Comparison Analysis of Energy Consumption of Atomic Diffusion Additive Manufacturing with Sand Casting: Towards a more Sustainable Future

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Abstract. Over the years, the cumulative environmental impact from human activity has disrupted the stability of the natural world, warming the planet above pre-industrial levels. Whilst unprecedented in many ways, reducing industrial emissions from greenhouse gases could help stabilise rising temperatures. Thus, the exploration for more sustainable manufacturing solutions that reduce carbon emissions is imperative. Some traditional manufacturing (TM) processes, such as sand casting, which, despite its versatility to produce products in many shapes and sizes from almost any metal or alloy, are typically energy-intensive activities. Conversely, metal additive manufacturing (MAM) enables users to manufacture more complex, lighter and near net shapes with the ability to consolidate manufacturing workflows. Consequently, MAM has been reported to be an energy-efficient alternative. Yet, evidence in the literature on the environmental impact of some MAM processes is limited, especially for material extrusion (ME) additive manufacturing (AM) methods such as the atomic diffusion additive manufacturing (ADAM) process. This paper explores the feasibility of performing a life cycle assessment (LCA) for the ADAM process compared to sand casting. Preliminary results indicate that the ADAM process demands 71.04 *kWh/kg* and 16.57 CO_2 *equivalent* (CO_2*-eq*) more for manufacturing 1*kg* of 17-4 precipitation hardened stainless steel (17-4 PH SS) compared to sand casting. Therefore, the findings collected from this pilot study justify future research efforts to converge on developing a novel model for performing a comprehensive cradle to grave LCA for ADAM to compare against sand casting and other TM processes such as CNC milling and investment casting.

Nomenclature

17-4 PH SS	17-4 precipitation hardened stainless steel	LCA	life cycle assessment
ADAM	atomic diffusion additive manufacturing	LCI	life cycle inventory analysis
AM	additive manufacturing	LCIA	life cycle impact assessment
CO_2	carbon dioxide	MAM	metal additive manufacturing
CO_2*-eq*	carbon dioxide equivalent	ME	material extrusion
FDM	fused deposition modelling	MIM	metal injection moulding
FM	formative manufacturing	SB	system boundaries
FU	functional unit	SEC	specific energy consumption
GSD	goal and scope definition	TM	traditional manufacturing

INTRODUCTION

The push to tackle the global climate emergency has raised questions around the sustainability of TM processes such as sand casting, where the production and processing of metals are among the most energy-intensive activities [1]. Indeed, in Europe alone, the iron and steel industry contributes to 22% of the overall total carbon dioxide (CO_2) emissions [2], with the World Steel Association estimating that for every one ton of steel produced, the process emits 1.85 *tonnes* of CO_2 [3]. As the global population of around 7.8 billion is projected to peak in 2100 at nearly 11 billion, metal consumption will likely increase, particularly as developing countries strive for comparable economic augmentation and domestic material consumption levels become homogenised with other industrialised nations. While urgent and exceptional, present-day ecological challenges for the metal industry coincide with a period of unprecedented technological innovation, particularly with recent processing and metallurgical developments in MAM. With an increasing number of companies now actively engaged with novel MAM technologies and many more considering its implementation, manufacturers should be able to evaluate the ecological credentials of MAM compared to more TM processes. For that reason, an LCA provides the most effective means for manufactures and researchers to holistically discern and quantify products environmental impact over the totality of its life cycle [4,5]. Here in this research, ADAM and sand casting are compared. However, the corpus of research around LCAs for MAM compared to TM processes is limited relative to the numerous publications concerned with MAM. Thus, as a nascent research subject in which the environmental impacts of MAM compared to TM processes are unknown, this paper aims to begin to understand the issues that exist by asking the question: *Is ADAM a more sustainable production method compared to sand casting*?

BACKGROUND

Sand casting process

Sand casting can be defined as a formative manufacturing process (FM). The basic sand casting process shown in **FIGURE 1** begins with manufacturing a pattern (typically from wood or plastic) in the shape of the final product. The pattern is positioned inside a metal box (the ‘flask’) comprising two halves, a top (the ‘cope’) and a bottom (the ‘drag’). Sand is forced in and around the pattern located inside the drag, filling the remaining volume in addition to completely backfilling the cope. The pattern is removed from the drag, leaving behind a mould cavity where passages are cut into the sand to form sprues and risers to pour and evacuate molten metal. The cope and drag are assembled, and locating pins align each section to create the complete flask. Molten metal is then poured through the sprue via a pouring cup into the mould cavity, where the molten metal is left to cool and solidify. After solidification, the cast is removed from the fragile sand (the ‘shakeout’ phase) and subjected to a fettling process that involves cutting and grinding away the sprue, risers and any other unwanted metal artefacts before the cast part can be machined or treated to achieve the desired surface finish or mechanical properties.

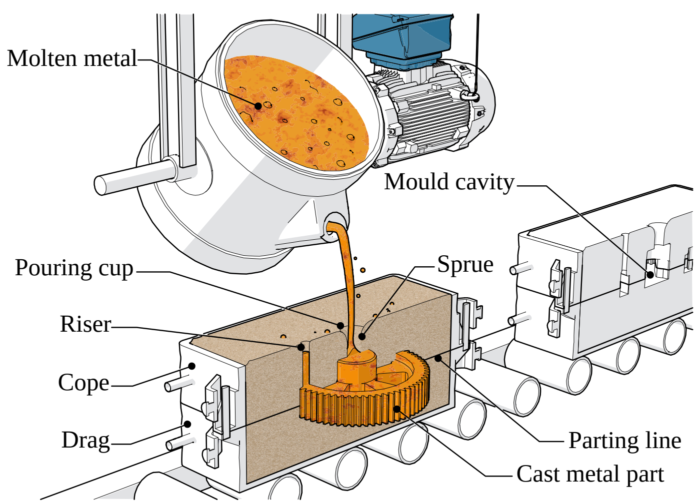

FIGURE 1 Schematic of the sand casting process

Atomic diffusion additive manufacturing (ADAM) process

The ADAM process represented in **FIGURE 2** is defined as a ME AM process in which material is selectively dispensed through a nozzle or orifice [6]. The modus operandi is a permutation of two technologies: fused deposition modelling (FDM) and metal injection moulding (MIM) [7]. The process consumes a feedstock composed of MIM media in a spooled filament of metallic powders bound in a two-part waxy polymer matrix that functions as the metallic powder's binding agent. Two spools containing the bound powder and another containing a ceramic release material are stored directly above the build plate in a heated chamber. The filament is fed into an extruder head and heated to a temperature above the polymer matrix's' melting point, extruding the softened material onto a heated build plate in a layer-by-layer fashion. After this stage, the as-built print is thermally debound in a 'wash' machine to dissolve the polymer binder. Then the part is placed inside a furnace where temperatures increase to 70-90% of the metals melting point [8]. As temperatures reach 50-75% of the metal's melting point, atomic diffusion of metal particles occurs, reducing porosity and transforming a lightly bound metal part into a 96-99.8% dense metal part [9,10].

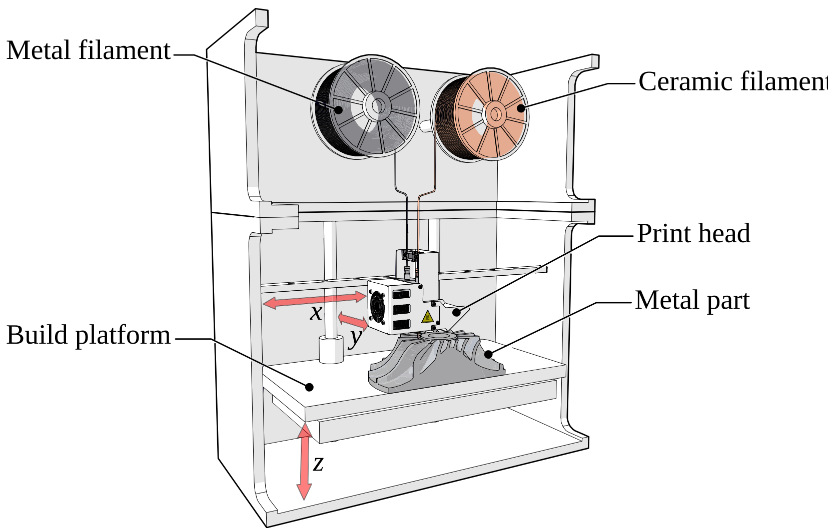

FIGURE 2 Schematic of the atomic diffusion additive manufacturing process

Life cycle assessment methodology

An LCA is an approach to address the environmental aspects and potential impacts throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal [11]. Four stages characterise an LCA: the goal and scope definition phase, the inventory analysis phase, the impact assessment phase, and the interpretation phase:

Goal and scope definition (GSD)

The goal and scope definition (GSD) considers the following aspects: the intended application, the reasons for carrying out the study, the intended audience and whether the results are designed to be used in comparative assertions intended to be disclosed to the public [11]. Thus, this preliminary paper aims to facilitate further research on the less understood sustainability characteristics of ADAM, compared to the sand casting process with the long term purpose of encouraging the uptake of alternative environmentally friendly metal production processes.

The functional unit (FU)

The functional unit (FU) defines the quantification of the product's identified functions and that its central purpose is as a reference to which the inputs and outputs are related, which is essential to ensure comparability of LCA results [11]. Thus, the FU selected for this study is defined as the impact per kg of 17-4PH SS. The production rate is taken from Markforged's cloud-based Eiger 3D printing software. Here the computer-aided design file of the FU is uploaded to the system. The software calculates various printing parameters based on geometry and material. 17-4 PH SS was selected, and a solid infill was chosen. Eiger scales the part by approximately 20% to account for uniform shrinkage. Production data is tabulated in **TABLE 1**.

TABLE 1 ADAM production data

Variables	**Measurements**
Printed dimensions, *mm* (pre-sintering)	250.7 × 95.6 × 12.9
Final part dimensions, *mm* (post-sintering)	209.7 × 80 × 10.8
Print time, *hrs*	59
Wash time, *hrs*	12
Dry time, *hrs*	4
Printed part mass, *kg* (pre-sintering)	1.36
Final part mass, *kg* (post-sintering)	1
Metal volume, *mm3*	2694.7
Material cost, *GBP*	129.59

System boundaries (SB)

The system boundaries (SB) identify all of the FU processes in the LCA, such as the acquisition of raw materials, inputs and outputs from manufacturing, transportation, fuels, electricity, heat, waste disposal, and the recovery of used products in addition to operations such as lighting and heating [11]. However, an initial boundary is proposed in **FIGURE 3** for sand casting and **FIGURE 4** for ADAM to characterise the SB for the FU. To compare the two processes, the format of this study and future research will attempt to compare the equivalent phases of each lifecycle. Thus, the phases that produce the FU are evaluated here (e.g., casting against printing), whereas melting will be compared against powder atomization in future studies.

Life cycle inventory analysis (LCI)

The life cycle inventory analysis (LCI) is a compilation of the resources used to produce the FU throughout its lifecycle, where resources are designated as inputs or outputs. This initial study will address only the rudimentary inputs and outputs required for the sand castings casting phase and the ADAM processes printing phase, where the SBs are illustrated by the dashed lines in **FIGURE 3** and **FIGURE 4**.

TABLE 2 Inputs and outputs for ADAM printing process only

Inputs	**Outputs**
Metal feedstock (e.g., metal powder, polymer)	Printed part
	Build plate (e.g., raft)
Ceramic feedstock (e.g., release material)	Ceramic waste
Energy	Emissions (e.g., air, water, land)

Markforged's Eiger 3D printing software defines the quantity of the material; thus, these inputs are easily quantifiable. For energy demand, Markforged was able to provide average consumption rates. For sand casting, figures for energy demand are found in the CES database. An initial effort has also been made to define the inputs and outputs for the raw materials required to produce 1*kg* of steel. However, we have found that the datasets for steel are limited where the most equivalent steel to complete an LCI is 304 stainless steel. **TABLE 3** indicates the inputs and outputs for a sand casting SB

TABLE 3 Inputs and outputs for casting process only

Inputs	**Outputs**
Molten metal (e.g., ingot and scrap)	Cast part
	Scrap metal
	Cooling water
Foundry sand	Sand (recycled)
Energy	Emissions (e.g., air, water, land)

Life cycle impact assessment (LCIA)

The life cycle impact assessment (LCIA) aims to assess the FU's potential human and environmental impact based on LCI data. The inventory of emissions and resources are interpreted into several ecological impact scores via characterisation factors which indicate the environmental impact per kg or emission discharged [12]. In this manner, the relative impact of two processes (e.g., ADAM versus sand casting) may be compared to ascertain which process has the most significant ecological effect. Many impact assessment methods exist; however, the most commonly used methodology in Europe is ReCIPe which is proposed for the broader study. There are two primary ways to obtain characterisation factors: at midpoints and endpoints. Midpoints indicate environmental dilemmas (e.g., climate change, acidification, and water eutrophication). Endpoints, however, reveal the ecological impact on three levels (e.g., effect on human health, natural environment, and resource scarcity). Thus, after selecting the relevant impact categories, an LCIA typically consists of four steps: classification, characterisation, normalisation, and weighting.

Life cycle interpretation

The interpretation phase follows the gathering of the results from the LCIA, which are interpreted systematically and summarised. According to ISO, the interpretation phase provides an easy to read and complete representation of the results of the LCIA, ensuring the findings are consistent with the GSD [11].

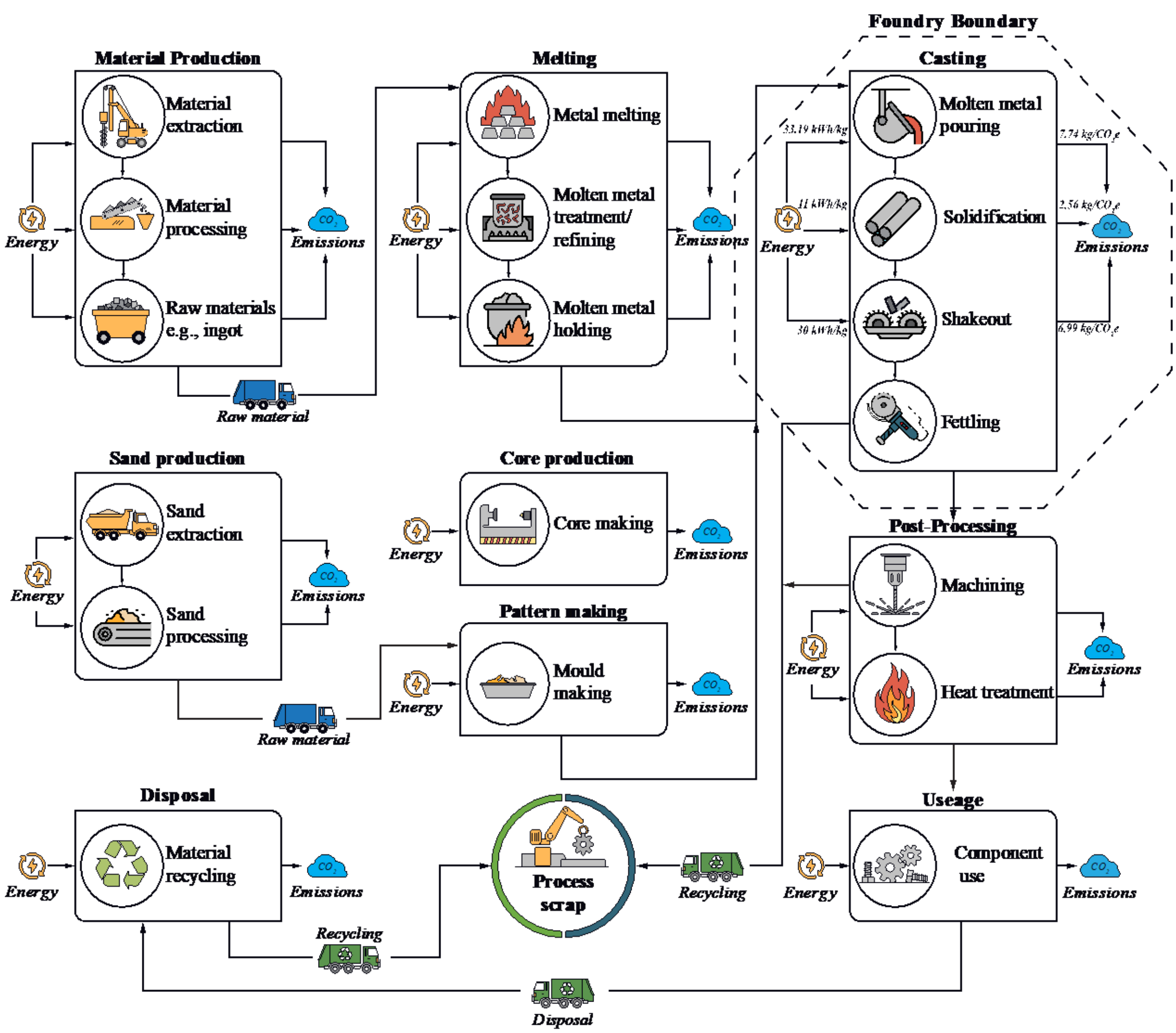

FIGURE 3 Schematic of the life cycle and system boundary for sand casting

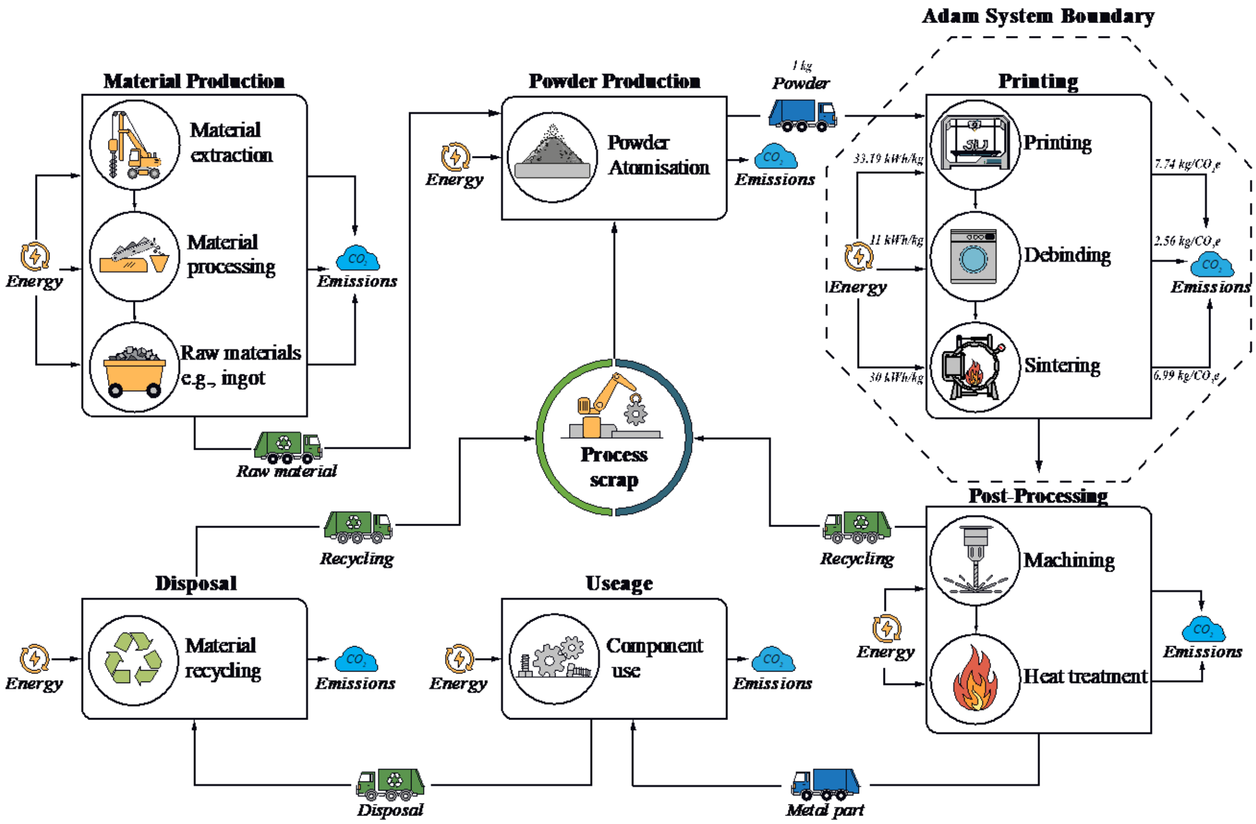

FIGURE 4 Schematic of the lifecycle and system boundary for ADAM

THEORETICAL RESULTS

An initial analysis has been carried out on the impact of ADAM and sand casting regarding the specific energy consumption (SEC), which can be used to determine CO_2-*eq*. SEC is typically used to represent how much energy is used for producing one FU and may also be used as an energy performance indicator to measure the performance or benchmark the energy efficiency. CO_2-*eq* measures how much gas contributes to global warming relative to CO_2. Results are compared in **TABLE 4**.

ADAM printing specific energy consumption (*SEC*)

Markforged Inc. has performed measurements for ADAM, and the figures were shared. However, the particulars on how these figures were derived have not been disclosed at this time. Nevertheless, the shared data shows an average of 12-15 *kWh* per day. Thus, to compare SEC, readings are averaged to 13.5 *kWh per day:*

$$(13.5)/24=0.56\ kWh \tag{1}$$

Therefore, to calculate the SEC for the FU, the number of printing hours is multiplied by average energy consumption represented in equation (2):

$$0.56\times 59h=33.19\ kWh/kg \tag{2}$$

Casting specific energy consumption (SEC)

The SEC for sand casting is taken from CES Edu Pack [13] for 17-4 PH SS, cast, H900. Under processing energy, a figure of 3.15 *kWh/kg* is given.

ADAM printing and casting CO_2 equivalent (CO_2-eq)

With the SEC data, it is possible to estimate CO_2*-eq* emissions output. According to the UK Governments Greenhouse gas reporting: conversion factors, the average carbon intensity is 0.23314 $kgCO_2/kWh$ [14]. Thus, an estimated equivalent (kg/CO_2*-eq*) is calculated in equation (3) for sand casting and equation (4) for ADAM.

$$3.15\times0.23=0.73\ \ kg/CO_2\text{-}eq \tag{3}$$

$$33.19\times0.23=7.74\ \ kg/CO_2\text{-}eq \tag{4}$$

Although energy and emissions have been considered for printing, the debinding and sintering process should also be considered to appreciate the ecological implications for the entire ADAM process. Thus, data provided by Markforged Inc. is also used to determine both impacts.

ADAM debinding specific energy consumption (SEC)

A figure of 22 *kWh* per day has been provided for the Wash-1 machine.

$$(22)/24=0.92\ kWh \tag{5}$$

Thus, to determine the energy demand for the FU, the amount of wash hours (**TABLE 1**) multiplied by the equipment energy consumption provides a cumulative energy demand in equation (6):

$$0.92\times12h=11\ \ kWh/kg \tag{6}$$

ADAM sintering specific energy consumption (SEC)

A figure of roughly 30 *kWh* per run has been provided for the Sinter-1 machine.

ADAM debinding and sintering CO_2 equivalent (CO_2-eq)

With the energy demand calculated, it is now possible to estimate kg/CO_2e for debinding and sintering shown in equation (7) and equation (8), respectively:

$$11\times0.23=2.56\ \ kg/CO_2\text{-}eq \tag{7}$$

$$30\times0.23=6.99\ \ kg/CO_2\text{-}eq \tag{8}$$

TABLE 4 SEC and CO_2-eq comparison of ADAM and sand casting

Process	**SEC, *kWh/kg***	**CO_2-eq, kg/CO_2-eq**
ADAM (printing, debinding and sintering)	74.19	17.30
Sand casting (pouring, solidification, shakeout and fettling)	3.15	0.73

ADAM SEC compared to other MAM technologies

The SEC for various other MAM technologies is shown in **TABLE 5**, which summarises the results per *kg* of printed steel grades. The literature indicates that the SEC is broad. Despite the relatively high SEC of the ADAM process, some laser-based systems appear to be much less energy efficient.

TABLE 5 SEC for various MAM technologies per kg of printed steel

Reported by	**Year**	**MAM Technology**	**Material**	**SEC, *kWh/kg***	**CO_2-eq, *kg/CO_2-eq***
Present study	2021	ADAM (printing only)	17-4 PH SS	33.19	7.74
Guarino et al. [15]	2020	Selective laser melting (SLM)	316L SS	17.55	4.09
Peng et al. [16]	2020	Selective laser melting (SLM)	316L SS	18.86	4.40
Bekker et al. [17]	2016	Wire and arc additive manufacturing (WAAM)	308L SS	1.84	0.43
Baumers et al. [18]	2011	Selective laser melting (SLM)	316 SS	29.44	6.86
Baumers et al. [18]	2011	Selective laser melting (SLM)	316 SS	163.33	38.08
Baumers et al. [18]	2011	Direct metal laser sintering (DMLS)	17-4 PH SS	94.17	21.95

CONCLUSION AND FUTURE RESEARCH

This paper's preliminary comparative assessment indicates that the ADAM process requires significantly more energy to produce 1*kg* of 17-4 PH SS than sand casting. It has also been shown that the ADAM process (excluding debinding and sintering) is also more energy-intensive compared to various other MAM technologies. The entire ADAM process summative SEC is 74.19 kWh/kg and 17.30 *CO_2-eq*. In contrast, the SEC and *CO2-eq* for sand casting are 3.15 *kWh/kg* and 0.73, respectively. The most energy-intensive subprocess is printing, which consumes 44.73% of the total energy required for the ADAM method, followed by 40.44% for sintering and 14.83% for debinding. Assuming an average cost of £0.20 per *kWh* of energy, the total cost of the ADAM process turns out to be £14.84, whereas the price to cast is £0.63. In the context of ecological matters, it can be reasoned that, theoretically, sand casting emerges as the most sustainable manufacturing process for producing the equivalent FU. One of the foremost advantages of all AM processes is optimising the geometry of a part topologically whilst still retaining necessary strength characteristics. From a practical point of view, the cast cube can also be printed with the same proportions yet be internally composed of infill type structures (e.g., triangular or gyroidal) that support the external walls having excellent rigidity with minimal weight. As a result, less material is required, significantly reducing print and debinding hours and reducing the SEC and *CO_2-eq* for the ADAM process. Printed parts are also typically produced near net-shaped, meaning that the final product is as geometrically as close as possible to the desired shape; thereby, the need to carry out laborious post-processing machining is significantly reduced or eliminated. However, the same FU (e.g., by mass) must be used for an accurate comparative assessment; therefore, this paper helps to understand the environmental impact of both processes by comparing like for like. A limiting factor of this research is that indirect data supplied by Markforged Inc. has been used to characterise the ADAM processes energy utilisation where the methods used to collect the data have not been shared with the authors.

Furthermore, this pilot study has only addressed the lifecycle phases responsible for manufacturing the FU. Considering that the melting phase is typically regarded as the most energy-intensive activity and given that three additional phases are included in the sand casting lifecycle (e.g., sand production, core production and pattern making), it is reasonable to assume that the cumulative energy demand for producing the FU is less for the ADAM process. To validate the results from this study and illustrate each process's ecological impact, future research efforts will focus first on performing empirical power monitoring experiments on the ADAM process. The goal of this preliminary study is to lay the groundwork for future research to benchmark ADAM against sand casting and other TM processes (e.g., investment casting and CNC machining) by performing a complete LCA and implementing the methodology described in this paper to further characterise each metalworking methods environmental credentials through ReCipe impact scores. Given the urgent need for the metal industry to reduce its environmental impact, it is vital to substantiate that MAM is more energy-efficient than TM processes. Consequently, forthcoming studies will support researchers and industrialists on which manufacturing process is better for the environment.

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