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Sustainability in AM – Data generation and evaluation using standardized methods

Alliance Deep Dive | 2023

exclusive

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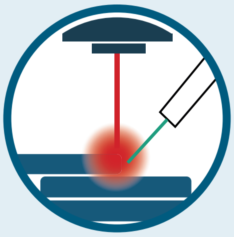
1. Abstract

Motivation



Directed Energy Desposition (DED) to...

… increase material efficiency

… reduce the specific energy demand

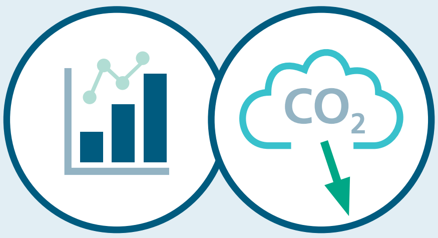
… enable more sustainable production routes

Approach

DED sustainability guide book

- Identification of impact factors
- Comparison to conventional manufacturing
- Overview of methods for Life Cycle Assesment (LCA)

Results



Database for DED process chains

- Analysis of material data
- Analysis of process data
- Impact analysis of the gathered data
- Identification of potential savings for CO_2 emissions

2. Content

3. Acknowledgement

Deep Dives are reports intended exclusively for the members of the Additive Alliance®. They provide the latest insights into the science behind Additive Manufacturing (AM). We extend our profound thanks to the members listed below. This Deep Dive could not have been created without their financial support.

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4. About the authors

In this Deep Dive, the authors Robert Lau and Hannes Zapf demonstrate the potential for reducing CO_2 emissions in manufacturing processes through the utilization of Directed Energy Deposition (DED). Both authors actively participate in leading research projects that employ various DED technologies, combining their extensive expertise with a focus on sustainability aspects.

Their goal is to provide detailed insights and comprehensive data on energy demands for both DED process steps and material processing stages. This effort aims to enhance our understanding of the factors influencing energy demand in DED processes and derive future steps for process optimizations, thereby advancing the field of sustainable manufacturing.

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5. Motivation

The industrial production sector holds a substantial responsibility for the rising global CO_2 emissions, compelling us to seek alternative approaches for more sustainable manufacturing practices. In this context, the metal Additive Manufacturing has emerged as a promising technology in the pursuit of resource conservation and energy efficiency. Through its unique layer-by-layer production process, Additive Manufacturing not only mitigates material waste, but also ushers in an era of innovative lightweight design possibilities.

Moreover, by enabling localized production, this technology drastically reduces the need for extensive transportation networks and associated carbon emissions. This localized approach aligns seamlessly with the global push towards reducing CO_2 emissions throughout the entire life cycle of a product – from creation, distribution, utilization, all the way to the product's eventual end-of-life stage.
As we journey into a future defined by stricter emissions regulations and heightened environmental awareness, optimizing additive manufacturing processes is pivotal. The convergence of advanced Additive Manufacturing techniques, such as Directed Energy Deposition (DED), with traditional manufacturing methods creates a dynamic synergy that can capitalize on the strengths of both worlds.

To achieve this transition towards more sustainable manufacturing routes, a better and specific understanding of the impact factors on resource and energy consumption is needed. Furthermore, the analysis of the available data is crucial to initiate future optimization steps. This Deep Dive focusses on the investigation of DED processes. It includes an overview of Life Cycle Assessment (LCA) methods, a presentation of material and process data and the impact analysis as well as comparison to conventional manufacturing.

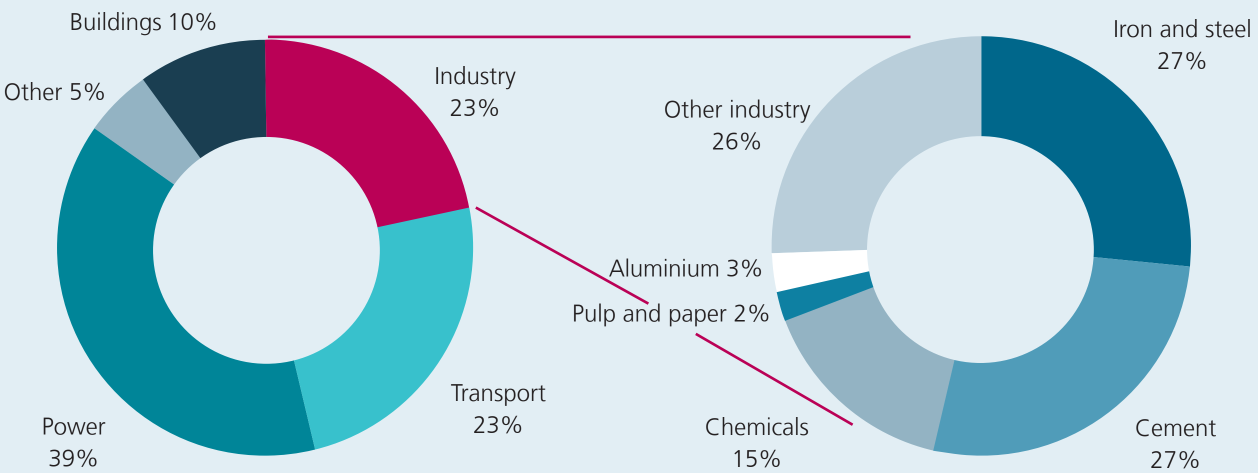
Insights to be gained:

1) Overview of Life Cycle Assessment methods

2) Presentation of data for material processing and DED manufacturing

3) Impact analysis and comparison to conventional manufacturing

Direct CO_2 emissions and allocation



Fact: Iron and steel production have a share of 7% of global CO_2 emissions [Int 20]

Figure 1: Direct CO_2 emissions by sector (left) and the allocation within the industrial sector (right) [Int 19]

»

In the quest for sustainability, Directed Energy Deposition illuminates every phase of the product life cycle with eco-innovation.«

6. Approach of the Deep Dive

6.1 Sustainability aspects in DED processes

DED describes a group of technologies where focused thermal energy is used to fuse materials by melting as they are being deposited. In the following, the most relevant processes of Wire and Arc Additive Manufacturing (WAAM), Laser Metal Deposition (LMD) and Wire Laser Additive Manufacturing (WLAM) are considered for the detailed evaluation of sustainability aspects.

These DED processes can be used to manufacture near-net-shape geometries and enable a significant reduction of raw material usage, especially in comparison to the sole use of machining. An extensive potential for the use of DED lies in the manufacturing of large-scale metal parts and within the repair of damaged parts.

Considered categories of DED processes

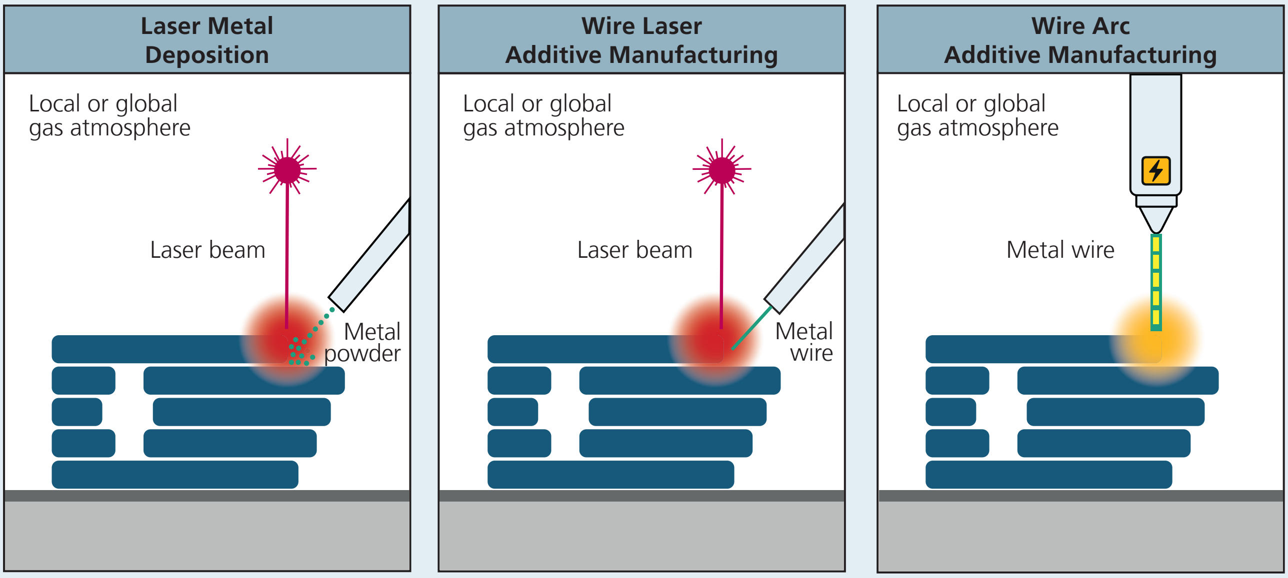


Figure 2: Categories of DED processes

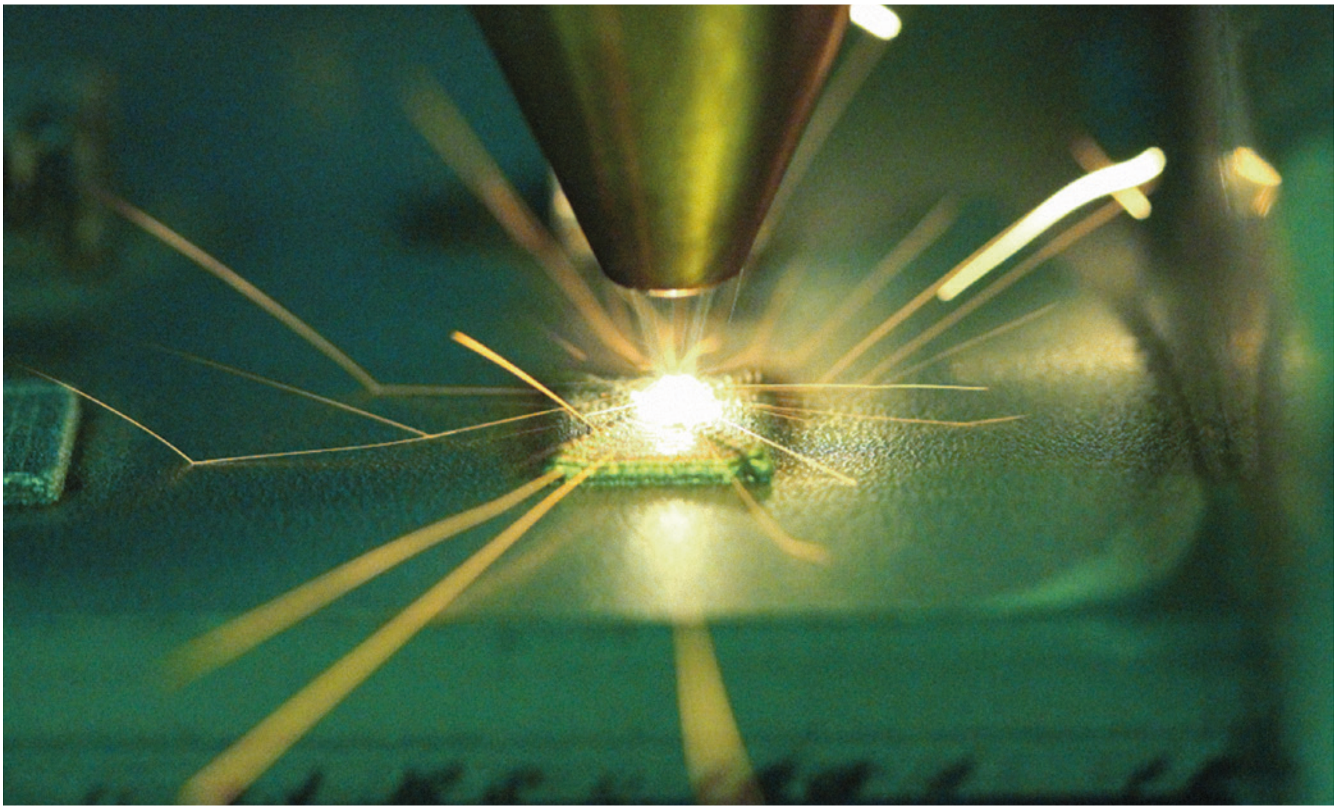


Figure 3: Laser Metal Deposition process

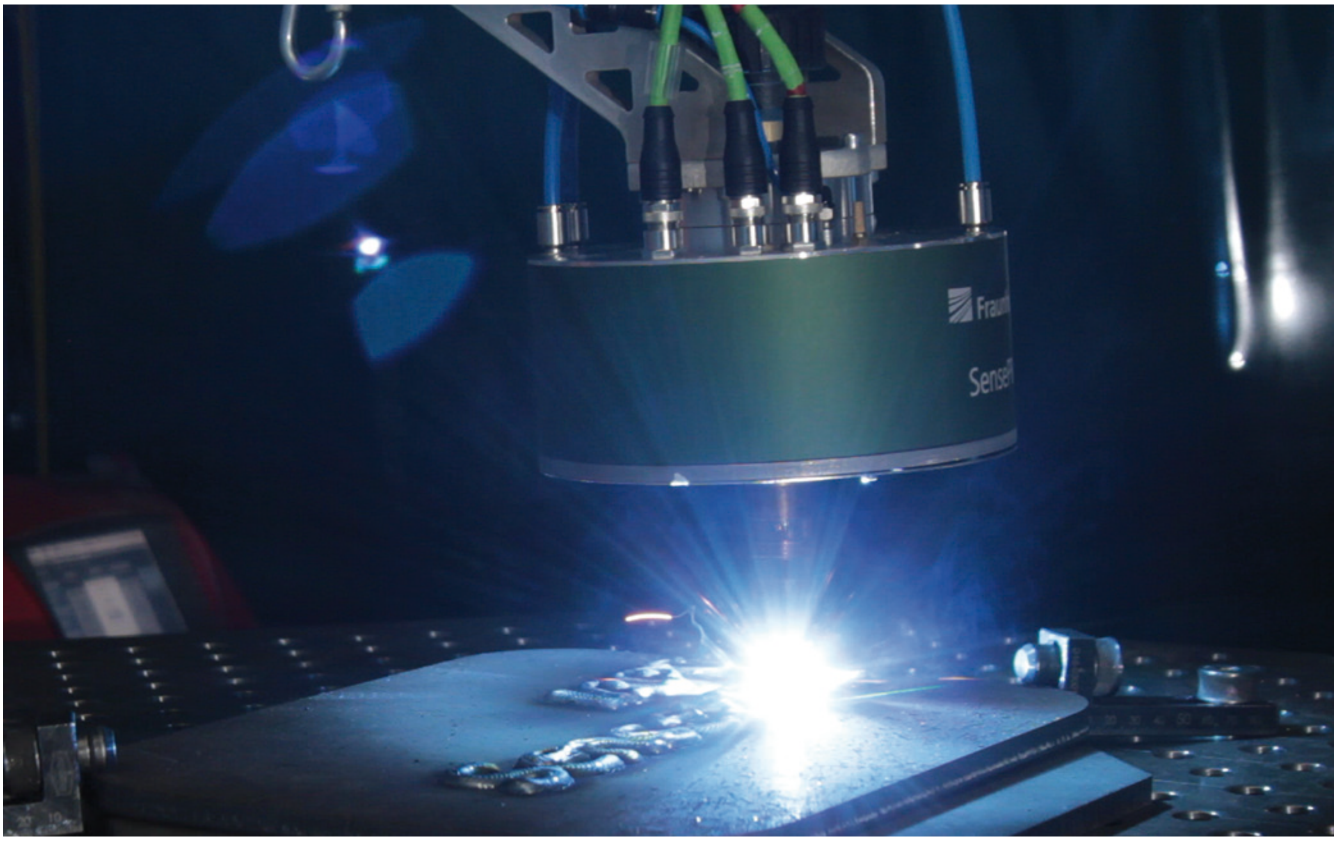


Figure 4: Wire Arc Additive Manufacturing process

6.1.1 Impact on different life cycle phases

The utilization of DED for the creation of products and parts can have various impacts in different phases of the product life cycle. The described impacts are mostly relevant for AM technologies in general.

Material production:
DED can potentially contribute to resource efficiency during material production. By enabling precise material deposition, DED reduces waste generation and optimizes material usage. This can lead to a more sustainable extraction and processing of raw materials, minimizing the environmental impact associated with material production.

Manufacturing:
In the manufacturing phase, DED offers several benefits. It allows for on-demand production, reducing the need for inventory and enabling a more streamlined manufacturing process.

DED's layer-by-layer approach enables the creation of complex geometries and customized designs, optimizing part performance and reducing material waste. This leads to energy and cost savings while improving overall manufacturing efficiency. The flexibility in choosing the location of the machine setup allows to use a local and sustainable energy mix.

Overview of product life cycle phases

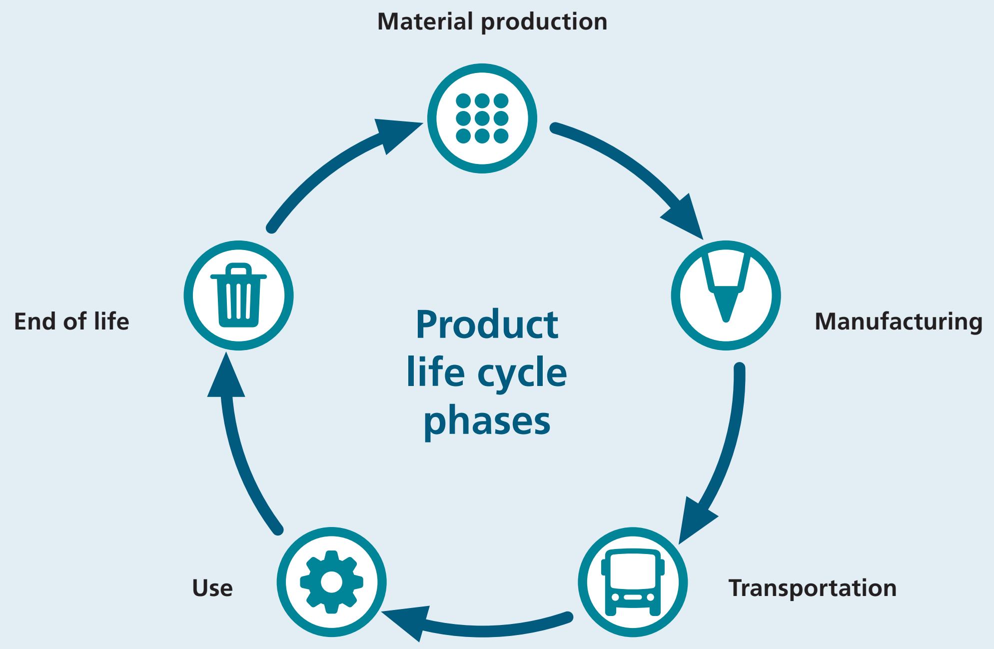


Figure 5: The life cycle phases material production, manufacturing, transportation, use and end of life

Distribution:
By enabling localized production, DED reduces the reliance on long-distance transportation of parts and components. This can minimize the associated carbon emissions, energy consumption, and logistical challenges, contributing to a more sustainable distribution process.

Use:
During the use phase, DED's impact can be seen in terms of improved product performance and efficiency. The ability to create lightweight designs and optimized part structures through DED contributes to reduced weight, which can lead to energy savings, especially in applications such as aerospace and automotive industries.
Enhanced part performance and durability can also extend the lifespan of products, further reducing the environmental impact associated with replacements. Furthermore, the repair of metal parts through DED may decrease lead times and reduce down times within the usage of the product.

End of life:
In the end-of-life phase, DED can support sustainability through its potential for material recyclability. DED-produced parts can be easily re-melted and reprocessed, facilitating the recycling and reuse of materials. This promotes a circular economy approach, reducing the need for raw material extraction and minimizing waste generation.

The following sections of this study will focus on the phases material production and manufacturing, since the later phases are highly dependent on the respective applications. Especially in the use phases the boundary conditions of the assessment may vary widely. The approach which considers material production and manufacturing is called »cradle-to-gate« (refer to section 6.2.3).

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Already with a buy-to-fly ratio exceeding two, Directed Energy Deposition emerges as the eco-conscious alternative to traditional machining.«

6.1.2 Impact factors on CO_2 emissions

In a cradle-to-gate LCA of DED process chains, several factors can significantly impact CO_2 emissions. To understand the available data better, an overview of the most relevant factors in this context is provided first. These factors are clustered into material and process related factors and a further breakdown is given in the Ishikawa diagram. The diagram shows a wide variety of possible combinations along the setup of a DED process chain. In the examination of the literature (refer to section 7.1), it was demonstrated that the foremost influence stems from the alloy and material type, along with the energy source category. Consequently, this study centers its attention on these key factors.

Material processing:
The provision of the raw material as well as the further processing for the feedstock and substrate show a large impact on the CO_2 emissions. This impact is driven by the type of material (wire or powder) and the kind of alloy (e.g. Ti, Al, St, Ni).

Type of Energy source:
Next to the kind of feedstock, which partly defines the DED process, the type of energy source has an important impact. The considered energy sources in the evaluation are arc and laser. Additionally, the use of plasma and electron beam sources is possible, but less applied in the field of DED.

Deposition rate:
The deposition rate varies through the different DED processes. Furthermore, the variations within one DED process can be significant and show an important impact on the productivity, moreover the consumption of energy and consumables.

Periphery and consumables:
Depending on the respective DED process as well as the processed material, different kinds of periphery and kind of consumables are required. A possible impact is given by the machine setup, e.g. process head handling and periphery, the type of shield gas as well as the shield gas consumption.

Post processing steps:
The DED manufactured near-net-shape geometry typically requires a machining and/or wire EDM processing step to achieve the desired final part properties. Depending on material and part geometry these steps may vary in terms of processing times and energy consumption.

Impact factors on CO_2 emissions in DED process chain

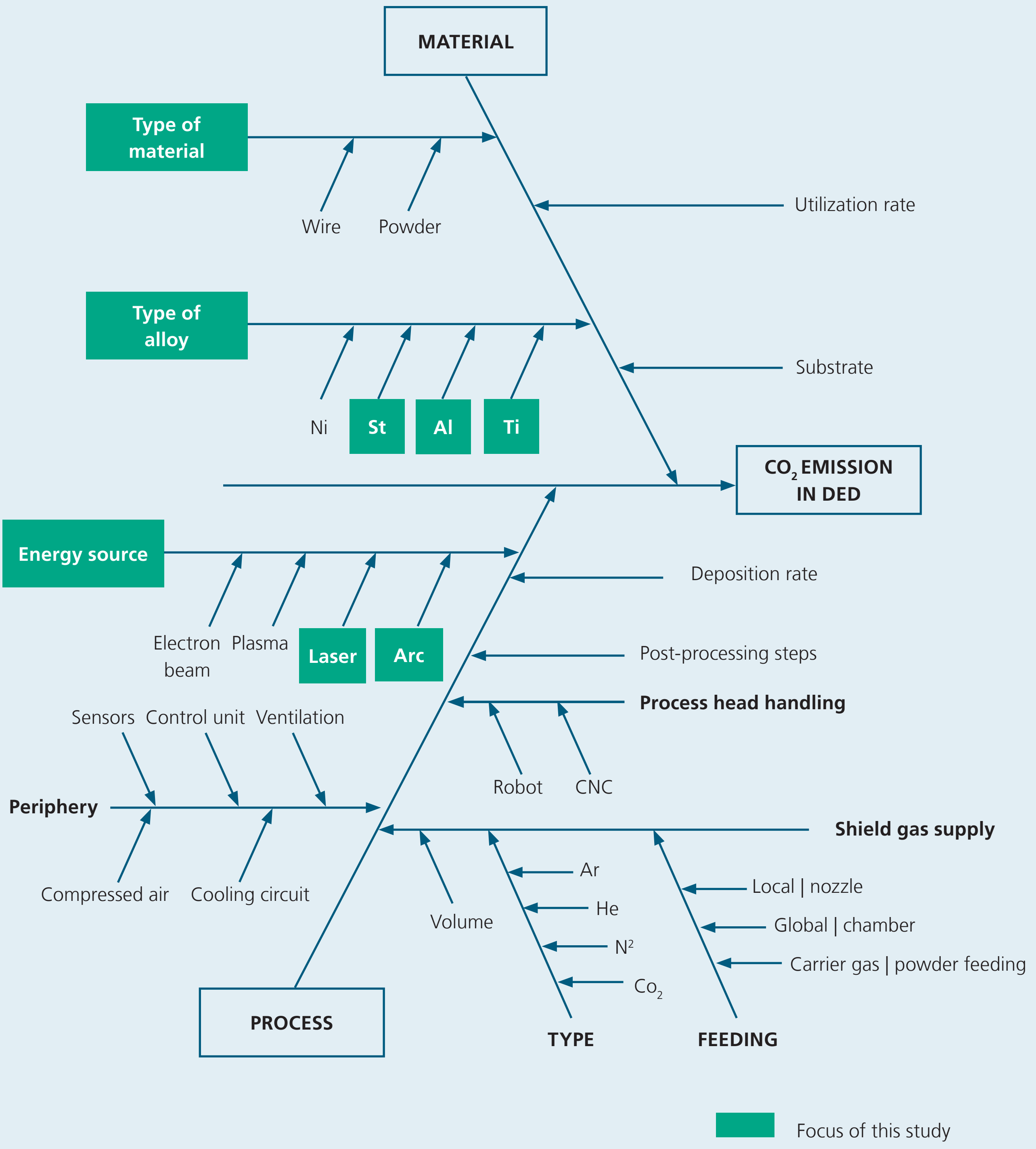


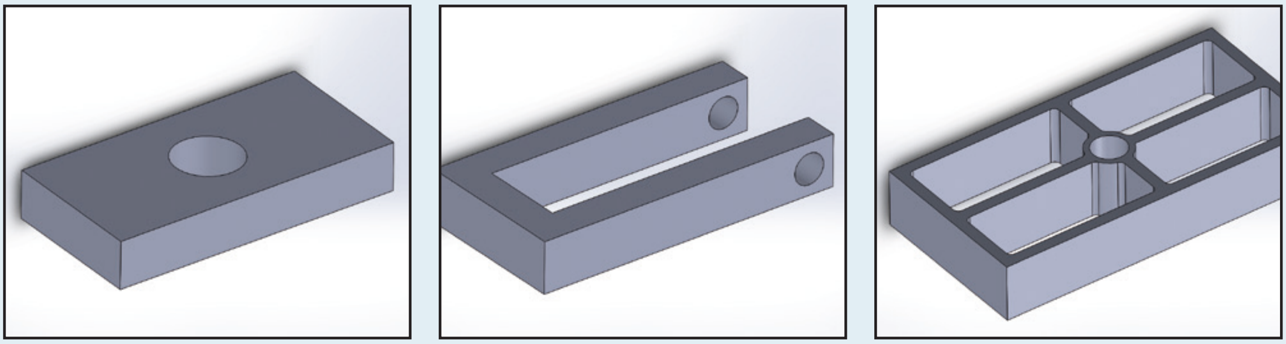
Figure 6: Summary of impact factors in Ishikawa diagram

6.1.3 Comparison to traditional manufacturing techniques

The comparison of DED processes and traditional manufacturing techniques is driven by different factors. Next to the recognized manufacturing techniques and the chosen materials, the part design has the main influence on the result of the LCA. A possible description for the geometry of the part is given by the solid-to-cavity ratio. The solid-to-cavity ratio refers to the ratio of material that ends up in the final part (solid material) to the material that is contained with bounded volumetric envelope of the part [Mor07].
An extensively employed and comparable metric is the buy-to-fly ratio, established through the reciprocal definition. Especially in the comparison between DED and machining, this ratio has a big influence. Furthermore, new design options coming with DED can reduce the total mass of the part. Numerous comparisons have been carried out in existing literature, with the comparison between WAAM and machining emerging as the predominant focus. LMD is being explored as an alternative DED process, while casting is considered as another conventional manufacturing method. The results of three different publications for WAAM of steel alloys are shown as followed. Further investigations are marked in table 4.

The evaluation of the literature states out that a manufacturing route with DED process steps is favorable in many cases. The exact break-even point for DED is dependent on material choice, part geometry and process factors.

What does the geometry look like?

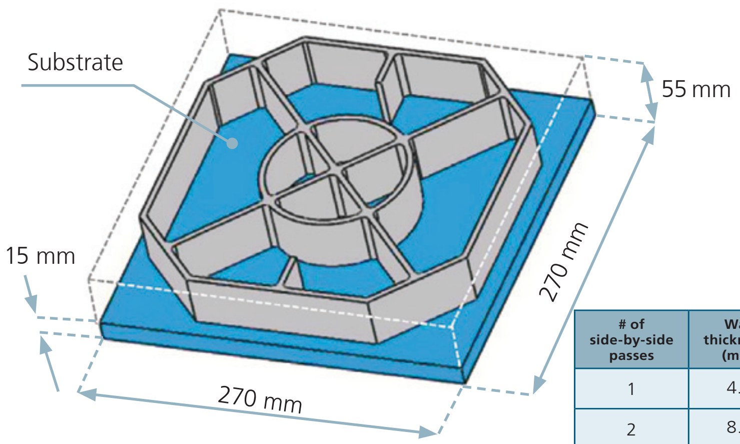


0.9 **0.5** **0.3**

Figure 7: Examples of different solid-to-cavity ratios

WAAM demonstrator part with different solid-to-cavity ratios

DED Technology	WAAM	Part
Traditional Technology	Machining	
Material	Stainless steel	
Evaluated factors	Climate change [$kgCO_2/kg$] Specific Energy Consumption (SEC) [MJ/kg]	
Source	[Pri19]	
Results	For WAAM the factors climate change and SEC remain almost constant for different solid-to-cavity ratios, which is influenced by the chosen wall thickness of the demonstrator part. For the machining option these factors increase with decreasing solid-to-cavity ratio due to poor material utilization rate. WAAM is beneficial for the following conditions. ■ Climate change: solid-to cavity ratio < 0.68 ■ SEC: solid-to-cavity ratio < 0.65 For a solid-to-cavity ratio of 0.3 the machining options impact on climate change is approximately 2.5 times higher in comparison to the WAAM approach	



# of side-by-side passes	Wall thickness* (mm)
1	4.6
2	8.0
4	14.8
6	21.6
8	28.4

* theoretical, as-deposited

Table 1: Summary of publication [Pri19]

Stuctural steel components with WAAM

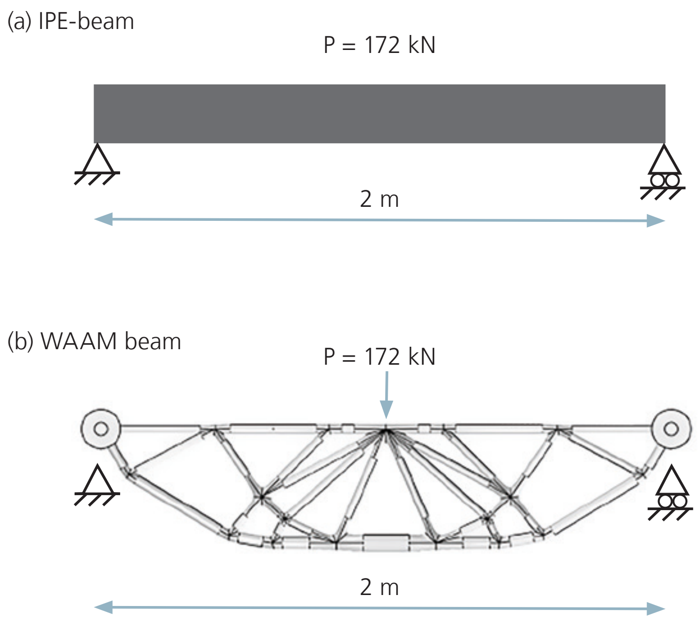
DED Technology	WAAM	Part
Traditional Technology	Rolling of IPE-beams	
Material	Stainless steel, Carbon steel	
Evaluated factors	Climate change [kgCO_2/kg] Specific Energy Consumption (SEC) [MJ/kg] ReCiPe midpoints	
Source	[Sha23]	
Results	WAAM beam option is compared to traditional beam manufacturing (rolling). Different IPE-beam to WAAM beam mass ratios were evaluated. The use of WAAM enables a topology optimized design and therefore less material usage. The LCA shows WAAM as beneficial in terms of climate change ▪ If the WAAM beams has less than half the weight compared to the IPE-beam ▪ If the WAAM beam has on quarter of the weight, the impact on climate change halves.	

Table 2: Summary of publication [Sha23]

Comparing WAAM with casting and machining

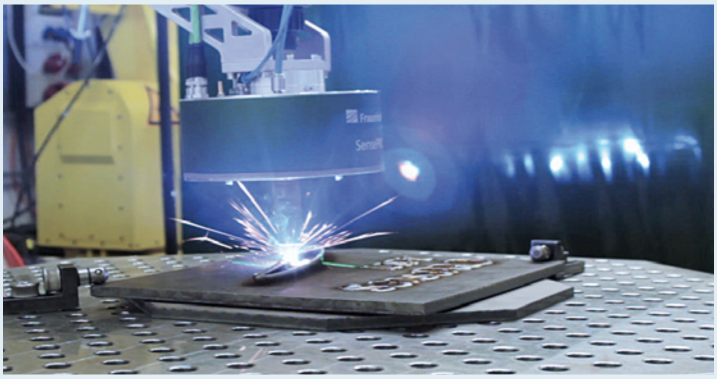
DED Technology	**WAAM**	**Part***
Traditional Technology	Machining, sand casting	
Material	Stainless steel	
Evaluated factors	ReCiPe endpoints	
Source	[Bek18]	*no specific part geometry evaluated
Results	The calculation of the environmental damage per manufactured kg shows a comparable result between WAAM (1832 PTS) and sand casting (1892 PTS), since the material efficiency is high. Assuming a solid-to-cavity of 0.5 for machining the damage increases to 2.825 PTS. Comparing different material efficiencies, WAAM is favorable for values below 0.7 for machining.	

Table 3: Summary of publication [Bek18]

Additional literature hints

Source	DED process	Conventional process	Material
[Liu18]	LMD	Casting	AISI4140
[Jac16]	LMD, WAAM	Machining	Carbon steel
[WAA23]	WAAM	Machining	TI-6AI-4V
[Kok23b]	WAAM	Machining	Steel
[Rei23]	WAAM	Machining	Steel

Table 4: Additional assessments between DED and conventional processes

The break-even point for DED technologies is contingent upon material selection

To extent the given overview of the literature Furthermore, a comparison of WAAM and machining is given, using the AMPower Sustainability Calculator [AM23] with different inputs for part geometries and materials to estimate the break-even points. The tool allows the comparison of different AM options as well as conventional manufacturing options, such as machining and sand casting.

As a geometry, a simple thin wall cylinder with a final volume of 127 cm^3 is chosen, which represents a mass of 1 kg in case of stainless steel. The evaluation of WAAM already includes machining steps and on oversize of 10 % is assumed, which means that a deposited volume of 140 cm^3 is needed. The lower flange was used as substrate and remains in the final part. For the machining option the solid-to-cavity ratio is set between 0.9 and 0.1 to be able to estimate the break-even point in terms of energy consumption.

Selected demonstrator geometry

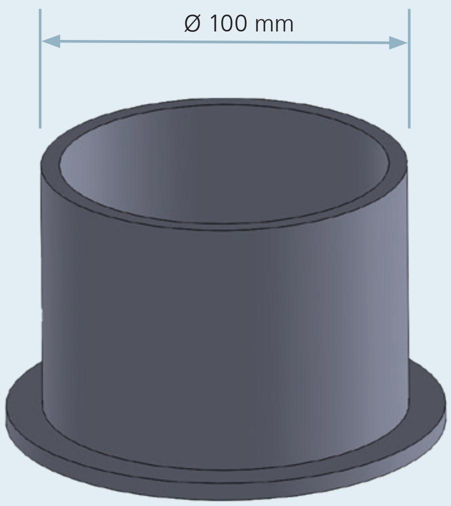


Figure 8: Geometry used in the AM Power sustainablity calculator

The different solid-to-cavity ratios represent varying blank volumes for the machining option. E.g. a 0.1 solid-to-cavity ratio means that a block rectangular block (125 x 125 x 80 mm^3) is used as blank volume.

The deposition rate is fixed at 700 cm^3, which represents a typical value for high deposition rates in WAAM with stainless steel, aluminum and titanium. All other material and process related variables were kept at the standard settings of the calculation tool. The calculated energy consumption (kWh/part) without consumables for stainless steel, aluminum and titanium is used for the comparison. This option includes the material processing steps. All values are converted to into the SEC (MJ/kg) with the respective masses.

The evaluation of the results reveals different flattening curves in the diagrams for aluminum, stainless steel and titanium. The SEC level for the WAAM option is marked for the comparison and the break-even-point. For titanium the WAAM option is beneficial for solid-to-cavity ratios below 0.5, for stainless steel below 0.25 and for aluminum below 0.2. For titanium, the material processing steps have a higher impact on the SEC, which explains the earlier break-even of the WAAM option, due to its good material utilization factor. For stainless steel and aluminum this material impact is lower and therefore a low solid-to-cavity ratio is less critical. For a more detailed view on the different material processing steps, refer to section 7.1. A comparison of the break-even-point for stainless steel in the calculation (< 0.25) with the result of [Pri19] (< 0.65) shows a wide range and the effect of varying assumptions and framing conditions.

In summary, the evaluation of literature and the estimations with the Sustainability Calculator show that DED can be a favorable choice for all material options. The presented break-even-points can only be seen as a coarse classification of DED in comparison to conventional manufacturing and do not replace an extensive LCA due to the large range of variables.

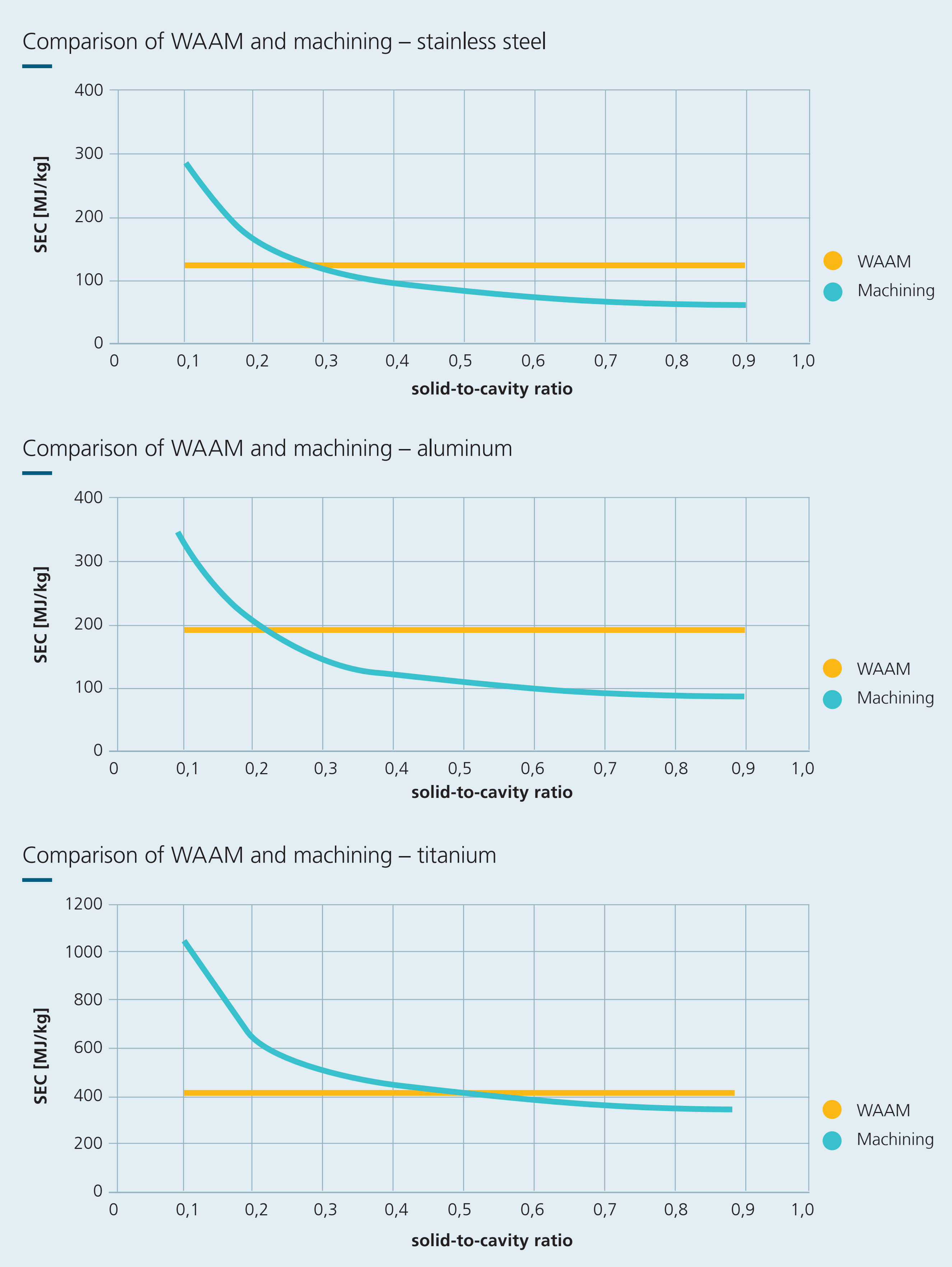


Figure 9: Examplary break-even points for DED technologies

6.2 Standardized methods for LCA

LCA is a methodology used to evaluate the environmental impacts of a product or process throughout its entire life cycle, from the extraction of raw materials to its disposal or recycling. Several standards and guidelines have been developed to provide a framework for conducting LCA studies.

6.2.1 Relevant standards in LCA

The most relevant standards for LCA of manufacturing processes are the ISO standards, since they have the highest global recognition and represent the international consensus, e.g., the

- ISO 14040 Environmental management – Life cycle assessment – Principles and framework [ISO06b]
- ISO 14044 Environmental management – Life cycle assessment – Requirements and guidelines [ISO06c]
- ISO 14025 Environmental labels and declarations – Type III environmental declarations – Principles and procedures [ISO06a].

They outline the fundamental framework and requirements for performing LCA studies in a consistent and transparent manner. They cover a wide range of environmental factors beyond greenhouse gas emissions, including resource use, pollution, and ecosystem impacts.

ISO standards for LCA are applicable to various sectors and industries and can be used by organizations to assess the environmental performance of their products, processes, or services. They provide a holistic approach to evaluating environmental impacts. The standards are developed through a consensus-based international process involving multiple stakeholders, including governments, industry representatives, and environmental experts. They undergo regular updates and revisions to incorporate new scientific knowledge and best practices. An integration into broader environmental management systems, such as ISO 14001 [ISO15], is possible to support organizations in managing their environmental impacts more comprehensively.
Clear reporting ensures that the study's methodology and outcomes can be reviewed, verified, and replicated by others. It underscores the importance of peer review and critical analysis of the LCA study. External experts should review the study to ensure its accuracy, reliability, and adherence to the standard's principles.

Beside the ISO standards, the Greenhouse Gas Protocol (GHG Protocol) is recognized and widely used. It focuses on the accounting of greenhouse gases, whereas the ISO standards cover a wider range of environmental factors and impacts on eco systems. The GHG Protocol covers three different scopes of emissions:

- Scope 1: Direct emissions from sources owned or controlled by the organization, such as emissions from combustion of fossil fuels in onsite facilities.

- Scope 2: Indirect emissions from the generation of purchased electricity, heat, or steam consumed by the organization.

- Scope 3: Indirect emissions from activities outside the organization's direct control, such as emissions from the extraction and production of purchased materials, transportation of goods, and disposal of waste.

It's important to note that while the ISO standards for LCA do not explicitly define scopes like the GHG Protocol, LCA studies can consider all three scopes of GHG emissions and can be individually defined as part of their assessment.

6.2.2 Phases in LCA according to ISO 14040

LCA consists of four phases: goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and interpretation [ISO06b]. In the goal and scope phase, objectives and system boundaries are set. This includes specifying the purpose of the assessment, the boundaries of the system being studied, the functional unit (the specific function that the product, system or process provides), and any assumptions made during the assessment.
For example, in a manufacturing scenario for metal parts, the system boundaries can be set from the beginning of the raw material extraction until the part leaves the factory. This approach is called »cradle-to-gate« and will be focused in this study. For further approaches and life cycle models, refer to section 6.2.3.
The functional unit can be the quantity of one specific manufactured part with defined dimensions and weight in the simplest case. Any assumptions made have to be clearly described to maintain the transparency requirements.

The inventory phase involves data collection on inputs, outputs, and environmental impacts. This step involves gathering information on resource consumption, emissions, energy use, and other relevant factors. Data can be collected from a variety of sources, such as published literature, industry databases, company records, and direct measurements. Ensuring data quality is essential to maintain the accuracy and credibility of LCA results. Data quality considerations include reliability, completeness, representativeness, and relevance. It is important to use up-to-date, relevant data that accurately represents the specific processes and technologies being assessed.
Transparent documentation of data sources and assumptions is also necessary. LCA acknowledges that data uncertainty is inherent in the assessment process. Uncertainty arises due to various factors, including data gaps, variability in data sources, and assumptions made during the analysis. Sensitivity analysis and uncertainty propagation techniques can be used to assess the influence of data uncertainties on the overall LCA results.
In the life cycle impact assessment phase, the environmental impacts identified in the life cycle inventory phase are evaluated and characterized. It involves assessing the potential effects of the identified inputs and outputs on various environmental impact categories, such as global warming, acidification, eutrophication and human toxicity, refer to section 6.2.4.
Lastly, interpretation analyses the results, considering uncertainties, and provides conclusions and recommendations. These phases enable systematic assessment and comparison of environmental impacts and identification of improvement opportunities.

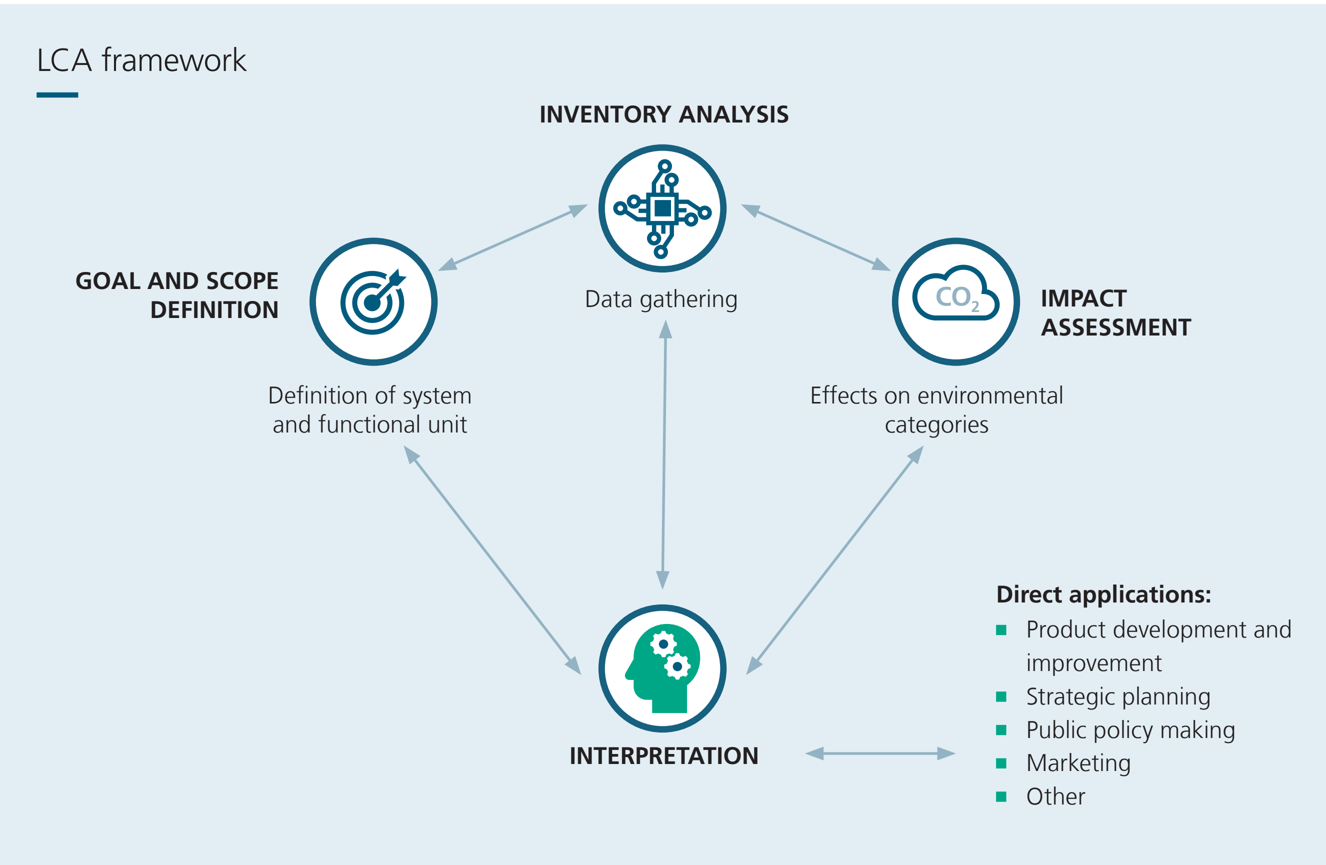


Figure 10: Phases of an LCA according to [ISO06b]

6.2.3 Product life cycle models

Depending on the evaluated life cycle phases, different models can be used. The most extensive approach is called »cradle-to-cradle« where the entire life cycle is considered. The goal is to create a closed-loop system where materials and resources cycle indefinitely, minimizing waste and reducing environmental impact. The cradle-to-grave model, also known as »end-of-life« assessment, focuses on analyzing the entire life cycle of a product from its creation to its ultimate disposal. The cradle-to-gate model assesses the environmental impact of a product from the beginning of its life cycle up to the point where it leaves the manufacturing facility. This approach is often used when the manufacturer has limited control over the product's subsequent stages, such as use and end-of-life. Cradle-to-gate analysis provides insights into the production phase's environmental implications, aiding in the optimization of manufacturing processes and materials selection.

6.2.4 Impact assement methods, categories and units in LCA

Different impact assessment methods are used in LCA to characterize and quantify the environmental impacts of a product or process. One relevant method is the Relevance and eCause-contribution in a normalized Impact Pathway Evaluation (ReCiPe) which is used in several publications for assessing manufacturing processes. It is categorized into two levels of assessment, the midpoint and endpoint approach.

Midpoint impact assessment focuses on intermediate environmental impacts that are closer to the specific emissions and stressors associated with a product or process. It quantifies the cause-effect relationships between emissions and environmental changes but doesn't directly address the ultimate consequences on human health or ecosystems.

Product life cycle models

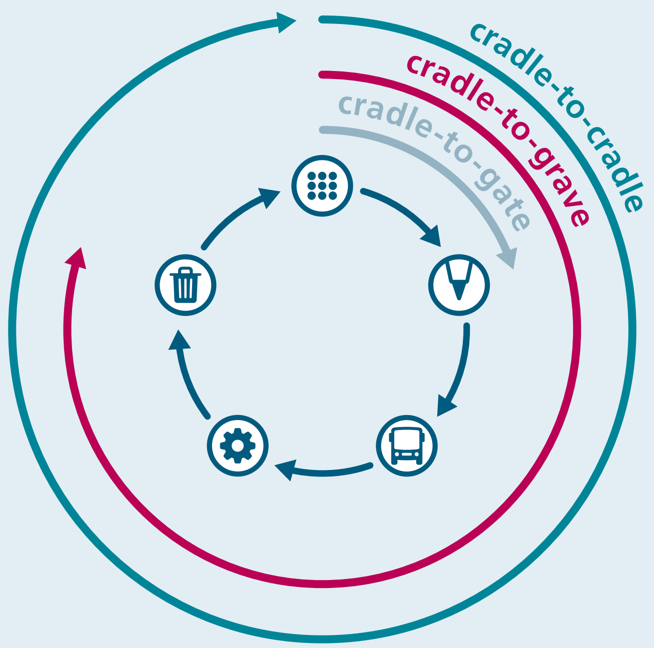


Figure 11: Overview on different scopes of LCA

Global warming potential: From midpoint to endpoint characterization

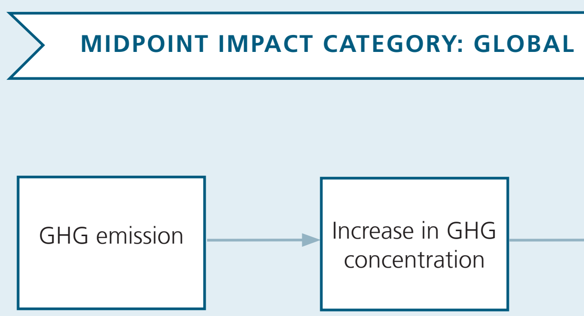
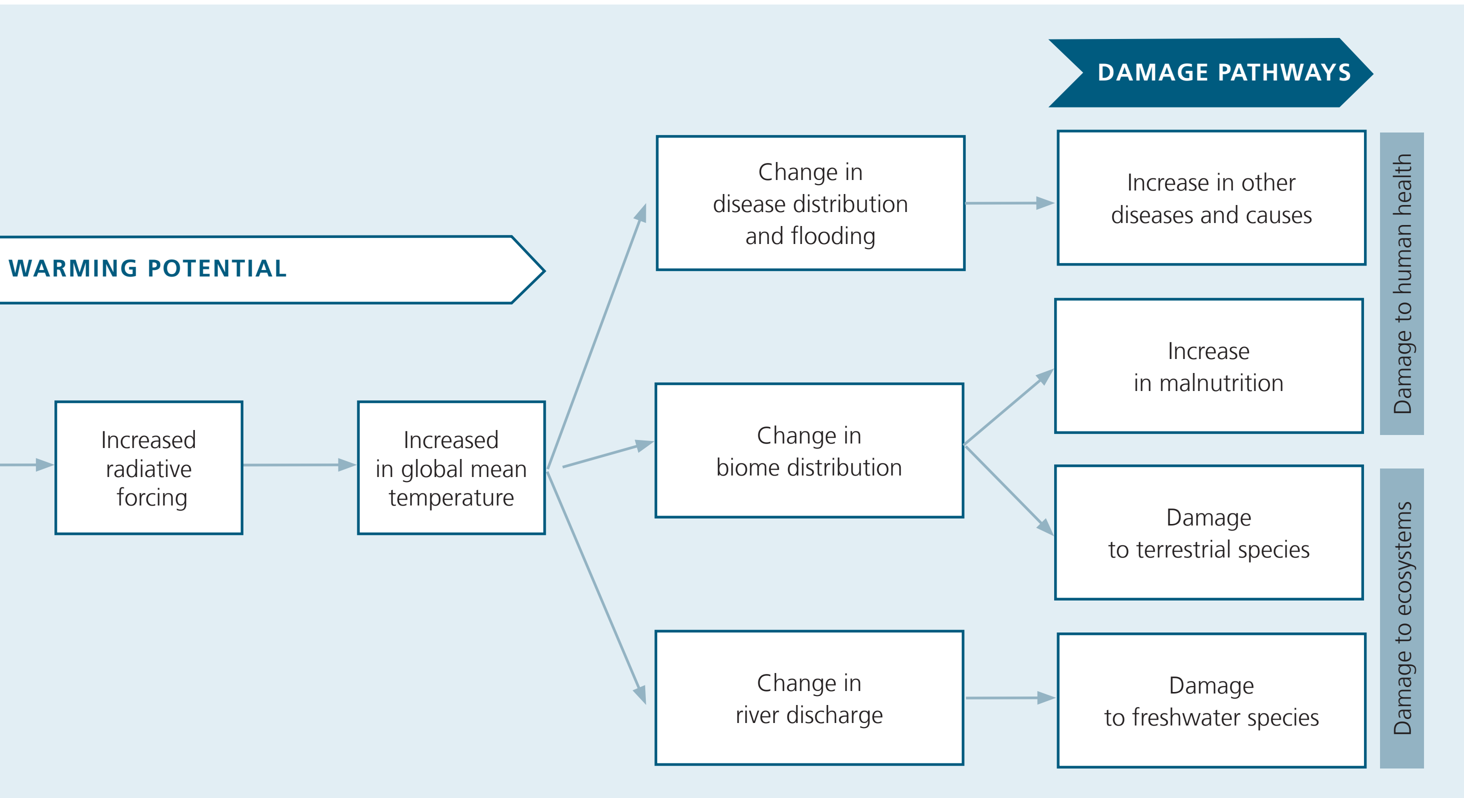


Figure 12: Cause-and effect chain for the GWP according to [Hui16]

Endpoint impact assessment goes a step further by linking the midpoint impacts to their ultimate consequences on human health, ecosystems, and resources. It provides a more holistic view of the overall environmental and human health impacts, which can be valuable for policy-making and strategic decision-making. Alternative methods are the Eco-indicator 99, IMPACT 2002+, CML, TRACI and ILCD. The choice of the method depends on the specific goals, the context of the study and regional regulatory requirements.

Various impact categories exist to describe the specific environmental impacts. Each impact category represents a specific aspect of environmental damage or stress. For example, in the ReCiPe 2016 midpoint method 18 different factors are used [Hui16].
The first listed and most widely known factor is the global warming potential (GWP) as a part of the climate change impact category. As unit, the carbon dioxide equivalent (or carbon footprint) is used and stated in kg ($kgCO_2eq$). Common gases assessed include carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Further examples for characterization factors are the human toxicity potential, ozone depletion potential, terrestrial acidification potential or freshwater ecotoxicity potential.

To achieve an ReCiPe endpoint characterization these factors are used to derive further damage pathways. Each midpoint factor may cause multiple damages to human health, ecosystems and resource availability. Dimensionless endpoint factors are used to be able to compare the severity of the effect of the specific midpoint factors.
An exemplary cause-and-effect-chain for the GWP to four damage pathways is shown in the following chart.



»A precise, transparent and comprehensive Life Cycle Assessment of products and processes is an increasingly vital necessity.«

7. Generation of a database for DED process chains

7.1 Analysis of available data

The available data plays a crucial role in conducting an LCA of parts manufactured by DED. Large databases can be used to implement data for the different material processing steps or traditional manufacturing steps within the LCA.
The quality of the used data and its adaption to the framing conditions and boundaries has a main influence on the result of the LCA. Assumptions and less transparent insights in external data may show an influence as well. Specific data for DED processes is not included in databases so far and varies due to many variables in the DED process chain.

Therefore, a deeper analysis of the available data in the literature and databases is conducted. Data values can be given as a SEC in [MJ/kg] or the Carbon footprint [kgCO_2eq/kg].

For this study, the SEC is chosen for as the main coefficient; since it ensures a clear comparability of different processing steps. Given values for the carbon footprint are converted into the SEC using the CO_2 emission intensity of the European grid[1].

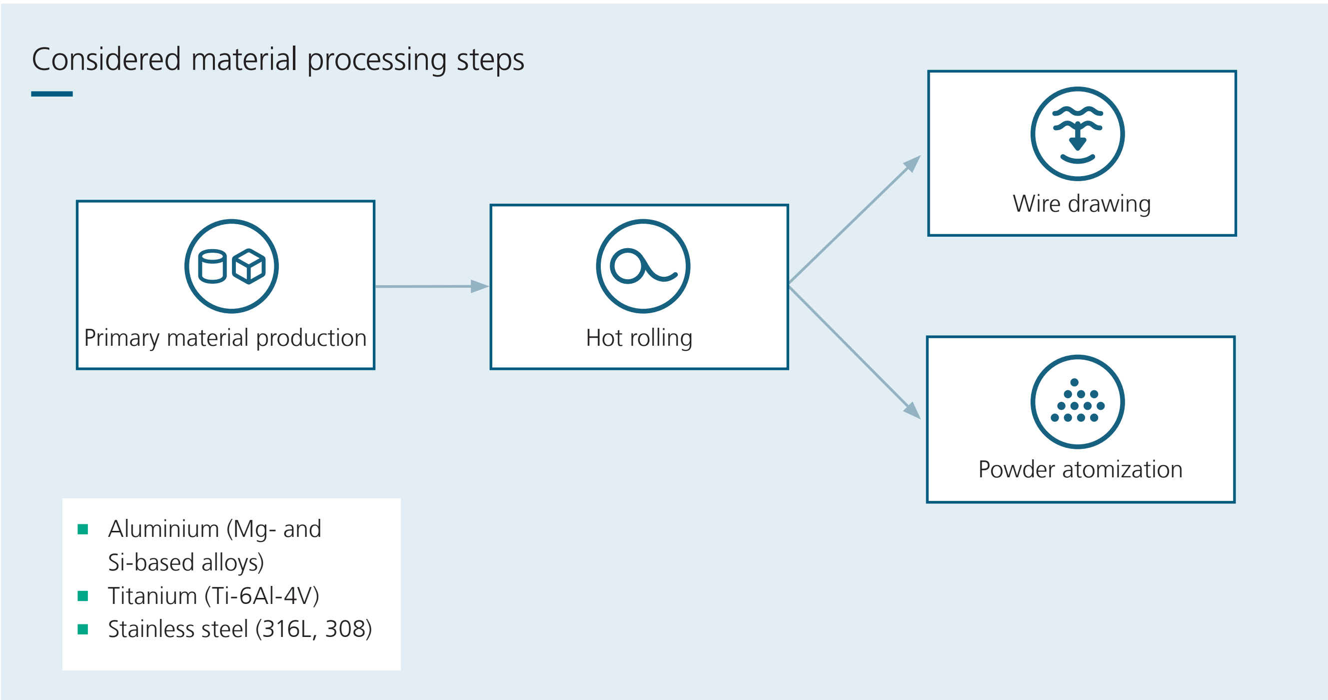


Figure 13: Overview of material processing steps

[1] A value of 238 g CO_2eq/kWh [Eur21] was used, which is relevant for electrical processes. For some process steps (e.g., primary material production), fossil fuels are needed in addition to electrical energy. This was taken into account when allocating the different energy demands.

A wide range of available material data complicates a precise LCA

7.1.1 Data for material processing steps

The first focus is set on the processing of material. Depending on the DED process, powder or wire is used as feedstock material. The material process chain can be summarized in a primary material production step to provide ingots. These are further processed by hot rolling and wire drawing or powder atomization. The analysis of the material data focuses on titanium, stainless steel and aluminium. Furthermore, common alloys for AM were handled as most relevant for the data evaluation. The reviewed data is clustered according to these materials.

Primary material production

Primary material production comprises the production of ingots, which serve as a standard starting point for the subsequent process steps and has been identified as the main contributor to CO_2 emissions along the process chain. The reviewed data shows a wide range between with the lowest value of 25 MJ/kg for stainless steel and the highest value of 973 MJ/kg for titanium. When comparing the mean values, titanium has by far the highest SEC (617 MJ/kg), followed by aluminium (154 MJ/kg) and stainless steel (62 MJ/kg). The extraction of titanium is highly energy intensive because the chemical reduction process involves multiple steps, each requiring high temperatures to

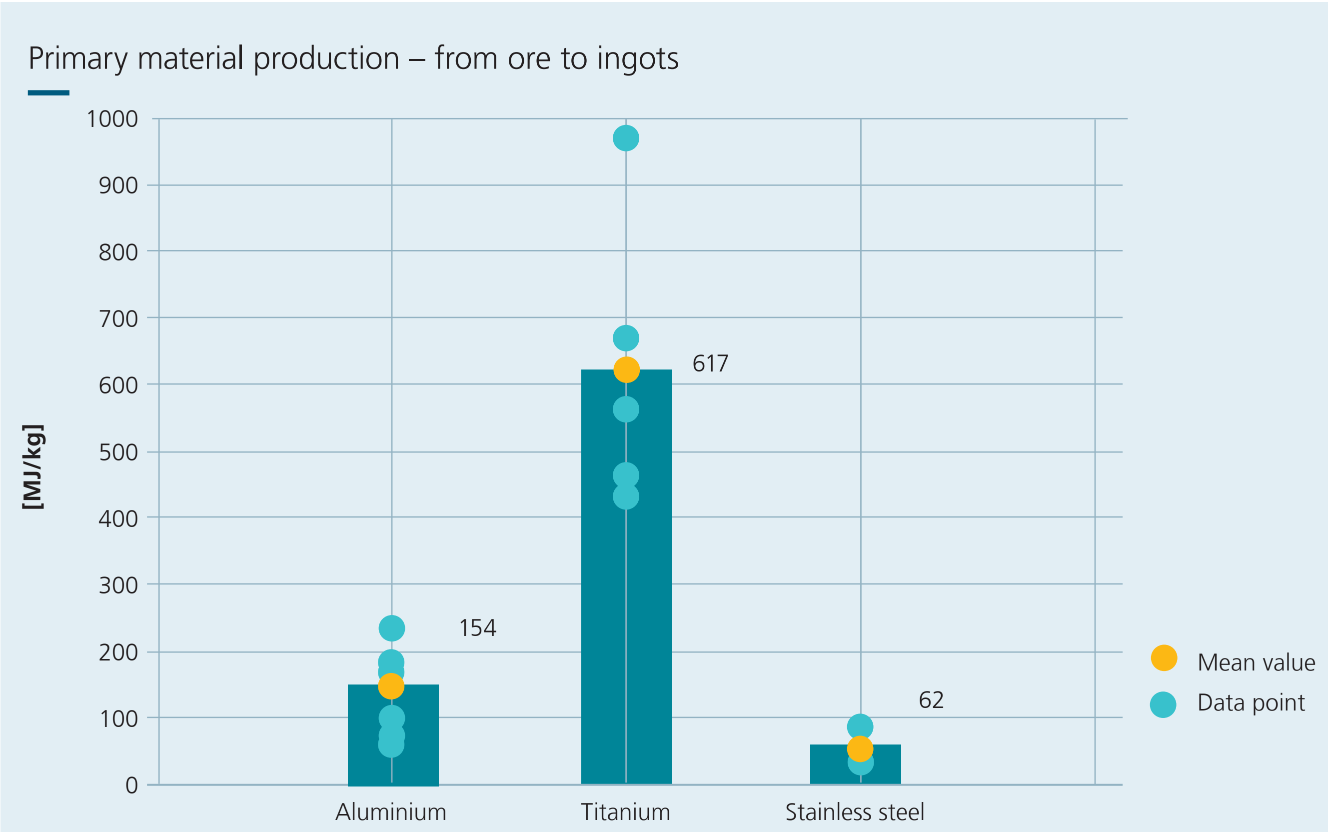


Figure 14: Summary of primary material production data with datapoints and mean value

overcome chemical bonds, e.g. between titanium and oxygen. Furthermore, its high reactivity and melting point necessitate energy-intensive processing techniques. In contrast, steel and aluminum benefit from relatively less complex extraction and processing methods, along with more abundant raw materials. These factors contribute to their comparatively lower energy requirements during primary material production.

Hot rolling

Within the hot rolling process, material rods are shaped as the next intermediate product. The exact shape and diameter of the rods is determined by the following process step, such as wire drawing or powder atomization.

The hot rolling process shows way lower values in comparison to the primary material production, since the temperature is usually elevated slightly above its recrystallization temperature. For titanium the processing has once again the highest SEC (16 MJ/kg), followed by aluminium and stainless steel. Once again this is explained by higher temperature levels for titanium as well as higher process forces.

Wire drawing and powder atomization

Comparing the use of powder and wire as feedstock material, the wire option can be beneficial in terms of SEC. Wire drawing demands lower energy as it operates through mechanical means. In contrast, the process of powder

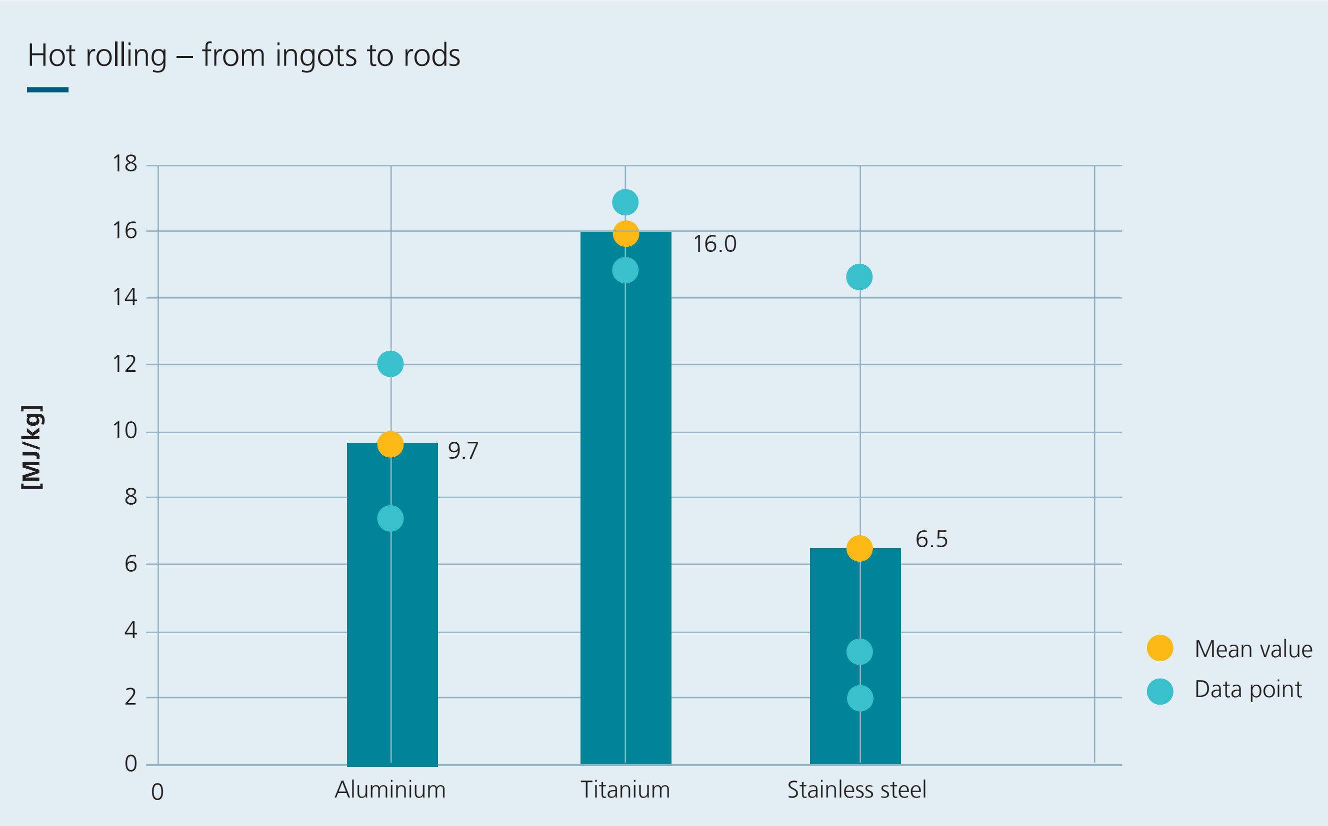


Figure 15: Summary of hot rolling data with data points and mean value

atomization encompasses several stages, including the melting and rapid cooling of particles. Especially for the powder production of titanium higher values were determined, since a plasma atomization is needed, due to its high reactivity. Furthermore, the wire drawing step requires higher forces for titanium, which increases the energy demand. For most of the reviewed values a simplified representation of the process steps was considered. A more detailed view on consumables, gas consumption and material waste are not a part of this comparison.

Summarizing the data examined in relation to the material processing stages required to transition from ore to the desired feedstock material, it has been demonstrated that titanium exhibits the highest energy demand owing to its distinctive properties. Conversely, the processing of stainless steel exhibits the least overall energy requirement.

All the presented values are denominated in MJ/kg, irrespective of the differing material characteristics. The specific strength, computed by dividing tensile strength by density, has superior values for titanium. Assuming an ultimate tensile strength of 900 MPa for titanium (Ti-6Al-4V) and 580 MPa for a stainless steel (316L) component, the specific strengths are 205 kNm/kg for titanium in contrast to 74 kNm/kg for stainless steel. This indicates that, for a direct comparison, only one-third of the material is necessary when utilizing titanium to maintain identical forces.

Wire drawing – from rods to wire

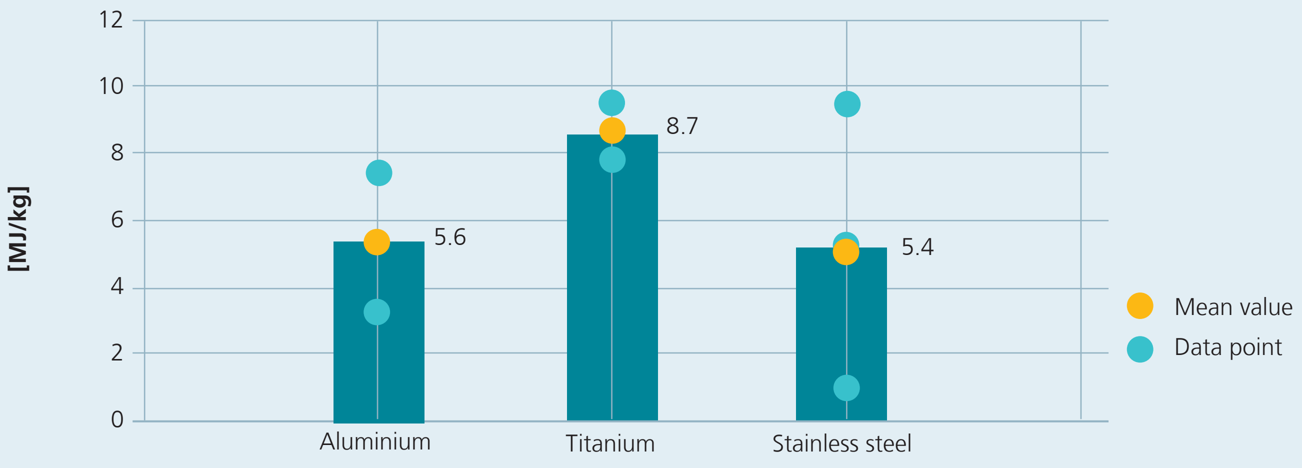


Figure 16: Summary of wire drawing data with data points and mean values

Powder atomization – from rods to powder

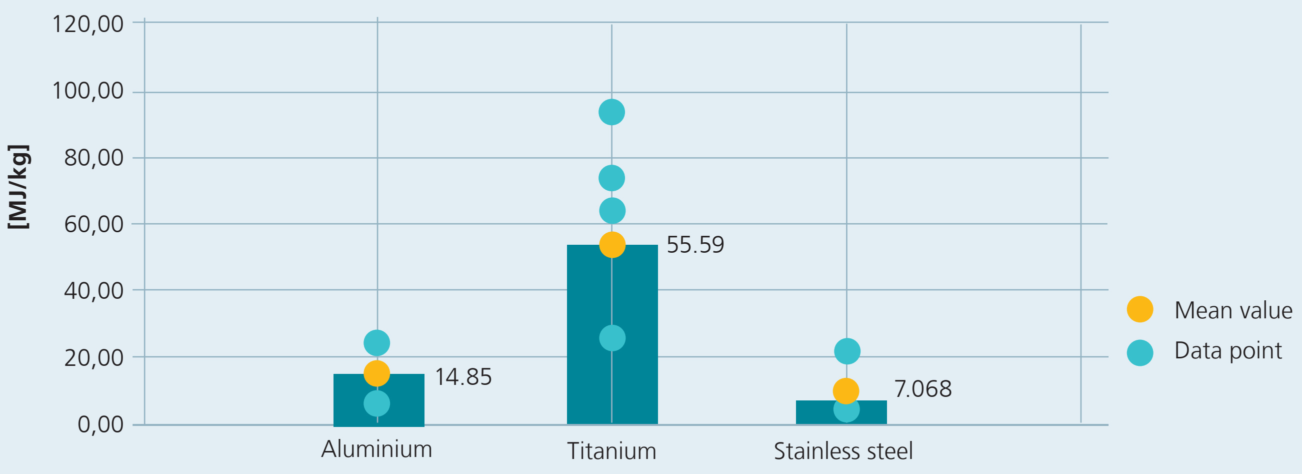


Figure 17: Summary of powder atomization data with data points and mean value

The shown values for the material processing steps are based on a literature research including the following publications [Pri19; Pri20; Kok23a; Kok23b; Bek 18; Sha23; Fal17; Ehm21; Pri17b; Lyo21; Ngo 18; Pri17a; Dav 20; AM23] Including databases CES selector, ecoinvent 3, EF secondary data

[3] Values for ultimate tensile strength referring to internal results with WAAM. Considered density for stainless steel 7.85 g/cm³ and for titanium 4.4 g/cm³.

7.1.2 Data for DED specific process steps

The second focus is set on DED specific process steps. The analyzed literature showed LCA in very different levels of detail and is focused on WAAM and LMD, extensive publications for WLAM where not found. Once again, the data is clustered by material classes. Steel and stainless steel alloys are merged because the impact on the SEC of the DED process step can be neglected and the extent of the data is enlarged. Factors which influence the result of the SEC are the size, design and weight of the evaluated part, the deposition rate of the process as well as the machine setup. In addition, varying boundary conditions explain the wide range of SEC values. Pre- and post-processing steps are not included.

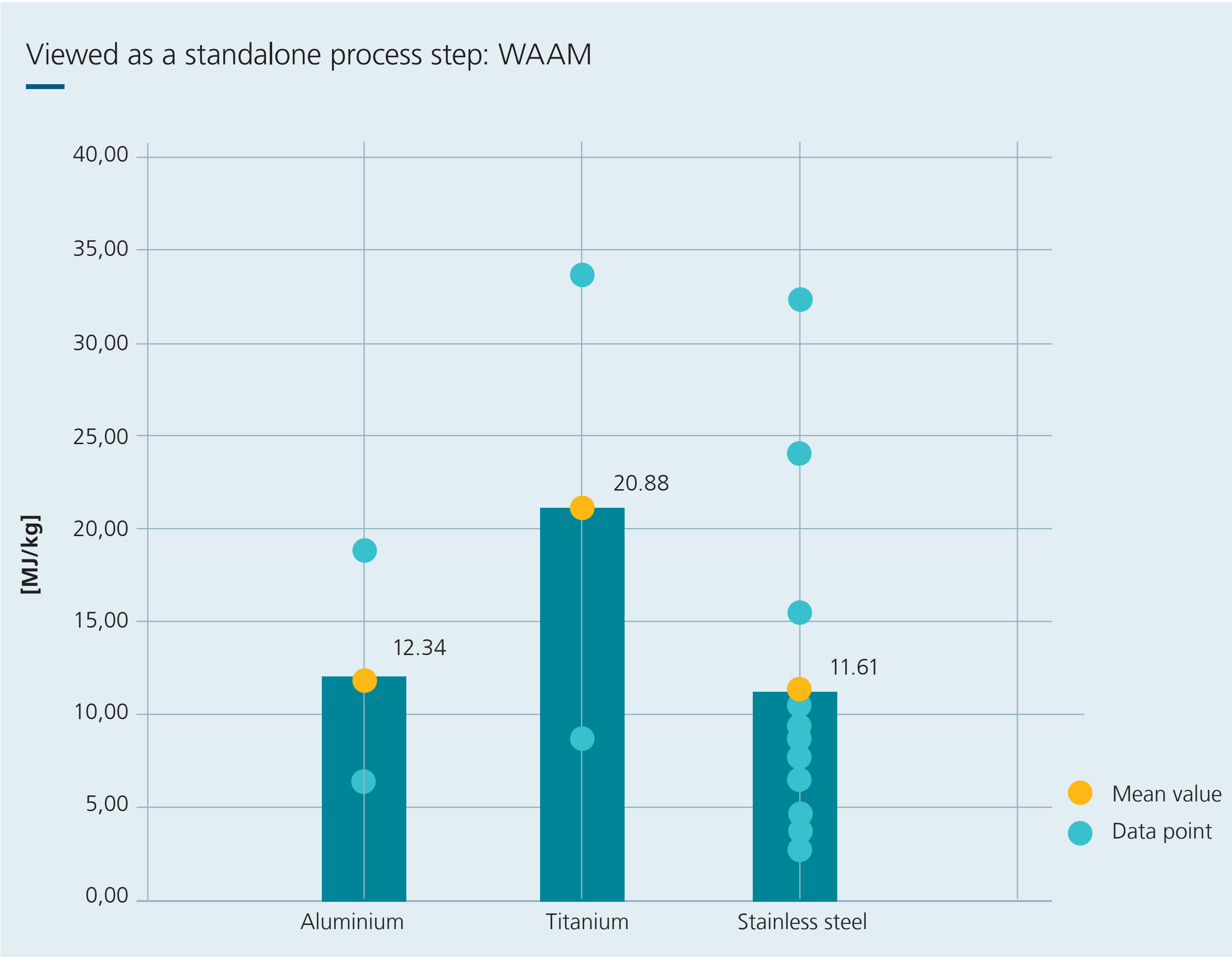


Figure 18: Summary of WAAM data with data points and mean value

An increasing deposition rate leads to a decreasing overall SEC, since periphery and handling energy consumptions are mostly time dependent. For example in [Sha23] a comparison of different WAAM deposition rates shows the potential to halve the SEC by increasing from 0.5 kg/h to 5 kg/h.

Furthermore, a more complex design will lead to an increasing SEC, because more idle times are needed. The comparison of energy sources highlights a significant drawback for laser sources attributed to their low efficiency. Specifically, when examining the average values for LMD (121.3 MJ/kg) and WAAM (12.9 MJ/kg), irrespective of the material, a nearly tenfold difference becomes evident.

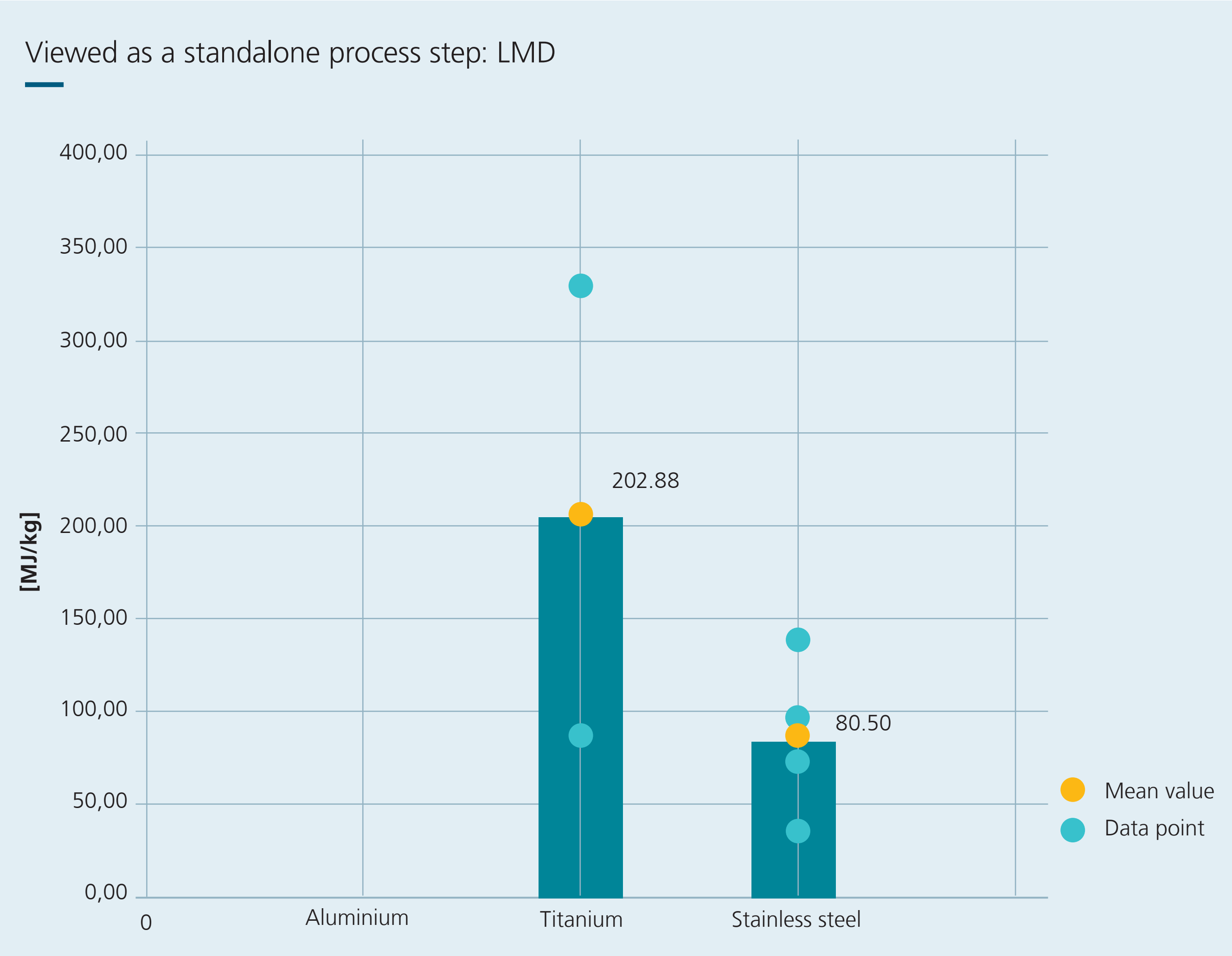


Figure 19: Summary of LMD data with data points and mean value

The shown values are based on a literature research including the following publications:
[Sha23; AM23; Bek18; Pri19; Pri20; Rei23; Kok23b; Jac16; Le13; Gou22; Pen17; Jia19]

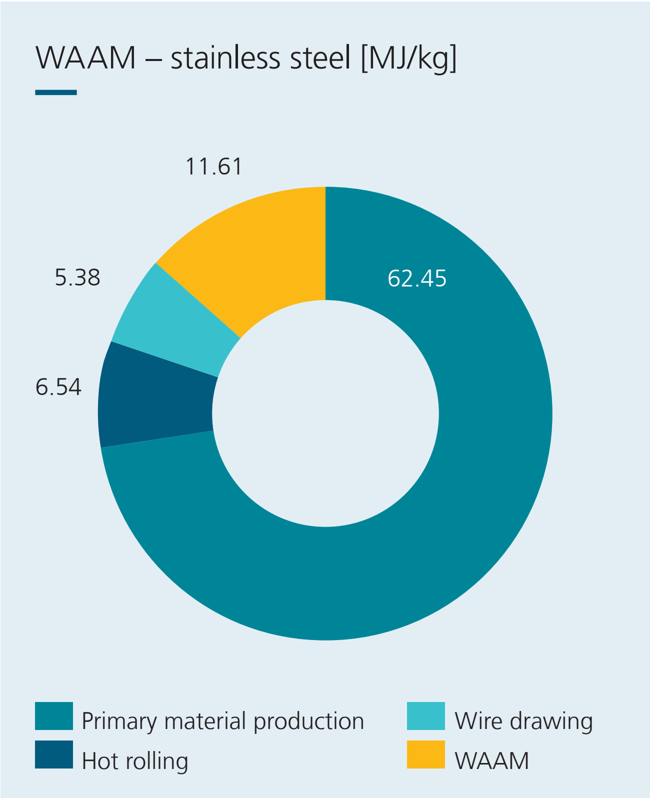
7.2 Impact analysis and comparison of the process phases

To compare the different phases of material processing and the DED process step, the material dependent mean values of the SEC are graphically presented.

As stated earlier, the material processing chain, in particular the primary material production, can be seen as one main impacting factor, even though the impact highly varies. E.g. for the WAAM option with titanium, the primary material production has a share of 93 % and the DED process step only 3 %. In contrast to this, the DED process step accounts for more than half, if Stainless steel is processed with LMD.

By far the overall energetically most favorable option, including material processing and DED, was determined for WAAM of stainless steel (86 MJ/kg). Contrary the processing of titanium with LMD considers approximately the tenfold (892 MJ/kg).

The second highest value was evaluated for WAAM processing titanium (663 MJ/kg). The processing of aluminum with WAAM results in 181 MJ/kg and the combination of LMD and stainless steel in 157 (MJ/kg). The comparison shows the importance to optimize the energy consumption in both fields, material processing and DED process steps.



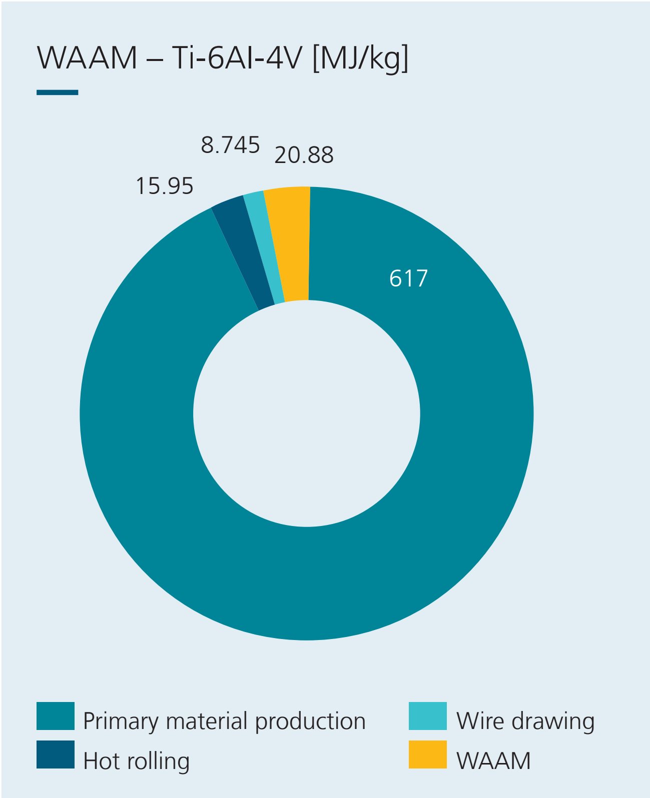


Figure 20: Summary of the SEC for WAAM

When examining material processing, optimizing material circulation holds significant potential for reducing the SEC through the incorporation of secondary materials. This entails a scenario where a substantial portion of the initial material production is satisfied by utilizing a greater quantity of recycled material. Conducting a precise analysis of the material processing, specific to the alloy in question, is therefore indispensable for assessing potential savings and the feasibility of incorporating secondary materials. A popular comparison is the use of secondary aluminum instead of the primary mining option. The energy demand can be reduced from 113 MJ/kg for the primary production to 13.6 MJ/kg for the secondary option [Rom 98]. The qualification of DED processes processing partly secondary material is therefore a promising development to reduce the energy demand. When utilizing powder as feedstock material in LMD, the powder utilization factor becomes of high importance. The literature presents a wide range of values [Ma17], with the reported value of 65 % for powder utilization [Ser11] falling within the middle of this spectrum. The efficiency of powder utilization is notably influenced by various factors, including the machine setup, particularly the choice of wire nozzle in comparison to the laser spot size.

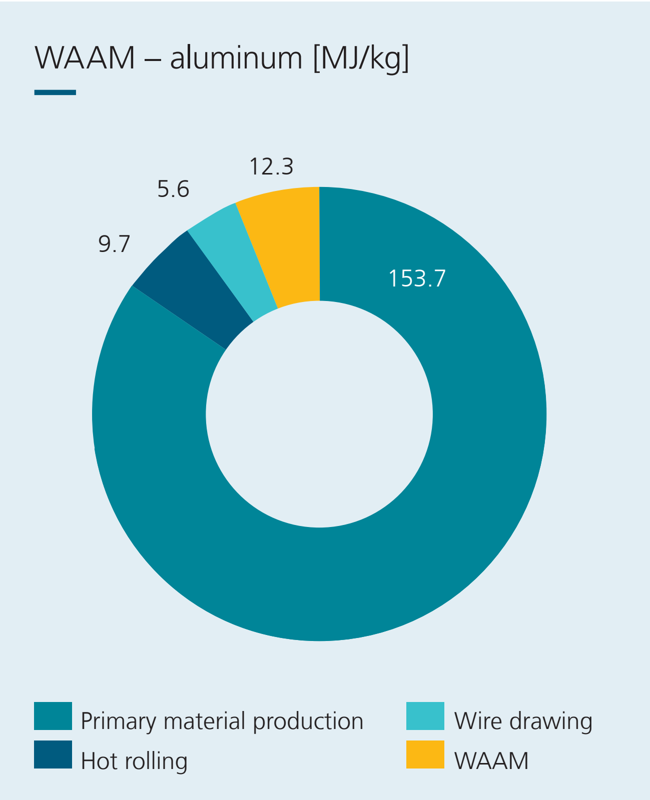


Figure 21: Summary of the SEC for WAAM

Additionally, the strategy employed for path planning, including cooling times, impacts the utilization factor by determining the extent of non-welding sections where the powder feed may partially remain. It is crucial to optimize the machine setup to facilitate the straightforward and reliable collection of unused powder. Subsequently, specific sieving and powder preparation processes are required to ensure recyclability.

Since all the shown values are given in SEC, the CO_2 emission intensity of the grid is of high importance to compare the impact on climate change. In case that energy intensive process steps cannot be avoided, the use of renewable energy sources is indispensable. Furthermore, the DED process step is likely linked to a local manufacturing, which means the CO_2 emissions can be significantly reduced if the energy demand is covered by on-site solar electricity or other green electricity.

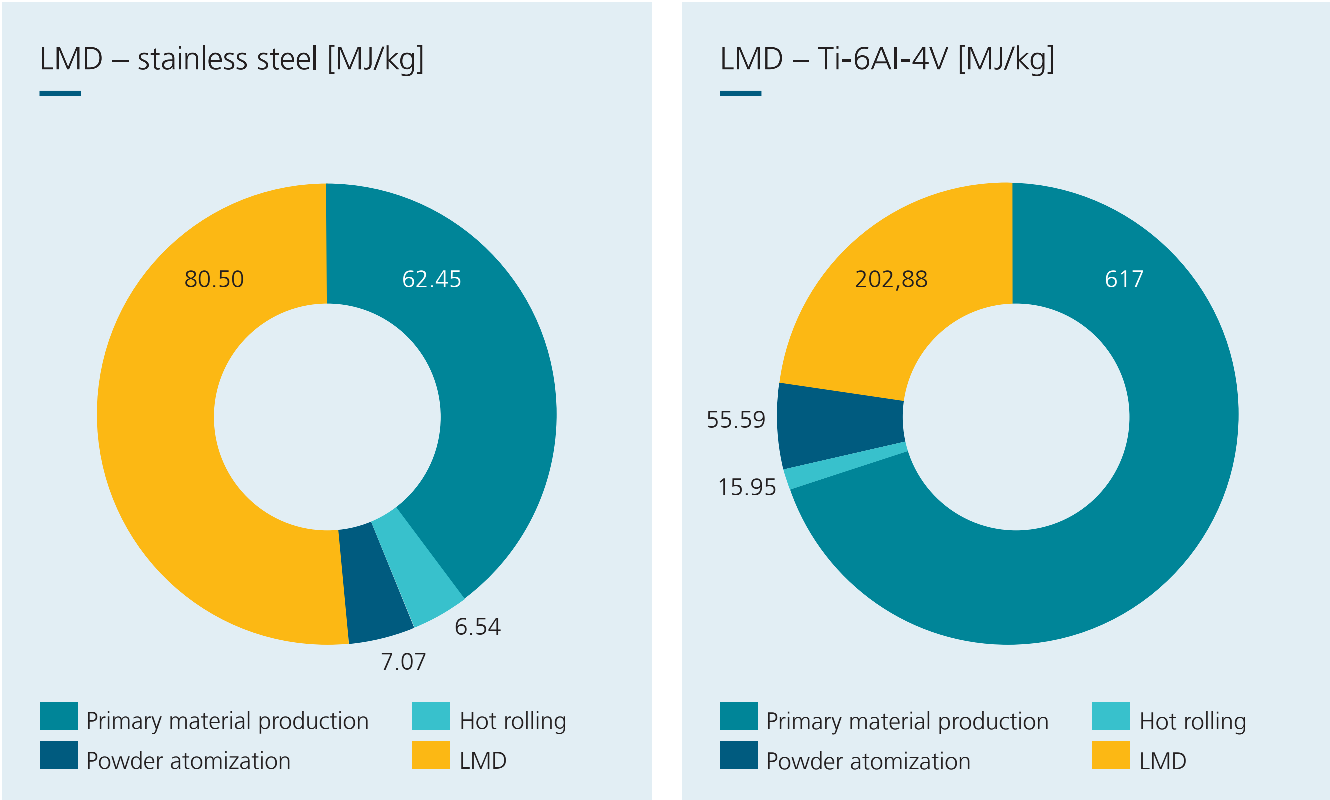


Figure 22: Summary of the SEC for LMD

Precise Life Cycle Assessments hinge on an extensive data foundation for material processing and Directed Energy Deposition steps.«

8. Summary & Conclusion

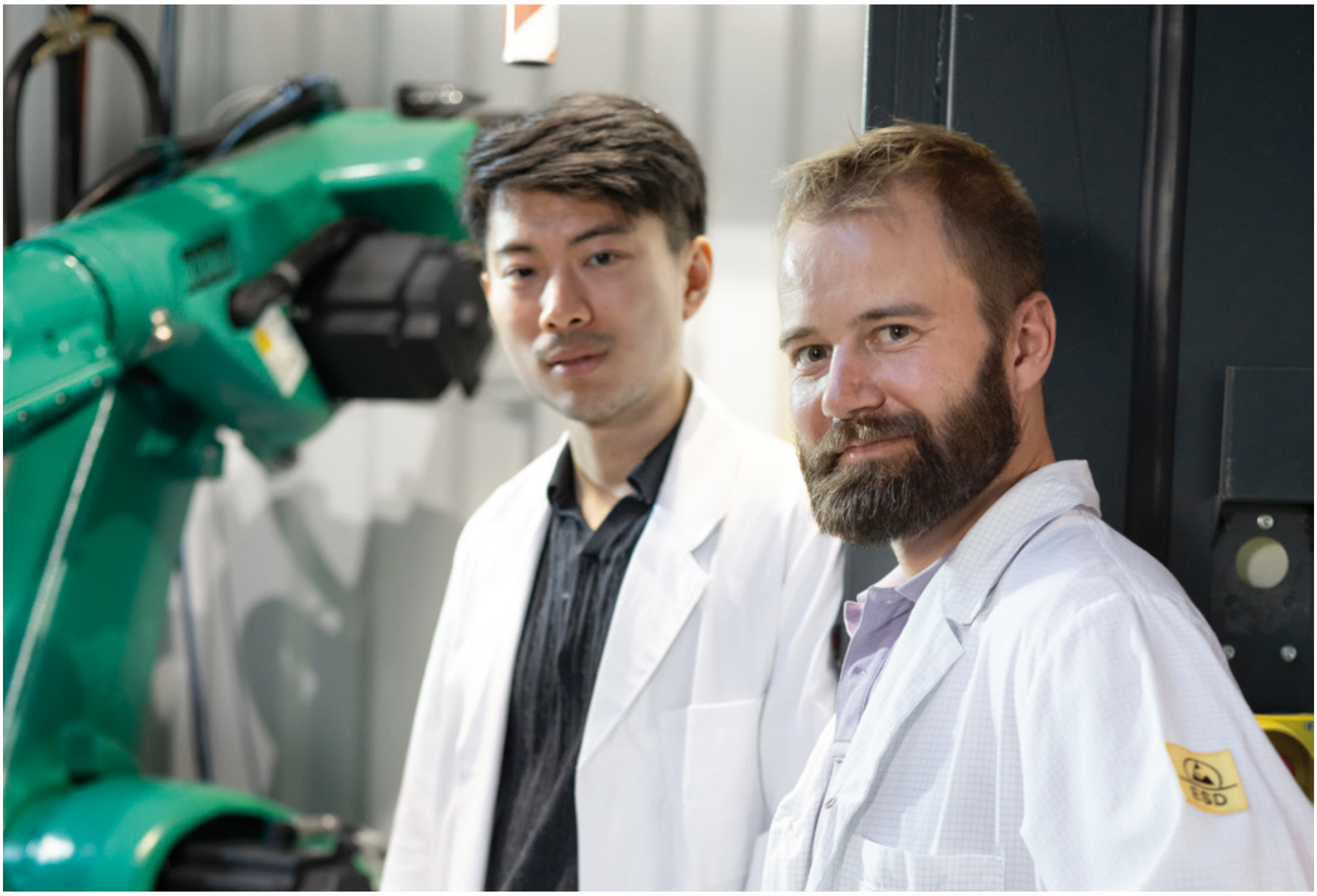
In this Deep Dive, the potential of addressing sustainability aspects in manufacturing through DED technologies is explored. Key motivating factors for utilizing DED to reduce carbon emissions include optimized primary material usage, lightweight design possibilities, and on-demand production scenarios. This study primarily focuses on a cradle-to-gate analysis of metal parts, encompassing all process steps, from the provision of feedstock materials to the DED manufacturing steps themselves. This emphasis aims to identify, comprehend, and quantify the primary influencing factors on energy demand and environmental impact. Several factors are compared, with the type of feedstock, material alloy, and DED energy source emerging as the most significant for further evaluation.

To facilitate a meaningful comparison between the DED manufacturing approach and traditional techniques, existing literature and LCA studies are reviewed. The comparison between DED and machining reveals a strong dependence on the solid-to-cavity ratio of the specific part. Particularly for low values, DED emerges as a less energy intensive approach. The analysis shows that the results are highly dependent on the selected boundary conditions, material type and the data used.

LCA studies follow a rigorous methodology and specific standards are employed to ensure broad comparability. ISO standards, such as ISO 14040 and 14044, provide an important framework for assessing products or processes. The main phases, goal and scope definition, inventory analysis, impact assessment and interpretation of the results are explained as well as impact categories and life cycle models. Clear reporting is essential in LCA to maintain transparency and facilitate the review process. The quality of the data used has a significant influence and helps clarify assumptions.

This Deep Dive provides an analysis of available data in the field of additive manufacturing, specifically focusing on material processing steps and DED manufacturing processes. Three distinct material categories, namely stainless steel, aluminum, and titanium, as well as two types of feedstock, powder and wire, are taken into account.
When comparing the mean values of available data, which are represented in terms of specific energy demand (SEC), it becomes evident that titanium has the most significant environmental impact due to its energy-intensive processing steps. For example, the overall SEC for processing titanium powder as feedstock is notably high at 689 MJ/kg, whereas processing stainless steel wire is considerably more energy-efficient at 86 MJ/kg.

Additionally, the two DED process types for LMD and WAAM are compared. It highlights a notable drawback associated with laser sources, which are characterized by their low efficiency. Specifically, when examining the average energy consumption values for LMD (121.3 MJ/kg) and WAAM (12.9 MJ/kg), regardless of the material being used, a nearly



tenfold difference in energy efficiency between the two methods becomes apparent. The data analysis section culminates in a comprehensive assessment of the DED process and material options, taking into consideration the respective mean values derived from the summarized data. This assessment consistently highlights the high impact of material processing steps in most cases. In summary, this deep dive reveals a wide array of sustainability aspects related to DED manufacturing scenarios, which contribute to a better understanding of the intricate path toward conducting LCA. It is essential to note that the success of an LCA study is highly contingent on the availability of accurate and relevant data, which must align with specific contextual factors. Consequently, a thorough evaluation of each potential application is imperative to yield a meaningful assessment of its environmental impact.

9. References

[AM23] AM POWER, AMPower Sustainablity Calculator Metal – v1.2.5, 2023.

[Bek18] BEKKER A. C., VERLINDEN J. C., "Life cycle assessment of wire + arc additive manufacturing compared to green sand casting and CNC milling in stainless steel", Journal of Cleaner Production, vol. 177, 2018, p. 438-447.

[Dav20] DAVIS W., LUNETTO V., PRIARONE P. C., CENTEA D., SETTINERI L., "An appraisal on the sustainability payback of additively manufactured molds with conformal cooling", Procedia CIRP, vol. 90, 2020, p. 516-521.

[Ehm21] EHMSEN S., YI L., AURICH J. C., "Process Chain Analysis of Directed Energy Deposition: Energy flows and their influencing factors", Procedia CIRP, vol. 98, 2021, p. 607-612.

[Eur21] EUROPEAN ENVIROMENT AGENCY, EU level – Greenhouse gas emission intensity of electricity generation 2021. www.eea.europa.eu/data-and-maps/daviz/co2-emission-intensity-13#tab-googlechartid_chart_11, accessed on May 15th, 2023.

[Fal17] FALUDI J., BAUMERS M., MASKERY I., HAGUE R., "Environmental Impacts of Selective Laser Melting: Do Printer, Powder, Or Power Dominate?", Journal of Industrial Ecology, vol. 21S1, 2017.

[Gou22] GOUVEIA J. R., PINTO S. M., CAMPOS S., MATOS J. R., SOBRAL J., ESTEVES S., OLIVEIRA L., "Life Cycle Assessment and Cost Analysis of Additive Manufacturing Repair Processes in the Mold Industry", Sustainability, vol. 14 no. 4, 2022, p. 2105.

[Hui16] HUIJBREGTS M., Z.J.N. STEINMANN, P.M.F. ELSHOUT, G. STAM, F. VERONES, M.D.M. VIEIRA, A. HOLLANDER, M. ZIJP, R. VAN ZELM, ReCiPe 2016 A harmonized life cycle impact assessment method at midpoint and endpoint level Report I: Characterization, 2016.

[Int19] INTERNATIONAL ENERGY AGENCY, Tranforming industry through CCUS 2019, www.iea.org/reports/transforming-industry-through-ccus, accessed May 15th, 2023.

[Int20] IINTERNATIONAL ENERGY AGENCY, Iron and steel technology roadmap 2020, www.iea.org/reports/iron-and-steel-technologyroadmap, accessed May 15th, 2023.

[ISO06a] ISO INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, "ISO 14025:2006 Environmental labels and declarations – Type III environmental declarations – Principles and procedures", ISO 14025:2006, 2006.

[ISO06b] ISO INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, "ISO 14040:2006 Environmental management – Life cycle assessment – Principles and framework", ISO 14040:2006, 2006.

[ISO06c] ISO INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, "ISO 14044:2006 Environmental management - Life cycle assessment - Requirements and guidelines", ISO 14044:2006, 2006.

[ISO15] ISO INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, "ISO 14001:2015 Environmental management systems – Requirements with guidance for use", 2015.

[Jac16] JACKSON M. A., VAN ASTEN A., MORROW J. D., MIN S., PFEFFERKORN F. E., "A Comparison of Energy Consumption in Wire-based and Powder-based Additive-subtractive Manufacturing", Procedia Manufacturing, vol. 5, 2016, p. 989-1005.

[Jia19] JIANG Q., LIU Z., LI T., CONG W., ZHANG H.-C., "Emergy-based life-cycle assessment (Em-LCA) for sustainability assessment: a case study of laser additive manufacturing versus CNC machining", The International Journal of Advanced Manufacturing Technology, vol. 1029-12, 2019, p. 4109-4120.

[Kok23a] KOKARE S., OLIVEIRA J. P., GODINA R., "Life cycle assessment of additive manufacturing processes: A review", Journal of Manufacturing Systems, vol. 68, 2023, p. 536-559.

[Kok23b] KOKARE S., OLIVEIRA J. P., SANTOS T. G., GODINA R., "Environmental and economic assessment of a steel wall fabricated by wire-based directed energy deposition", Additive Manufacturing, vol. 61, 2023, p. 103316.

[Le13] LE BOURHIS F., KERBRAT O., HASCOET J.-Y., MOGNOL P., "Sustainable manufacturing: evaluation and modeling of environmental impacts in additive manufacturing", The International Journal of Advanced Manufacturing Technology, vol. 699-12, 2013, p. 1927-1939.

[Liu18] LIU Z., JIANG Q., CONG W., LI T., ZHANG H.-C., "Comparative study for environmental performances of traditional manufacturing and directed energy deposition processes", International Journal of Environmental Science and Technology, vol. 15 no. 11, 2018, p. 2273-2282.

[Lyo21] LYONS R., NEWELL A., GHADIMI P., PAPAKOSTAS N., "Environmental impacts of conventional and additive manufacturing for the production of Ti-6Al-4V knee implant: a life cycle approach", The International Journal of Advanced Manufacturing Technology, vol. 1123-4, 2021, p. 787-801.

[Ma17] MA K., SMITH T., LAVERNIA E. J., SCHOENUNG J. M., "Environmental Sustainability of Laser Metal Deposition: The Role of Feedstock Powder and Feedstock Utilization Factor", Procedia Manufacturing, vol. 7, 2017, p. 198-204.

[Mor07] MORROW W. R., QI H., KIM I., MAZUMDER J., SKERLOS S. J., "Environmental aspects of laser-based and conventional tool and die manufacturing", Journal of Cleaner Production, vol. 15 no. 10, 2007, p. 932-943.

[Ngo18] NGO T. D., KASHANI A., IMBALZANO G., NGUYEN K. T., HUI D., "Additive manufacturing (3D printing): A review of materials, methods, applications and challenges", Composites Part B: Engineering, vol. 143, 2018, p. 172-196.

[Pen17] PENG S., LI T., WANG X., DONG M., LIU Z., SHI J., ZHANG H., "Toward a Sustainable Impeller Production: Environmental Impact Comparison of Different Impeller Manufacturing Methods", Journal of Industrial Ecology, vol. 21S1, 2017, S216-S229.

[Pri17a] PRIARONE P. C., INGARAO G., "Towards criteria for sustainable process selection: On the modelling of pure subtractive versus additive/subtractive integrated manufacturing approaches", Journal of Cleaner Production, vol. 144, 2017, p. 57-68.

[Pri17b] PRIARONE P. C., INGARAO G., DI LORENZO R., SETTINERI L., “Influence of Material-Related Aspects of Additive and Subtractive Ti-6Al-4V Manufacturing on Energy Demand and Carbon Dioxide Emissions”, Journal of Industrial Ecology, vol. 21S1, 2017, S191-S202.

[Pri19] PRIARONE P. C., CAMPATELLI G., MONTEVECCHI F., VENTURINI G., SETTINERI L., “A modelling framework for comparing the environmental and economic performance of WAAM-based integrated manufacturing and machining”, CIRP Annals, vol. 68 no. 1, 2019, p. 37-40.

[Pri20] PRIARONE P. C., PAGONE E., MARTINA F., CATALANO A. R., SETTINERI L., “Multi-criteria environmental and economic impact assessment of wire arc additive manufacturing”, CIRP Annals, vol. 69 no. 1, 2020, p. 37-40.

[Rei23] REIS R. C., KOKARE S., OLIVEIRA J. P., MATIAS J. C., GODINA R., “Life cycle assessment of metal products: A comparison between wire arc additive manufacturing and CNC milling”, Advances in Industrial and Manufacturing Engineering, vol. 6, 2023, p. 100117.

[Rom98] ROMBACH G., “Integrated assessment of primary and secondary aluminium production. Material for the Future: Aluminium Products and Processes.”, DMG Business Media, Ltd., 1998.

[Ser11] SERRES N., TIDU D., SANKARE S., HLAWKA F., ”Environmental comparison of MESO-CLAD® process and conventional machining implementing life cycle assessment”, Journal of Cleaner Production, vol. 199-10, 2011, p. 1117-1124.

[Sha23] SHAH I. H., HADJIPANTELIS N., WALTER L., MYERS R. J., GARDNER L., “Environmental life cycle assessment of wire arc additively manufactured steel structural components”, Journal of Cleaner Production, vol. 389, 2023, p. 136071.

[WAA23] WAAM3D LIMITED, Case study – Wire Arc Additive Manufacturing (WAAM) minimises envirmental impact for marine components, www.waam3d.com/resources/downloadables, accessed June 12th, 2023.

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