**Solid Freeform Fabrication 2023: Proceedings of the 34th Annual International Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference**
**Reviewed Paper**

# Resource Efficiency of the Robot-Based Hybrid Additive Manufacturing Chain

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## Abstract

Combining additive and subtractive metal processes to a hybrid additive manufacturing chain not only enables the production of parts with application-oriented design but also leads to increased resource efficiency especially when combined in an industrial robotic cell.
Compared to parts manufactured through subtractive processes from full material the hybrid additive manufacturing chain is considered to be resource efficient due to reduced material consumption. However, the energy consumption of the hybrid additive process is considered higher because of the use of laser for the additive process.
It is assumed that the decreased material consumption outweighs the higher energy consumption regarding the resource efficiency but until now it is not investigated. Therefore, in this paper the resource consumption of the robot-based hybrid additive manufacturing chain including the wire based direct energy deposition process and the milling process is analysed through measurements during experiments and compared to subtractive processes using the carbon footprint as a reference.

**Keywords**: Resource efficiency, hybrid-additive manufacturing, DED, robot

## Introduction

Today's manufacturing industry is facing the challenge to produce not only economically but also ecologically sustainable. The shortage of resources due to supply bottlenecks and increasing demand forces the industry to optimize the use of resources and decouple from material suppliers. Resource efficiency and sustainable processes are crucial for economic success [1].
The implementation of resource efficient production processes not only reduces the manufacturing costs but also leads to competitive advantages by implementing new processes and new technologies in the production chain such as hybrid manufacturing processes.
Hybrid manufacturing is defined as the combination of machines or processes to make use of the benefits of the individual processes and to overcome disadvantages of these [2]. [3] expanded this definition by including the combination of traditional and additive manufacturing routes, which are referred to as hybrid-additive manufacturing. The combination of additive and subtractive processes, in this paper referred to as hybrid manufacturing, offers new processing possibilities, greater design freedom in component construction, and reduced production costs [3].
The hybrid manufacturing chain offers a high saving potential in terms of resource consumption due to the lower machining rates and higher material efficiency resulting from the near-net-shape building process [4]. For instance, the door frame of an Airbus A350 can have a buy-to-fly ratio, the ratio of the weight of raw material and the weight of the end part, of over 20 which is due to machining rates up to 95 % [5]. To reduce this high buy-to-fly ratio, the hybrid manufacturing chain combining the wire-based direct energy deposition process and the milling

process can be employed [5]. The wire-based directed energy deposition (DED) process is an additive manufacturing process in which a wire is deposited layer by layer on a substrate or existing workpiece, using laser energy [6]. The DED process produces near-net-shape parts that require only a minimal milling operation as a post-processing step [4]. The integration of the wire-based DED process and the milling process in a robot cell enables the execution of the manufacturing chain in a single location without the need for reclamping between the steps. This allows not only a cost-efficient process, but also provides flexibility and a larger working space [7].

However, the use of a laser system in the additive process, including a longer production time, leads to increased energy consumption, which raises questions about the overall resource efficiency of the wire-based DED process [8]. A comprehensive analysis of the resource consumption in hybrid manufacturing and a comparison with conventional milling processes is currently lacking. This makes an economic and ecological evaluation difficult, especially regarding wire-based DED and its execution on a robot.

In this paper the resource efficiency of the hybrid manufacturing chain, which includes the wire-based DED process and a milling process executed in a robot cell, is analysed and compared to the conventional milling process carried out on a machine tool. At first, the resource efficiency is defined, and the system boundaries of the processes are set. Afterwards, the experiments for the resource measurements are described and the results are shown before the comparison with the conventional milling process based on the carbon footprint is given. Finally, the results are discussed and a conclusion is given.

## Resource efficiency and system boundaries

Resource efficiency is a key figure that expresses a certain benefit in relation to the resources consumed to achieve that benefit, and it is typically expressed as a dimensionless ratio [9]. The definition and evaluation of resource efficiency depends on the economic or ecological context, as the benefit can be defined in terms of maximum profit or minimum costs, for example. Resources refer to the natural resources of a material nature, such as raw materials or energy [10]. To evaluate resource efficiency, a system boundary is needed. The system boundary should be defined based on the purpose of the analysis and the availability of data. If the entire life cycle is analysed, the system boundary is called cradle-to-grave [11]. Cradle-to-grave requires the evaluation of resources and benefits throughout the entire life cycle of a product, which includes the extraction of raw materials, manufacturing, transportation, usage, and end-of-life disposal or recycling. This approach can provide a comprehensive assessment of the resource efficiency of a product, but it also requires a significant amount of data collection and analysis, which can be time-consuming and costly [12].

A less complex approach is the cradle-to-gate analysis, which starts with the raw material and ends with the product leaving the production [12]. This approach is suitable for the phases of usage and disposal in case of insufficient data. Another approach is the gate-to-gate system boundary, which focuses solely on the manufacturing steps within the company, analysing only a single section of the life cycle of a product [12].

In the context of evaluating the resource efficiency of the hybrid manufacturing chain, the system boundary includes the manufacturing processes of the wire-based DED and milling, as well as the energy and material inputs required for these processes. Given that the system boundary defines the sections of the product life cycle to be integrated into the analysis, the choice of boundary is critical for an accurate resource efficiency evaluation.

In this paper, the resource efficiency of the hybrid manufacturing chain is analysed with the cradle-to-gate system boundary as can be seen in Figure 1. Compared to the conventional milling process, the resource material is compensated by the resource energy for the hybrid manufacturing process. The material consumption is reduced but the energy consumption is expected to be higher due to the laser-based additive process [4]. Therefore, the production of the raw material must be included in the resource efficiency analysis and a gate-to-gate system boundary is not suitable. For the reference part, the phases of usage and disposal are not specified and therefore no data is available for these phases. Moreover, the conventional produced part and the hybrid manufactured part have the same usage. Therefore, the cradle-to-gate system boundary is applicable in this context [13].

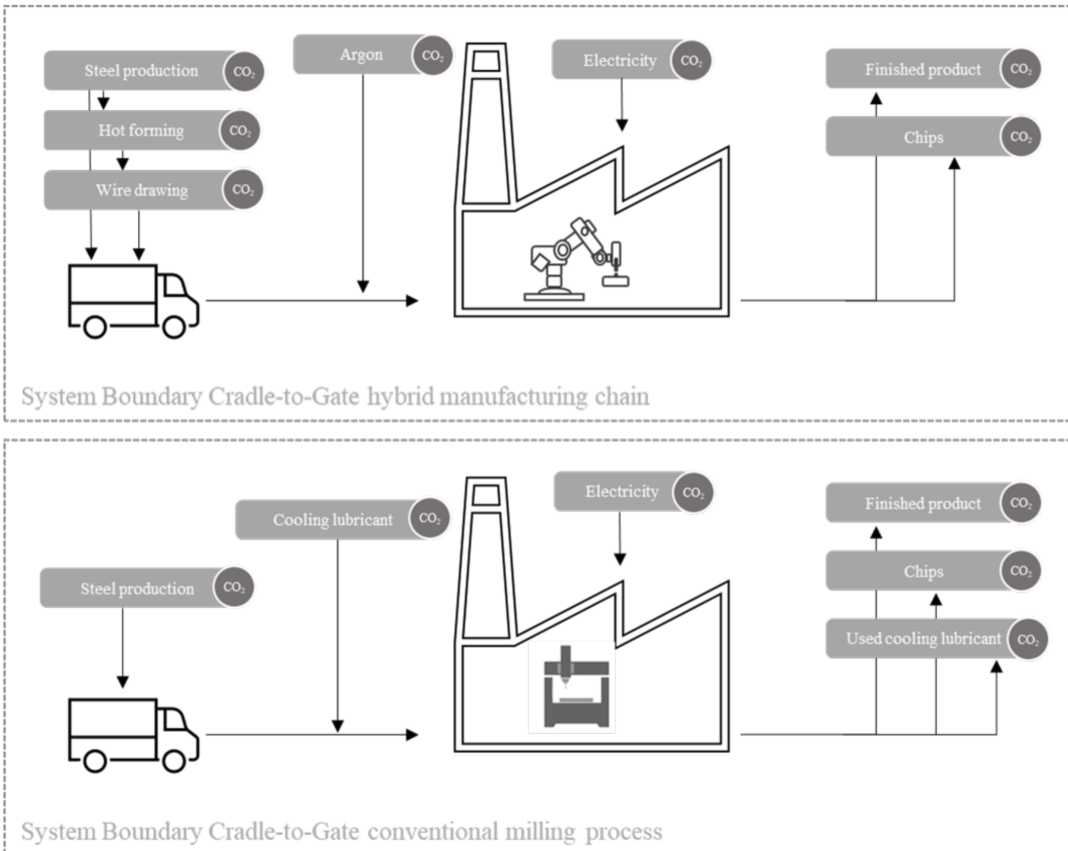


Figure 1: Cradle-to-gate system boundary for the hybrid manufacturing chain and conventional milling process.

The analysis of the resource efficiency of the hybrid manufacturing chain includes multiple resources such as energy, material, and operating resources. These different types of resources cannot be directly compared due to their distinct nature. For this reason, the global warming potential (GWP) for each resource is measured by its carbon footprint to enable a comparative assessment of the different resource categories. The carbon footprint is a method to quantify the ecological impact by quantifying the resource consumption in units of $CO_2$ equivalent [14]. It allows a standardized quantification of all resources on the same basis. Additionally, the carbon footprint is used as a scale by the European Union (EU) as a direct coupling between emissions and resulting costs [15]. In this paper, the comparison of the resource efficiency for the hybrid manufacturing chain and the conventional milling process are based on their GWP using the carbon footprint.

## Experiments and measurements

The hybrid manufacturing chain is executed within a robotic cell using a six-axis heavy-duty robot with an interchangeable end effector. The end effector can be configured with the CoaxWire additive manufacturing head, which utilizes a wire DED laser optic as well as a spindle for milling and drilling.

The cell is also equipped with various components such as the main control cabinet, a laser generator, robot control systems, a wire feeder with control, and a hydraulic unit. Furthermore, the cell includes a work table, an end effector docking system to change between the spindle and additive manufacturing head, a laser measuring system for tool measurements as well as a monitoring and a touch probe to determine the position of the work piece.
For the resource analysis the input and output of the hybrid manufacturing chain are defined as well as the methods for measuring them.
The electricity as energy source, the wire and the substrate materials, argon and compressed air are defined as input.
The outputs include the manufactured part and the chips produced during the subtractive process. However, due to the minimal impact on resource consumption and the significant expense involved in analysing them, compressed air and chip recycling are not further considered in the analysis. The input and output into the robot cell can be seen in Figure 2.

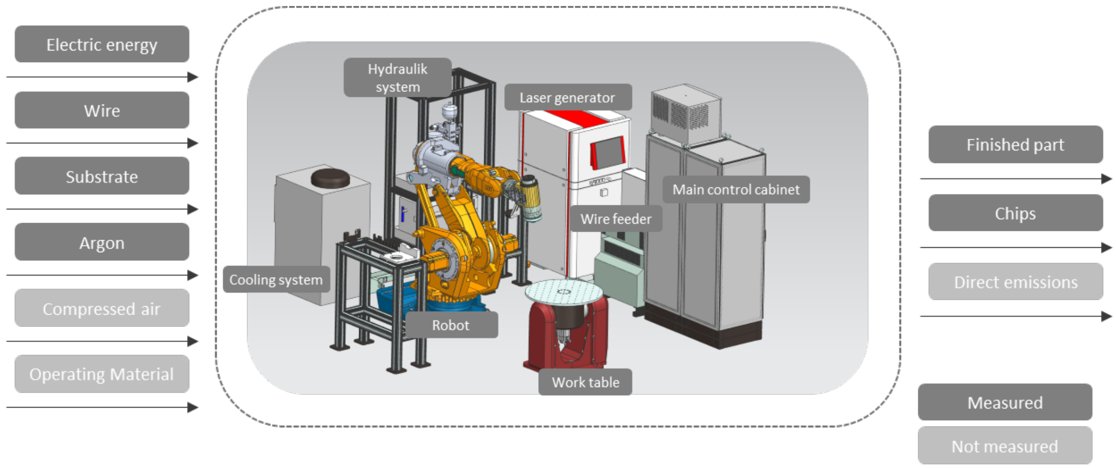


Figure 2: Input and output of the hybrid manufacturing chain.

Stainless steel, specifically 316L, is selected as material for the reference part. The simple design as seen in Figure 3 ensures that the reference part can be manufactured as well in the conventional milling process. It consists of a pre-manufactured base plate on which a hemisphere is additively generated and then post-machined by conventional milling.

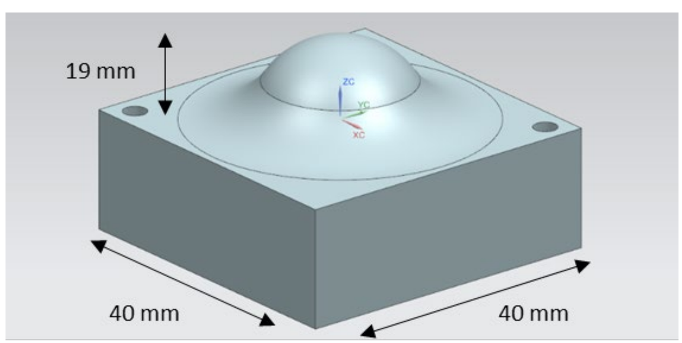


Figure 3: Reference part.

The two most important inputs for the hybrid manufacturing processes are electric energy and raw material. The measurement methodology is based on a bottom-up concept where individual consumptions are measured and then combining them into larger units to determine the total resource consumption. To measure the electric energy consumption, several clamps are applied on the components of the robot cell for direct energy measurements. The clamps are attached

near the main switch for each component, and record energy consumption at a frequency of 1 Hz.
The hybrid manufacturing chain consists of an additive manufacturing process followed by two milling steps, roughing, and finishing. The milling procedures are performed without cooling lubricant. In total 14 parts are manufactured in the robot cell. To analyse the impact of parameter variation on the energy consumption of the additive process, different parameter sets are used by combining the laser power, process speed, and wire speed. Also, for the milling process, different cutting speeds are used to determine their effect on the energy consumption.
For material consumption, the substrate, the additive manufactured part, and the post-processed part are weighed to determine the applied and removed material. Additionally, the amount of used wire is calculated from the data obtained from the wire conveyor. The consumption of argon is detected by the set volume flow and the process time. For the experiments an increased argon volume flow was used to ensure stable processes.
To compare the hybrid manufacturing process with the conventional milling process, the reference part is also manufactured conventionally on a machine tool by milling a block of 316L. The material and energy consumption are measured using a similar approach to the measurements in the robotic cell through using clamps at the machine tool and weighing the material before and after the milling process. In addition to the directly measured energy consumption with clamps, the data from the edge device of the machine tool are used to determine the energy consumption of the spindle and feed axis. The parameters for the milling process are kept constant using standardised parameters, and cooling lubricant.
Tool wear was not considered as this is classified as similar for both processes. Other operating materials apart from argon and cooling lubricant were also not considered as these had a comparatively low influence on resource efficiency [16].

## <u>Results of the experimental measurements</u>

The results of the experimental measurements are divided into the measurements of the energy consumption, the material consumption, and the consumption of other resources.
The overall energy consumption for the hybrid manufactured part is 5064 kJ as shown in Figure 4. The laser is the biggest consumer of energy with a share of 35,7 % followed by the robot and spindle. Almost half of the consumed energy is used for the additive process even though it only accounts for 20 % of the process time of the hybrid manufacturing chain. The processing time of the additive processes takes about 6 min and is shorter than the process time of the milling processes with about 20 min.
The analysis of the power consumption of the laser shows that increasing the parameter laser power which leads to faster processing times results in a disproportionately higher energy consumption. For the parameter laser power of 2000 W, the average power consumption of the laser is about 6550 W during the process, for a laser power of 2250 W, the power consumption is 7200 W, and for a laser power of 2500 W, the power consumption is 7900 W. A higher laser power in the process reduces the processing time, therefore, the overall energy consumption under higher laser power is not significantly increased, for a high laser power of 2500 W even decreased because of the significantly reduced process time. The energy consumption of the laser during the additive process with a laser power of 2000 W is 1935 kJ, with a laser power of 2250 W is 2065 kJ and with a laser power of 2500 W is1774 kJ.

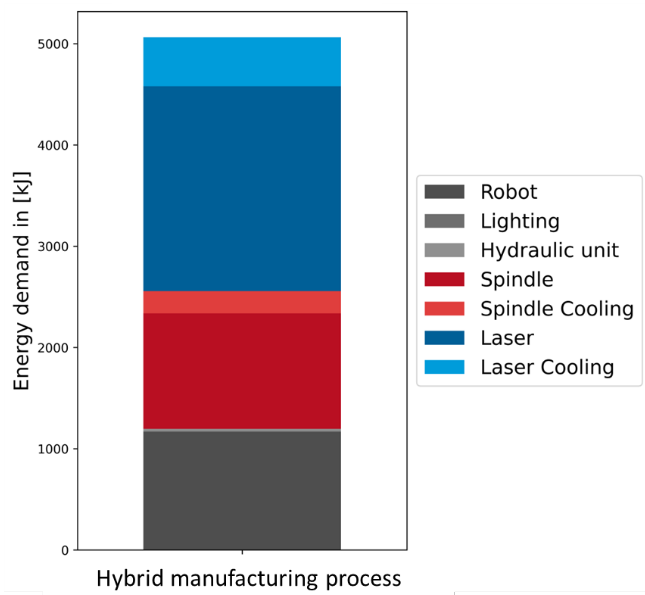


Figure 4: Energy consumption of the hybrid manufacturing process. Used parameters: Laser power 2000 W and cutting speed 100 m/min.

The power consumption of the robot is stable during the additive and the milling process, with about 765 W during movements. The components spindle, hydraulic, and cooling of the spindle are used for the milling process. Here, the spindle is the highest consumer of power with about 980 W. Overall, for the milling process executed on the robot, the spindle is with 1104 kJ the highest energy consumer followed by the spindle cooling aggregate with 210 kJ. The measurements also show that the energy consumption of the spindle is increasing with higher cutting speed from 1104 kJ for a cutting speed of 100 m/min up to 1155 kJ for a cutting speed of 110 m/min.

To compare the energy consumption of the hybrid manufacturing process and the conventional milling process, the reference part was also manufactured conventionally on a machine tool. The energy consumption per part adds up to 4222 kJ and is therefore about 16.6 % lower than in the hybrid manufacturing process. Here, the aggregates of the machine tool have the highest share of the energy consumption as shown by the peripheral devices in Figure 5.

For the milling process the measurements show that the power consumption of the robot cell including spindle, hydraulic aggregate, and cooling system is with an average of 1970 W lower than the milling process on the machine tool with an average power consumption of 4550 W.

The results of the measurements of the material consumption show that the material consumption of the conventional milling process is higher than for the hybrid manufacturing process as shown in Figure 6. During the additive process, about 44 g of material is added to the substrate, while approximately 13 g of 316L is removed during the post-processing. In contrast, the conventional milling process removes 294 g of material.

It is evident that the hybrid manufacturing process generates less waste in the form of chips than the conventional process. The buy-to-fly ratio for the conventional process is 2.03, which is twice as high as that of the hybrid manufacturing process at around 1.05.

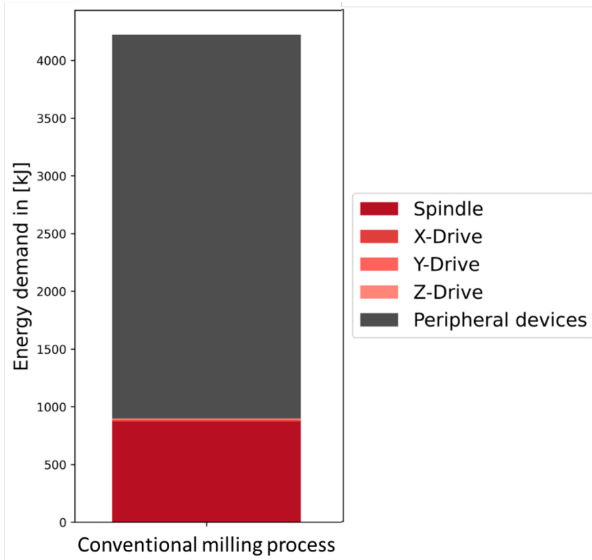


Figure 5: Energy consumption of the conventional milling process. Used tools and parameters: End mill 115 m/min, ball end mill 250 m/min.

Furthermore, aside from energy and material consumption, the consumption of other resources such as argon for the additive process and cooling lubrication for the conventional process is also considered. For the additive process, the argon consumption for one part with a process time of 194 s is 97 l in the experiments. For the conventional milling process, the consumed lubricant can be estimated by using 10 % of the weight of the mass of the removed material, which for the reference part amounts to 29.4 g. A summary of the used resources can be seen in Table 1.

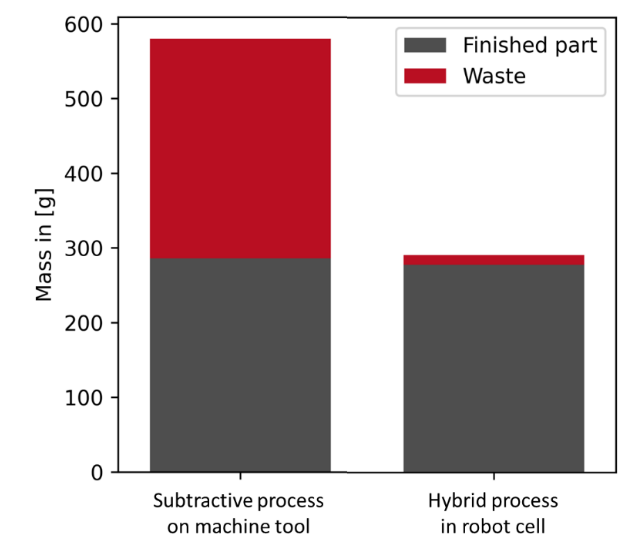


Figure 6: Material consumption for the conventional milling process and the hybrid manufacturing process.

Overall, the measurements of the consumed resources show that the electric energy consumption of the hybrid manufacturing chain is higher than the conventional milling process for the same reference part. However, the material waste during the conventional milling process is more than 22 times the amount of material waste compared to the hybrid manufacturing process.

Table 1: Summary of the resources of the hybrid manufacturing process and the conventional milling process.

| Resources | Hybrid manufacturing process | Conventional milling process |
|---|---|---|
| Substrate | 247 g | 580 g |
| Chips | 13 g | 294 g |
| Electric energy | 5064 kJ | 4222 kJ |
| Cooling lubricant | - | 29.4 g |
| Argon | 97 l | - |

Each manufacturing process consumes different resources apart from energy and material, such as argon and cooling lubricant. These categories of resources cannot be directly compared with each other. A common base is therefore required for the evaluation of resource efficiency.

## Comparison of the different resources

To establish a common base for comparing different resource categories, the carbon footprint is used. This approach requires making certain assumptions such as using the German electricity mix as the basis for electric energy resources and neglecting the transportation of raw materials due to their low mass. Since the resource categories have different dimensions, the GWP for 100 years is used as the basis for comparison in this paper. This involves converting the resources into $CO_2$-equivalent emissions using the ecoinvent database [17], which lists the $CO_2$ emissions for each resource taking into account the energy mix used and the region of production of the raw material. The CO2-equivalent used in this paper are listed in Table 2.
To calculate the carbon footprint for the material consumption of the additive process, the stainless steel production for the wire, the wire drawing process and hot rolling are included into the calculation of the carbon footprint.

Table 2: $CO_2$-equivalent used for the different resources.

| Resource | $CO_2$-Equivalent |
|---|---|
| Stainless steel production | 4.8137 kg $CO_2$-Eq./kg stainless steel |
| Wire drawing | 0.3574 kg $CO_2$-Eq./kg drawn steel |
| Hot rolling | 0.2612 kg $CO_2$-Eq./kg rolled steel |
| Electric energy | 0.5524 kg $CO_2$-Eq./kWh |
| Argon | 1.3582 kg $CO_2$-Eq./kg liquid argon |
| Cooling lubricant | 2.85 kg $CO_2$-Eq./l |

The results show that the carbon footprint of the hybrid-manufactured part is with 2.749 kg $CO_2$ about 22 % lower than that of the conventionally milled part, with 3.523 kg $CO_2$ emissions, as seen in Figure 7.
The raw material production has the most significant impact on the $CO_2$ emissions of the part. Therefore, the higher material use of the conventional milling process leads to higher $CO_2$ emissions than the increased energy consumption of the hybrid manufacturing process. For the hybrid manufacturing process, the used argon increases the $CO_2$ emissions of the hybrid-manufactured part enormously.

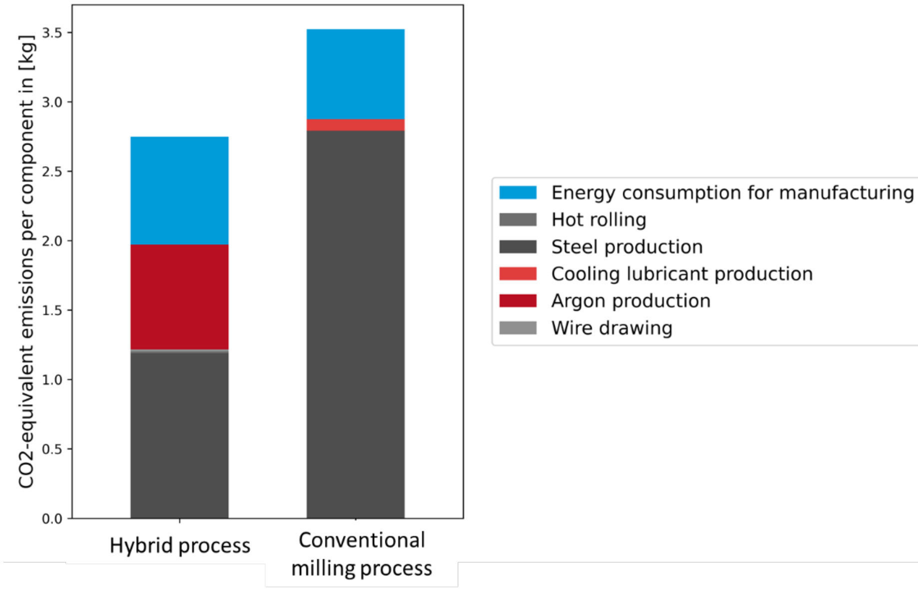


Figure 7: Carbon footprint of the hybrid manufactured part and the conventional milled part.

## Discussion and conclusion

This paper gives a comparison of the resource efficiency of the hybrid manufacturing chain and the conventional milling process based on the carbon footprint. The analysis shows that the hybrid manufacturing process is more resource efficient in terms of $CO_2$ emissions compared to conventional milling processes for a simple reference part. Although the energy consumption of the hybrid process is higher, the material waste is significantly lower which influences the $CO_2$ emissions more than the energy consumption.

The benefits of the additive process were not fully realized in this paper due to the simplicity of the part, and it is expected that the resource efficiency will be even higher for more complex parts. In addition, an increased argon volume flow rate was used, which can be significantly reduced under normal conditions, further lowering $CO_2$ emissions.

The hybrid manufacturing process can also be used in repair processes as it enables longer use and service life of the parts, resulting in lower emissions.

The energy efficiency of robot-assisted milling processes is higher compared to machine tool-assisted milling processes, but the surface quality of the parts produced with the robot-based milling process can be compromised due to the lower rigidity of the robot. While this may be acceptable for roughing operations, it may be preferable to use a machine tool for finishing operations.

This paper demonstrates the potential of the hybrid manufacturing chain as a sustainable technology that not only offers greater flexibility, but also improves the sustainability of production. Incorporating both subtractive and additive processes into a single production system can lead to significant resource efficiencies as demonstrated by the lower $CO_2$ emissions of the hybrid process compared to conventional milling. The hybrid process can also extend the life of parts through repair and remanufacturing, which further reduces emissions associated with material production and transportation. Therefore, the hybrid manufacturing chain has the potential to make production more sustainable while maintaining or even improving production efficiency.

## Acknowledgements

The research was created within the project EnerClad funded as part of the call 7. Energieforschungsprogramm by the Federal Ministry of Economics and Climate Protection (BMWK). The author would like to thank the project management organization Projekträger Jülich for the financial support.

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