AMPOWER INSIGHTS

Sustainability of Metal Additive Manufacturing

Analysis of the CO_2 footprint along the Additive Manufacturing process chain

INSIGHTS GAINED:

- When is Additive Manufacturing more sustainable than traditional manufacturing?
- What are significant influencing factors for a low carbon footprint?
- How can users leverage Additive Manufacturing to reach their carbon goals?

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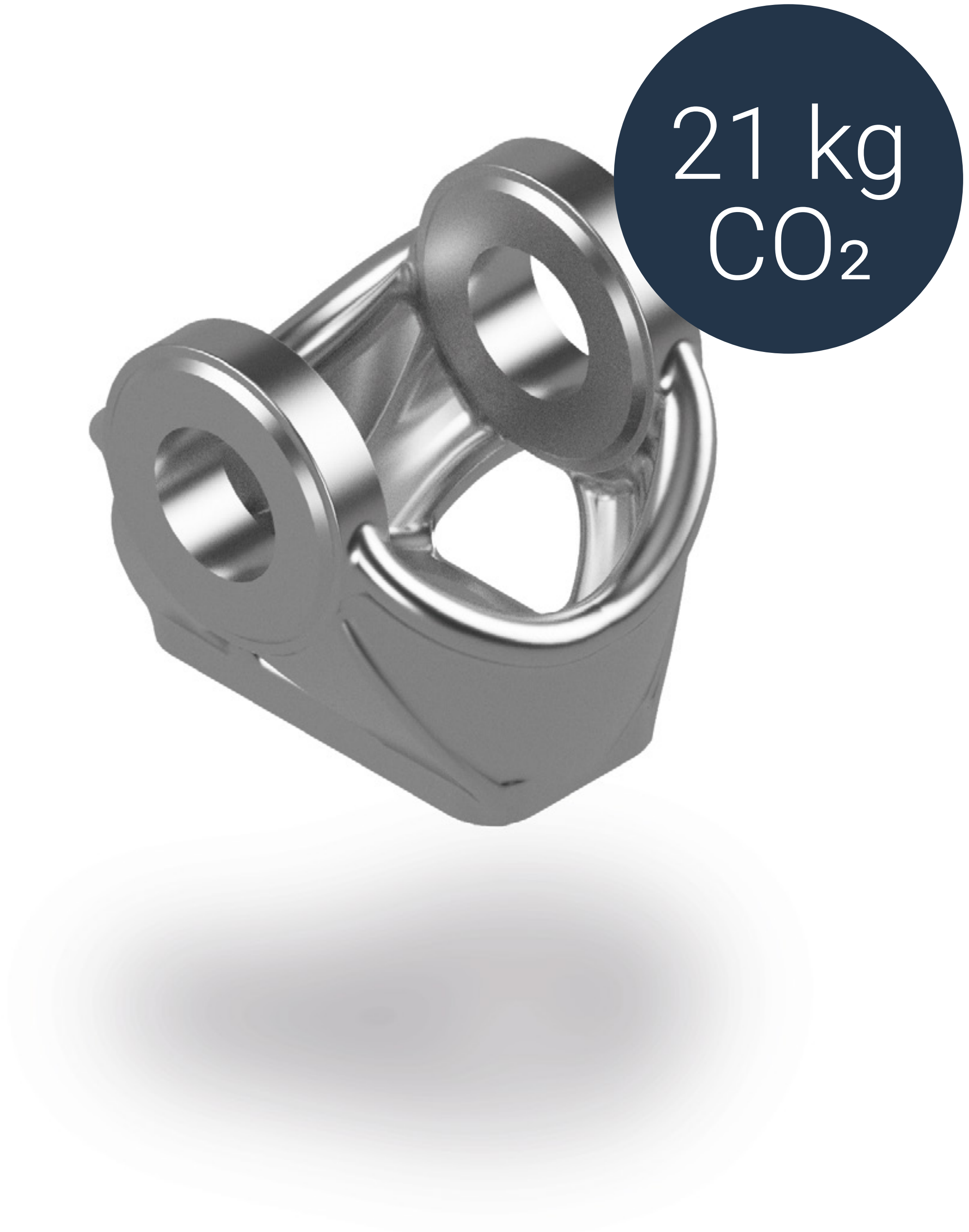

L-PBF TITANIUM PART, MANUFACTURED IN EUROPE

Insights gained

When is Additive Manufacturing more sustainable than traditional manufacturing?
What are significant influencing factors for a low carbon footprint?
How can users leverage Additive Manufacturing to reach their carbon goals?

Management summary

Rising atmospheric CO_2 level and resulting weather phenomena have finally changed the general mind set of people, politics and industry regarding fossil fuel emission over the last 5 years. The majority now strives towards reduced carbon emission and a more sustainable way of living.

In this environment Additive Manufacturing has been promoted as one production technology to reduce emissions and consequently the carbon footprint of the part production and complete product life cycle. However, detailed calculations looking at the complete production route and objective comparisons against conventional manufacturing have been scarce.

There is no general answer to which manufacturing technology has the lowest carbon footprint. The overall footprint is heavily influenced by the alloy group as well as the part geometry. Complex geometries with high buy-to-fly ratio are favorable for net-shape technologies such as AM and casting, while simple parts might be most sustainable if milled.

In the framework of this study, AMPOWER developed a Sustainability Calculator for the CO_2 footprint. This tool enables the assessment of a variety of alloy and technology combinations as well as customization of the process routes.

Considering titanium alloys, AM technologies of PBF can reduce the carbon footprint significantly when compared to milling. Due to the ability to manufacture weight optimized designs, the material input and therefore the embodied energy is significantly smaller and compensates for higher energy consumption in the part manufacturing process. The embodied energy is less prominent for aluminum alloys and stainless steels. A surprisingly positive outlook can be seen for high productivity Binder Jetting technologies. Achieving a high utilization across the whole process chain from 3D printer to debinding and sintering oven can lead to low carbon footprint of future applications.

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MACHINED TITANIUM PART, MANUFACTURED IN EUROPE

Content

About AMPOWER

AMPOWER is the leading strategy consultancy and thought leader in the field of industrial Additive Manufacturing. The company advises investors, start-ups as well as suppliers and users of 3D printing technology in strategic decisions, due diligence investigations and provides unique access to market intelligence. On operational level, AMPOWER supports the introduction of Additive Manufacturing through targeted training programs, support in qualification of internal and external machine capacity and technology benchmark studies. The company was founded in 2017 and is based in Hamburg, Germany, operating worldwide.

Sustainability

Transforming manufacturing

Rising atmospheric CO_2 level and resulting weather phenomena have finally changed the general mind set of people, politics and industry regarding fossil fuel emissions over the last 5 years. The majority now strives towards reduced carbon emissions and a more sustainable way of living. The carbon footprint of each product has become an increasing incentive for purchase. Consequently, manufacturers are facing the challenge to reduce or even eliminate the carbon footprint of their products in order to meet today's and tomorrow's sustainability requirements.

Resource efficient and sustainable manufacturing transforms more and more into a key decision maker in the metal manufacturing industry. While today the demand is pushed by society and customers, in the future governmental regulations and penalties will be getting more severe and further drive the change towards sustainable manufacturing processes. As a major instrument for change, regulators around the globe are increasing the cost for carbon emissions for issued emission certificates. It is expected that the cost of emitting CO_2 will continuously increase over the next decades. Hence, in a few years, companies with a low carbon footprint will have a major competitive advantage on the market, especially selling into markets promoting zero-emission policies such as the EU.

However, today, industrial production still plays a major role in global carbon emission. Manufacturers are searching for ways to reduce their overall carbon footprint along the whole value chain and are directing investments to achieve this goal. For example, ARCELORMITTAL announced to run their steel plant in Bilbao, Spain, completely on renewable energy sources.

In this environment Additive Manufacturing has been promoted as one production technology to reduce emissions and consequently the carbon footprint of the part production and complete product life cycle. However, detailed calculations looking at the complete production route and objective comparisons against conventional manufacturing have been scarce.

"The European Union has committed to climate neutrality in 2050 and intends to increase its 2030 climate ambitions by cutting its emissions by at least 55% compared to 1990."

JOINT STATEMENT: THE UNITED STATES AND THE EUROPEAN UNION COMMIT TO GREATER COOPERATION TO COUNTER THE CLIMATE CRISIS, MARCH 9, 2021

"The allocation of energy resources will be further rationalized, and utilization efficiency will be greatly improved. Energy consumption and carbon dioxide emissions per unit of GDP will be reduced by 13.5% and 18% respectively, total emissions of the main pollutants will continue to fall, and the rate of forest coverage will increase to 24.1%."

CHINA'S 14TH FIVE-YEAR PLAN, MARCH 12, 2021

"With our commitment to turn our operations carbon neutral by 2030, SIEMENS has set a clear signal that companies must take leadership in driving decarbonization. It is our firm belief that companies play a pioneering role in the fight against climate change. Our goal is clear: All SIEMENS production facilities and buildings worldwide are to achieve a net zero-carbon footprint by 2030."

SIEMENS SUSTAINABILITY STATEMENT, 2022

"The company intends to be net carbon neutral by 2050 at the latest. A new interim milestone is the targeted 40-percent reduction in CO_2 emissions per vehicle in Europe by 2030. As well as ensuring the green use of its vehicles, VOLKSWAGEN is also working to decarbonize both production and supply chain."

VOLKSWAGEN WAY TO ZERO STRATEGY, APRIL 29, 2021

"GE is setting a goal to become carbon neutral in our facilities and operations by 2030. As part of our longstanding commitment to environmental stewardship, human rights, and a culture of integrity and compliance, we've been working for years to reduce our greenhouse gas emissions."

GENERAL ELECTRIC CLIMATE CHANGE STATEMENT, OCTOBER, 2020

Sustainability and the impact of manufacturing technologies

Sustainability is commonly described along the lines of three dimensions: environmental, economic and social.

Manufacturing processes predominantly impact the environmental aspect of the three sustainability dimensions. The sourcing of metal materials and further downstream processing of metal components consumes large amounts of resources and energy. The sourcing of raw materials is associated with a strong social impact since many alloy components are found in countries with low health and safety as well as general social standards.

The recent pandemic unveiled the fragility of current global supply chains. Additive Manufacturing offers the tools to enable a refocus on local supply chain. Products can be manufactured right at the assembly location or end user location. This has an additional impact on the economic sustainability pillar, since local sourcing leads to local value creation and to a higher supply chain resilience in case of a crisis.

> "Sustainability is meeting the needs of the present without compromising the ability of future generations to meet their own needs."
>
> UNITED NATIONS BRUNTLANDCOMMISSION, 1987

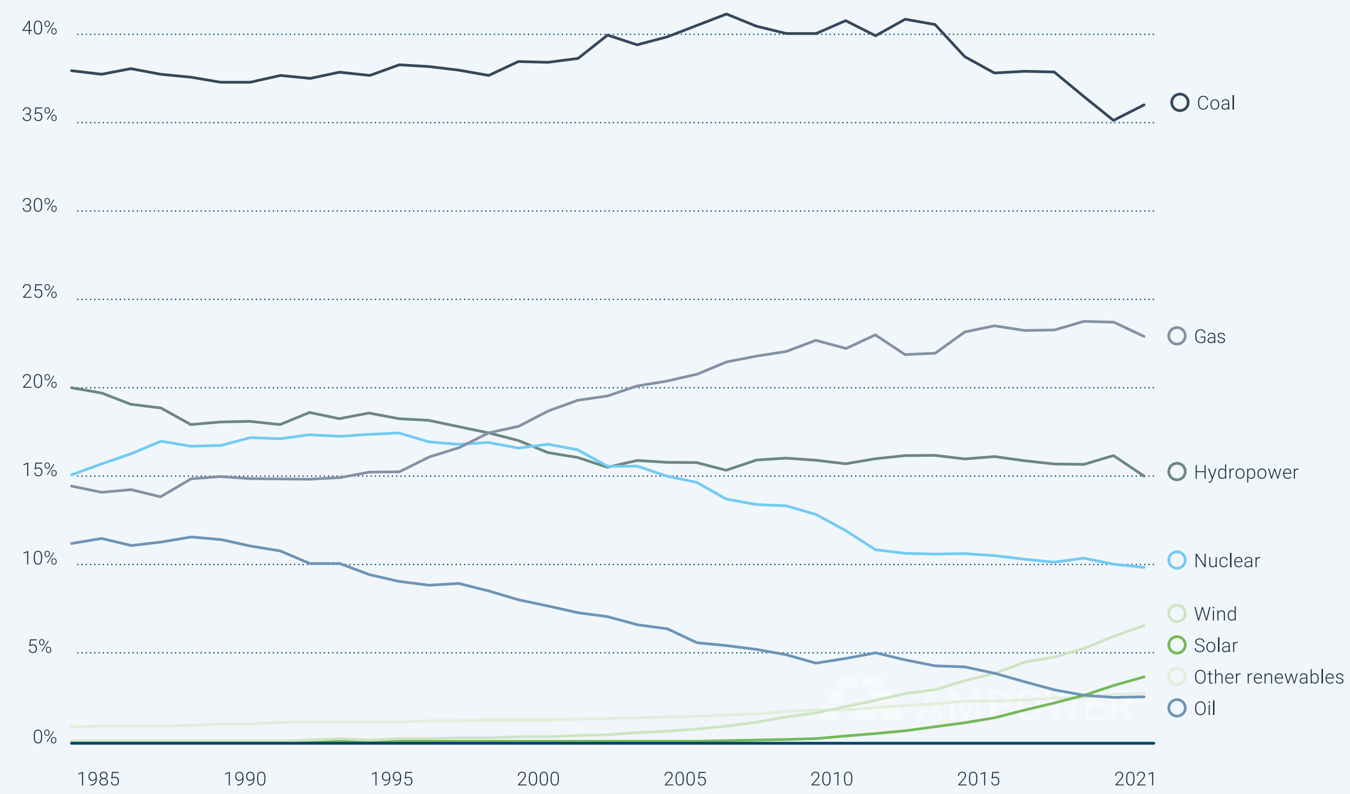
Saving energy means saving CO_2

Carbon emission in manufacturing are directly linked to the energy consumption throughout the process chain. Thus, CO_2 emission can be most effectively reduced by sourcing renewable energy or reducing energy consumption overall.

Compared to other industrial processes and manufacturing technologies such as casting, where heat and direct CO_2 emission are created by burning fossil fuels, metal Additive Manufacturing is only using electric energy. The required electric energy results in varying amounts of carbon emission, depending on where it is sourced.

Subsequently, manufacturing companies can reduce or eliminate their carbon footprint by sourcing renewable energy. However, calculations show, that the overall increase of global energy consumption makes it nearly impossible to simply switch to renewable energy. Currently carbon emission goals can only be reached, if the overall energy consumption is reduced at the same time.

Share of global electricity production by source



SOURCE: OUR WORLD IN DATA BASED ON BP STATISTICAL REVIEW OF WORLD ENERGY & EMBER 2017

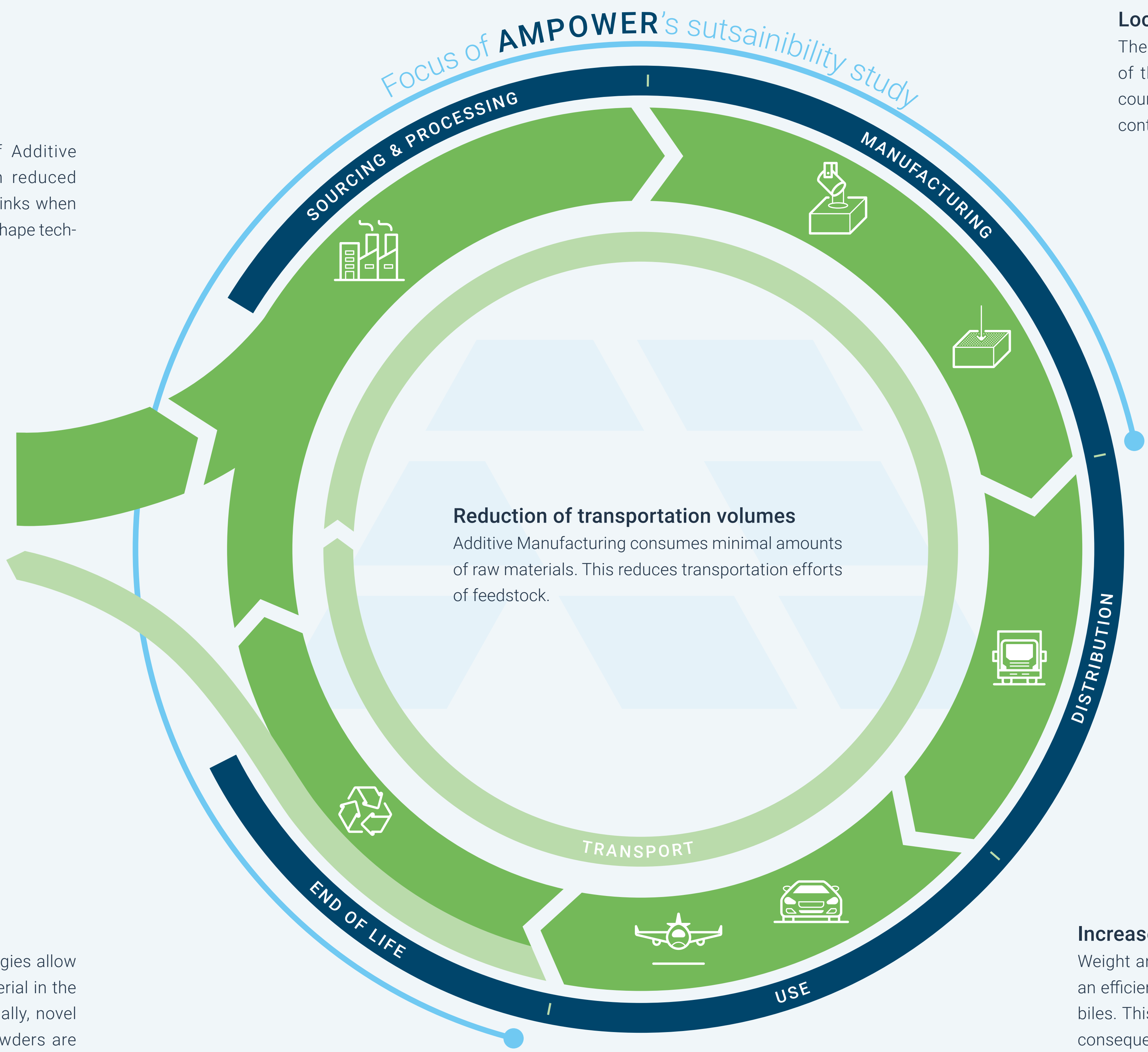
Potential of Additive Manufacturing along the product lifecycle

Material need
The near-net-shape characteristic of Additive Manufacturing technologies result in reduced raw material needs. This advantage shrinks when comparing AM to conventional near net shape technologies such as casting.

Raw materials & ressource extraction

Landfill & energy recovery

Material recycling
Reduced material need for AM technologies allow for higher percentage of reclaimed material in the production of fresh feedstock. Additionally, novel processes for 100% recycled metal powders are currently introduced into the market.



Machining volume
The reduced need for machining due to near-net-shape manufacturing can equalize the typically higher energy needs of AM processes compared to conventional technologies.

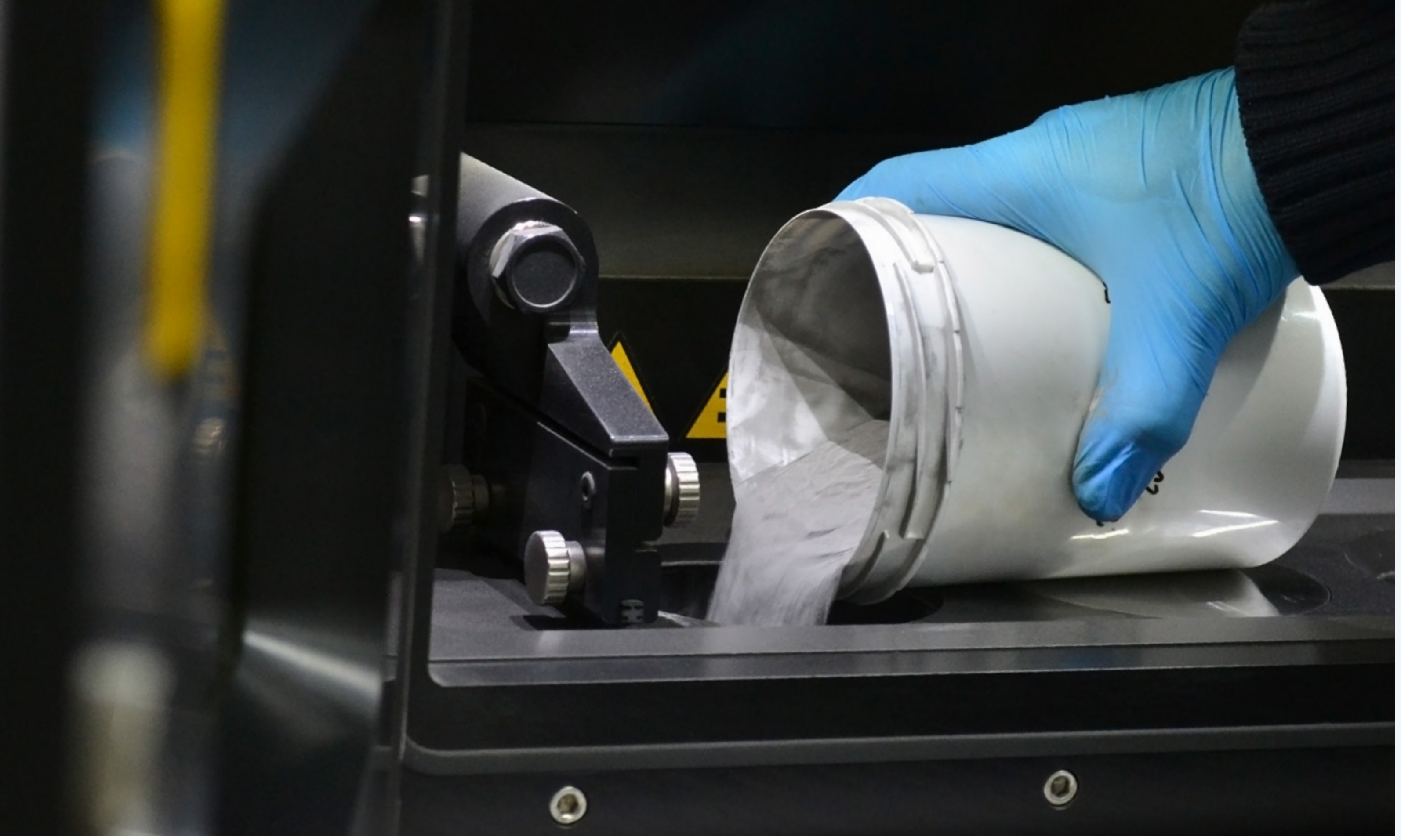
Localized manufacturing
The local energy mix is one of the major drivers of the CO_2 footprint. Localizing the production in countries with high percentage of renewable energy contributes largely to a more sustainable production.

Manufacturing route
AM enables integrated designs, reducing components assembled from multiple parts into one single AM part. Reduced manufacturing, transport and assembly efforts, often additionally to reduced weight, can lead a reduced CO_2 footprint of integrated AM designs.

On demand manufacturing
On demand manufacturing will potentially reduce storage capacities and transportation from large warehouses or manufacturing centers. However, Additive Manufacturing, companies currently tend to centralize manufacturing sites. Typical demands do not yet justify localized, on-demand manufacturing.

Increased product efficiency
Weight and performance optimized designs, unique to AM, allow for an efficiency increase of e.g. turbines, hydraulics, aircrafts or automobiles. This can result in significant savings in operational energy and consequently CO_2 emission over the complete in-use timespan of the AM part or end product. These savings effects can be multitudes larger than the actual production emission. However, the absolute in-use savings of AM parts are strongly depending on the application.

Sustainability Calculator



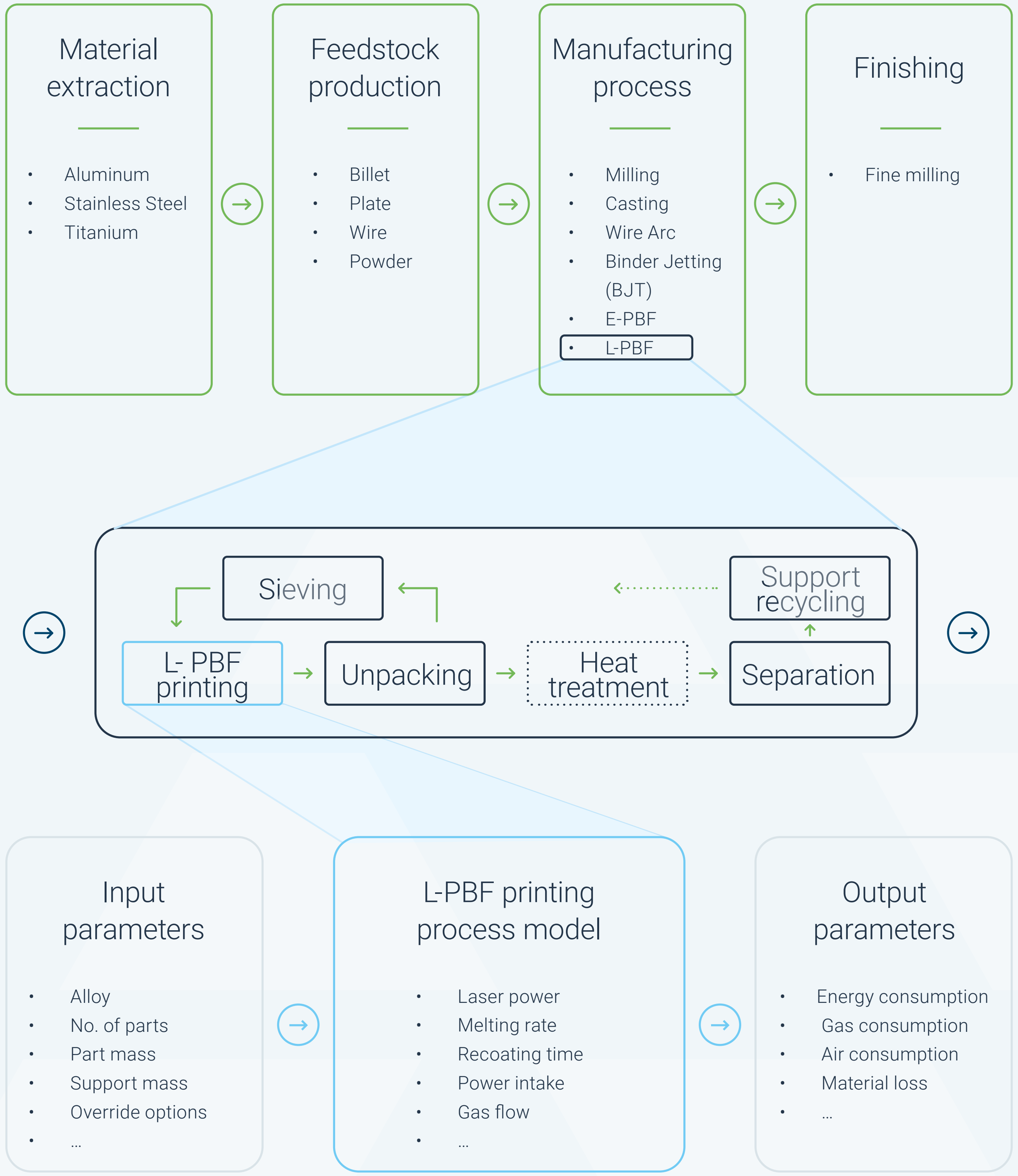
A detailed look at the complete process chain

The AMPOWER Sustainability Calculator allows the calculation of a variety of alloy and technology combinations as well as customization of the process routes. To create a comprehensive tool, the complete process chain from material extraction and feedstock production all the way to the finishing machining operations are considered and implemented.

Each manufacturing process is detailed and broken down to a granular level of its process steps. The description of the different production and manufacturing processes includes all mandatory and optional process steps such as heat treatment for an individualization of the process route. Additionally, material recycling is considered at all sensible stages. The recycling rate can be individually adapted for the feedstock production and within the manufacturing process steps where excess material is produced (e.g. support material or milling chips).

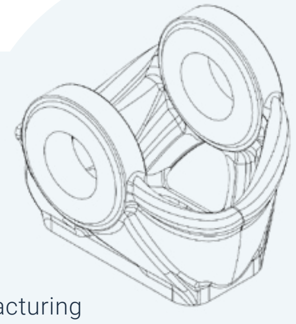
For each process step a detailed process model including all input and output parameters is created. Based on this model the Sustainability Calculator calculates consumption of energy and consumables and converts it into CO_2 emission.

AMPOWER sustainability calculation model



Generic input parameters and easy process comparison

Early in the development and design phase many details needed for an extensive Life Cycle Assessments (LCA) are not known, yet. However, the estimation and comparison of the CO_2 footprint of alternative designs and manufacturing technologies might be a valuable decision parameter. AMPOWER's Sustainability Calculator enables a fast and easy evaluation and comparison. Based on a generic approach, the tool needs minimal input parameters to calculate the CO_2 footprint for a multitude of different manufacturing technologies. Additionally, if alternative or optimized part designs are known, the tool allows a direct comparison of conventional to optimized part designs. This yields the highest result accuracy and a "fair" comparison between different manufacturing technologies.



Conventional part vs. AM optimized design

1:1 comparison
Adopting identical part properties for an early-stage evaluation or if no further part optimization has been done.

Process specific part geometry
Detailing part properties for each manufacturing technology increases calculation accuracy and allows for a "fair" comparison between technologies.

Volume		L-PBF	Wire Arc	BJT	Milling	Sand Casting	
Final part	100						cm^3
Raw part	110						cm^3
Supports	10						cm^3
Surface finished part	333						cm^3
Dimension X	90						mm
Dimension Y	81						mm
Dimension Z	80						mm
Material	Titanium alloy						
Quantity	1,000					AMPOWER	parts

Material choice
The choice of alloy group influences the resulting CO_2 footprint significantly. The drop-down menu allows the selection of aluminum, titanium and stainless steel alloys.

Production volume
AM technologies allow for one-of part production. However, low part quantities might result in low machine utilization and an increased CO_2 footprint.

Besides the required input variables regarding part design and alloy group, the tool offers a variety of options and overrides. If process parameter settings or build job configurations are known, the supplemental information is used to improve the calculation model's accuracy. Additionally, variation in the consumables, process route or part design can be defined.

The Options & Overrides are continuously expanded and updated to further improve the Sustainability Calculator's capabilities and accuracy.

Options & Overwrites

Shielding gas (AM proc. & atomization)		
for Stainless steel	Nitrogen	
for Aluminium alloy	Argon	
L-PBF		
Parts per build job		parts
Build time (melting)		h
Build time (Recoating)		h
Layer height	90	µm
Laser power	1.00	Watt
Heat treatment	included	
Wire Arc		
Melting time		h
Cooling time		h
Heat treatment	included	
Base plate volume		cm^3
% Plate of finished part		%
BJT		
Parts per build job		parts
Build time		h
Layer height	50	µm
Milling		
Blank volume		cm^3

Process overrides
If specific process variables are known, the overrides improve the implemented process model and increase the result accuracy.

Process parameters
Multiple process parameter settings allow for adoption of the model to the user's individual production set up.

Hybrid AM production
In Direct Energy Deposition technologies the baseplate is often part of the final component. An option is available to replicate this in the calculation tool.

Optimized configuration
Optimized configuration to fully utilize powder bed AM processes and actual production times result in the most accurate calculation, if the final build job is known.

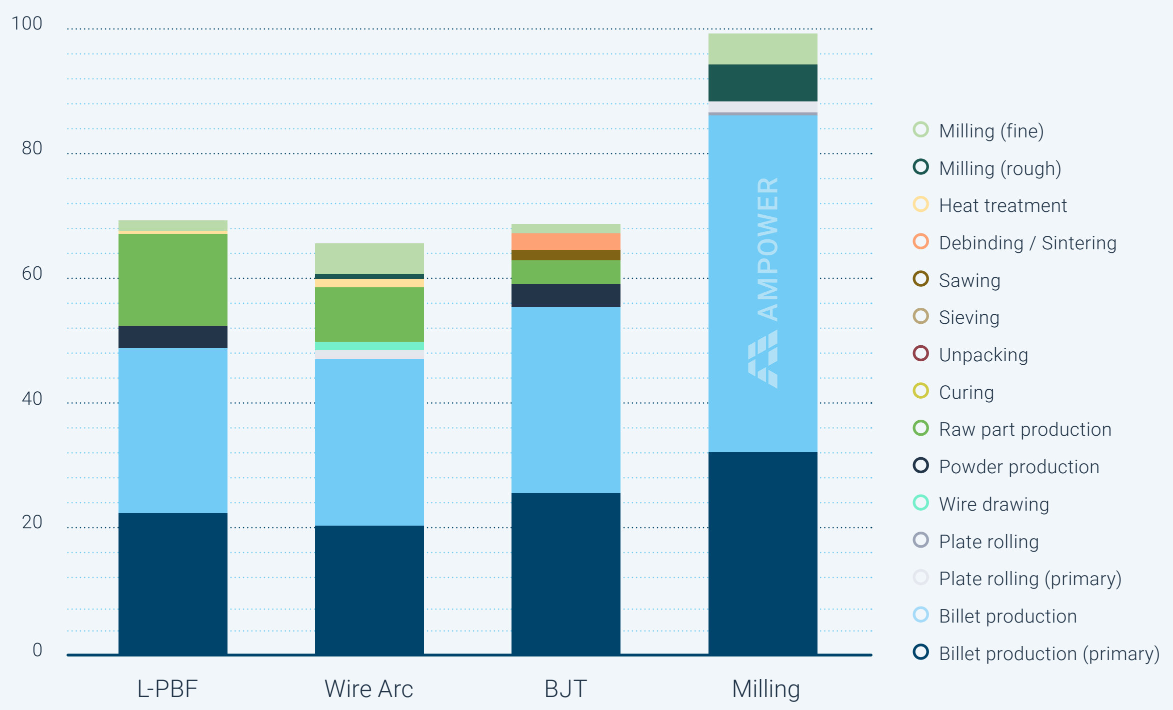
Granular break down of energy consumption and CO_2 emission

Detailing the energy consumption of each single process step enables an exact analysis which are the drivers of energy use and CO_2 emission along the process chain.

The model of the AMPOWER Sustainability Calculator is based on energy consumption per kg and part to allow generic part evaluations. On the dashboard the calculation results are illustrated as energy consumption per part for each single process step.

The main graphs show electric and primary energy separately. The granular break down and differentiation of energy source allows an individual assigning of CO_2 emission per kWh depending on the local electric grid the production process is located in. This enables the user to model multiple scenarios for their globally distributed process chain.

Energy consumption (kWh/part)



Energy (kWh/part) – Embedded energy in material

To produce metal alloys a large amount of energy is needed to process the extracted ore into final ingots. In Life Cycle Assessments the energy needed to excavate, process and produce the ingots is often referred to as embedded or embodied energy per kg metal alloy.

Depending on the alloy type, electro-chemical processes (electric energy) and process heat (primary energy) are needed to separate naturally occurring chemical compositions into the single metallic elements. Typically, these processes are very energy intensive. On teh other hand, recycling scrap metal to create new ingots uses significantly less energy than the original process route from ore to ingot.

Therefore, recycling credits are considered in the calculation depending on the amount of scrap metal in the original ingot production as well as considering recycling of scrap along the complete manufacturing route of the part (e.g. milling chips).

The AMPOWER Sustainability Calculator allows individual recycling rates from 0 to 100% for ingot production and all process waste. To illustrate the effect of material recycling the tool shows the embedded energy originally needed (0% recycling), the recycling credit depending on the chosen recycling rates and the resulting energy actually accredited to the evaluated part.

Sustainability of Additive Manufacturing

SOURCE: SOLUKON MASCHINENBAU

CO_2 emission in comparison

There is no general answer to which manufacturing technology has the lowest carbon footprint. The overall footprint is heavily influenced by the alloy group as well as the part geometry. Complex geometries with high buy-to-fly ratio are favorable for net-shape technologies such as AM and casting, while simple parts might be most sustainable if milled.

Comparing CO_2 emission for an identical part manufactured from different alloys, the large impact of the energy needed for the material production is evident. This embodied energy is especially high for titanium alloys.

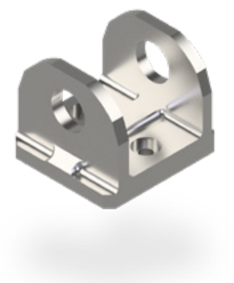
Going forward companies are well advised to increase the recycling rate and use of scrap in the ingot production as well as urge material suppliers to use renewable energy sources for their processes to reduce the CO_2 footprint of the raw material.

Considering titanium alloys, AM technologies of PBF, Wire Arc and highly utilized BJT technologies can reduce the carbon footprint significantly when compared to milling. Due to their near-net shape nature the material input and therefore the embodied energy is smaller and compensates for higher energy consumption in the part manufacturing process.

The embodied energy is less prominent for aluminum alloys and stainless steels. Here, manufacturing technologies with low process energy consumption such as casting and milling, have an advantage in comparison to Additive Manufacturing.

Considering typical raw material production sites such as Russia and China with their unfavorable CO_2 footprint of their electric grid, the embodied energy in the raw material will increase and the overall sustainability can tip towards AM technologies.

A surprisingly positive outlook can be seen for high productivity Binder Jetting technologies. Achieving a high utilization across the whole process chain from 3D printer to debinding and sintering oven can lead to a low carbon footprint of future applications. However, currently only very few BJT setups run at a high utilization rate.

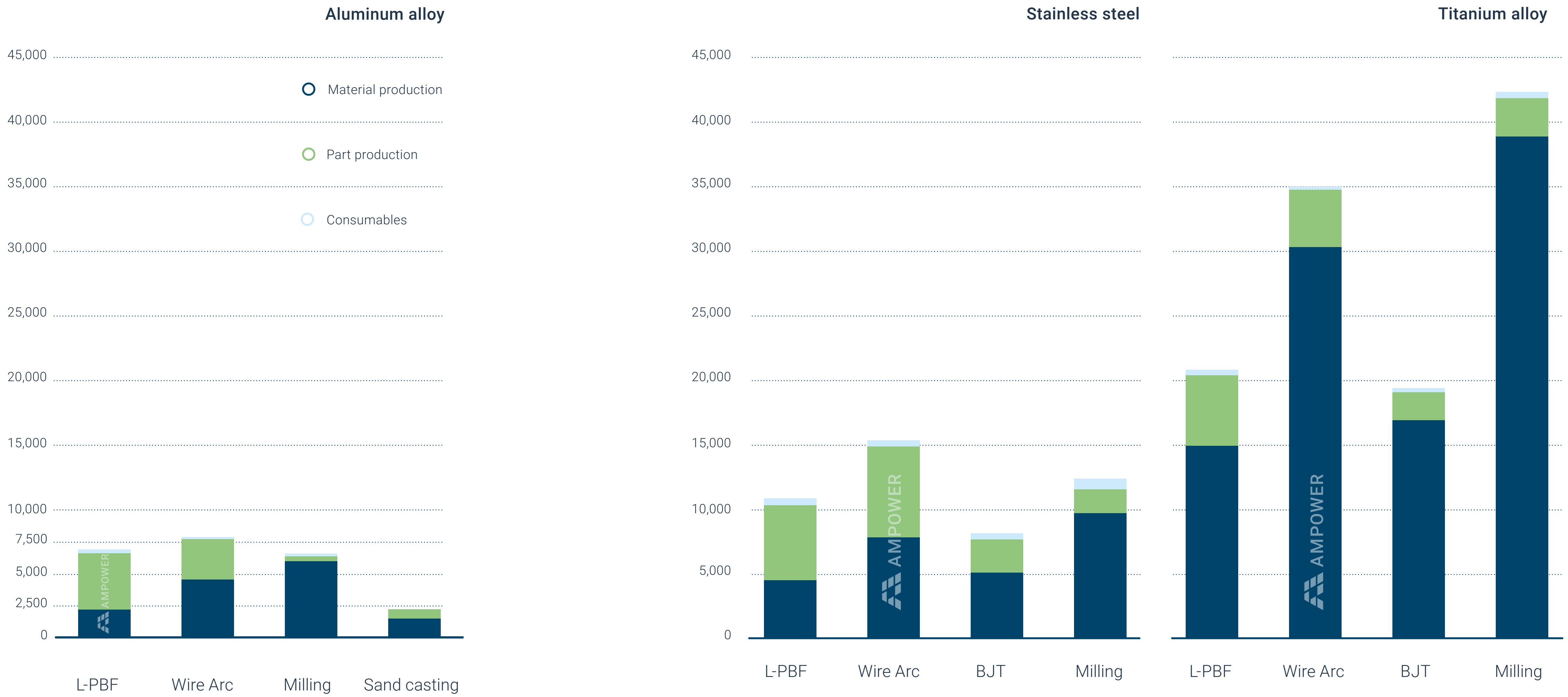


Original design for milling and Wire Arc process

Optimized L-PBF, BJT and casting design with 50 % weight saving

Quantity	1,000
Layer height	60 µm
Laser power	400 W
Heat treatment	yes
gCO_2/kWh	230 (EU Ø)

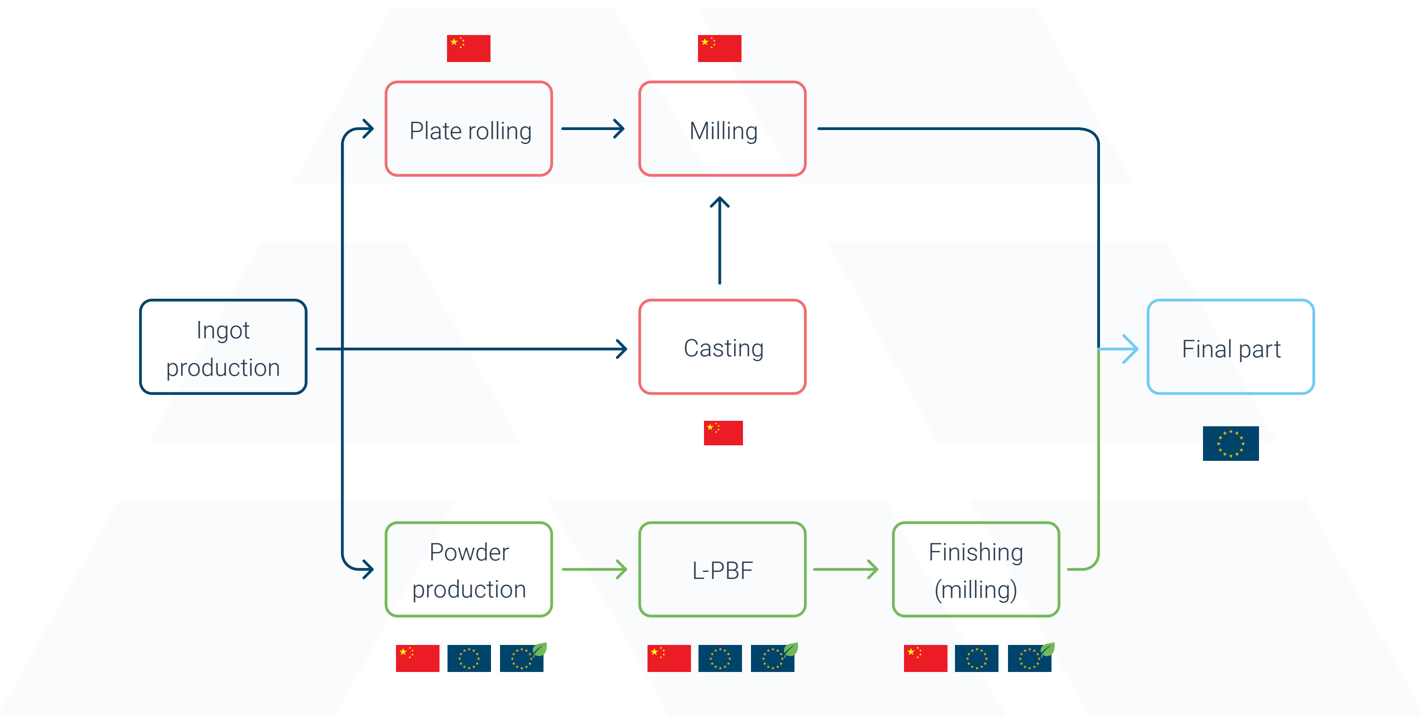
CO_2 emission (g/part)



Regional influence on CO_2 emission

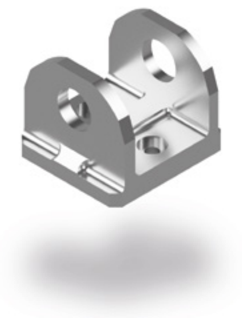
Today's value chains are globally distributed with raw materials being mined in regions such as China, Russia and Africa. Those raw materials are further processed either in the mining region itself or downstream at a distant metal processing plant. Today, China has established itself as the leading raw material producers for almost any alloy group. The high CO_2 emission of the Chinese electric grid of 555 gCO_2/kWh, results in large amounts of CO_2 already embodied in the raw material.

The effect of differences in CO_2 emissions of the local electric grid is illustrated with the process chain of an aluminum part using milling, casting and L-PBF technology.



IMPLEMENTED VALUE CHAIN FOR THE EXEMPLARY EVALUATION OF REGIONAL INFLUENCES

CO2 emission (g/part)



MILLING DESIGN

CASTING AND L-PBF DESIGN

The results show the large influence the local grid has on the proportional distribution of CO_2 emission from material production and part manufacturing. This becomes especially evident when comparing the data for the aluminum part from the previous page, calculated with identical grid parameters.

When considering aluminum ingots sourced from regions like Russia, China and the USA, a local L-PBF production using predominantly renewable energy (11 gCO_2/kWh) results in a carbon footprint lower than sourced casting parts.

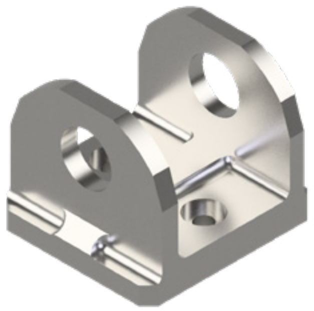
High impact by in use savings of optimized AM components

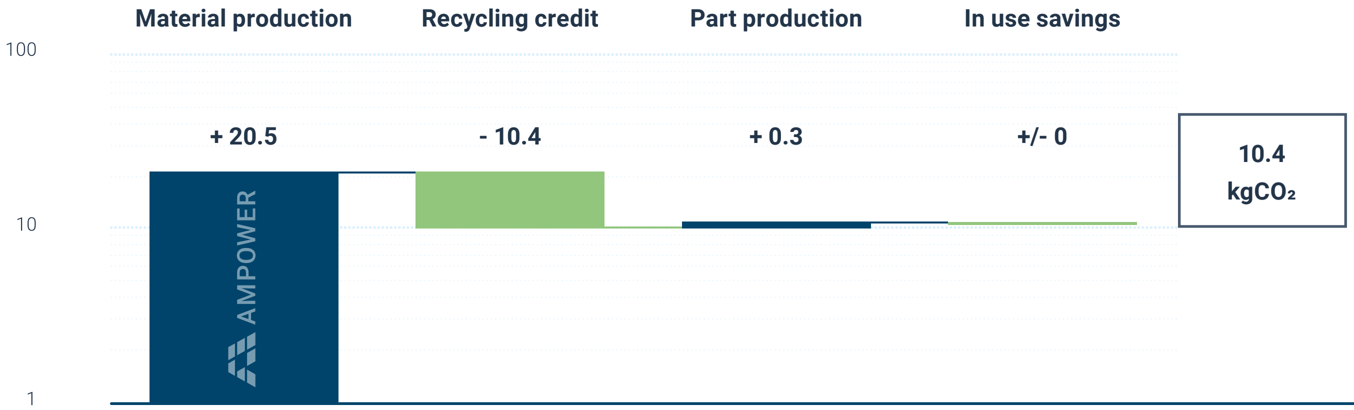
The AMPOWER Sustainability Calculator evaluates only the emission in the product lifecycle up to the finished part. Considering the CO_2 emission of the product in use requires additional and individual, application specific data. In case of aircraft parts, the weight is often linked directly to the fuel consumption and therefore the CO_2 emission. A potential weight saving of a component can be directly translated into fuel savings. In aviation, a typical value of annually 2,500 liter saved kerosine per kg weight saved is used to express this benefit. Assuming a 20 year lifetime of the aircraft this results in savings of up to 50,000 liter kerosine or 126,000 kg CO_2 for every weight reduction of 1 kg per aircraft.

Translating this calculation to AMPOWER's exemplary aviation bracket, the CO_2 savings accumulate to 43 tons over the lifetime of the aircraft which is magnitudes above potential savings in the production. Similar savings can be made for many other applications, such as engines, pumps or turbines, where weight reduction or performance increase have a large impact on in use emission.

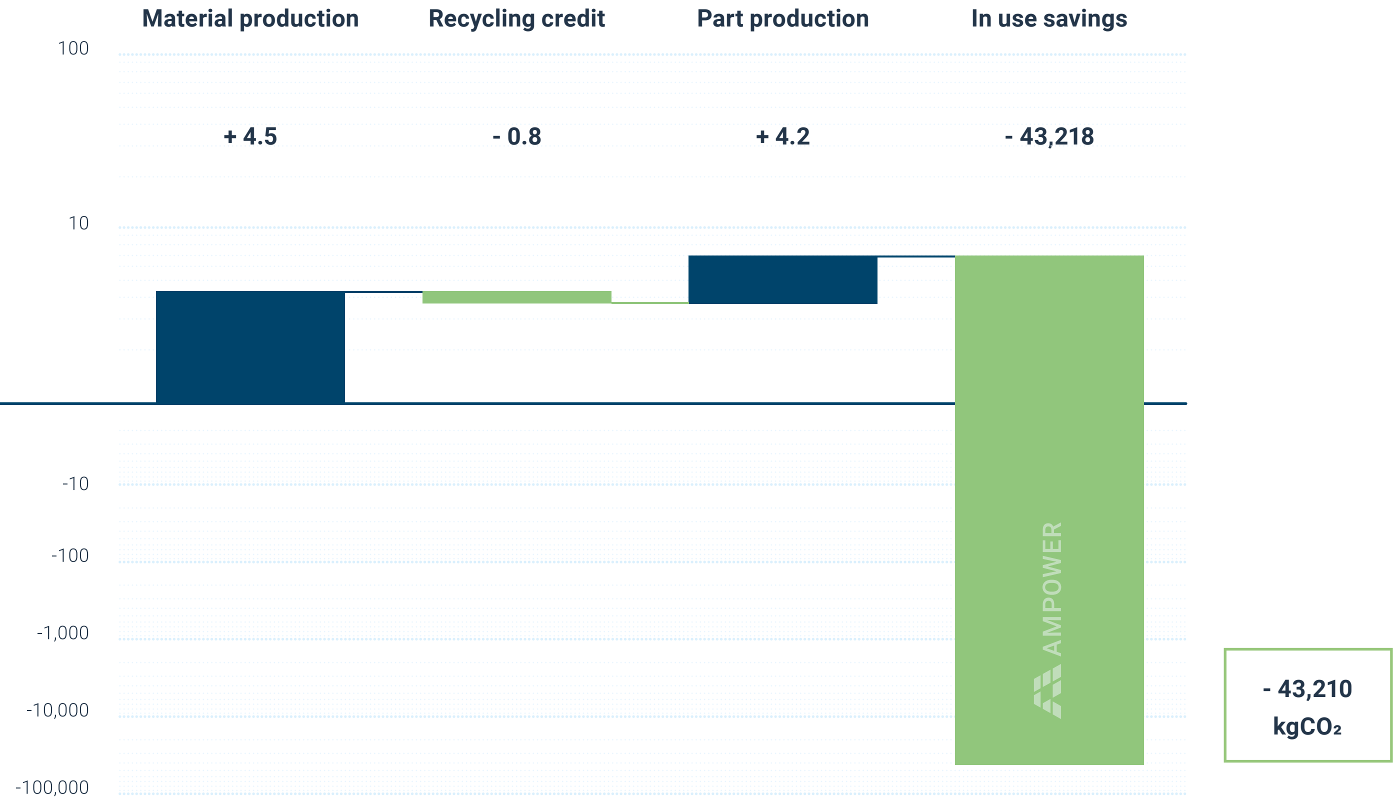
43 tons CO_2 saved

CO_2 emission of conventional aerospace bracket ($kgCO_2$)





CO_2 emission of topology optimized L-PBF aerospace bracket ($kgCO_2$)



Sustainability of Additive Manufacturing

1

AM technologies are not self-evidently the most sustainable manufacturing solution. Utilized conventional near net-shape technologies will most likely exhibit a similar or smaller CO_2 footprint compared to AM technologies.

2

Weight optimized AM part designs strongly reduce the CO_2 emission compared to conventional part designs, due to the high amount of embedded CO_2 in the raw material.

3

Use of renewable energy in the raw material production process has the biggest influence on the overall CO_2 footprint, especially for titanium alloys.

4

For aluminum and steel alloys the regional energy mix of the part production site has a large influence on the overall CO_2 footprint. This favors local AM production powered by renewable energy sources.

5

Recycling rates in raw material production and new powder production technologies from 100% recycled material will have a significant impact in reducing the CO_2 footprint.

6

In-use savings of weight or efficiency optimized AM designs can be multitudes larger than the emission from part production itself. However, in-use savings, if any exist, are strongly depending on the application.

The Additive Manufacturing Sustainability Calculator is now available!

How sustainable is your metal Additive Manufacturing application? Calculate the CO_2 footprint of your parts and compare the results with conventional manufacturing technologies. Adjust all parameters to your needs and get an independent evaluation of the true sustainability potential of Additive Manufacturing.

- Calculate the CO_2 footprint of your part
- Compare 7 manufacturing technologies
- Analyze the full process chain break down
- Including steel, aluminum and titanium alloys
- Adjust every parameter to your needs

Sustainability Calculator available at
www.ampower.eu/tools

About the authors

Dr.-Ing. Eric Wycisk

Since 2008 Eric successfully supports OEMs from aerospace, medical and automotive to identify Additive Manufacturing applications and implement production capacities in their regulated environments. With a background in topology optimization, titanium alloys and fatigue he is focused on achieving the maximum part performance with the right AM technology. As Managing Partner at AMPOWER, Eric focuses on technology evaluation and benchmarking, AM material and part properties as well as sustainability.

Freerik Haskamp

With a master's degree in mechanical engineering and a background in numerical simulations, Freerik has successfully developed multiple tools to calculate different aspects of Additive Manufacturing.
At AMPOWER Freerik focusses on market monitoring and knowledge management. Freerik Haskamp is a member of the AMPOWER team since 2019.

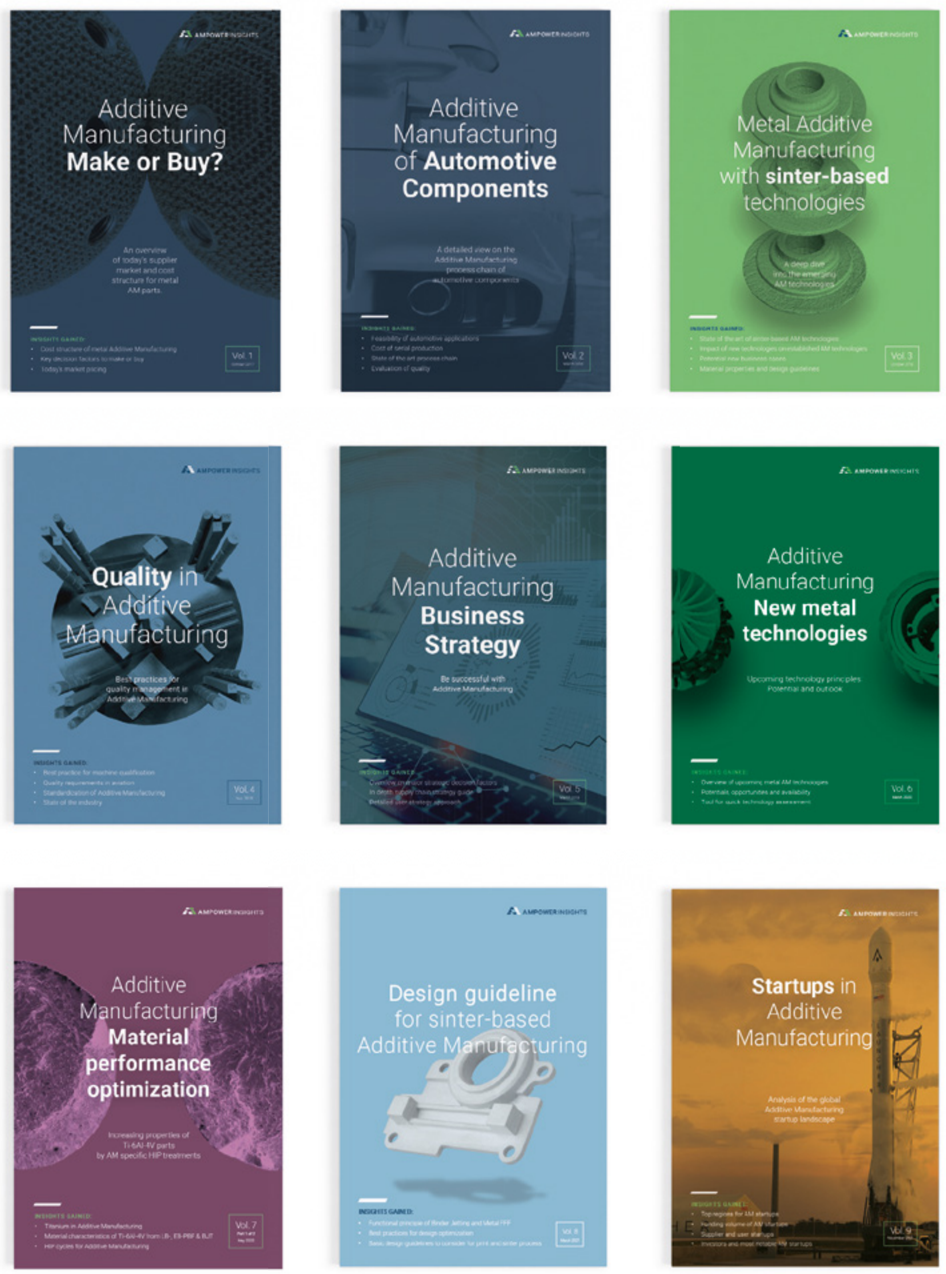
Matthias Schmidt-Lehr

Matthias Schmidt-Lehr successfully managed countless projects in Additive Manufacturing with focus on part screening, business case development, AM design optimization and production in both metal and plastic materials. With a history in the consulting business, he can provide a systematic approach to strategy development and scenario analysis. In his former positions Matthias gathered experience in business development, customer relationship management, as well as marketing and sales.

Dr.-Ing. Maximilian Munsch

Maximilian is a professional user of Additive Manufacturing since 2007. After finishing his dissertation on reduction of residual stresses in metal Additive Manufacturing in 2012, he acquired extensive hands-on experience with different Powder Bed Fusion processes in regulated industry before co-founding AMPOWER in 2017. As Managing Partner at AMPOWER, Max focuses on data analysis, market intelligence and due diligence investigations.

Missed out on our previous issues?



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