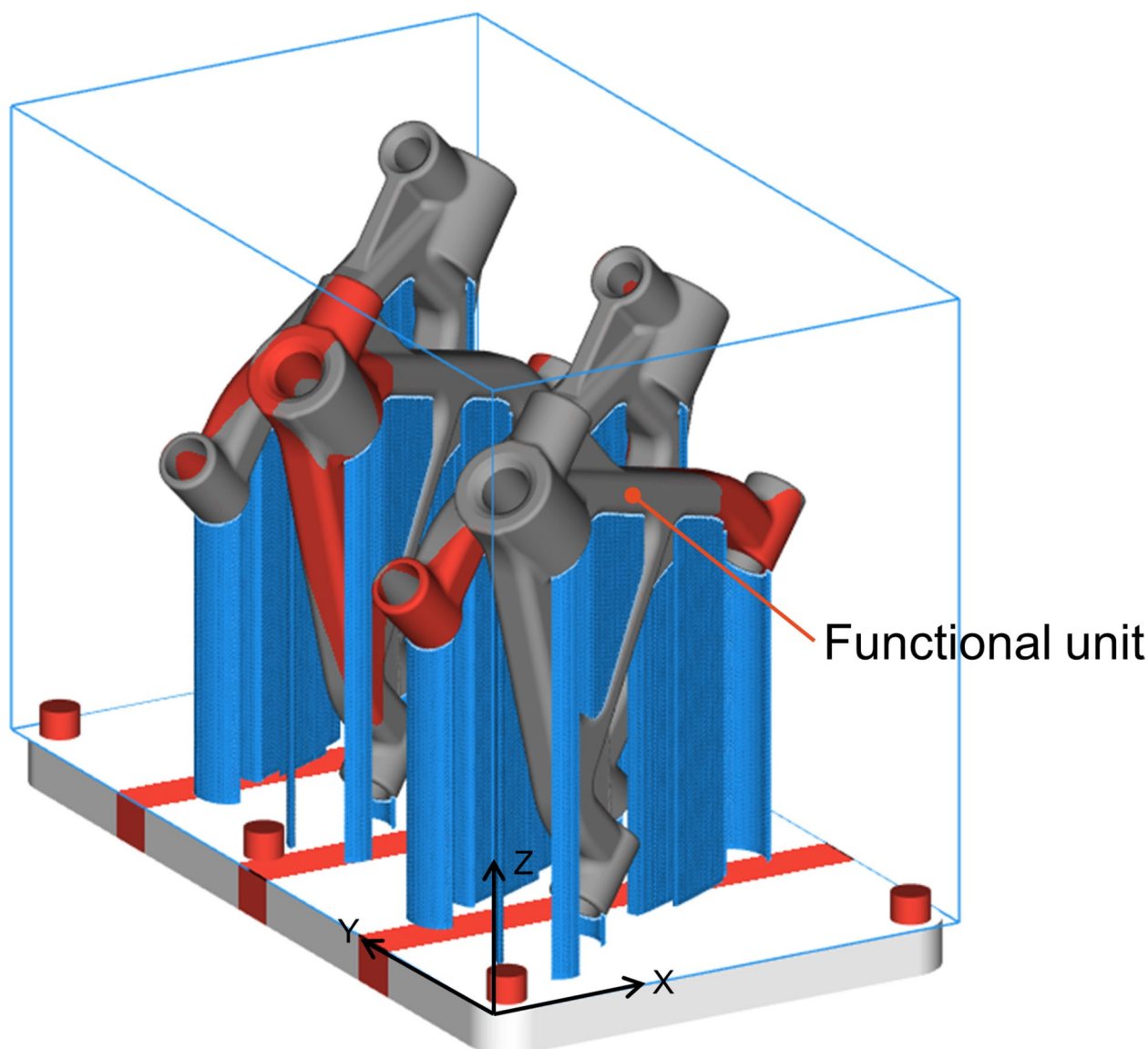


Fig. 2 Illustration of the functional unit (1 of the 4 parts) within the industrialized build configuration, optimised to maximise the production capacity of the PBF-LB/M system

and PRS unit during the production, the power absorption is measured continuously during the job with a Fluke 435 three-phase current metre connected directly to the main control panel with a sampling time of 10 s. The consumption of metal powder and argon is determined by directly measuring the level of all powder containers and the argon reservoir on site for the entire duration of the job.

The experimentally determined usage of resources serves as input data for the LCA of the PBF-LB/M process in accordance with the guidelines of the ISO 14040–14044 standards (ISO 2006). In addition to the measured

consumptions, complementary inventory data on powder production is taken from the literature and adapted to the present case study (Cappucci et al. 2020; Colombini et al. 2024). Energy consumption is modelled using the standard Italian electricity mix, without taking into account the specific energy mix of the analysed plant. To take into account the environmental impact of material and equipment transport, an estimated transport distance of 1500 km is considered for both the metal powder and the SLM500 machine, while an average distance of 100 km is assumed for the other transports. Road freight transport is modelled with EURO6 trucks with a capacity

of 16–32 tonnes. All data is modelled with SimaPro 9.6.0.1 software (Pré Sustainability, LE Amersfoort, The Netherlands) and the Ecoinvent database (version 3.10), following an attributional approach using the APOS system model (allocation at the point of substitution). The environmental impact assessment is performed using the widely used ReCiPe2016 methodology at the midpoint level, but for the purposes of the study, among the 18 impact categories considered, the Global Warming (GW) category is selected as the key indicator for its effectiveness in measuring impacts, as it quantifies the global greenhouse gas emissions released into the atmosphere, also defined as the carbon footprint (Huijbregts et al. 2017; Pandey et al. 2011; International Organization for Standardization. 2006a, 2006b).

2.2 Identification and quantification of the CFP reduction steps

A critical analysis is performed to identify strategies to reduce the environmental impact through both process optimisation and geometric redesign of the component.

A comprehensive assessment of the process within the system boundaries is first carried out to identify the main contributors to the environmental footprint. Progressive mitigation measures are then evaluated by comparatively analysing the CFP resulting from specific system Changes. The assessment of the sequence of improvements focuses exclusively on the major factors and ignores minor contributions, as they do not significantly affect the CFP results and are therefore held constant across different scenarios. Once the process is optimised in all its aspects for the lowest CFP, the focus is extended to the part design. In order to maximise the potential of the technology and approach the theoretical minimum environmental impact, i.e., the lower asymptote that combines all available greening approaches, a lightweight redesign of the part is applied according to the principles of design for AM. Based on standard practises in the field that ensure an optimal balance between structural integrity and material efficiency, it is assumed that a redesign of the geometry is feasible, allowing a 20% mass reduction (Dalpadulo et al. 2023; Mantovani et al. 2022; Merulla et al. 2019). The effects are quantified in the form of a CFP reduction. In a final step, the study is extended to a second build configuration in order to take a first step towards a more comprehensive sensitivity analysis and to quantify the robustness of the proposed minimum.

3 Results and discussion

3.1 Environmental impact of PBF-LB/M process

The preliminary result of the experimental evaluation is presented in Fig. 3, showing the trend of power consumption over the three phases of the manufacturing

technique. Specifically, the process required approximately 43 min for the pre-processing steps, 25 h of effective build time and 38 min for post-processing. A detailed inventory of the power demand for the individual steps, including their duration, can be found in Table 2. The cooling phase lasted 3 h, as the job was completed overnight and not dismantled until the next morning. An extended cooling and idle phase is common in industrial practise due to the operating schedule of the machine and results in prolonged activity of the auxiliary systems, sometimes over the weekend, and is therefore included in the evaluation model. Of the three phases, the melting phase had the highest energy consumption, at an average of 4.04 kW, with peak values reaching 7.74 kW. This considerable demand results from the simultaneous operation of all four lasers and of the auxiliary systems such as the Chiller, gas flow pump and platform heater, which are essential to ensure stable processing conditions. The total electrical energy required to complete the job was measured at 106.5 kWh.

The other two important resources required during the manufacturing process and the corresponding quantities determined during the experimental assessment are listed in Table 3. The on-site evaluation shows that the powder loss in this technology is 4.3% of the total powder used to fill the build volume for the completion of the job. These losses are due to several factors, including powder collecting in the overflow containers, agglomerates getting trapped in the sieves during the initial and final stages, and residual powder getting stuck in the part and its support structures after cleaning. In this particular case study, the waste powder was 45% of the total weight of the parts produced. In terms of argon usage, the measured consumption reflects the total amount required during the entire production cycle, including the initial oxygen purging phase, the build process itself and the depowdering phase carried out within the PSV system.

The analysis of the environmental impact results in a total carbon footprint of 234.4 kgCO₂eq. or the evaluated job. As can be seen in Fig. 4, when analysing the GW midpoint impact category across the various contributing elements of the production stages, powder production is clearly the largest contributor with 117.8 kgCO₂eq, despite the extensive powder recycling and a net material consumption of only 11.3 kg. This corresponds to an impact of 10.43 kgCO₂eq per kilogramme of powder produced, which is primarily due to the energy-intensive extraction and refinement of the base aluminum alloy and the additional processing required for gas atomisation (Weiss et al. 2022). That the powder overrides the impact of energy is partly in contrast to the primary role that various studies in the literature attribute to energy instead, but which consider

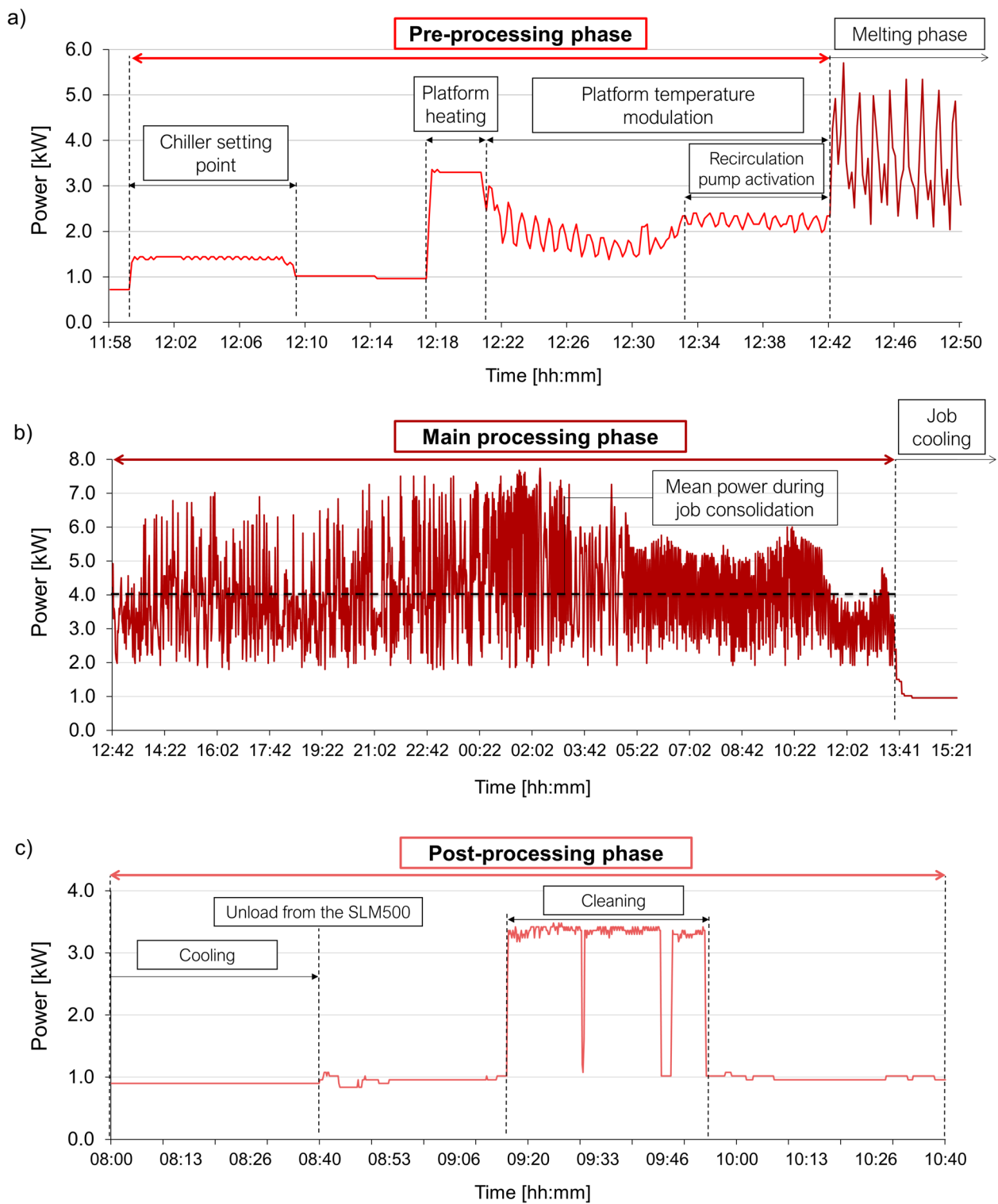


Fig. 3 Experimentally assessed power consumption profile during the PBF-LB/M job, segmented into three characteristic phases: (a) pre-processing, (b) job build-up, and (c) post-processing

Table 2 Power, electrical energy consumption and time interval required to complete each step of the considered PBF-LB/M job

	Action	Power consumption [kW]	Duration [h]	Electrical energy [kWh]
Pre-processing phase	SLM 500 idle condition	0.96	-	-
	Chiller activation	1.41	0.16	0.23
	Platform heating to 80 °C	3.10	0.07	0.23
	Platform temperature modulation and oxygen purging by the recirculation pump (67% of max. power)	2.23	0.14	0.32
Main processing phase	Construction	4.04	24.84	100.35
Post-processing phase	Job cooling	0.96	3.0	2.88
	Job cleaning	3.19	0.63	2.02

Table 3 Experimentally determined total raw materials consumption for the production of the test-case, broken down by the main resources involved in the manufacturing process, i.e., metal powder and inert gas

Metal powder	
Total initial powder [kg]	80.20
Total fused mass [kg]	7.76
Total waste powder [kg]	3.49
Recycled powder [kg]	68.98
Powder recycling ratio	96%
Inert gas	
Total argon consumption [kg]	35.31

different configurations than the one analysed in this study. Faludi et al. (2017) analysed a PBF-LB/M process in which gas consumption is greatly reduced by the fact that no continuous flow is used during construction, and also consider non-primary data for the powder waste fraction, resulting in a lower estimate than the one directly measured in this study (Faludi et al. 2017). Even in studies that consider the same process configuration analysed here, but which are characterised by the production of a relatively small component in relation to the build volume and thus by a non-optimised use of machine capacity, energy is responsible for most of the carbon footprint (Colombini et al. 2024). In addition to

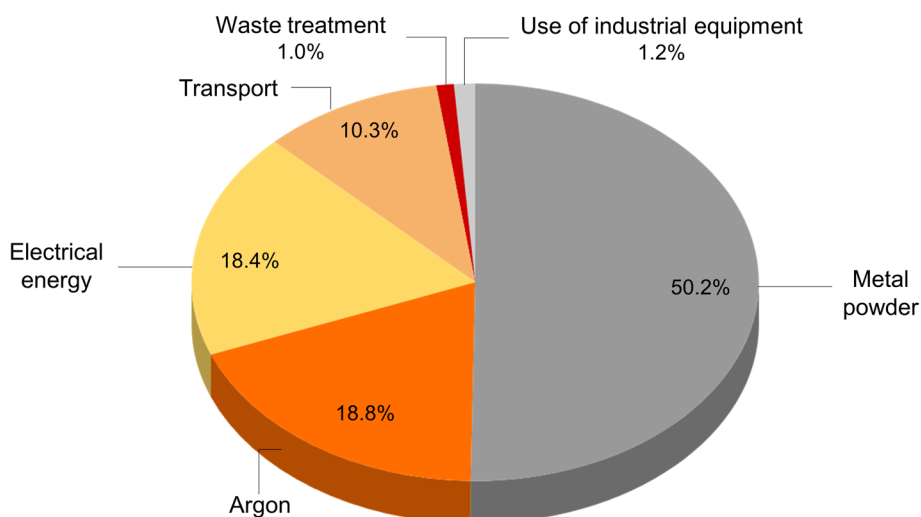


Fig. 4 Breakdown of the impact on global warming for all characteristic contributions of the PBF-LB/M process in relation to the production of a 7.76 kg job

powder production, electricity and argon consumption also play a decisive role in the overall impact, which amounts to 44.5 kgCO₂eq and 43.4 kgCO₂eq, respectively. Electricity-related emissions are estimated at 0.42 kgCO₂eq per kWh, reflecting the Characteristics of the Italian energy mix, in which natural gas remains the dominant energy source and makes a major contribution to the environmental impact. In parallel, argon consumption contributes an estimated 1.23 kgCO₂eq per kilogramme, largely due to the high energy requirements of its production. Taken together, these three factors account for around 87.5% of the total environmental impact. If these emissions are further analysed using a mass-based metric, a component mass of 5.73 kg in the PBF-LB/M process results in a CFP/kg impact of 35.7 kgCO₂eq per kilogramme of product manufactured. Although this approach does not fully capture the design benefits and material efficiency enabled by

AM, it serves as a direct factor that is beneficial for comparing the sustainability of different technological solutions.

This result applies to a well-defined manufacturing scenario, encompassing both specific process parameters and the broader industrial framework in which the job is executed. As the environmental performance is highly dependent on these variables, a sensitivity analysis is performed to assess the influence of these factors. PBF-LB/M is governed by a wide array of process settings, from part orientation and build strategy to laser exposure parameters. Accordingly, an alternative industrialization approach is evaluated in which the same functional unit is produced in a batch of 3 instead of 4 components. In this case, the best orientation allows for a slightly lower overall height to avoid overlapping support structures (Fig. 5). This second setup involves a lower consolidated volume, with an overall mass of 6.50 kg split into 4.30

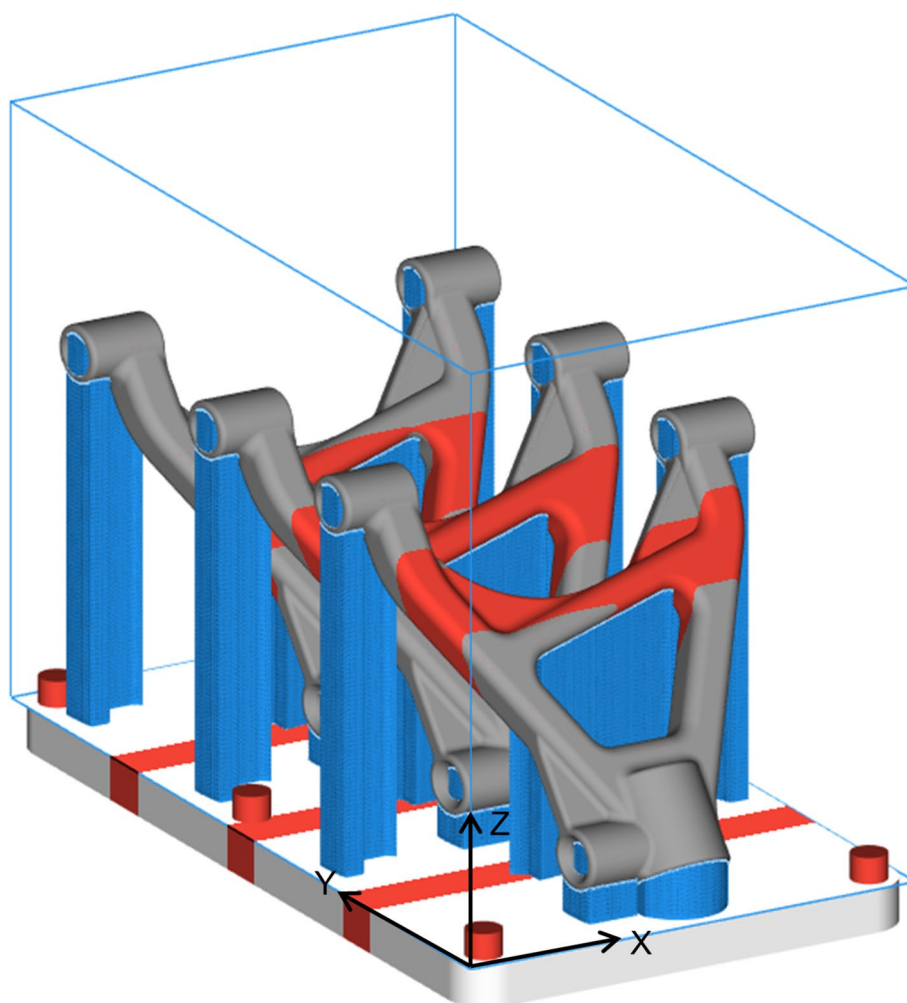


Fig. 5 Second build configuration for the same functional unit in the case of 3 copies, analysed to assess the impact on the environmental performance of the PBF-LB/M process

kg of parts and 2.20 kg of supports. The new orientation lowers the build height from 304 mm in the previous configuration to 227 mm, reducing the build duration and time-related consumption of resources, i.e., energy and argon. Due to the smaller melt volume, powder losses are also decreased, leading to a net powder usage of 9.43 kg.

A comparative overview of the input parameters and the corresponding CFP results for both configurations in Table 4 show that the second layout is clearly characterized by a higher environmental impact per part. While the alternative configuration shows a 10% reduction in overall impact, this benefit is offset by a higher impact per unit produced, due to a less efficient usage of the build volume. This emphasizes the critical role of maximising build platform utilisation and part nesting efficiency to spread the burden of resource inputs, such as energy and inert gas, over a greater functional output. A serious limitation of this insight is that such a greening approach is constrained by industrial demand and lead time considerations.

Beyond the technical process parameters and manufacturing Choices, operational practices and geographic location also have a significant influence on the environmental footprint. For instance, relocating the job production in the 4-part configuration to the UK, a country with a cleaner energy mix (0.27 kgCO₂eq/kWh compared to Italy) would reduce emissions associated with electricity consumption and also positively change the logistical impact due to reduced transport distances from the machine and the powder supplier. However, under these conditions, the total impact of the 4 parts would decrease to 215.0 kgCO₂eq, which is a marginal improvement compared to the baseline. On the other hand, optimising operations, such as increasing the efficiency of powder recovery to the best practises observed in the field assessments, i.e., 98%, could reduce powder waste to 1.6 kg. This would yield a CFP improvement of approximately 9% and reduce the overall impact to 213.1 kgCO₂eq. These

analyses confirm that the overall footprint of the process in the “as-is” condition is only marginally affected by changes in the standard industrial practices, to an overall impact in the order of ten percentage points, while a more substantial reduction in CFP requires a more radical and integrated approach that addresses the three main resource drivers: energy consumption, inert gas usage, and material usage.

3.2 Asymptotic reduction of the CFP through process optimisation

To substantially reduce the environmental footprint of the technology, targeted strategies must address the most important factors and steer development towards greater sustainability. In the test case examined, the process requires 18.6 kWh/kg, which corresponds to an energy demand that is around ten times higher than conventional casting (Salonitis et al. 2019).

In the case considered, energy represents the third largest contribution, with CO₂ emissions directly tied to the national energy mix. For the Italian automotive industry fossil fuels (particularly natural gas) still dominate despite the growing integration of renewables. A first straightforward approach to mitigate the environmental impact is to switch to a renewable energy supply, either by generating electricity on site or by sourcing certified green electricity through Guarantees of Origin (GO). In Italy, solar energy is a feasible alternative with an estimated emission factor of 0.075 kgCO₂eq per kilowatt hour (Wernet et al. 2016). This switch can lead to an 82% reduction in electricity-related emissions, which significantly improves the sustainability profile of the process.

In the case of this research, optimised for high productivity and full utilisation of the machine's production capacity, metal powder contributes the most to the carbon footprint, making material selection a key area for impact reduction. Aluminium alloys are typically produced from a mixture of primary aluminium, which is extracted from bauxite ore, and secondary aluminium, sourced from recycled industrial and post-consumer scrap. Studies have shown that secondary aluminium plays a crucial role in achieving sustainability goals due to its lower energy requirements and the elimination of mining and refining processes (Paraskevas et al. 2015; Zhang et al. 2023). Increasing the share of recycled aluminium in powder production is a viable strategy to reduce environmental impact. Trends in the industry confirm this change: atomized powders with a high proportion of recycled aluminum are now commercially available and have half the carbon footprint of powders made from fully virgin alloy. Accordingly, the analysis includes a scenario in which the CFP of the metal powder used is lowered from 10.43 kgCO₂eq/kg to 5.21

Table 4 Comparison of main input quantities and corresponding CFP values that determine the sensitivity of environmental performance to variations in job configuration

	4-part build configuration	3-part build configuration
Build time [h]	25.0	23.6
Total electrical energy [kWh]	106.5	100.6
Total fused mass [kg]	7.76	6.50
Total waste powder [kg]	3.49	2.93
Total argon consumption [kg]	35.31	33.34
Total CFP [kgCO ₂ eq.]	234.4	211.1
Total CFP per part	58.6	70.3

kgCO₂eq/kg. Progress towards an even more sustainable approach to the production of metal powders could be achieved by increasing the recycled content to almost 100%, with only a minimal additional amount of primary material required to maintain the stability of the composition and control impurities. The literature estimates an 88% reduction in emissions with this approach, resulting in a final CFP for this case study that can be estimated at approximately 1.25 kgCO₂eq/kg, which is a dramatic improvement over conventional methods of powder production (Hong et al. 2012).

The consumption of inert gas is a notable environmental factor, especially in the case of prolonged jobs, and is the second most impactful contribution in the case under consideration. A continuous flow of gas is required to ensure process stability and laser performance and, since the system is not completely airtight, maintaining an oxygen-depleted atmosphere requires continuous gas consumption. Recent studies have identified nitrogen as a promising alternative to argon for the manufacturing of AlSi10Mg parts, demonstrating comparable mechanical properties, such as tensile strength and hardness, and no significant effect on surface roughness, porosity, or mechanical performance (Xiao et al. 2022; Ch et al. 2019, 2020). With a CFP of 0.19 kgCO₂eq/kg for nitrogen, this transition could reduce gas-related emissions by around 84% (Wernet et al. 2016). In addition to direct substitution, environmental benefits can also be achieved through on-site nitrogen generation, which promotes self-sufficiency and minimises the footprint associated with gas cylinders transportation. According to the SLM500 datasheet, gas flow rates of 16 L/min are required during the build phase and 250 L/min for the initial oxygen purge, values that are expected to remain unchanged when switching from argon to nitrogen (Ch

et al. 2019). Figure 6 shows a hypothetical configuration using the Parker N2C-4 nitrogen generator (Parker-Hannifin Corporation, Mayfield Heights, Ohio), which was selected for its ability to generate nitrogen with an impurity level as low as 10 ppm, ensuring compliance with the required purity standards (Pauzon et al. 2019). The proposed layout is consistent with the nitrogen demand of the PBF-LB/M system. The primary environmental impact of this approach is related to the electricity required to operate the generator, as the impact over the lifetime of the generator system is minimal and therefore negligible. In this scenario, the total energy requirement for nitrogen generation, taking into account the required equipment Chain, is 0.875 Wh/kg of gas, which is significantly lower than the 3.43 kWh/kg required for argon (Wernet et al. 2016). Based on the total gas usage across the two phases of purging and melting, the estimated energy requirement is 25.81 kWh, corresponding to a carbon footprint of 1.95 kgCO₂eq when powered by renewable electricity, which is significantly lower than the conventional argon supply.

By systematically integrating the previously identified optimisation strategies, a progressive reduction of the carbon footprint of the PBF-LB/M process can be evaluated. Specifically, the proposed approaches are implemented step by step, leading to the development of several scenarios that illustrate the gradual reduction of environmental impacts. These are outlined in Table 5, starting with Scenario 1, which reflects the current as-is state based on experimental data and serves as the baseline against which each improvement is compared. Scenario 2 introduces the first optimisation step with a transition to electricity from renewable sources. Building on this, Scenario 3 considers a higher proportion of secondary aluminium in metal powder production, followed

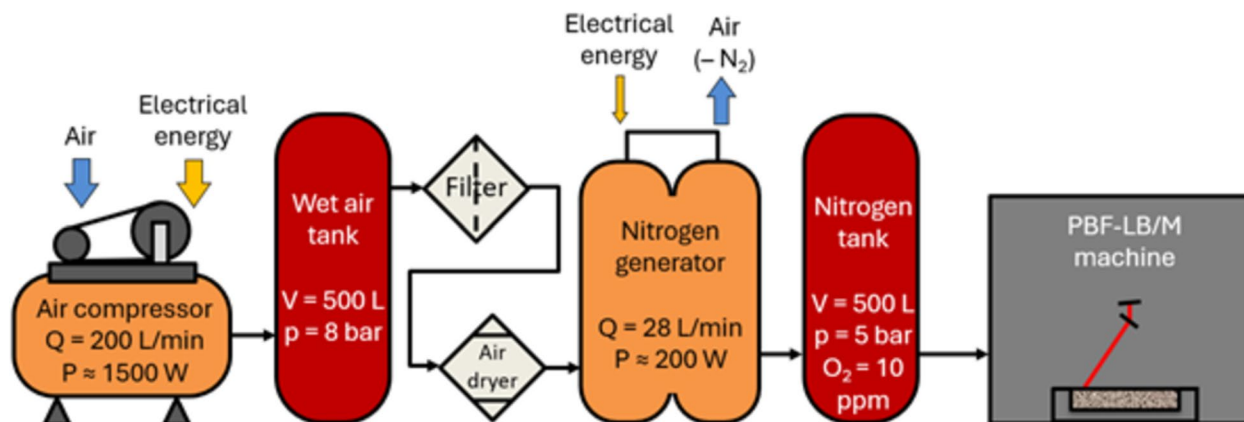


Fig. 6 Layout for an on-site nitrogen generation system integrated with the SLM 500 machine designed to eliminate the need for externally supplied shielding gas

Table 5 Stepwise reduction of the carbon footprint according to the different proposed scenarios of process optimisation

	Scenario 1: PBF-LB/M as is	Scenario 2: renewable energy	Scenario 3: primary/ secondary alloy	Scenario 4: argon replaced by nitrogen	Scenario 5: nitrogen generated on site	Scenario 6: secondary alloy
Electrical energy [kgCO ₂ eq.]	44.5	8.0	8.0	8.0	8.0	8.0
Metal powder [kgCO ₂ eq.]	117.8	117.8	58.5	58.5	58.5	14.1
Inert gas [kgCO ₂ eq.]	43.4	43.4	43.4	6.7	1.9	1.9
Total CFP [kgCO ₂ eq.]	205.7	169.2	109.2	73.2	68.4	24.0
Percentage variation	-	-18%	-47%	-64%	-67%	-89%

by Scenarios 4 and 5, which envisage a switch from argon to nitrogen or on-site nitrogen generation, respectively. In the final configuration, Scenario 6, all measures are combined, resulting in an 89% reduction in the overall impact compared to the baseline. In Fig. 7, the incremental reduction of the carbon footprint in the different optimisation scenarios is evaluated per unit mass of final product (CFP/kg), which offers a clearer perspective on the environmental efficiency of each strategy and serves as a valuable decision-making tool in the production phase.

To complete the identification of a minimum carbon footprint, the analysis incorporates the effect of a 20% reduction in component mass, achieved by optimisation and additive design. The results, shown in Fig. 8, illustrate

the impact of producing a 0.8 kg component in the previously defined optimisation scenarios. For comparison, the dotted bars represent the original results calculated for 1 kg. The asymptotic lower limit of the environmental impact for this technology is thus determined at 3.4 kgCO₂eq/kg, achieved through the combined use of nearly 100% secondary aluminium, on-site nitrogen generation, and fully renewable electricity across all process stages.

The results demonstrate that the asymptotic condition is the cumulative outcome of integrating all the proposed environmental improvements. While each of these strategies is individually compatible with the technological constraints, their simultaneous implementation has not yet been demonstrated in a unified, real-world setting.

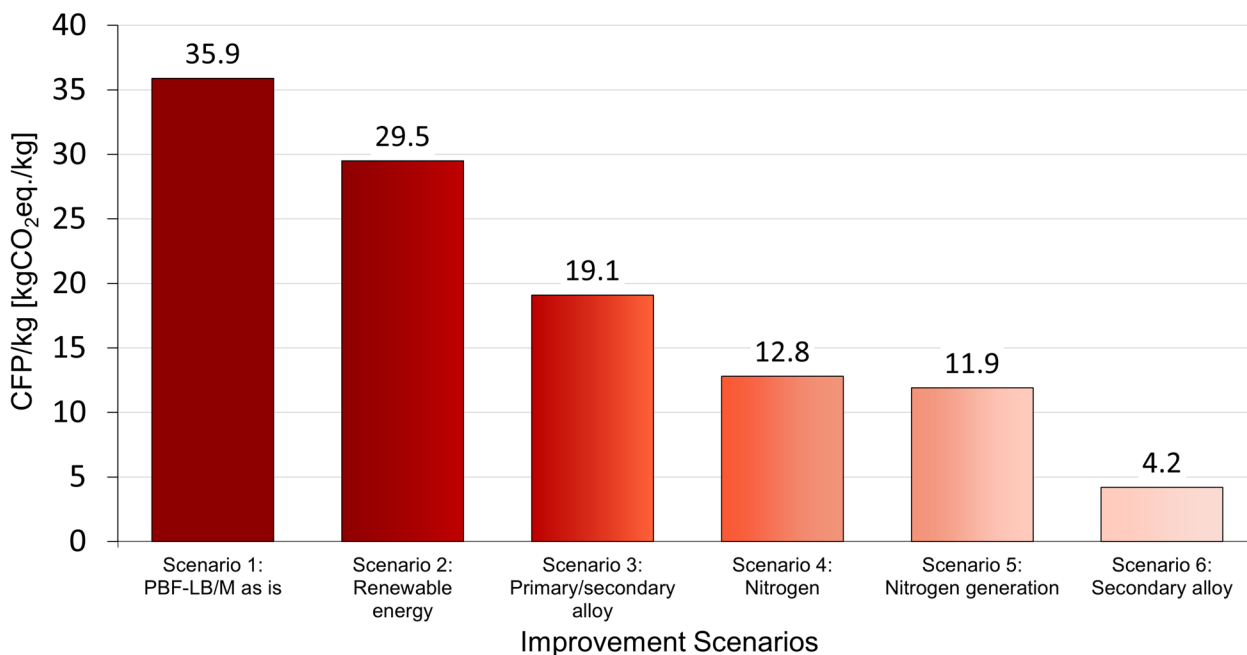


Fig. 7 CFP reduction pathway through sequential process optimisation steps, expressed as CFP per unit mass of manufactured part

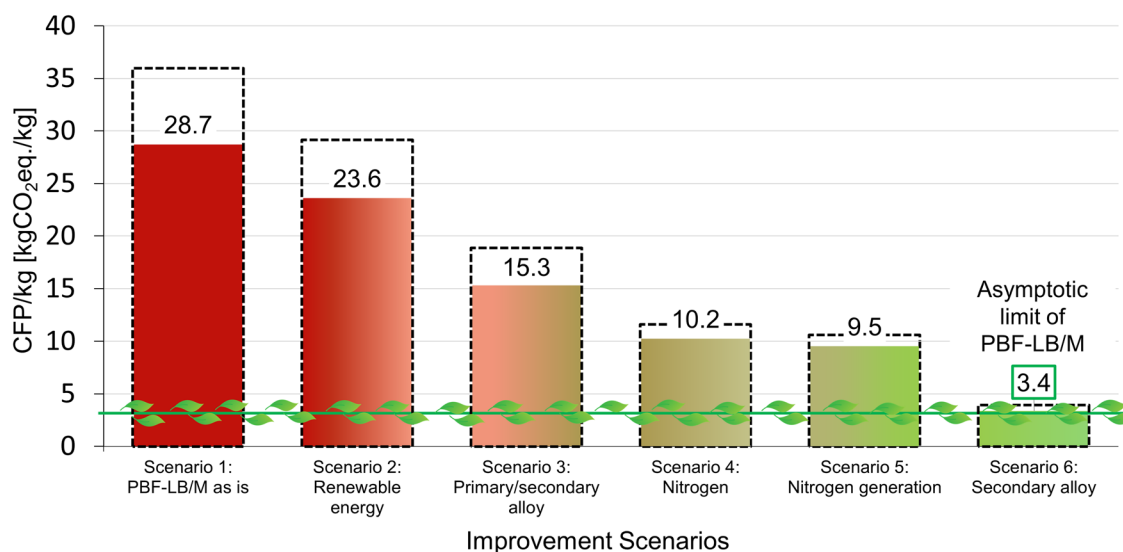


Fig. 8 Step-by-step reduction of the carbon footprint through the sequence of process optimisation steps for a functional unit weighing 0.8 kg instead of 1 kg thanks to design optimisation

Therefore, the asymptotic condition should not be interpreted as an immediately attainable configuration, but as a directional benchmark—a theoretical lower bound that indicates the residual potential for carbon footprint reduction under realistic but idealised conditions. This framing supports its use as a strategic tool for guiding incremental improvements and prioritising interventions based on their relative environmental benefit.

To clearly compare the current process state with the optimised scenario, a Sankey diagram is presented in Fig. 9. It illustrates the resource flows associated with the production of 1 kg under the current conditions and 0.8 kg in the optimized asymptotic scenario, both of which are evaluated within identical system boundaries.

3.3 Comparison with conventional manufacturing: PBF-LB/M vs. High Pressure Die Casting

One of the distinguishing features of the environmental impact of PBF-LB/M is the absence of a tooling phase, which generally makes the process competitive for a small number of parts. In the context of the proposed greening solutions, it is interesting to see how the environmental competitiveness varies in terms of production volume, as compared to a traditional technology. A comparative analysis is carried out using casting as a benchmark, given its widespread industrial use for aluminium components. Despite significant differences in system complexity, production volumes and geometrical flexibility between the techniques, casting remains a reference option (Al-Ketan et al. 2023; Abdelshafy et al. 2023; Katti et al. 2024). In addition, Al-Si alloys are widely used due to their excellent castability, which further emphasises

the relevance of this comparison between the two manufacturing processes (Tonolini et al. 2021). Therefore, an ex-ante analysis is conducted, evaluating and predicting the potential impact of this solution using a case study from the literature, chosen to reflect the AM scenario in terms of component mass and material selection. High Pressure Die Casting (HPDC) is selected due to its relevance and the availability of robust literature data. The comparison is based on a representative case study with a 7.28 kg AlSi10Mg component produced in a batch of 40,000 units (Roberts 2003; Salonitis et al. 2019; Liu et al. 2021). In the HPDC process, aluminium ingots are melted in natural gas-fueled furnaces using a stream of nitrogen gas for metal purification. The molten metal is then injected under high pressure into a single-cavity steel mould, with a lubricant sprayed on to prevent sticking during part removal. All life cycle inventory data covering material and energy inputs, and emissions, are modelled under consistent cradle-to-gate boundaries and using the same LCA methodology that was applied for the PBF-LB/M scenario (Table 6).

The assessment for this case study gives a CFP of 73.6 kgCO₂eq which, when normalised to the final mass of the component, corresponds to 10.1 kgCO₂eq/kg. For a similar part, HPDC exhibits a lower carbon impact compared to PBF-LB/M, in a fair evaluation of the two processes within their respective appropriate scope. It is important to emphasise that the two processes are extremely different in terms of target production volume and design flexibility. In conventional manufacturing processes, such as HPDC, the dedicated tooling accounts for a significant portion of the overall environmental impact due to its

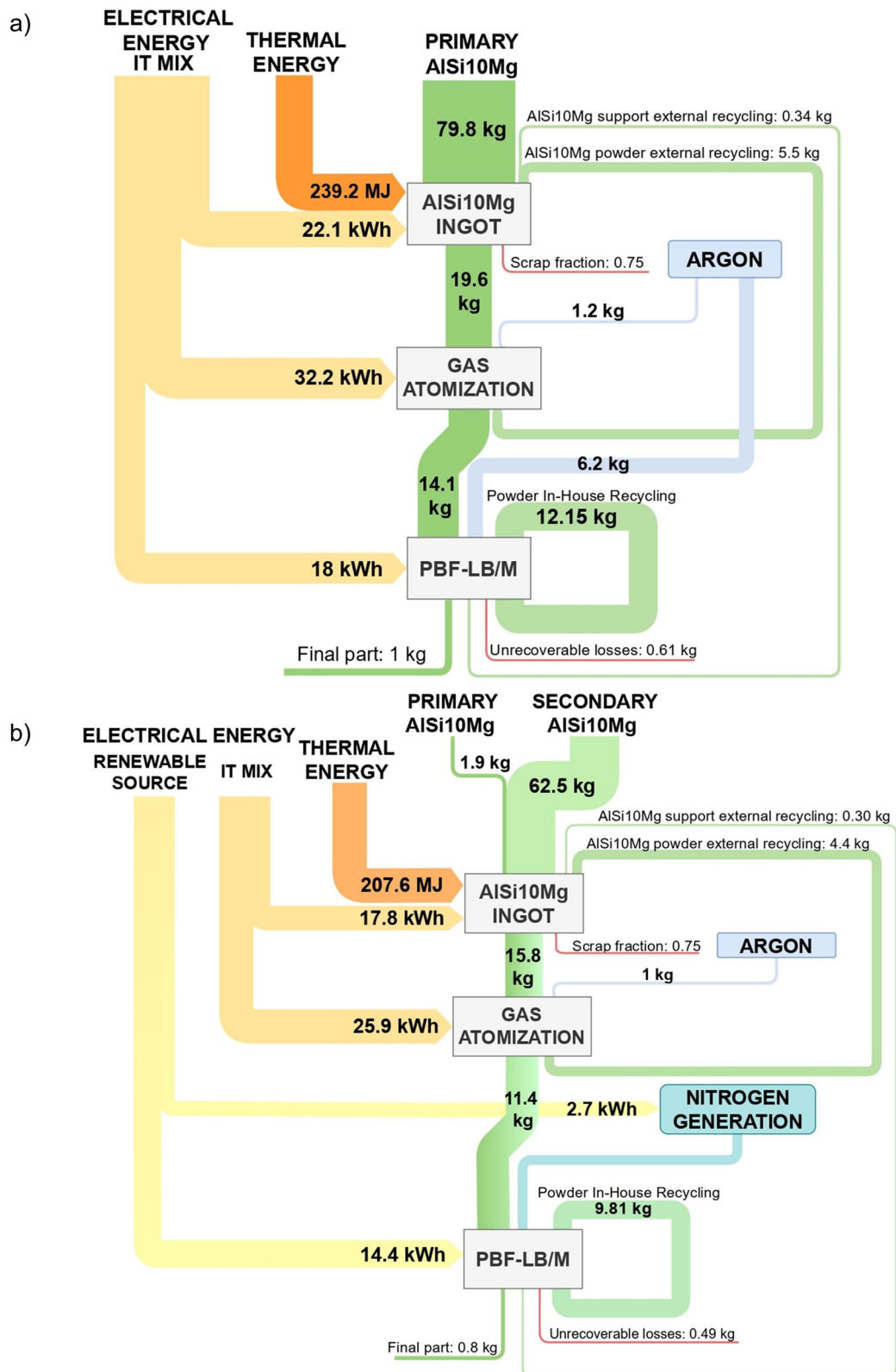


Fig. 9 Sankey diagrams showing the energy and material flows for: a) the production of 1 kg of final product with the PBF-LB/M process in the as-is state; and b) the production of 0.8 kg of final product with the ultimate improved asymptotic state PBF-LB/M process

Table 6 LCI for the production of a 7.28 kg AlSi10Mg component with HPDC process, calculated for a production volume of 40,000 units

Input data	
Final part mass [kg]	7.28
Shot mass [kg]	10.23
Die mass [kg]	10382
Die tooling mass [kg]	15.00
Spray die separator [kg]	0.04
Nitrogen [kg]	1.25
Natural gas consumption [MJ]	24.02
Electrical energy consumption [MJ]	22.11

high material requirements and the use of special alloys. However, as these tools are used over many production cycles, the associated carbon footprint is distributed over a large number of parts, significantly reducing the impact per unit. In contrast, no such tools are required for AM. This means that resource consumption is directly attributed to each individual job, resulting in a relatively constant environmental impact per part regardless of production volume. The only way to benefit from economies of scale is to fully saturate the machine’s build plate in order to spread the impact of the job over as many parts produced as possible. To assess the influence of the number of units produced on the CFP, Fig. 10 shows the downward trend for the HPDC compared to the values for the PBF-LB/M resulting from the combined process

and design optimisations described in detail in Fig. 8. The analysis shows that the PBF-LB/M solution in the as-is configuration, without greening solutions, reaches a break-even point with HPDC in terms of CFP when fewer than about 230 units are produced. A second key distinction is the intrinsic difference in the geometric complexity achievable by the two manufacturing processes. Consequently, the comparison serves primarily as a benchmark and not as a direct equivalence, since the two techniques typically serve distinct application areas. Nevertheless, by comparing a 1 kg casting with a 0.8 kg AM counterpart, a fair assessment of CFP per unit can be ensured. In this case, PBF-LB/M becomes advantageous from Scenario 4 onwards. The full integration of all proposed improvements and the lowest achievable CFP result in a viable and sustainable option for high-complexity, low-volume production.

3.4 Classification under the GHG Protocol

To support the potential adoption of the strategies outlined in this study by industry, the results are structured according to the widely accepted GHG Protocol framework for categorising greenhouse gas emissions in corporate sustainability reporting (Fig. 11). Emissions are divided into three scopes: Scope 1 direct emissions from company operations, Scope 2 indirect emissions from purchased electricity, and Scope 3 other indirect emissions along the value chain, both upstream and downstream (2024 GHG Protocol; Kasperzak et al. 2023).

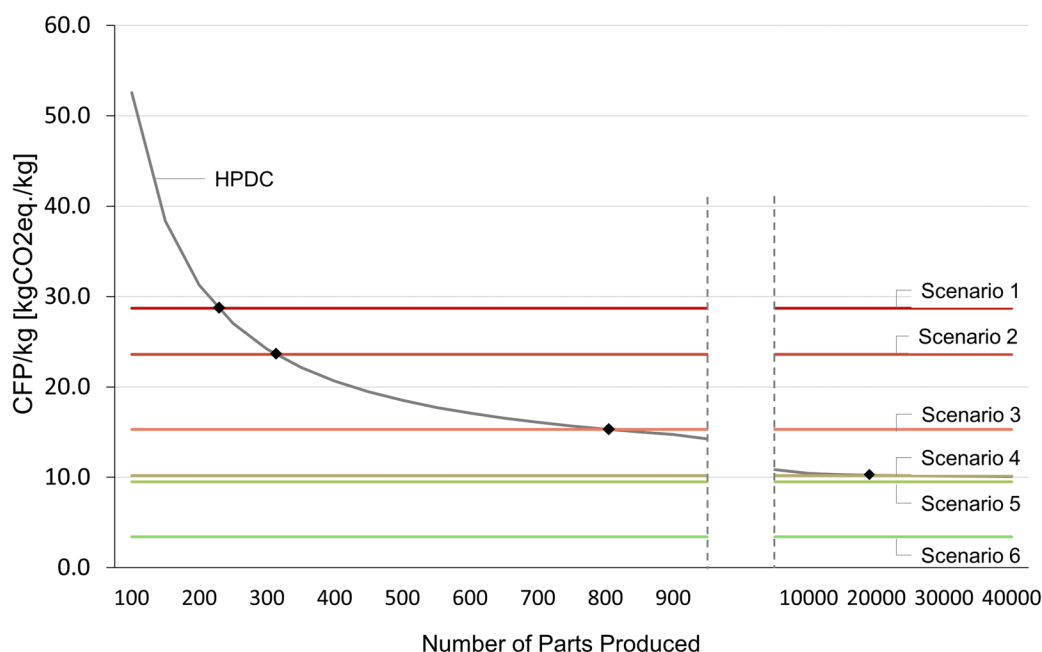


Fig. 10 Change in the carbon footprint of HPDC as a function of the production volume, balanced with that of PBF-LB/M in the various scenarios of process and parts optimisation

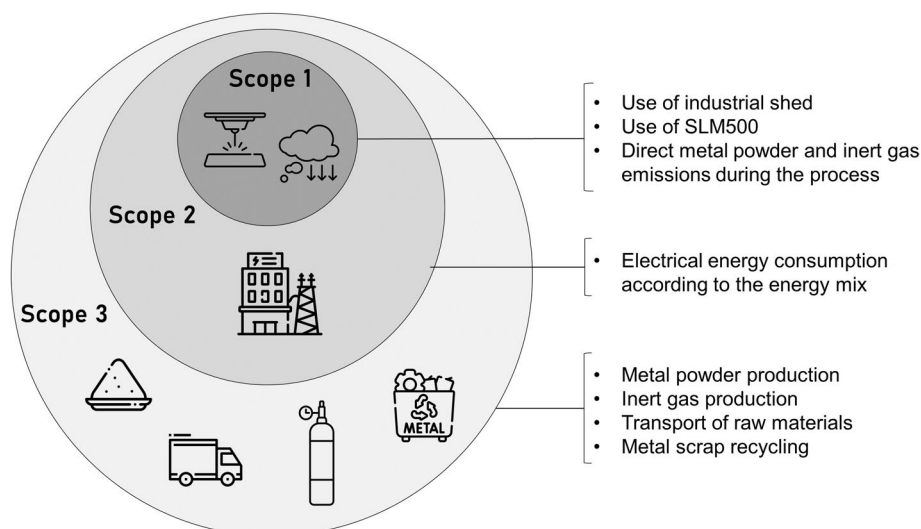


Fig. 11 PBF-LB/M emissions classified according to the GHG Protocol

Scope 1 includes emissions from the SLM500 system and the handling of metal powder and inert gas. Scope 2 covers emissions from electricity consumption based on the energy mix. Scope 3 includes upstream emissions from raw material extraction, metal powder production, inert gas production, transport, and scrap recycling. This classification underlines the fact that the sustainability improvements for PBF-LB/M go beyond the company's direct emissions and include optimisations across multiple scopes. Applying this framework to the strategies discussed, the switch from fossil fuel-based electricity to renewable energy sources is categorised under Scope 2. The use of lower impact materials, such as the replacement of argon with nitrogen and the increased use of secondary aluminium in metal powder, falls under Scope 3. The measures in Scope 1 primarily include the redesign of components and the integration of an on-site nitrogen generation system.

Beyond these important improvements, additional strategies to further reduce the environmental footprint have been identified, categorized and summarised in Table 7.

Each proposed measure represents an opportunity for further investigation, both for its environmental relevance and due to the complexity of the system under investigation, which offers multiple opportunities for optimisation. Among the most influential areas for improvement are the optimisation of process parameters, in conjunction with a proper industrialisation of PBF-LB/M jobs, allowing improvements in process efficiency, material consumption, waste reduction and energy requirements for production. Starting from this narrow perspective of the process under study, which

focuses primarily on what happens in the build chamber, the analysis can be extended to the process in its entirety, including all stages and associated equipment. This opens up further opportunities such as better powder recovery, defect prevention systems and reduced energy consumption of machines through optimised job scheduling. By broadening the perspective even further and evaluating the entire manufacturing process, the supply chain can be optimised by, for example, selecting more sustainable suppliers, refining logistics and adopting best practises from other manufacturing industries. The Ishikawa diagram in Fig. 12 provides a comprehensive overview of all the factors that contribute to the emissions of the PBF-LB/M process.

4 Conclusions

Through a comprehensive assessment of the environmental impact of the PBF-LB/M process with a cradle-to-gate LCA approach, this study focuses on the identification of strategies to asymptotically reduce its carbon footprint. Starting from an experimental investigation of the resources required to produce an AlSi10Mg part with an SLM500 machine, electricity consumption, metal powder production and the use of inert gas were identified as the main factors contributing to the environmental impact of the analysed process. This led to the main final considerations of the study, which are listed below.

- The experimental evaluation shows that the production of metal powder, in particular the AlSi10Mg alloy, has the largest share of the total carbon footprint, accounting for about 50% of the total impact. This is followed by the electricity

Table 7 Further improvements for the reduction of the carbon footprint of the PBF-LB/M process

Improvement strategies	
Scope 1	
1. Enhancement of process efficiency	Process optimisation to decrease post-processing operations. Maximise build platform occupation Reduction of the build time by optimised scanning strategies Improved job scheduling to reduce idle time
2. Waste reduction	Implementation of a recirculation system for argon gas to reduce leakage and waste Reduction of scrap powder through improved process control Optimisation of process parameters to reduce the possibility of failures Implementation of stringent quality control measures to minimize rejected products Increase of the powder recycling ratio
3. Design optimisation	Optimisation of the support structures Implementation of design for sustainability criteria
Scope 2	
1. Optimisation of the energy consumption	Optimisation of the job industrialisation to minimize electric consumption Optimisation of laser parameters to reduce electricity usage without compromising part quality Reduction of the energy consumption in idle condition
Scope 3	
1. Sustainable supply chain	Development of a greener upstream and downstream supply chain Adoption of materials with lower embodied energy
2. Transport efficiency	Localize the supply chain to reduce overall transportation emissions Optimisation of the logistics Use hybrid/electric vehicles to reduce emissions

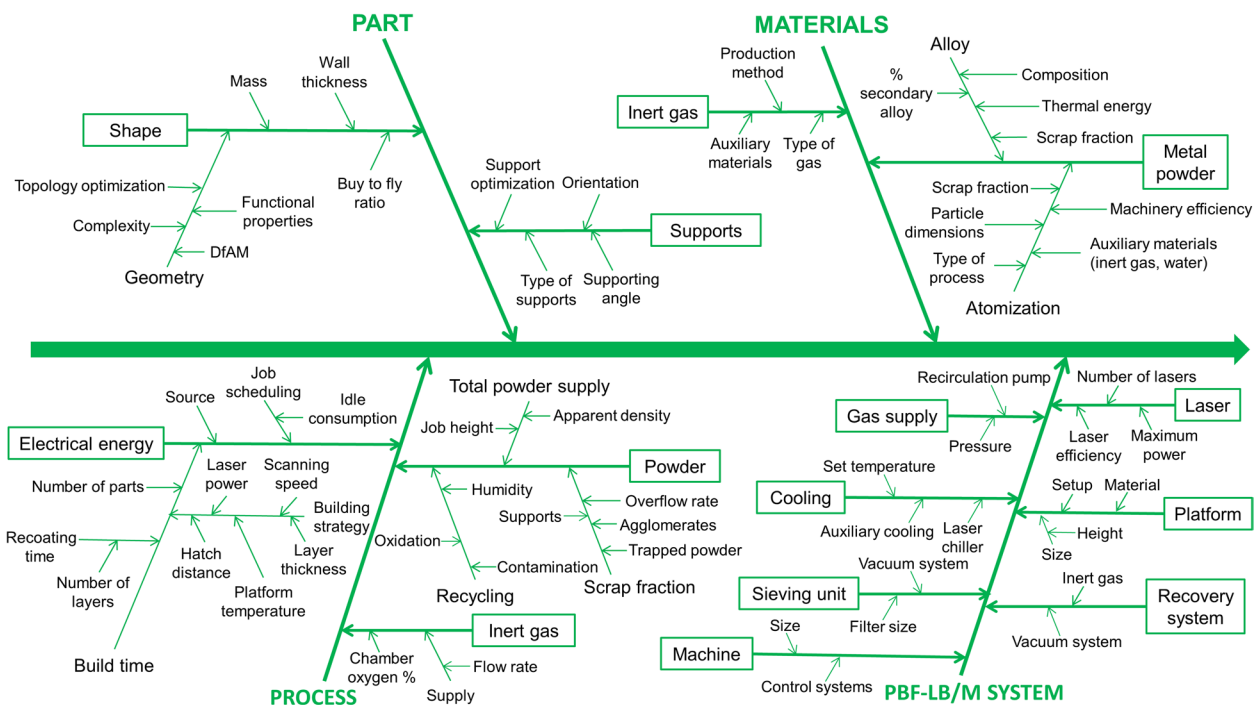


Fig. 12 Ishikawa diagram of all the factors contributing to the carbon footprint in PBF-LB/M

required for the process (approx. 18.8%) and the consumption of argon gas (approx. 18.4%).

● The gradual introduction of targeted measures for each resource is proposed and quantified in its expected benefit. In particular, switching to renewable energy can reduce the carbon footprint of electricity consumption by up to 82%, reducing the overall impact from 43.3 kgCO₂eq to 7.8 kgCO₂eq. By increasing the proportion of secondary aluminium in metal powder production, carbon emissions can be reduced by around 50% from 117.8 kgCO₂eq to 58.5 kgCO₂eq, with the further limit of almost 100% secondary material being reached with a reduction of 88%. The use of nitrogen instead of argon as an inert gas in the L-PBF process can reduce the impact of the inert gas by 84%, from 43.4 kgCO₂eq to 6.7 kgCO₂eq. In addition, on-site nitrogen generation can further minimise the associated emissions to 1.9 kgCO₂eq.

● By combining process optimisations and lightweight construction through topology optimisation, a further reduction in the carbon footprint is achieved, leading to an asymptotic limit of 3.4 kgCO₂eq per kg of product.

Through LCA methodology and the GHG Protocol, this research identifies key areas for improvement and proposes solutions across Scopes 1, 2, and 3. These include transitioning to renewable energy, utilizing lower-impact gases like nitrogen, increasing recycled material use, on-site nitrogen generation, and component redesign. Further optimization strategies target enhanced process efficiency, waste reduction, energy optimization via improved job scheduling and laser parameters, and promoting a sustainable supply chain. This work provides a roadmap towards sustainable PBF-LB/M, aligning industrial needs with environmentally responsible manufacturing.

Authors' contributions

All authors contributed to the study conception and design, material preparation, data collection and analysis. The first draft of the manuscript was written by Giulia Colombini and Elena Bassoli and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data availability

The datasets used or analysed in this study are available from the corresponding author on reasonable request.

Declarations

Competing interests

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

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