

Article

Comparative Environmental Insights into Additive Manufacturing in Sand Casting and Investment Casting: Pathways to Net-Zero Manufacturing

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Abstract

As manufacturing industries pursue net-zero emission (NZE) goals, hybrid manufacturing processes that integrate additive manufacturing (AM) with traditional casting techniques are gaining traction for their sustainability potential across the globe. Therefore, this work presents a “gate-to-gate” life cycle assessment (LCA) comparing AM-assisted sand casting (AM-SC) and AM-assisted investment casting (AM-IC), for Al-Si5-Cu3 alloy as a case material, under various energy scenarios including a conventional grid mix and renewable sources (wind, solar, hydro, and biomass). This study compares multiple environmental impact categories based on the CML 2001 methodology. The outcomes show that AM-SC consistently outperforms AM-IC in most impact categories. Under the grid mix scenario, AM-SC achieves 31.57% lower GWP, 19.28% lower AP, and 21.15% lower EP compared to AM-IC. AM-SC exhibits a 90.5% reduction in “Terrestrial Ecotoxicity Potential” and 75.73% in “Marine Ecotoxicity Potential”. Wind energy delivers the most significant emission reduction across both processes, reducing GWP by up to 98.3%, while AM-IC performs slightly better in HTP. These outcomes of the study offer site-specific empirical insights that support strategic decision-making for process selection and energy optimisation in casting. By quantifying environmental trade-offs aligned with India’s current energy mix and future renewable targets, the study provides a practical benchmark for tracking incremental gains toward the NZE goal. This work followed international standards (ISO 14040 and 14044), and the data were validated with both foundry records and field measurements; this study ensures reliable methods. The findings provide practical applications for making sustainable choices in the manufacturing process and show that the AM-assisted conventional manufacturing process is a promising route toward net-zero goals.

Keywords: additive manufacturing; sand casting; investment casting; life cycle assessment; environmental impact assessment; net-zero manufacturing



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1. Introduction

For centuries, metal casting has been a cornerstone of industrial manufacturing, supplying essential components to sectors as diverse as automotive, aerospace, energy, and

construction [1,2]. At the heart of this tradition lie SC and IC, two widely employed methods that collectively account for a significant proportion of global metal part production. Yet, while these foundry techniques have continually evolved to enhance product quality and operational efficiency, their environmental impact remains a pressing concern in the modern era. Traditional foundries are energy-intensive operations. The processes of melting metals, preparing moulds, post-processing castings, and managing waste streams demand large quantities of fossil fuel-derived electricity and heat [3]. Globally, the foundry sector has been identified as a major contributor to greenhouse gas (GHG) emissions, not only through direct energy use but also by virtue of upstream activities such as extraction, refining, and transportation of raw materials [4]. In countries heavily reliant on coal-based energy grids and carbon-intensive logistics, the footprint of casting operations becomes even more pronounced. Apart from emissions, the environmental challenges encompass significant generation of solid waste (spent foundry sand, slag, refractory materials), emissions of particulate matter and volatile organic compounds, and extensive water use for cooling and cleaning [5]. These environmental externalities place traditional foundries at the forefront of regulatory scrutiny and transformation, as both policymakers and customers increasingly demand cleaner, greener industrial practices [6].

Considering accelerating climate change and mounting societal pressures, industry has embarked on an unprecedented sustainability journey. In alignment with the Paris Agreement and various national pledges, manufacturers are setting ambitious “net-zero” targets and commitments to reduce or offset their total GHG emissions such that they no longer contribute to atmospheric carbon increases [7,8]. These net-zero goals have catalysed a paradigm shift, reframing manufacturing not just as an economic engine but as a critical participant in planetary stewardship [9]. For foundries and casting operations, the path to net zero introduces both challenges and opportunities. Decarbonising legacy processes often demands innovative approaches that rethink material flows, energy sources, and production methods at the system level. Achieving NZEs requires a holistic reconsideration of every process stage, from raw material extraction and part fabrication to downstream logistics and end-of-life recovery [10]. Technologies that can demonstrably lower environmental challenges while maintaining productivity are now seen as strategic imperatives in forging a more sustainable industrial future.

In the drive for net-zero manufacturing, robust and credible measurement of environmental impacts is essential. LCA has therefore emerged as a promising method for quantifying the environmental burdens of products and processes [11]. Unlike conventional energy audits or simple carbon accounting, LCA encompasses a wide array of environmental indicators, including GHG emissions, energy consumption, water usage, air and water pollution, and resource depletion, systematically mapped across every process boundary. Within the context of casting, LCA enables manufacturers, researchers, and policymakers to pinpoint “hot spots” of environmental impact, evaluate the trade-offs between different process choices, and benchmark innovations against established baselines [12].

To address the intertwined challenges of cost, complexity, and environmental impact in casting, advanced hybrid manufacturing approaches are rapidly gaining traction [13]. In particular, the integration of AM techniques with traditional casting methods, leading to concepts such as AM-SC and AM-IC, offers unprecedented opportunities for process improvement and emission mitigation. AM, often referred to as 3D printing, enables the precise, digitally driven fabrication of complex geometries directly from CAD models, typically by successively layering materials. When synergised with casting, AM can be employed to produce optimised patterns, moulds, and cores, components that profoundly influence casting quality, efficiency, and material use. AM-SC involves the creation of sand moulds or cores using AM technologies (such as binder jetting or selective laser sinter-

ing), replacing or augmenting conventional patternmaking and mould assembly [14,15]. This allows intricate internal channels, reduced waste, faster prototyping, and enhanced near-net-shape manufacturing. AM-IC, on the other hand, leverages AM to fabricate wax or polymer patterns for investment casting shells. These patterns may incorporate designs not feasible through traditional subtractive tooling, and the process potentially minimises pattern waste and shortens lead times. Both hybrid approaches hold promise for improving product performance and manufacturing sustainability, yet their comparative environmental profiles remain ambiguous, especially as AM itself can be energy- and material-intensive [16].

Existing studies have explored the environmental impacts of traditional and advanced manufacturing routes, with many studies focusing either on classical casting or standalone AM processes [17,18]. Recent works have highlighted the potential for energy and material savings in AM-assisted casting, as well as qualitative benefits such as shorter supply chains and lower transportation emissions. There is a notable lack of systematic, side-by-side comparisons between AM-SC and AM-IC from an environmental sustainability perspective. Most of the existing studies consider only technical performance, unit costs, or isolated emissions factors, often under disparate operational assumptions or differing system boundaries [5,19]. As such, manufacturers and decisionmakers currently lack clear, evidence-backed guidelines to select the most environmentally sustainable hybrid approach for specific applications. Much of the LCA work conducted to date has not harmonised input datasets, functional units, or allocation procedures, undermining cross-study comparability. Therefore, there is a critical need for a robust, transparent, and directly comparative “gate-to-gate” LCA analysis that accounts for identical process scopes, material flows, and realistic production scenarios [20,21].

The primary objective of this study is to address the gap by providing a comprehensive, comparative “gate-to-gate” LCA of AM-SC and AM-IC techniques by addressing the following research questions (RQs):

RQ1. To evaluate and compare the environmental impacts of AM-SC and AM-IC through LCA to assess their alignment with net-zero manufacturing objectives.

RQ2. To assess how the integration of renewable energy sources influences the environmental performance of AM-SC and AM-IC and how it contributes to accelerating the transition toward net-zero manufacturing.

RQ3. To deliver LCA-based empirical insights that inform decision-making by policymakers and industry stakeholders in selecting environmentally sustainable casting technologies.

The aluminium alloy Al-Si5-Cu3 (LM04) was selected due to its widespread use in automotive and aerospace components requiring high thermal conductivity, excellent casting properties, and moderate strength. Typical industrial applications include engine housings, pump casings, compressor bodies, and precision tooling components. Its balanced silicon and copper composition allows reliable performance across both sand and investment casting routes, making it an ideal candidate for comparative sustainability assessment.

The remainder of this work is structured as follows: Section 2 presents the literature review; Section 3 outlines the research methodology; Section 4 provides the data analysis and results; Section 5 discusses the findings and their implications; and Section 6 concludes the study, outlining its limitations and suggesting directions for future research.

2. Literature Review

2.1. LCA in Casting and AM

LCA is widely acknowledged as the most effective methodology for evaluating the environmental impact of industrial processes, including both casting and AM [22–24].

In the context of traditional metal casting (such as SC and IC), LCA studies consistently identify high energy use and GHG emissions during melting and moulding stages as primary environmental “hot spots”. These impacts highlight the need for optimisation and decarbonisation in foundry operations [25]. LCA tailored to AM processes has revealed unique trade-offs. While AM may reduce material waste and enable localised production, it often results in higher electricity consumption per part, particularly for metal fabrication. Recent literature reviews have also suggested that the full potential of AM for reducing the environmental impact depends greatly on production volume, part geometry, and material selection, making comprehensive LCA crucial for fair technology comparison [26,27].

2.2. AM-Assisted Casting

Existing studies on integration between AM and traditional casting, specifically AM-SC and AM-IC, have expanded over the last decade. Many studies document how AM integration streamlines the production of complex patterns and moulds, significantly reducing lead times and enabling design innovations unfeasible with conventional tooling [28]. Initial environmental assessments often focus on case studies, suggesting that although AM integration increases energy demand for pattern fabrication, these inputs can be offset by reductions in scrap, material waste, and multi-stage processing. Binder jetting and polymer-based AM processes have proven effective in producing sand moulds and IC patterns with high detail and efficiency. Comparative studies of AM-SC and AM-IC remain limited, most only addressing isolated applications or using varying LCA system boundaries. Table 1 presents a structured overview of past studies, highlighting how LCA is used as a decision-making tool.

Table 1. Structured overview of past studies.

Source	Focus Area	Key Outcomes
[29]	LCA comparison of Wire Arc Additive Manufacturing (WAAM) and sand casting for stainless steel parts.	WAAM and sand casting had similar environmental impacts per kg of stainless steel, while CNC milling exhibited higher impacts.
[19]	LCA of Green Sand Casting (GSC) vs. Low-Pressure Die Casting (LPDC) for AlMg3-TiO ₂ Metal Matrix Composite.	GSC had slightly higher CO ₂ emissions than LPDC, while LPDC offered 17% cost savings.
[30]	Sustainability assessment of AM processes using LCA.	AM reduces material waste and enables localised production but has higher energy consumption.
[31]	Design strategies to eliminate sand casting defects using LCA.	Optimised design reduced carbon emissions by 21–24%, enhancing efficiency and sustainability.
[32]	Effectiveness of 3D printing for mould-making in sand casting.	3D-printed moulds reduced emissions by up to 20%, improved geometrical complexity, and shortened production time.
[33]	LCA comparison of AM and traditional manufacturing for aerospace applications.	AM reduced material waste by 60% but had higher energy consumption per part due to laser sintering.
[34]	Energy consumption analysis of AM vs. sand casting.	AM was energy-intensive, but material savings and design flexibility made it competitive in small-batch production.
[35]	Environmental impacts of binder jetting vs. sand casting for metal components.	Binder jetting showed a 30% reduction in material use and improved recyclability compared to sand casting.

Table 1. *Cont.*

Source	Focus Area	Key Outcomes
[36]	LCA of metal casting vs. direct metal AM for automotive parts.	AM provided weight reduction benefits and lower material waste, but energy consumption was a limiting factor.
[37]	Sustainability evaluation of AM and sand casting in small-scale manufacturing.	AM reduced raw material usage and production waste but required higher operational energy.
[38]	LCA-based assessment of sustainability improvements in AM.	Suggested integrated approaches combining AM with traditional casting to optimise energy efficiency and reduce waste.
[39]	Impact of process parameters on AM and sand casting sustainability.	Process optimisation in AM significantly reduced energy consumption, making it competitive with traditional casting.

2.3. Benefits of AM in Patternmaking

Implementing AM for patternmaking delivers several sustainability and performance advantages. AM facilitates the creation of intricate patterns and core geometries, unlocking lightweight structures, internal cooling channels, and other advanced design features. This design flexibility directly supports the manufacture of functionally optimised castings, often with reduced scrap rates and less excess material [40,41]. Material efficiency is achieved because AM typically builds only the required geometry, in contrast to subtractive processes that generate significant offcuts and waste. AM can eliminate or greatly reduce the need for traditional tooling, a significant environmental benefit, as toolmaking is energy- and resource-intensive. By enabling rapid iteration and deployment without retooling, AM also shortens product life cycles and accelerates innovation.

2.4. Environmental Challenges in Foundries

Despite advancements, foundries continue to grapple with considerable environmental challenges. Energy demand during melting and casting, combined with emissions from metal sourcing and post-casting treatments, positions foundries as significant industrial emitters of CO₂ and other pollutants. Additional environmental issues include the generation of solid waste (such as used sand, slag), air emissions (like volatile organic compounds, particulates), and water use for cooling and cleaning. These factors contribute to regulatory pressures and societal expectations for greener manufacturing. As both traditional and hybrid casting integrate more advanced digital workflows, addressing these pressing environmental challenges remains critical.

2.5. Literature Gaps

AM has increasingly been integrated with traditional casting methods to enhance design flexibility, reduce tooling complexity, and improve overall process efficiency. Among these, AM-SC and AM-IC have shown promising environmental and operational benefits [5,14]. The present work deliberately confines its scope to the comparative environmental assessment of two hybrid processes (AM-SC and AM-IC), to address a critical gap in the existing studies. Most existing studies either contrast conventional casting with additive manufacturing in isolation or compare standalone AM with traditional methods, but very few studies provide a direct, systematic analysis of these emerging hybrid manufacturing approaches under standardised conditions. By focusing specifically on AM-SC and AM-IC for the same alloy, functional unit, and boundary conditions, this work offers clear empirical insights into the incremental sustainability benefits attributable to AM integration. While comprehensive comparisons with conventional SC and IC are informative, recent

reviews and our existing study already establish their baseline performance. Therefore, this focused approach avoids redundancy and maximises the precision and practical value of the findings for practitioners and policymakers seeking evidence-based guidance on the transition to hybrid, low-impact manufacturing routes.

Despite the increasing interest, studies in this area remain fragmented and lack a unified sustainability perspective. Therefore, the following are the research gaps based on the literature:

1. Most existing studies evaluate AM-SC and AM-IC independently, without direct, side-by-side comparisons. This limits the ability to understand their relative sustainability performance.
2. Variations in system boundaries, functional units, and impact categories across studies prevent standardised environmental benchmarking of AM-SC and AM-IC processes.
3. Few studies explicitly assess AM-assisted casting methods in the context of NZEs. As a result, manufacturers and policymakers lack evidence-based guidance for selecting the most sustainable hybrid casting approach aligned with long-term decarbonisation goals.

2.6. Novelty of This Study

This work presents one of the first comprehensive, gate-to-gate LCA studies that directly compares the environmental performance of two hybrid manufacturing processes, AM-SC and AM-IC, for Al-Si₅-Cu₃ alloy. The novelty lies in its holistic evaluation across multiple impact categories using the CML 2001 method under realistic energy scenarios that include India's current grid mix and various renewable energies. It integrates scenario analysis of renewable energy adoption, showing the compounded benefits of process optimisation coupled with clean energy transitions for achieving net-zero manufacturing. By delivering site-specific, data-driven insights tailored to emerging net-zero commitments, this work fills a critical knowledge gap in selecting the most sustainable AM-assisted casting route, offering a practical benchmark and decision support framework for foundries and policymakers aiming to decarbonise metal casting industries.

3. Methodology

3.1. Goal and Scope Definition of This Study

The present work aims to offer a comprehensive comparison of the environmental performance of the AM-SC and AM-IC processes for fabricating parts from aluminium LM04 (Al-Si₅-Cu₃) alloy. By systematically quantifying and comparing their key environmental impacts, this research supports data-driven, sustainable decision-making for foundries and policymakers seeking to align with net-zero manufacturing targets.

Functional unit used in this study: To ensure a fair and practical comparison, the functional unit for this analysis is set as one finished aluminium casting product, weighing 240 g, representative of industrial applications.

The functional unit of one 240 g casting was selected as it represents the average part size for small to medium production batches in Indian foundries using AM-assisted hybrid processes. Although industrial parts often range from kilograms to tons, scaling analyses in prior LCA studies suggest that environmental indicators for casting processes scale non-linearly but proportionally with part weight within the same geometry and alloy family. Therefore, the selected functional unit captures the relative environmental trends of both AM-SC and AM-IC while maintaining data reliability and experimental control.

System boundary: A gate-to-gate analysis is adopted, beginning with patternmaking (using AM for patterns in both processes), proceeding through mould or shell making, metal melting and pouring, and ending with cleaning and finishing of the cast prod-

uct. This boundary focuses exclusively on the environmental impacts arising during the manufacturing phase and excludes upstream activities (raw material extraction, transportation) and downstream stages (product use, end of life). This approach enables the direct comparison of foundry-level process alternatives and emphasises the operational improvements most relevant to net-zero objectives. Figure 1 represents the system boundaries for both processes.

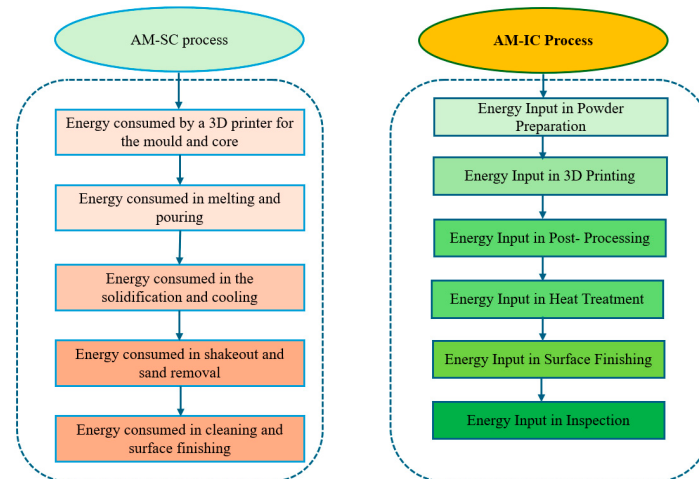


Figure 1. System boundary and energy acquisitions for both processes (source: author’s own work).

Cut-off criteria followed the ISO 14044 mass, energy, and relevance thresholds of 1%. Excluded elements include alloy production, transportation of raw materials, pattern master fabrication for IC, and end-of-life treatment of cast parts. These exclusions are documented to maintain a consistent gate-to-gate focus.

3.2. Life Cycle Inventory (LCI) Data

The LCI involves the detailed accounting of all material and energy flows for both AM-SC and AM-IC. Inputs and outputs at each stage (patternmaking, mould/shell preparation, metal melting and pouring, post-processing) are based on a combination of primary industrial data, experimental measurement, and the validated literature. Tables 2 and 3 represent the LCI data for both processes.

Table 2. LCI data for AM-SC (functional unit: 1 unit (240 g) of aluminium casting).

Process Stage	Material/Energy	Quantity per Unit	Unit	Data Source
Pattern Printing	PLA filament	0.065	kg	Primary + literature
Mould Preparation	Silica sand	2.200	kg	Foundry data
	Sodium silicate binder	0.110	kg	Foundry data
	CO ₂ for hardening	0.220	kg	Literature (AM-SC)
Melting and Pouring	Aluminium LM04 alloy	0.255	kg	Primary
	Electricity (grid mix)	2.85	kWh	Monitored consumption
Finishing	Abrasives and grinding aids	0.045	kg	Process estimates

Table 3. LCI data for AM-IC (functional unit: 1 unit (240 g) of aluminium casting).

Process Stage	Material/Energy	Quantity per Unit	Unit	Data Source
Pattern Printing	PLA filament (master)	0.050	kg	Primary + literature
Pattern Production	Wax (lost-wax)	0.120	kg	Foundry + literature
Shell Preparation	Ceramic slurry (Zircon)	0.450	kg	Foundry data
	Stucco (silica)	0.350	kg	Foundry + secondary
	Colloidal silica binder	0.180	kg	Primary
Shell Burnout	Electricity (grid mix)	3.95	kWh	Process data
Melting and Pouring	Aluminium LM04 alloy	0.260	kg	Primary data
Finishing	Abrasives and polishing	0.055	kg	Foundry average

Materials Used: Patterns/cores: these include PLA filament for AM-based sand casting patterns and wax or polymer for AM-based investment casting patterns.

Mold/Shell Materials: These include silica sand and binders (for sand casting), ceramic slurries (for investment casting shells), and auxiliary materials (e.g., water, cleaning agents).

Metal: Aluminium LM04 (Al-Si5-Cu3) alloy was utilised consistently in both process routes.

Energy Consumption: This includes electricity consumed by AM pattern printing (Fused Deposition Modelling, selective laser sintering, etc.), sand or shell preparation, core baking, and post-processing. There is also energy demand for metal melting (typically electric induction or gas-fired furnaces) and for thermal operations such as dewaxing or mould firing (in AM-IC). All energy values are measured or estimated per functional unit (one part) and normalised to gate-to-gate system boundaries.

Primary Data: This includes site visits, batch-wise recording of raw material and energy use, and production logs from Indian foundries (see Appendix A).

Secondary/Literature Data: This includes established LCI datasets from GaBi 9.2.1, international benchmarking, and previous validated studies.

Inventory data were measured directly from North Indian foundries; all flows were cross-validated per ISO LCA protocols for temporal and regional representativeness. Where regional data were lacking, documented global proxies were used, as detailed in Appendix A.

The modelling employed GaBi 9.2.1 with the following plan names: Electricity Mix India 2023 for grid power, Electricity Mix Wind, and Electricity Mix Solar for renewables. All electricity-dependent processes, printing, shell drying, burnout, melting, and finishing, were uniformly switched to the renewable mix during analysis to ensure scenario consistency.

3.3. Impact Assessment

Environmental performance was assessed using the CML 2001 impact assessment method, widely recognised for its relevance in manufacturing LCA studies. This approach enables the characterisation of environmental challenges across a comprehensive set of categories, ensuring consistency with the ISO 14040 and 14044 standards. The environmental impact factors considered in this study are outlined in Table 4.

Table 4. Description of environmental impact categories.

Category	Unit	Description
GWP	kg CO ₂ eq.	Measures greenhouse gas emissions contributing to climate change.
AP	kg SO ₂ eq.	Emissions causing acid rain and acidification of ecosystems.
EP	kg PO ₄ ^{3−} eq.	Nutrient enrichment of water bodies causing oxygen depletion.
ODP	kg CFC-11 eq.	Emissions contributing to stratospheric ozone layer depletion.
HTP	kg 1,4-DCB eq.	Toxic effects of substances on human health.
FAETP	kg 1,4-DCB eq.	Toxic effects on freshwater aquatic organisms.
MAETP	kg 1,4-DCB eq.	Toxic effects on marine organisms.
TETP	kg 1,4-DCB eq.	Toxic impacts on soil organisms and terrestrial ecosystems.

Each category captures distinct environmental pressures, from carbon footprint to toxicity and local ecosystem impacts, providing a robust basis for comparative analysis. All calculations and scenario modelling were performed using GaBi 9.2.1 software, which provides extensive, up-to-date LCI datasets and validated algorithms for impact assessment. This ensures methodological transparency and repeatability.

4. Data Analysis and Results

In this section, we analyse the LCA data to present the results of the comparative LCA between AM-SC and AM-IC for Al-Si₅-Cu₃ alloy. The assessment is designed to quantify key environmental impacts under various energy scenarios, providing insights into how process characteristics and energy choices influence sustainability performance. The analysis is structured into two main components:

- I. Comparative evaluation of environmental impacts under India's conventional grid mix electricity scenario, including energy consumption, emissions, and toxicity profiles across both the AM-SC and AM-IC processes.
- II. Assessment of how integrating renewable energy sources (wind, solar, hydro, and biomass) alters the environmental performance of each process, highlighting the potential for emission reduction and alignment with net-zero manufacturing goals.

These findings serve to guide process selection, energy optimisation, and sustainability benchmarking in foundry operations aiming to reduce carbon footprints and transition toward net-zero manufacturing. Figure 2 shows the GaBi model for the patternmaking for both processes without recycling.

4.1. Comparative Evaluation of Environmental Impacts Under Grid Mix

The comparative analysis of AM-SC and AM-IC under the grid mix energy scenario shows that AM-SC consistently exhibits superior environmental performance. It achieves notable reductions in environmental impacts across a range of impact categories. Table 5 outlines the percentage reductions achieved by AM-SC in comparison to AM-IC, emphasising its contribution toward achieving NZE goals. These percentage reductions were calculated using Equation (1).

$$\% \text{ Reduction} = \frac{(\text{IF}(\text{AM} - \text{IC}) - \text{IF}(\text{AM} - \text{SC})) \times 100}{\text{IF}(\text{AM} - \text{IC})} \quad (1)$$

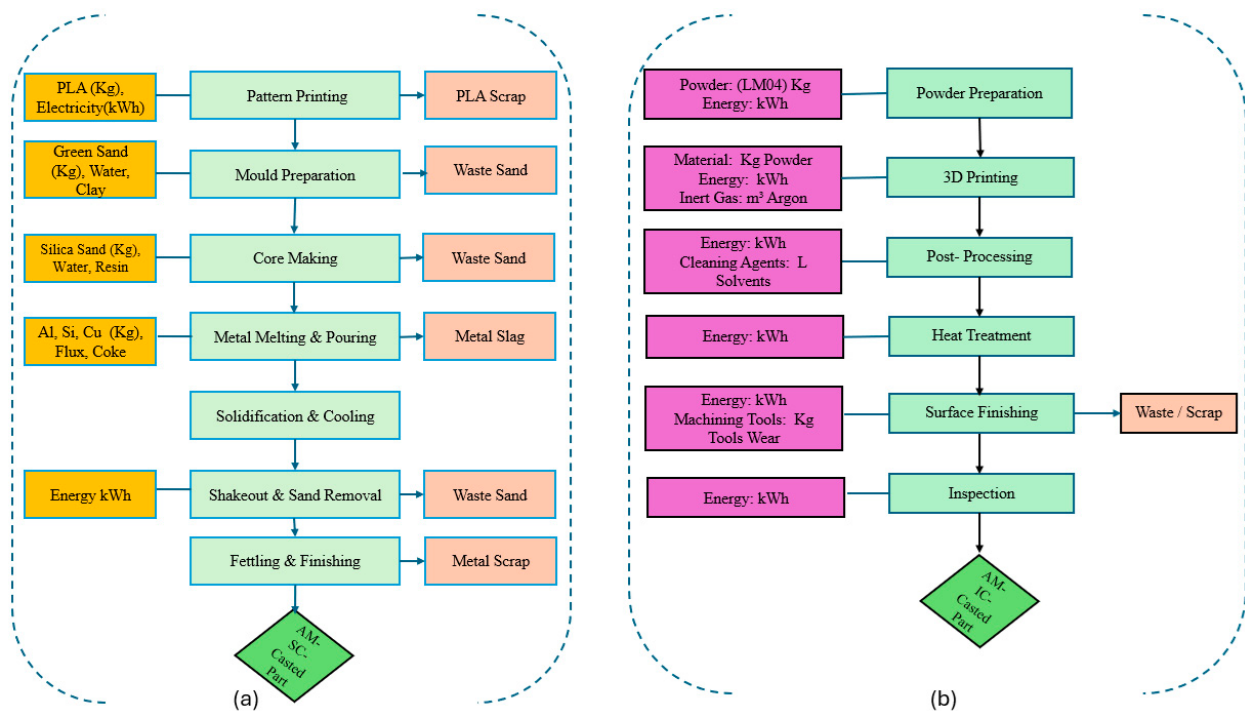


Figure 2. (a) GaBi model for AM-SC. (b) GaBi model for AM-IC. (Source: author's own work.).

Table 5. Environmental impact results (grid mix scenario).

Serial NO.	Impact Category	Unit	AM-SC	AM-IC	% Difference (AM-SC vs. AM-IC)
1	GWP	kg CO ₂ eq.	2.84	4.15	31.57% ↓
2	AP	kg SO ₂ eq.	0.0134	0.0166	19.28% ↓
3	EP	kg PO ₄ ^{3−} eq.	0.00287	0.00364	21.15% ↓
4	HTP	kg 1,4-DCB eq.	0.645	0.604	6.78% ↑
5	TETP	kg 1,4-DCB eq.	0.00265	0.0278	90.5% ↓
6	MAETP	kg 1,4-DCB eq.	0.0441	0.1817	75.73% ↓
7	FAETP	kg 1,4-DCB eq.	0.00388	0.00832	53.34% ↓
8	ODP	kg CFC-11 eq.	1.08×10^{-7}	1.39×10^{-7}	22.3% ↓
Functional unit: 1 aluminium casting (240 g); electricity = Indian grid mix.					

↓ indicates a decrease in percentage, ↑ indicates an increase in percentage.

4.2. Comparative Evaluation of Environmental Impacts Under Renewable Energy

In the completion of the second research question, this work conducted a comparative environmental impact analysis of AM-SC and AM-IC by using LCA as a decision-making tool. The enhancements in Table 6 outline the environmental impact and percentage reduction between the two processes under consideration of renewable energy sources (wind, solar, biomass, hydropower).

Table 6. Environmental impacts of AM-SC and AM-IC under renewable energy scenarios. (Functional unit: 1 aluminium casting (240 g); all values per FU).

Impact Category	Energy Source	AM-SC	AM-IC	% Difference	Impact Category	Energy Source	AM-SC	AM-IC	% Difference
GWP (kg CO ₂ eq.)	Wind	0.048	0.099	51.52	HTP (kg 1,4-DCB eq.)	Wind	0.045	0.034	−32.35
	Solar	0.097	0.181	46.41		Solar	0.089	0.065	−36.92
	Hydro	0.189	0.27	30.00		Hydro	0.142	0.089	−59.55
	Biomass	0.248	0.354	29.94		Biomass	0.178	0.124	−43.55
AP (kg SO ₂ eq.)	Wind	0.00022	0.00044	50.00	FAETP (kg 1,4-DCB eq.)	Wind	0.00056	0.00102	45.10
	Solar	0.00036	0.00071	49.30		Solar	0.00089	0.00149	40.27
	Hydro	0.00058	0.00091	36.26		Hydro	0.00122	0.00188	35.11
	Biomass	0.00089	0.00114	21.93		Biomass	0.00156	0.00213	26.76
EP (kg PO ₄ ^{3−} eq.)	Wind	0.000045	0.000089	49.44	MAETP (kg 1,4DCB eq.)	Wind	0.0063	0.0158	60.13
	Solar	0.000083	0.000151	45.03		Solar	0.0121	0.0294	58.84
	Hydro	0.000105	0.000177	40.68		Hydro	0.0155	0.0342	54.68
	Biomass	0.000131	0.000201	34.83		Biomass	0.0212	0.0427	50.35
ODP (kg CFC-11 eq.)	Wind	1.89×10^{-9}	3.25×10^{-9}	41.85	TETP (kg 1,4 DCB eq.)	Wind	0.00071	0.00333	78.68
	Solar	2.76×10^{-9}	4.69×10^{-9}	41.15		Solar	0.00109	0.00548	80.11
	Hydro	3.56×10^{-9}	5.22×10^{-9}	31.80		Hydro	0.00134	0.00673	80.09
	Biomass	4.23×10^{-9}	6.01×10^{-9}	29.62		Biomass	0.00174	0.00826	78.93

It should be noted that the ecotoxicity and human toxicity categories are highly sensitive to inventory completeness and regional emission factors. Therefore, these results should be interpreted qualitatively, acknowledging potential variability arising from data aggregation and gate-to-gate system boundaries.

5. Discussion and Implications

This work was designed to analyse the environmental sustainability of two hybrid manufacturing processes (AM-SC and AM-IC) for aluminium LM04 alloy, using a gate-to-gate LCA approach. Through a systematic analysis of process-level emissions, resource consumption, and the influence of various energy sources, the study aimed to offer a data-driven perspective on the contribution of these technologies to the broader vision of net-zero manufacturing. Section 5 is structured around the three primary RQs and shows how the study findings align with NZE objectives across the globe.

RQ1. To evaluate and compare the environmental impacts of AM-SC and AM-IC through LCA to assess their alignment with net-zero manufacturing objectives.

The comparative LCA of AM-SC and AM-IC for Al-Si₅-Cu₃, conducted under real-world manufacturing conditions and India's grid electricity mix, decisively reveals that AM-SC holds a clear advantage across most environmental impact categories. AM-SC achieves a substantial 31.57% lower GWP, demonstrating its superior efficiency in minimising GHG emissions, a core metric for net-zero alignment. A similar trend extends to AP and EP, where AM-SC records 19.28% and 21.15% lower impacts, respectively, compared to AM-IC. The benefits are even greater in ecotoxicity-related categories: TETP and MAETP are reduced by 90.5% and 75.73%, respectively, with AM-SC. These substantial reductions can be attributed to fewer harmful emissions from sand and binder use, lower pattern material losses, and more straightforward process flows. Interestingly, HTP emerges as an exception, where AM-IC performs marginally better, likely due to reduced direct contact with sand-related compounds and potentially lower hazardous emissions during shell burnout. Despite this, the overall environmental balance woven by AM-SC aligns more

closely with net-zero objectives, as it consistently delivers lower environmental emissions in categories most relevant to climate action and sustainable resource management. This comprehensive advantage not only positions AM-SC as an environmentally preferable pathway for aluminium casting but also strengthens the business and regulatory case for its broader adoption in decarbonising foundry sectors.

It is acknowledged that environmental impact factors scale non-linearly with the mass of the part due to process energy intensity, melt yield, and furnace efficiency. The 240 g part provides a conservative baseline to evaluate process-level efficiency differences rather than product-scale impacts. Future studies could extend this assessment to multiple mass ranges to establish a generalised scaling function for hybrid AM-assisted casting.

RQ2. To assess how the integration of renewable energy sources influences the environmental performance of AM-SC and AM-IC and how it contributes to accelerating the transition toward net-zero manufacturing.

The analysis of renewable energy scenarios marks an inflexion point in the environmental narrative of both casting routes. Substituting conventional grid electricity with renewables (such as wind, solar, hydro, or biomass) radically transforms the sustainability profile of both AM-SC and AM-IC. The most significant improvement is observed in GWP, where the use of wind energy results in an impressive 98.3% reduction compared to the baseline scenario using grid electricity. This decarbonisation trend extends across all other impact categories, AP, EP, and many ecotoxicity measures, showing substantial declines with the adoption of renewable energy. The environmental gap between AM-SC and AM-IC narrows; however, AM-SC consistently retains its performance advantage, even under renewable energy scenarios. These outcomes deliver a two-fold insight: First, achieving net-zero manufacturing is most effectively driven by the widespread integration of renewable energy, which can transform both conventional and hybrid casting processes into environmentally sustainable options. Second, process-level optimisation, such as selecting AM-SC over AM-IC, provides notable emission reductions on its own, which are significantly amplified when combined with renewable energy sources. The combined effect redefines what is achievable for industrial foundries. Incremental process improvements and systemic energy transitions must operate in tandem to unlock full progress toward decarbonisation and sustainable growth.

Implications of the Study

RQ3. To deliver LCA-based empirical insights that inform decision-making by policymakers and industry stakeholders in selecting environmentally sustainable casting technologies.

The findings of this “gate-to-gate” LCA analysis provide actionable insights for both practitioners and policymakers navigating the road to net-zero manufacturing. The data-driven evidence firmly supports the prioritisation of AM-SC, particularly for applications where large-scale manufacturing, lower complexity, or recyclability of materials is critical. The demonstrable reductions across multiple impact categories offer a compelling argument for its deployment as a low-carbon, resource-efficient alternative in both existing and new foundries. At the same time, the study underscores the necessity for site-specific process selection. Although AM-IC offers advantages in applications requiring high surface quality and complex geometries, its comparatively higher environmental impact across most categories necessitates careful consideration in relation to specific project needs and end-use demands. The adoption of renewable energy emerges as a powerful equaliser capable of reducing, or in some cases nearly eliminating, the environmental footprint of even the more impact-intensive processes. For policymakers, these insights support the development of targeted incentives, modernisation of energy infrastructure, and creation of technology roadmaps that promote both renewable energy adoption and manufacturing

process optimisation. For industry stakeholders, this study offers a solid benchmarking framework and quantifiable environmental performance indicators, enabling informed decision-making and systematic tracking of progress toward India's 2070 NZE goal. This work supports a shift away from reliance on intuition or legacy methods, toward a data-driven paradigm defined by comprehensive environmental assessment, integrated system-level thinking, and a focused commitment to achieving net-zero manufacturing.

Based on the comparative findings, practical decision guidance is proposed to support process selection under different manufacturing scenarios (refer to Table 7).

Table 7. Decision guidance for choosing between AM-SC and AM-IC.

Criterion	AM-SC Preferred	AM-IC Preferred
Geometry complexity	Low–medium	High
Surface finish	Moderate	Excellent
Batch size	Large	Small/medium
Recycling infrastructure	High sand recovery	Efficient wax recovery
Site electricity mix	Renewable or grid	Renewable (for burnout steps)

This guidance aligns environmental and technical criteria to assist manufacturers in selecting the most sustainable hybrid casting route.

6. Conclusions, Limitations, and Future Work

This work presents a comparative gate-to-gate LCA of two hybrid casting techniques, AM-SC and AM-IC, using Al-Si₅-Cu₃ alloy under different energy scenarios. The findings clearly establish that AM-SC is more environmentally sustainable than AM-IC across most impact categories, particularly under India's current grid mix. AM-SC demonstrates 31.57% lower GWP, 19.28% AP, and 21.15% lower EP, among other significant reductions. These results highlight AM-SC's potential as a strategic solution for foundries aiming to decarbonise their operations.

When the processes are powered by renewable energy sources, the environmental impacts for both AM-SC and AM-IC are reduced. The GWP is reduced by over 98% with wind energy compared to the grid mix, and other impact categories, including toxicity and AP, also decrease. Even within this renewable energy context, AM-SC consistently maintains its edge in eco-efficiency. This dual insight confirms that renewable energy adoption and process-level optimisation are complementary levers in advancing toward net-zero manufacturing. This study provides a robust, empirical framework to guide industry leaders and policymakers in selecting environmentally optimal casting techniques. AM-SC proves advantageous for use cases prioritising lower emissions, recyclability, and less intricate designs, while AM-IC remains preferable for components requiring high surface finish quality or complex geometries, albeit with a higher environmental trade-off.

The robustness of this work stems from primary LCI data collection and adherence to ISO 14040/44 for methodological consistency. This ensures credibility and reproducibility. The study's approach and findings can guide practitioners and policymakers in integrating hybrid AM-assisted processes within broader sustainability and decarbonisation strategies.

Limitations and Future Work

The scope of the present study is limited to a detailed comparative analysis of two hybrid processes, AM-SC and AM-IC, due to resource and experimental constraints.

The present work adopted a gate-to-gate system boundary, focusing solely on the manufacturing phase of the AM-SC and AM-IC processes. This boundary was selected to maintain data accuracy and ensure comparability of primary foundry operations. It is

recognised that ecotoxicity and human toxicity are significantly influenced by upstream processes such as raw material extraction and alloy production. The reported magnitudes and rankings may vary under a cradle-to-gate scope. Future research should incorporate cradle-to-gate analysis to capture the full life cycle contributions of upstream stages and validate the robustness of the comparative results. Future work, integrating circular economy models such as closed-loop recycling of patterns and materials, can help refine pathways to achieve NZEs holistically.

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Abbreviations

AM	Additive Manufacturing
AM-SC	AM-Assisted Sand Casting
AM-IC	AM-Assisted Investment Casting
SC	Sand Casting
IC	Investment Casting
LCA	Life Cycle Assessment
NZEs	Net-Zero Emissions
GWP	Global Warming Potential
AP	Acidification Potential
EP	Eutrophication Potential
ODP	Ozone Depletion Potential
HTP	Human Toxicity Potential
TETP	Terrestrial Ecotoxicity Potential
METP	Marine Ecotoxicity Potential
FETP	Freshwater Ecotoxicity Potential
GaBi	Ganzheitliche Bilanzierung (LCA software)
kWh	Kilowatt-Hour
CO ₂ eq.	Carbon Dioxide Equivalent
Al-Si ₅ -Cu ₃	Aluminium Alloy (LM04)

Appendix A. Data Collection Questionnaire

Section and Process Stage	Question/Parameter	Units/Options	Data Required per (240 g) Part
General Information	Name of facility		
	Location		
	Contact person/position		
Patternmaking (AM)	Process type	AM-SC / AM-IC / both	
	AM technology used	FDM/binder Jetting/SLA/other	
	Type and amount of pattern material (PLA, wax/polymer, etc.)	Type (text)/ quantity (kg)	
	Energy used in pattern/core AM printing	kWh	
	Time taken for each pattern/core	Minutes/hours	
	Material waste/scrap generated in AM patternmaking	% of input	
	Pattern recycling (if any)	% recycled	
Mould/Core Preparation (AM-SC)	Silica sand per casting	kg	
	Binder used (type and quantity)	Type/kg	
	CO ₂ or curing agent used	Quantity (kg or m ³)	
	Energy for mould/core preparation	kWh	
	% reclaimed sand used	%	
Shell Preparation (AM-IC)	Ceramic slurry used (type/amount)	Type/kg	
	Stucco (silica) used	kg	
	Binder type and quantity	Type/kg	
	Energy for shell preparation/drying/firing	kWh	
	Number of dips/shell thickness	Number/mm	
Metal Melting and Pouring (Both)	Type and amount of alloy melted	Type/kg (aluminium LM04)	
	Furnace type used (electric, gas, etc.)	Type	
	Energy used for melting/pouring	kWh	
	Flux/additives used (and amount)	Type/kg or L	
Casting/Solidification/Shakeout (Both)	Energy for shakeout/sand or shell removal	kWh	
	Scrap produced (metal/mould) per batch	Amount (kg or %)	

Section and Process Stage	Question/Parameter	Units/Options	Data Required per (240 g) Part
Cleaning and Finishing	Scrap/waste management/recycling practices	Text/description	
	Abrasives/polishing aids used per casting	Type/kg or g	
	Energy consumed during cleaning/finishing	kWh	
	Water or cleaning agent use	L	
Emissions and Wastewater	Air emissions (dust, VOCs, fumes)	Estimated/measured	
	Wastewater or effluent per casting	L (if any)	
	Solid waste disposal method	Landfill/recycled/other	
Utilities and Energy Mix	Source of electricity (grid mix/renewable, % share)	Specify mix	
	Grid emission factor	kg CO ₂ /kWh	
Process Data/Quality	Casting yield (final–input mass)	Ratio or %	
	Defect or rejection rate	%	
	Surface roughness of finished part (Ra)	µm	
	Post-processing requirements		
Other Observations	Process deviations, optimisations, unusual consumption, general notes		

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