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Reviewed Paper

Evaluation of the Ecological Footprint for Parts from AlSi10Mg manufactured by Laser Powder Bed Fusion

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Abstract

The manufacturing industry contributes immensely to the global emissions and therefore is a key factor that has to be addressed when a more sustainable production is desired. Laser Powder Bed Fusion (LPBF) is an AM technique that offers the possibility to manufacture metal parts in a more material efficient way due to the layer-by-layer build-up. Nevertheless, the processing chain for parts from LPBF contains additional steps like powder atomization, which also influence the ecological footprint of the production chain. Within this work, a life-cycle model for the production step of parts from AlSi10Mg powder material is developed. The model is supplied with data from the powder atomization up to the production step, either by literature, database or experimental measurements during production. The footprint in terms of CO_2 emissions is then analyzed and emission-intense steps are identified. Two manufacturing scenarios are considered to evaluate the sensitivity on the emissions.

Introduction

One of the major challenges of recent times is dealing with the man-made climate change. The main driver of climate change is based on CO_2 (carbon dioxide) emissions [1]. As part of the "Agenda2030," the United Nations (UN) has defined 17 goals for sustainable development, one of which includes sustainable manufacturing of products [2]. In Germany, for example, industry is responsible for approximately 30% of the country's total energy consumption and associated emissions [3]. Despite efforts by the German government to reduce emissions, the level for the industrial sector has remained almost constant since 2009 until today [4]. This puts the German government's stated goal of becoming largely climate-neutral by 2050 at great risk [5]. Therefore, there is a need for action, among others in the industrial sector, to counteract this trend and to support the achievement of the climate targets in a sustainable manner.

Lightweight design and manufacturing of components can contribute to the conservation of resources, raw materials and energy. The weight- and performance-optimized design of components can reduce climate-damaging emissions both during production and during the use of the components. In addition to the ecological benefits, lightweight design also offers economic potential [6]. Additive manufacturing (AM) processes in particular offer the possibility to produce geometrically optimized lightweight structures. Function-integrating and topologically optimized high-performance metal components are primarily manufactured using the Laser Powder Bed Fusion (LPBF) process. In this manufacturing process, powdered raw material is melted locally by means of a laser beam, thus producing a solid body. Unmelted powder material can be reused after the process through reconditioning procedures. The industry has recognized the great potential of this process and is already applying the manufacturing technology in a wide field of sectors such as aerospace and automotive. At the current time, though, a lot of work is going into the further development of the additive manufacturing technology to increase productivity as well as to expand the materials that can be processed in LPBF [7].

Under the current challenge of climate protection, the manufacturing industry plays an important role . A holistic view of the emissions of process chains from the raw material to the end of the life cycle (end-of-life) is therefore necessary in terms of sustainability. However, the LPBF method has so far mostly only been quantified in terms of economic benefits [8]. The consideration of sustainability or ecology with regard to energy and resource saving potentials, on the other hand, has so far only been of secondary relevance. Life cycle assessments (LCA) of process chains can help to generate a deeper understanding of the influence of the sustainability of LPBF-manufactured components through holistic balancing. However, since existing solutions for life cycle analysis only partially consider the LPBF process chain (usually only on the basis of the manufacturing process), there is a need for action to fill this knowledge gap. Furthermore, the methodology of LCA is usually limited to products and has not yet been used as standard in manufacturing [9].

Most available publications on LCA of LPBF focus mainly on the manufacturing stage of the respective components. It was consistently found that the electrical energy consumed is the largest factor with regards to sustainability in this phase. As an example, Huang et al. [10] analyze the influence of the different materials on energy consumption. Due to the lower melting point of aluminum, 73 - 94 MJ/kg are consumed to produce a component. In comparison, 110 - 141 MJ/kg of electrical energy must be expended for a titanium alloy. The publications also show that the figures for electricity consumption are highly dependent on the used system. On another LPBF system (Concept Laser M3 Linear), it can be seen that the consumptions are not only higher, but exceed them by a factor of five (aluminum: 374 - 520 MJ/kg and titanium: 561 - 780 MJ/kg).

Neither found publication considers the maintenance and cleaning of the equipment used. Furthermore, the utilization phase of the components is hardly considered either, since they are mostly individual parts that only form a holistic product after assembly. Böcking and Tillman [11] take an in-depth look at utilization and found that AM brings potential benefits for the environment and resources, but also disadvantages that need to be circumvented. In the application example of a Volvo diesel engine, the reduced impacts in the use phase more than offset the increased impacts in production. This is due to lightweight-optimized components, which reduces fuel consumption and thus lifecycle impacts. Similar effects are observed for all products with high and weight-dependent energy consumption in the use phase. According to the authors, the results are comparable with similar assessments in the literature.

Since investigations along the rather complex LPBF process chain are scarce, the present work will first establish the product life cycle of a component manufactured using the LPBF technology. Based on databases, publications and experimental measurements, the LCA will then be established to holistically consider and analyze the environmental impacts and thus identify the ecological footprint of this AM technique.

Introduction to Life-Cycle Assessment

Life Cycle Assessment is a method used to assess the potential environmental impact of the production and use of products. LCA thus considers the entire life cycle of the product, from raw material extraction to disposal. Due to increasing awareness for environmental sustainability, this method has been developed and is gaining more and more importance [12]. Life cycle assessment can help to find ways to improve the environmental characteristics of the product and thus create information for decision making. Aditionally, life cycle assessment also serves marketing through the implementation of environmental labels [13].

When analyzing a product life cycle, a distinction is made between mainly three different approaches with varying extents [13]:

- *Cradle-to-grave* analysis includes the complete life cycle assessment from resource extraction to final disposal
- *Cradle-to-gate* is an assessment of a specific product life cycle, which is defined from resource extraction to product manufacturing
- *Gate-to-gate*, which is a partial LCA that considers only one value-adding process in the entire production chain.

In general, the LCA analysis can be divided into four phases, which are closely connected with each other. Figure 1 shows these phases and interrelationships. These are explained in more detail below.

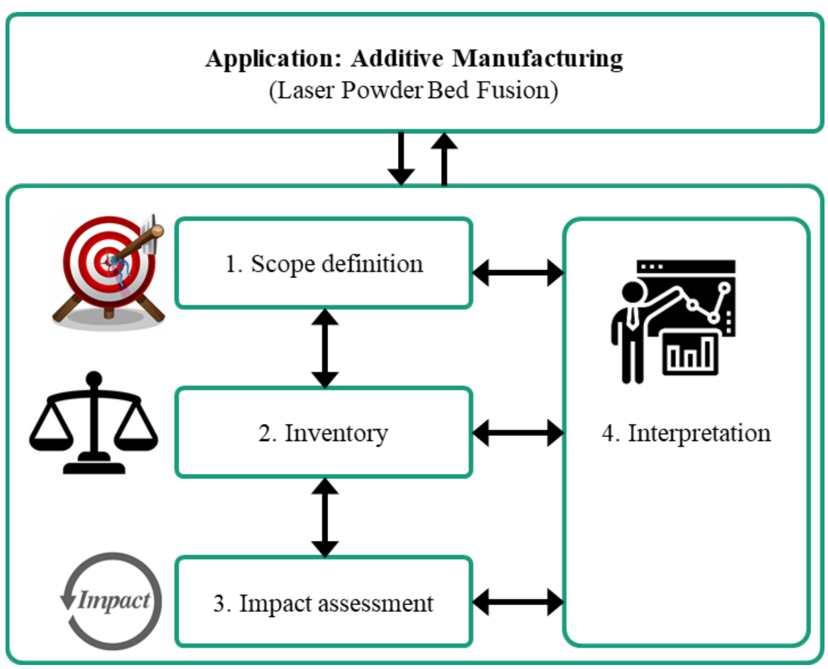

Figure 1: The four phases of Life Cycle Assessment

Phase 1: Definition of the objective and the scope of the investigation

In the first phase, the system boundaries and the functional unit are defined. The latter is hereby defined as the " *quantified performance of a product system for use as a reference unit*" and determines what good is being investigated [13]. The subsequent analyses then relate to this functional unit. If individual process steps or even life cycle stages of the product are not included in the scope of the assessment, this must be justified in this stage as well [13]. In addition, the necessity of the study is justified in this phase [14]. Likewise, the various system boundaries, which can be divided into technical, geographical and temporal boundaries, must be specified in this step. Depending on the data availability, possible cut-off criteria and simplification must then be applied [15].

Phase 2: Life cycle inventory (LCI)

In the life cycle inventory, the inputs and outputs of the system under investigation are determined. This results in a collection of the data necessary to achieve the objective of the investigation. If necessary, these data must be standardized to the previously defined functional unit by calculation procedures [13].

The input variables (raw materials, auxiliary materials, etc.) are often related to the output variables (pollutants, waste, etc.). The outputs can be further differentiated into "desired" and "undesired". “Desired” outputs are mostly semi-finished products, components or entire products, while “undesired” outputs are almost unavoidable like emissions and waste [16].

The data that is entered into a LCI can be divided into two different data types: generic data and primary data. Generic data is composed of available data sets from material and process databases, which are integrated in a computer-based tool. Primary data are collected experimentally for process steps. It is important at this point that the data sets are sufficiently documented and thus comprehensible to third parties [15]. Based on the collected data of the different processes, a product system can subsequently be created. Ideally, this is modeled in such a way that the inputs and outputs at the boundaries are elementary flows. Elementary flows are the substances or energies that are added to or leave the defined system. Due to the complex products and the resulting strong interconnectedness of the systems, this is rarely possible [13]. In order to present such a product system in a more manageable way, these are usually structured according to technical subsystems, which represent successive process modules.

Phase 3: Impact assessment

In the third phase, the Life Cycle Impact Assessment (LCIA), the previously generated data is examined and evaluated with regards to environmental impacts. After the selection of impact categories and impact indicators (quantifiable representation of an impact category), the most important elements of this phase include classification and characterization [13]. In the classification, resource consumption and emissions are divided into categories according to their effects on the environment, such as greenhouse effect, human toxicity or eutrophication. It is also possible that an emission has several effects in different impact categories. The characterization takes place within an impact category. Here, the emissions and consumptions are weighted with a so-called equivalence factor, which are related to a reference substance in order to make them comparable [14].

Phase 4: Evaluation

Evaluation is the final phase in which the previously obtained results are summarized in accordance with the objective as a basis for conclusions or recommendations. One of the main objectives is always to identify main influencing factors [17].

Goal and Scope Definition

The aim of this work is to analyze the influences of the input and output variables generated by components made of AlSi10Mg, manufactured by the LPBF process. The effects of the different product life cycle stages from raw material extraction to manufacturing (cradle-to-gate) are considered. Within the life cycle phases and stages described, intermediate steps such as raw material and powder production, transportation and others are considered in addition to the technical factors associated with each operation. Data is collected in a number of ways. Data is either collected experimentally the process modules or, if this is not possible, supplemented with extensive literature research and databases in the software used (OpenLCA). The determined mass values along the entire process chain are measured with a scale (measuring accuracy 0.1 kg). The meter used to record the power consumption is a Fluke 435 series II, which is connected between the equipment and the power supply.

The investigated component is an impeller. The diameter of the component is 100 mm with a height of 35 mm, a component volume of 44.3 mm^3 and a weight of 119 g. The CAD data for the impeller is openly available at GRABCAD [18] and rescaled by a factor of 0.5.

For the definition of the functional units, two scenarios are considered in order to investigate influences of packing density during LPBF, which are represented in Figure *2.*:

1. the production with the LPBF process of one impeller per build job from AlSi10Mg, assuming that production takes place once per working day over 8 years.
2. the production with the LPBF process of four impellers per build job from AlSi10Mg, under the assumption that production takes place once per working day over 8 years.

In this work, the cradle-to-gate scope ranges throughout the individual steps that are further described in the following and depicted in Figure *3*. The beginning of this life cycle assessment is the extraction of the raw materials aluminum, silicon, magnesium, etc. and their transportation. Based on this, the production of the AlSi10Mg alloy is considered. Since the LPBF process requires the material to be in powder form, it is essential to also consider the powder production process by means of gas atomization. In the LPBF process, the defined component is manufactured from the powder material and data is recorded. In the present work, , the manufacturing of the LPBF system itself and its cleaning after processing are also considered. After the LBPF process, the powder that has not been melted is cleaned of process-induced by-products, such as spatter, using a sieving system and returned to the process chain. The build job is then heat treated to increase strength and reduce residual stresses. To complete the manufacturing step, the components are separated from the build platform using a milling machine. The subsequent use phase and disposal of the components are not accounted for. This results in the examination frame (red) in Figure 3.

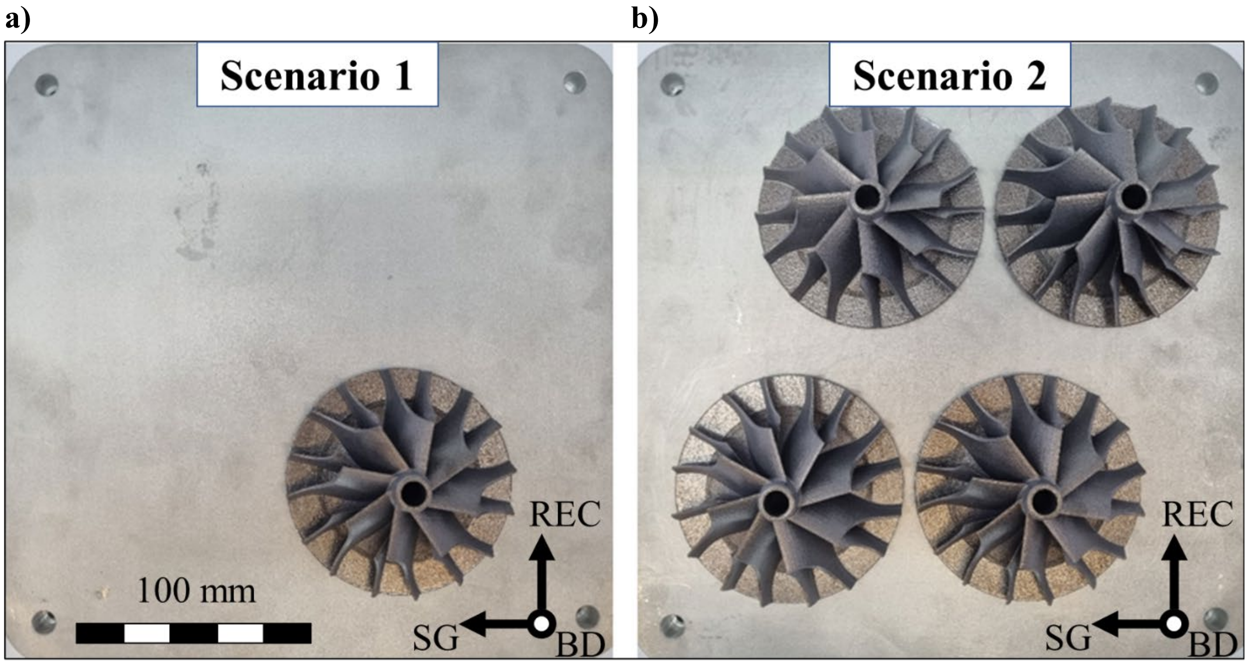

Figure 2. Illustration of investigated scenarios for experimental data generation; a) single build; b) maximum build (SG = shielding gas, REC = recoating direction, BD = build direction)

The process steps mentioned are often connected with upstream chains. This means that the auxiliary materials and energy flows used are also considered in the balancing. Thus, the two life cycle assessments present all relevant material and energy flows out of and into the environment, with reference to the defined functional unit.

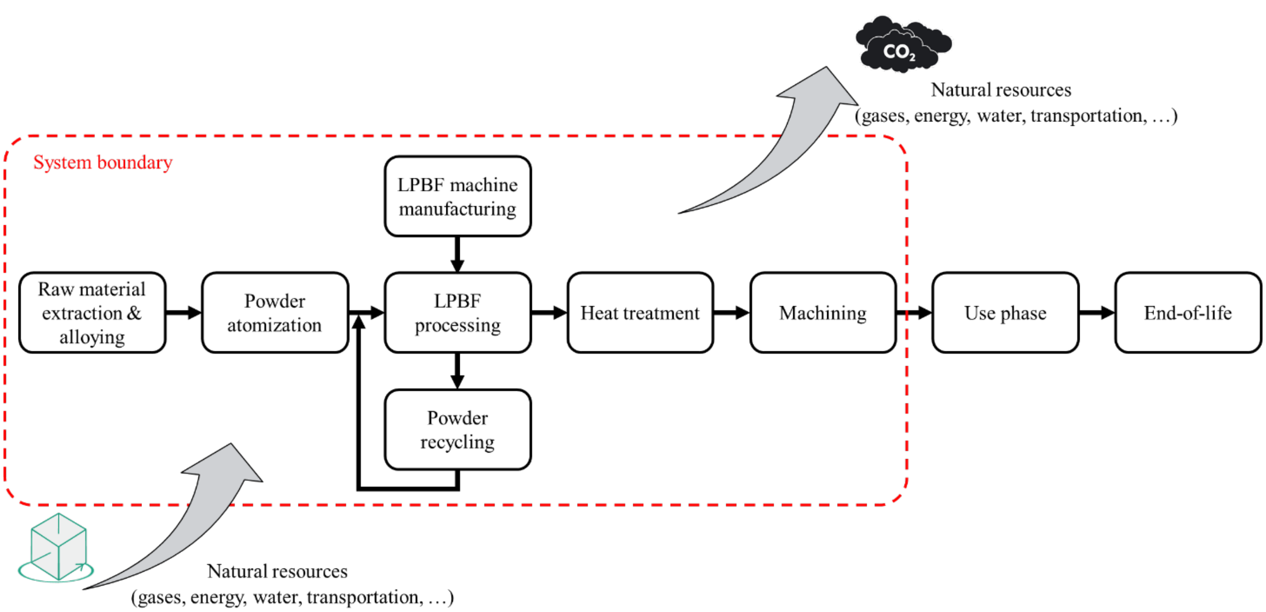

Figure 3. System boundary of the LCA study along the typical LPBF process chain

Assumptions for the investigations:

Due to the large number of processes and associated raw materials, semi-finished products, etc. on the one hand, and limited time and human resources on the other, it is unavoidable to make assumptions and constraints for the product system. Without assumptions, many process steps would be omitted and thus it would not be possible to estimate whether the resulting pollutant emissions are relevant [12]. In general, it must also be mentioned that the data sets used from the ecoinvent database are also based on case-specific framework conditions. A detailed explanation of the assumptions is given during the preparation of the life cycle inventory in the respective process step in the LCI.

Life Cycle Inventory (LCI) for LPBF Process Chain

Raw Material Extraction & Alloying:

The individual weight-percentage [wt.-%] for composition of the alloy must first be extracted, processed and melted to produce the AlSi10Mg raw material. For this process, no information can be found in the literature regarding the electrical energy consumed. In the ecoinvent database used, there is only one product system for the production of AlMg3 alloy. Therefore, a simplification is made at this point. The AlMg3 data set is modified to the raw materials of the AlSi10Mg alloy.

From the used database, a value of 13.86 kWh per kilogram for the extraction of primary aluminum (Al) can be found. For the same quantity of silicon (Si) and magnesium (Mg), 11 kWh/kg and 1.52 kWh/kg are used, respectively. Under consideration of the wt.-% for the investigated aluminum alloy, the total consumption for the AlSi10Mg alloy is 13.52 kWh/kg. Comparatively, 5.2 kWh/kg are consumed for the production of steel [19] . After this process step, the AlSi10Mg alloy is available as a semi-finished product.

For scenario 1, 44 kg of the alloy are required to produce 13.2 kg of powder material with a particle size of 20 – 63 µm. This results in an electricity consumption of 594.83 kWh and is accounted for with the Chinese electricity mix. In the second scenario, not one but four impellers are manufactured additively in one build job. This results in different inputs and outputs in the life cycle inventory. The raw material extraction and alloy production entails an electrical energy consumption of 599.29 kWh to produce the required quantity of 44.33 kg AlSi10Mg raw material. Equivalently, the inputs of the individual raw materials also increase.

Powder Atomization:

For powder production by gas atomization, in addition to the raw material, the electrical energy and nitrogen consumption must be declared as inputs. Since atomization is carried out externally, and manufacturers do not publish precise details, available literature studies are used to collect data. Aluminum alloys mostly are atomized via gas atomization due to the high reactivity of the alloy in powder state [20].

Faludi et al. [21] consider the production of an aluminum alloy using gas atomization. Here, the electrical energy requirement is put at 8.1 MJ/kg (2.25 kWh/kg). For this and the following process steps, the European electricity mix is used. Nitrogen is used as atomization medium in this specific application. According to [22], a liquid metal flow of 20 kg/min consumes approx. 8 m³ of gas per minute. From this, a gas volume of 0.4 m³ per kg can be derived.

Since it is not possible to gain complete control over the particle size of the atomized powder, the distribution can be influenced by varying the ratio of gas to melt flow rate. Research in the field of gas atomization shows that finer particle size distributions can be achieved by using hot gas atomization [20]. The required particle size of 20 - 63 µm accounts for only about 30 % of the total particle size distribution [23] (Figure *4* b). The remaining 70 % are used for other processes such as isostatic pressing. Thus, for one kilogram of AlSi10Mg powder in the required particle size, more than three kilograms of raw material have to be atomized. The nitrogen gas, which is relevant for the atomization process, is purchased from a nearby company located in Austria. For this purpose, an assumption of 100 km is accounted for in the process, which is covered by a truck. The AlSi10Mg powder produced at the end of the process is transported by truck over a distance of approx. 970 km to the production site in Aachen, Germany.

The raw material, which is atomized with 22.16 kg nitrogen, requires 99.75 kWh for the production of 13.3 kg AlSi10Mg powder, with a particle size of 20 - 63 µm. The remaining 70% of the powder (> 63 µm) will not be considered further in this scope of investigation, as it can be used for other manufacturing processes.

a)

Chemical composition [wt.-%]				
Al	Si	Mg	Fe	Zn
Balance	9,6	0,34	0,11	0,02
Mn	Ni	Cu	Pb	Sn
>0,01	>0,01	>0,01	>0,01	>0,01

Properties	
Particle size	20-63 µm
Atomization medium	Nitrogen

b)

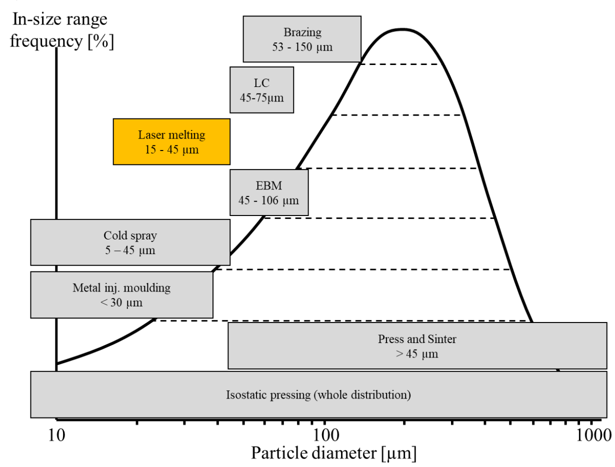

Figure 4. a) Chemical composition and properties of AlSi10Mg powder for this study; b) typical yield of gas powder atomization and LPBF range (marked yellow), adapted from [24]

LPBF machine & LPBF manufacturing:

It is not usually possible to account for the manufacturing of a complex machine, such as an LPBF system in this case. One reason for this is that the exact manufacturing steps and materials used represent internal company information that is protected accordingly. One option would be to disassemble the available plant itself and thus estimate the production steps with the materials.

However, the effort and the risk of not reassembling the system in a functional way are high. However, since manufacturing of the system should not be neglected in the consideration of the entire process chain, literature and data thanks to Faludi et al. [21] is used. As the Renishaw AM250 (investigated by Faludi et al. [21]) and the SLM Solutions 280HL (used in this work) have a similar overall size and weight, the data from the Renishaw in openLCA is transferred to the present work. At this point, therefore, a simplification of the analysis takes place, since the assumption is made that the two machines have an identical design. Only the laser components were considered twice in the balancing.

Since the LPBF manufacturing process is a complex one, a large number of inputs and outputs have to be considered. In addition to the equipment and CAD component already mentioned, other inputs must be considered. The aluminum building platform has a weight of 8.3 kg. Before starting the build job, the build area must be flooded with the inert gas (argon). Approximately 3.52 kg or 1700 liters are required for this [25]. A standard parameter from the machine manufacturer is used for manufacturing. During manufacturing, the overpressure in the build chamber of 30 mbar is slightly readjusted by the machine itself, since the system is not 100% sealed. Based on previous scientific work, this is calculated to be 1.357 g/min.

An overview for the needed durations and measured power consumptions for both investigated scenarios is given in Table *1*. A more detailed overview of the inputs and outputs of the LPBF production step is shown in Table 2. The 51.16 kWh of consumed electrical energy can be divided. During the preparation time of 1 h 23 min, the build platform is aligned and preheated to T_{Pre}=200 °C. In addition, the build area is flooded with argon during this time. This results in a consumption of 3.78 kWh. The build process takes 4 h 34 min from the first to the last exposure, requiring 16.41 kWh (exposure time 2 h 9 min, coating time 2 h 24 min from machine log files). The argon consumption amounts to 3.52 kg. In the subsequent post-processing time of one hour, the build platform cools down and the powder that has not melted is removed. During the downtime, the system is not disconnected from the power supply, consuming 1.74 kWh per hour. The high downtime results from the assumption that only one build job is produced per day. This time results in a power consumption of 29.24 kWh. The output of the build job, consisting of the component and the construction platform, is 8.5 kg. The unused powder, which is present in the overflow container at the end of the process (12.7 kg), is carried on for reprocessing. The argon evaporates as soon as the build chamber is opened.

For scenario 2, many inputs of the LPBF process remain unchanged, such as the required equipment and transport routes. Of great interest in this case is the amount of electrical energy consumed, which is measured at 59.35 kWh. In the preparation time of 1 h 41 min, which serves for the alignment and preheating of the construction platform as well as the flooding of the build chamber with argon, there is a consumption of 5.076 kWh. The build process takes 6 h 43 min and requires 27.177 kWh (exposure time 4 h 16 min, coating time 2 h 23 min) to simultaneously produce four components with two lasers. The post-processing of the manufacturing process takes one hour. During the subsequent downtime of 14 h 36 min, the system is not taken off power, consuming 1.742 kWh per hour. The argon consumption amounts to 3.798 kg. In this scenario, as well as before, the used silicone lip in the recoater has to be disposed of at the end due to wear. On the output side, the weight of the build job (build platform + components) is 8.9 kg. The non-solidified powder residues have a weight of 12.4 kg. As in the first scenario, the argon evaporates as soon as the build chamber is opened.

	Scenario 1		Scenario 2	
	Duration	Power consumption	Duration	Power consumption
Preparation	01 h 23 min	03.78 kWh	01 h 41 min	05.07 kWh
LPBF processing	04 h 34 min	16.41 kWh	06 h 43 min	27.17 kWh
Post-processing	01 h 00 min	01.73 kWh	01 h 00 min	01.73 kWh
Idle	17 h 03 min	29.24 kWh	14 h 36 min	25.26 kWh
Total	24 h 00 min	51.16 kWh	24 h 00 min	59.26 kWh

Table 1. Time and power consumption overview for scenario 1 and scenario 2

Heat treatment:

The heat treatment is carried out according to the T6 process. In this process, the construction job is first heated to 525 °C for five hours, cooled in water and then aged at a temperature of 165 °C for seven hours. According to Scharf et al. [26], this step in the process chain requires 25.96 kWh of electrical energy. The cooling basin has a volume of 50 liters. The evaporation of the water during the interim quenching is accounted for with one kilogram per construction job. After treatment, the build job is taken to a nearby company for further processing.

LPBF manufacturing							
	Inputs			Outputs			
Description	Amount		Source	Description	Amount		Source
-	Scenario 1	Scenario 2	-	-	Scenario 1	Scenario 2	-
LPBF system	+1	+1	Faludi [21]	Build Job	-8.5 kg	-8.9 kg	Exp.
LPBF cooling system	+1	+1	Faludi [21]	Powder remains	-12.7 kg	-12.4 kg	Exp.
CAD part	+52.05 cm³	+208.21 cm³	Materialise Magics	Argon	-3.52 kg	-3.79 kg	Exp.
Aluminum substrate	+8.3 kg	+8.3 kg	Exp.	Silicone lip	-0.028 kg	-0.028 kg	Exp.
AlSi10Mg powder	+13.20 kg	+13.30 kg	Exp.				
Electrical power	+51.16 kWh	+59.26 kWh	Exp.				
Argon	+3.52 kg	+3.79 kg	Exp.				
Silicone lip	+0.028 kg	+0.028 kg	Exp.				

Table 2: Detailed overview of input and output data for the LPBF manufacturing steps in scenario 1 and scenario 2 (Exp. = Experimentally measured)

Machining

The balancing of the post-processing is carried out exclusively with the database and without the electrical discharge machining (EDM) procedure. The amounts of electrical energy (0.336 kWh) and the coolant are deposited depending on the material waste. The material waste here refers to the weight of the support structure to be removed of 63.31 g (scenario 1). After a build job is defined as an input, this results in two outputs, firstly the component without the support structure and secondly the construction platform, which can then be reused.

Reworking and separating the impellers in scenario 2 from the build platform requires 1.22 kWh of electrical energy, as well as some coolant. Wear of indexable inserts is not considered, as the AlSi10Mg alloy has quite soft material properties. Outputs are defined as the four components (0.476 kg) and the build platform. The material waste is composed of the removed support structures and the face milling of the build platform.

Impact Assessment and Interpretation

To perform an impact assessment (LCIA) with openLCA, the impact assessment method must be selected at the beginning. In this case, the CML baseline method is used. The basis of the calculation is the classification and the characterization of resource consumptions and emissions. With the help of the method, different impact categories can be selected. In the following analysis, the impact of the product life cycle on the "Global Warming Potential 100a" (greenhouse potential) is considered. Using the calculation model, the environmental impacts are expressed in kg CO_2.-eq. and assigned to the respective material and energy flows. The index expresses the warming effect of a specific quantity of a greenhouse gas over a defined period (100 years) compared to that of CO_2.

Table 3 shows both the percentage distribution over the entire process chain and the quantity data for the individual process steps of both scenarios. In order to obtain a more accurate representation of the respective shares within a process step, the energy or material flows with the largest environmental impacts are additionally listed in the subcategories.

The production and associated process steps of 1840 components produced from AlSi10Mg over 8 years using the LPBF process result in total CO_2-eq. emissions of 241,396 kg in scenario 1. This results in a value of 131.19 kg CO_2-eq per component. At almost 50%, raw material extraction and alloy production entail the largest carbon dioxide emissions. In particular, the energy required to extract primary aluminum predominates with 71,591 kg CO_2-eq. The other alloying elements also have a much smaller effect due to their low mass fraction. After the individual raw materials of the alloy are available, electrical energy is again required to produce the alloy. This step causes emissions of 7,404 kg CO_2-eq. The subsequent powder production by atomization accounts for 5.14% of the total emissions; here, the electrical energy required clearly predominates. The contribution of the LPBF process is 86,023 kg CO_2-eq. Consumables, such as the build platform or silicone lips as well as transport to the post processing (heat treatment etc.) can be neglected. The consumed shielding gas, in this case argon, causes emissions of 9,401 kg CO_2-eq. The value is exceeded by the electrical energy required, which makes a total contribution of 74,299 kg CO_2-eq. (30.78%). The subsequent powder preparation and cleaning of the LPBF system have a small contribution of 1.55% and 0.3% respectively. For the heat treatment of the build jobs, too, the electricity demand represents almost the entire contribution of 8,625 kg CO_2-eq. Milling, which separates the component from the build platform, does not have a significant impact on the overall balance (0.69 %).

The production of four instead of one component per construction job results in correspondingly higher pollutant emissions (scenario 2). A total of 304,309 kg CO_2-eq. is emitted into the environment for the 7360 components. This results in a value of 41.35 kg CO_2-eq. per component. At 53.79% (163,676 kg CO_2-eq.), raw material extraction and alloy production account for the largest share of the environmental impact in the overall product life cycle. A further breakdown of the process step reveals that the electrical energy used to extract the aluminum in particular predominates at 32.29%. Added to this is a further 8.76% due to the aluminum oxide obtained. The extraction of other alloying elements, as well as the transport of the materials, have a significantly lower influence (< 2.7 %) on the balance. In the powder atomization step, 5.59% of the total amount of CO_2-eq. is emitted, which corresponds to 17,026 kg. Also in this process step, the consumed electrical energy dominates with 4.85 %. The influences of the LPBF system and cooling unit remain unchanged in terms of quantity. The LPBF process causes an emission of 94,874 kg CO_2-eq. Also in this case, the electricity demand is the main factor. The resulting environmental impact due to argon consumption amounts to 10,144 kg CO_2-eq. Both the powder reconditioning (1.23%), in which the excess powder is sieved, and the cleaning (0.25%) of the LPBF system have only a minor share. The post-processing of the components by means of heat treatment and milling have a share of 2.83 % and 2.18 %, respectively. These process steps are also dominated by the associated power consumption.

The following analysis is done for scenario 1, but observations are in accordance with scenario 2. The impact assessment shows that two process steps along the product life cycle dominate the balance for the processing route. On the one hand, the production of raw materials has the greatest negative environmental impact with almost 50 %, corresponding to 119,257 kg CO_2-eq. In particular, primary aluminum extraction with its associated electricity consumption has a major impact on the life cycle assessment (29.66%). The main reason for the high electricity consumption is electrolysis. At this point, the first lever for a more sustainable process can already be identified. According to Ostermann [27], if secondary aluminum is used instead of primary aluminum, up to 95% of the energy can be saved in the production phase. Since only aluminum that has already been produced is remelted for secondary aluminum, the electrolysis process is not required. For this, additional monitoring of the material properties must take place at this point to ensure high component reliability. In addition, the production of the secondary material does not take place exclusively in countries such as China or similar. By using recycled aluminum, the transport routes can be eliminated and resources can be conserved.

The second point of the analysis takes a closer look at the LPBF process itself. The emission of 86,023 kg CO_2-eq. corresponds to 35.63% of the total emission. As in the case of raw material production, the electrical energy consumed predominates, accounting for 30.78 % of the carbon dioxide equivalent emission. This statement is consistent with the results known from publications (Faludi et al. [21]).

	Scenario 1		Scenario 2	
Process step	**Share [%]**	**Mass [kg CO_2-eq.]**	**Share [%]**	**Mass [kg CO_2-eq.]**
Raw material extraction & Alloying	49.40 %	119.257,00	53.79 %	163.676,00
Aluminum production	└ 42.84 %	103.422,00	└ 46.64 %	141.944,00
Electr. energy	└ 29.66 %	71.591,50	└ 32.29 %	98.257,40
Aluminum oxide	└ 08.05 %	19.425,60	└ 08.76 %	26.661,10
Silicon production	└ 02.47 %	5.970,56	└ 02.69 %	8.194,44
Magnesium production	└ 00.21 %	511,66	└ 00.23 %	702,23
Electr. energy	└ 03.07 %	7.404,70	└ 03.34 %	10.162,80
Transportation	└ 00.79 %	1.909,25	└ 00.87 %	2.620,40
Powder production	05.14 %	12.414,72	05.59 %	17.026,07
Electr. energy	└ 04.46 %	10.755,50	└ 04.85 %	14.761,60
Transportation	└ 00.44 %	1.072,36	└ 00.48 %	1.471,79
Nitrogen consumption	└ 00.24 %	578,00	└ 00.26 %	793,28
LPBF system	03.27 %	7.896,25	02.59 %	7.896,25
LPBF cooling	00.45 %	1.086,56	00.36 %	1.086,56
LPBF process	35.63 %	86.023,52	31.18 %	94.874,81
Electr. energy	└ 30.78 %	74.299,50	└ 27.08 %	82.402,80
Argon	└ 03.89 %	9.401,73	└ 03.33 %	10.144,20
Substrate plate	└ 00.86 %	2.064,58	└ 00.68 %	2.064,58
Silicon recoater	└ 00.06 %	152,42	└ 00.05 %	152,42
Transportation	└ 00.05 %	105,26	└ 00.03 %	110,69
Powder reconditioning	01.55 %	3.730,54	01,23 %	3.730,54
Electr. energy	└ 01.49 %	3.594,12	└ 01,18 %	3.594,12
Rubber gloves	└ 00.06 %	136,43	└ 00,04 %	136,43
Cleaning	00.30 %	715,14	00.25 %	768,85
Heat treatment	03.57 %	8.625,26	02.83 %	8.625,26
Electr. energy	└ 03.57 %	8.624,60	└ 02.83 %	8.624,60
Water	└ 00.00 %	0,64	└ 00.00 %	0,63
Milling	00.69 %	1.656,11	02.18 %	6.623,86
Total	**100.00%**	**241.396,00**	**100.00%**	**304.309,00**
Mass per part		**131.19**		**41.35**
Mass per kg molten powder material		**940.45**		**296.39**

Table 3: Overview of total impact assessment for scenario 1 and scenario 2 per process step

Since it can be recognized from the evaluation that electricity consumption over the entire process chain accounts for the largest share of the environmental impact, this will be examined in more detail. Figure *5* shows the consumption of electrical energy over the entire process chain of the functional unit. 57% of the electricity requirement is incurred for the LPBF process. It should be noted that this percentage is made up of three process steps. The preparation time (flooding the build chamber and heating the build platform to 200 °C) accounts for only 3 % of the total consumption. The manufacturing of the impeller component consumes 13% of the electrical energy and is therefore not the main part of the process chain. The LPBF system and the associated cooling unit consume 42% of the total electricity during the downtime. The downtime is the period between the end of the build job and the start of preparation for the next build job. The process steps whose influence is less than one percent are not shown in the diagram. The total consumption of electrical energy amounts to 238,696 kWh for the defined functional unit.

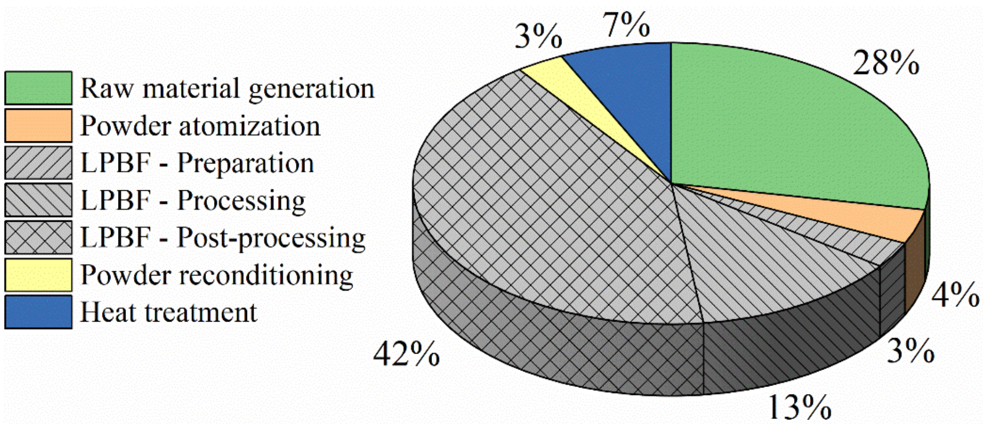

Figure 5. Electrical energy consumption per process step for scenario 1

At this point it can already be stated that the downtime of the SLM 280 HL should be kept as low as possible. There are two different approaches to this. Firstly, if the demand is there, an increase in capacity utilization can be considered. Instead of one build job per day, three can be produced per day. The second option is to shut down the plant after each build job and thus remove it from the power grid. This measure could save approx. 97,000 kWh over the 8 years.

To illustrate the differences and the associated environmental impacts of the two scenarios, they are compared with each other. The following Figure 6 illustrates this along the entire process chain.

Both raw material extraction and atomization show significant differences between the two scenarios, as more material must be available for four impellers per build job (scenario 2) than for one impeller per build job (scenario 1). Other process steps, such as manufacturing of the LPBF system or powder preparation, show no difference and result in the same amounts of CO_2-eq., regardless of the scenario. The CO_2 emissions of the LPBF process itself shows significantly smaller deviations between the scenarios than is the case for raw material production. One reason is that a basic consumption of energy is needed in the system regardless of the exposure of the powder. In addition, there is no difference in cooling, because with the help of the aggregate, the LPBF system is cooled at a certain interval, regardless of the build job. Individual steps in the preparation process, such as flooding the build area or preheating the build platform, are also independent of the component. The same applies to the recoating process. The only difference between the scenarios is that the exposure time is increased by 2 h 9 min. In the first scenario, the build job is produced with one laser, while in the second scenario, two lasers operate simultaneously to produce four components. This results in a difference of about 8,800 kg CO_2-eq. The subsequent post-processing of the components by heat treatment remains the same in terms of emissions. In the case of post-processing using a milling machine, the results correspond to the expected differences due to the number of components to be processed.

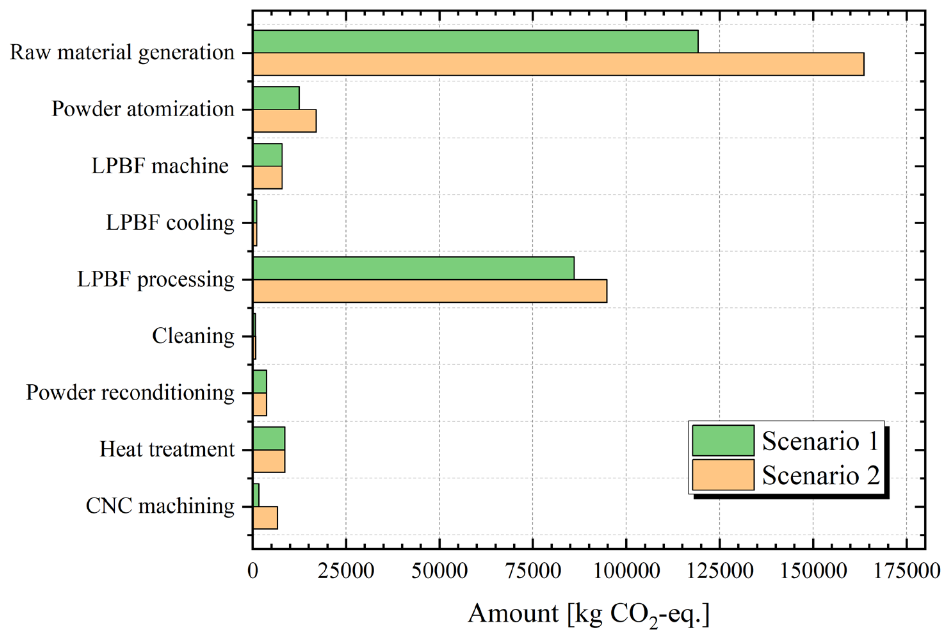

Figure 6: Comparison of CO_2-eq. emissions per processing step for scenario 1 and scenario 2

In the following step, the two scenarios were optimized with regards to the identified levers. In this case, optimization can be understood as an improvement of existing processes [28]. Secondary aluminum was used instead of primary aluminum and the LPBF system was switched off after each build job. The results of these process chain alterations are shown in Table 4. The first control lever reduced CO_2-eq. emissions during aluminum extraction by 94.7%. This corresponds to approximately 99,000 kg CO_2-eq. in the first scenario and approximately 135,000 kg CO_2-eq. in the second scenario. The second lever showed that regardless of the scenario, about 90,000 kWh, which correspond to about 50,000 kg CO_2-eq., could be saved by taking the production system offline. In the overall consideration of the respective scenarios, the levers showed a positive effect in favor of the environmental impact. Total CO_2-eq. emissions were reduced from 241,396 kg to 89,947.2 kg in the first scenario. This corresponds to a percentage saving of 63%. The second scenario resulted in a saving of 184,388 kg, or 60.3%. Thus, if the utilization of the build job is maximized, secondary aluminum is used instead of primary aluminum, and the LPBF system is shut down during downtime, this results in an optimized product life cycle for components made of AlSi10Mg, which are manufactured using the LPBF process. This was proven by the amount of CO_2-eq. per component. Instead of the 131.19 kg CO_2-eq. per component in the first, non-optimized scenario, the emission in the optimized scenario 2 is only 16.29 kg CO_2-eq. per component. This results in a total saving of 87.6% in environmentally emissions.

	Scenario 1		Scenario 2	
		Optimized		Optimized
Process step	**Share [%]**	**Mass [kg CO_2-eq.]**	**Share [%]**	**Mass [kg CO_2-eq.]**
Raw material extraction & Alloying	119.257,00	20.283,10	163.676,00	37.149,36
Aluminum production	103.422,00	4.449,10	141.944,00	6.106,36
Powder production	12.414,72	12.414,72	17.026,07	22.826,08
LPBF system	7.896,25	7.896,25	7.896,25	7.896,25
LPBF cooling	1.086,56	1.086,56	1.086,56	1.086,56
LPBF process	86.023,52	33.547,62	94.874,81	46.324,41
Electr. energy	74.299,50	21.823,60	82.402,80	33.852,40
Powder reconditioning	3.730,54	3.730,54	3.730,54	3.730,60
Cleaning	715,14	715,14	768,85	768,85
Heat treatment	8.625,26	8.625,26	8.625,26	8.625,26
Milling	1.656,11	1.656,11	6.623,86	6.623,86
Total	**241.396,00**	**89.947,20**	**304.309,00**	**119.920,96**
Mass per part	**131,19**	**48,88**	**41,35**	**16,29**
Mass per kg molten powder material	**940,45**	**350,42**	**296,39**	**116,80**

Table 4: Overview of total impact assessment for scenario 1 and scenario 2 per process step in the optimized state

Critical Remarks

The openLCA study, which was carried out within the framework of this work using the LPBF method, multiple simplifications had to be made. To generate such an extensive process chain with only self-measured data is not possible in this framework for many reasons. In order to be able to represent the product life cycle nevertheless, data from various publications or databases was used.

Since there is no usable data on the production of the AlSi10Mg alloy, another data set of an aluminum alloy was modified to the corresponding alloying elements and the assumption was made that the electrical energy required as well as the emissions are the same regardless of the respective alloy. In addition, it is assumed that the raw material is sourced in China and the material is transported to Germany for use. It is not possible to say exactly from which regions of China the individual parts are procured. The information on the transport distances is therefore subject to fluctuations and can lead to deviations in the transport energy given.

The powder production process was presented with sources from various publications, which also refer to different materials. Furthermore, only the primary inputs and outputs could be determined. Emissions resulting from chemical reactions during the atomization process could not be accounted for. The powder with a particle size >63 µm was not considered as waste, as it can be used for other processes.

Other assumptions that had to be made relate to the equipment used. The LPBF system was accounted for according to Faludi et al. [21]. Although a Renishaw AM250 was analyzed in their work, the assumption was made based on similar weight and size information that the composition is identical. For the cooling unit and vacuum cleaner, the existing data sets were multiplied by an appropriate factor to arrive at the existing weight of the actual machines used. The electrical energy required to assemble the individual components was not accounted for. This also applies to the disposal of the equipment.

Due to the material properties of aluminum according to the LPBF method, it was also necessary to consider heat treatment. However, the electrical energy balanced for this relates to a different component with undefined mass values. The evaporated water during quenching, could neither be determined experimentally nor mathematically, so an assumption had to be made. However, this assumption does not show any relevant effects in the impact estimation.

The milling considered in the following is rarely used in reality for finishing and cutting the components. In most cases, the components are reworked using the EDM process or, if necessary, separated from the building platform using a band saw. However, no input and output values could be found in the literature for the EDM process.

The previously mentioned assumptions can influence the result and lead to inaccuracies. However, it can be assumed that these inaccuracies are not so large that a completely different result is produced. The analysis has shown that the greatest environmental impact is caused by aluminum extraction (42.8% and 46.6%) and the LPBF process (35.6% and 31.2%). The electrical energy required for the LPBF process was determined using a measuring device (Fluke 435 series II) and therefore represents a reliable value.

In general, it can be stated that the LCA results provide guide values that can be used to identify the ecological weaknesses of the LPBF process. The more precisely all product life cycle phases such as manufacturing processes, transport routes, etc. are quantified, the more reliable the LCA result.

Conclusion and Outlook

Based on this finding, the objective of the present work was first to present the entire product life cycle for LPBF components made of AlSi10Mg from raw material extraction to production. Raw material extraction and alloy production mostly take place in China. Aluminum extraction in particular has proven to be environmentally critical. One kilogram of aluminum oxide consumes 13.56 kWh of electrical energy. Silicon extraction requires a similar amount of electricity. Subsequently, the individual raw materials are processed to the desired alloy, which results in an electricity consumption of 1.59 kWh/kg. Since the LPBF process requires the material to be in powder form, powder production by gas atomization was also considered. In this process, the alloy is melted and pulverized under high pressure. However, the LPBF process requires a certain particle size (20 - 63 µm), which accounts for only 30% of the total yield in atomization. Per kilogram of melt, 8.1 MJ of electrical energy and 0.4 m^3 of nitrogen are required. The LPBF system used was balanced using the publication by Faludi et al. [21]. The LPBF process itself is composed of various inputs. In addition to the powder, LPBF requires argon as a shielding gas, a recoater lip and electrical energy. The component can then be removed and the system be cleaned. The powder, which is not melted, is reconditioned and can then be reused. Since in this case the material is an aluminum alloy, it is necessary that the build job is subsequently heat treated. The T6 heat treatment entails a consumption of 25.96 kWh of energy. To complete the manufacturing process, the components are separated from the build platform using milling. This is followed by the individual utilization phase, followed by disposal.

The life cycle assessment carried out includes two different utilization models for the build layout. In addition to the general product life cycle analysis, the difference between the production of one and four impellers per working day on a building platform over a period of 8 years was examined. The life cycle inventory was prepared using values from experimental measurements, publications and databases. Only the utilization phase was not considered in this work.

The 1840 components manufactured in scenario 1 result in total CO_2-eq. emissions of 241,396 kg. This results in a value of 131.19 kg CO_2-eq. per component. For the 7360 components in scenario 2, a total of 304,309 kg CO_2-eq. is emitted into the environment, resulting in a value of 41.35 kg CO_2-eq. per component. In both scenarios, aluminum extraction dominated with 42.84% and 46.64%, respectively, and electrical energy consumed during the LPBF process dominated with 30.78% and 27.08%, respectively. The influence of individual process chains such as powder production, heat treatment, etc. was in the single-digit percentage range. If the product life cycle phases are considered, it can be seen that, regardless of the different scenarios, the consumption of electrical energy predominates in each phase. Raw material extraction with 28 % and the downtime of the LPBF system with 42 % had the largest influence. A comparison of the two scenarios with regards to the quantity of emissions emitted shows that the scenario with four components per build job in raw material extraction and atomization has a significantly lower impact on the energy consumption.

During the LPBF process, however, this difference was very small. The reasons for this are that many energy flows are independent of the component, such as the basic load of the system, cooling or individual steps in preparation such as flooding of the build area or preheating the build platform. When looking at the electricity consumption, it was also noticeable that 42% and 33% of the electricity demand of the entire product life cycle was attributable to the downtime time of the system for the investigated scenarios.

However, the LCA study carried out also has various simplifications. Since it was not possible to generate a comprehensive product life cycle analysis using only self-measured data within this framework for a variety of reasons, data from different publications or databases had to be used. The assumptions mentioned above can influence the results and lead to inaccuracies. In general, it can be stated in conclusion that the results provide guide values by which it can be seen which ecological weak points the LPBF method has.

One of the results of the present work is that an improved CO_2-eq. balance is achieved if secondary aluminum is used for the alloy production. However, no publications could be found that deal with this solution approach for the LPBF process. Accordingly, the use of recycled aluminum raises many questions that still need to be answered before it can be used. One crucial question is whether the material properties of the secondary aluminum are suitable for atomization and subsequent melting by LPBF. In literature, it is only generally stated that undesirable dross can occur during the preparation of the secondary aluminum. How this affects powder materials for the LPBF process is not known. In addition, recycled materials or reprocessed powder cannot be used in every industry. For powder used in the manufacture of components, for example in the aerospace industry, there are certification processes with high safety requirements regarding powder quality. A first step would be to look at the material properties of secondary aluminum for the LPBF process. In addition, a comparison must also be made with conventional manufacturing processes such as casting or milling, since these processes are traditionally used in series production.

Furthermore, a consideration of the product life cycle in an overarching cooperation with the manufacturers of the alloy and the powder would be useful in order to generate up-to-date and more specific data, since the technologies are always evolving and the manufacturers themselves have an increasing desire for sustainable production. In addition, companies could help generate a realistic use case for the use phase.

With the impact assessment data generated, other impact categories beyond global warming potential can be considered and analyzed. This should be done, as it is possible that process steps that were previously hardly considered can have a strong influence in other impact categories. In the evaluation, an already known problem of life cycle assessment becomes apparent. Due to the many different investigation and calculation methods, results from publications are often not comparable with each other. In addition, despite the existing standards, the investigation framework is also calculated with different assumptions and data sets for each analysis. Here it would make sense for a uniform calculation to take place for defined areas.

In general, further research focuses on the improvement of component quality and the LPBF method. This gives rise to many scientific questions regarding topology, support design, manufacturing time, etc., which still need to be answered.

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