The International Journal of Advanced Manufacturing Technology
https://doi.org/10.1007/s00170-026-17666-w

CRITICAL REVIEW

# Strategic sustainability in additive manufacturing: A comprehensive review

**Ismail Fidan**[1] · **Mushfig Mahmudov**[2] · **Kaitlyn Gee**[3] · **A. John Hart**[3] · **Vivekanand Naikwadi**[1] · **Elijah Hudson**[2] · **Seymur Hasanov**[4]

Received: 24 January 2026 / Accepted: 3 February 2026

## Abstract

Additive Manufacturing (AM) has several important attributes including material efficiency, flexibility, and design freedom that justify its consideration as a more sustainable, resource-efficient production technology . Despite the growing body of literature on AM, there remains a lack of comprehensive reviews that strategically integrate environmental, economic, and social dimensions of sustainability within AM practices. This critical review addresses this gap by examining the strategic sustainability components of AM, focusing on Life Cycle Assessment (LCA) methodologies, the role of Design for Additive Manufacturing (DfAM) in resource efficiency, advancements in sustainable materials, and waste minimization strategies. Further, the integration of AM with green energy systems and its contributions to sustainable energy storage and generation are analyzed. The paper also examines operational challenges and opportunities in the AM industry, including energy-intensive processes, scalability, and material limitations, and highlights technological advancements aimed at mitigating these issues. Finally, an operational framework for sustainable AM is proposed, encompassing innovations in information technology (IT), supply chain management, and lifecycle optimization. This comprehensive approach not only reinforces AM's role in advancing sustainability but also provides actionable insights for academia, industry, and policymakers. By synthesizing these elements, this review highlights AM's pivotal role in shaping the future of sustainable manufacturing.

**Keywords** Additive manufacturing · Sustainability · Sustainable design · Sustainable materials · Green energy · Circular economy

---

✉ Ismail Fidan
ifidan@tntech.edu

Mushfig Mahmudov
mmahmudov42@tntech.edu

Kaitlyn Gee
kgee@mit.edu

A. John Hart
ajhart@mit.edu

Vivekanand Naikwadi
vnaikwadi@tntech.edu

Elijah Hudson
ebhudson42@tntech.edu

Seymur Hasanov
shasanov@seas.harvard.edu

[1] Department of Manufacturing and Engineering Technology, Tennessee Tech University, Cookeville, TN 38505, USA

[2] Department of Mechanical Engineering, Tennessee Tech University, Cookeville, TN 38505, USA

[3] Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

[4] Paulson School of Engineering and Applied Sciences, Harvard John A, Harvard University, Cambridge, MA 02138, USA

## 1 Introduction

Sustainability is increasingly recognized as a cornerstone of modern manufacturing, necessitating innovative approaches to balance environmental, economic, and social goals. AM, with its unique capability to build complex geometries layer by layer, has emerged as a promising technology in this context. Beyond its inherent resource efficiency, AM facilitates lightweight designs, reduces material waste, and supports localized production, aligning closely with sustainability principles.

Despite the growing literature on AM, several knowledge gaps remain. Existing studies often focus on single aspects, such as material efficiency, LCA, or design optimization, without integrating environmental, economic, and social dimensions. In addition, operational challenges, including energy-intensive processes, scalability, end-of-life material management, and the practical implementation of sustainable frameworks, are underexplored. This review addresses these gaps by providing a holistic perspective on strategic sustainability in AM and consolidating recent advancements across multiple dimensions.AM can influence industrial production by enabling the creation of high-quality, precision-engineered components at an unprecedented scale [1]. Advanced technologies, such as laser powder bed fusion (LPBF), allow the fabrication of intricate parts with layers thinner than a human hair, meeting the stringent demands of applications such as medical implants, heat exchangers, and aircraft engines. By integrating AM with digital production systems and supporting processes such as post-processing and precision machining, manufacturers can create components that are difficult or impossible to produce with traditional methods [2].

Beyond precision and innovation, AM can make significant strides toward sustainability. The process drastically reduces material waste, especially with energy-intensive materials like titanium alloys, by using only what is necessary to build the part (alongside other consumables). This efficiency can translate to substantial energy savings compared to traditional subtractive manufacturing methods. Additionally, AM accelerates advancements in clean energy technologies, enabling the development of components for more efficient jet engines and future fusion reactors. With its capacity for material efficiency and sustainability, AM is setting new benchmarks for modern manufacturing while supporting the transition to a cleaner, more resource-efficient industrial future [3].

This paper explores how AM can contribute strategically to sustainable manufacturing. Through a comprehensive analysis, the paper delves into key facets of sustainability in AM, including environmental impact assessments [4], design optimization strategies [5], and material innovations. The significance of integrating AM with green energy, as well as the role of advanced operational frameworks in enhancing sustainability, is also discussed.

To ensure a cohesive narrative, the paper is structured into seven sections, each addressing a critical aspect of AM sustainability. The initial section evaluates LCA methodologies applied to AM, emphasizing energy consumption and environmental trade-offs across various processes. Subsequent sections examine the role of DfAM [6] in enabling sustainable practices, the development and application of sustainable materials, and strategies to minimize waste. The paper also explores the integration of AM in green energy systems and energy storage solutions, underscoring its potential to revolutionize green energy technologies [7–9]. Finally, an operational framework is proposed to streamline sustainable practices across the AM supply chain, leveraging innovations such as big data analytics and artificial intelligence (AI).

While several reviews have addressed aspects of AM sustainability, they vary in focus, scope, and depth. To clarify the positioning of this study, Table 1 summarizes the key findings of some recent articles published between 2023 and 2025. This collective synthesis highlights the fragmented nature of current knowledge and underscores the lack of an integrated framework that combines environmental, economic, and operational dimensions. Building on these identified gaps, our review advances the field by offering a holistic perspective, articulating cross-cutting challenges, and proposing a future research agenda.

Although many papers present sustainability concepts in the AM field, this study is distinct in its strategic focus on integrating multiple sustainability dimensions and operational strategies [25]. By addressing these components, this review not only highlights AM's current capabilities for advancing sustainability but also identifies areas for future research and development. The findings aim to inform stakeholders across academia, industry, and policymaking, fostering collaborative efforts toward a sustainable manufacturing future.

## 2 Life cycle assessment for additive manufacturing

Understanding and exploring how sustainability can be maintained in AM begins with LCA. It evaluates the environmental impacts associated with each stage of a product's lifecycle, from raw material extraction to disposal. In the context of AM, LCA highlights critical factors such as energy consumption, material usage, and emissions. By identifying hotspots within these processes, manufacturers can implement strategies to reduce their environmental

**Table 1** Summary of recent articles on AM sustainability and their key findings

| Authors | Article Type | Core Finding | Source | Year |
|---|---|---|---|---|
| Yadav et al. | Research | AM is more sustainable than investment casting, especially when powered by renewable energy | [10] | 2025 |
| Yadav et al. | Research | The main barriers to the sustainable use of smart polymers in AM are end-of-life management and a lack of standardization. | [11] | 2025 |
| Qureshi et al. | Research | Polymer-based smart materials can make AM more sustainable by reducing waste, energy use, and environmental impact. | [12] | 2024 |
| Jayawardane et al. | Review | Sustainability studies in AM need better integration of technical feasibility with environmental, economic, and social assessments. | [13] | 2023 |
| Ferreira et al. | Research | Metal AM technologies are advancing quickly, but their environmental impacts need more precise data for sustainable decision-making. | [14] | 2024 |
| Shah et al. | Review | AM reduces waste and energy use, but its global sustainability is limited by energy optimization, Volatile Organic Compounds (VOC) emissions, and scaling challenges. | [15] | 2024 |
| Rahmani et al. | Research | Metal AM, especially Selective Laser Melting (SLM), supports sustainability by reducing waste and enabling efficient, circular manufacturing in Industry 4.0/5.0. | [16] | 2025 |
| Agrawal et al. | Review | Using eco-friendly, biodegradable materials in AM can improve sustainability, but it still requires further optimization for functionality. | [17] | 2025 |
| Kokare et al. | Review | Current LCA studies show AM's sustainability potential, but they lack full coverage of economic, social, quality, and post-manufacture impacts. | [18] | 2023 |
| Singh et al. | Review | AM in medicine can be sustainable, but clear guidelines are needed to balance environmental, economic, and social impacts. | [19] | 2024 |
| Saqib et al. | Review | Sustainable AM can reduce environmental impact, but challenges in material performance and printing quality must be addressed. | [20] | 2024 |
| Bigliardi et al. | Review | AM improves economic and environmental sustainability through waste reduction, localized production, and energy savings, but its social impacts remain underexplored. | [21] | 2024 |
| Mehta et al. | Research | Optimizing materials, processes, and post-processing in AM can improve sustainability by reducing waste and energy use. | [22] | 2025 |
| Bello et al. | Review | AM can reduce waste and support sustainability through design optimization, recycling, smart manufacturing, and advanced technologies. | [23] | 2025 |
| Chea et al. | Research | End-of-life management in AM is often unsustainable, with low recycling and high energy costs, but process improvements can reduce waste and hazards. | [24] | 2025 |

footprint, ensuring that AM practices align with sustainability objectives.

LCA is a methodological tool for assessing and quantifying the environmental impact of a product's life cycle, including raw material extraction and refinement, manufacturing and processing, use in application, and end-of-life management [26].

Two primary approaches for LCA will be discussed in this section: ReCiPe and unit process life cycle inventory (UPLCI). First developed in 2008, ReCiPe is a specific LCA method that provides a harmonized set of modeling principles and choices, enabling the calculation of the life-cycle impact of a product [27]. The approach condenses life cycle inventory results into standardized indicator scores, including 18 midpoint indicators (e.g., acidification, climate change, ecotoxicity) and 3 endpoint indicators (e.g., damage to human health and ecosystem quality). Initially intended to compare end product alternatives, it has since been leveraged to inform decision-making and policymaking within firms [27].

UPLCI is a set of engineering analysis rules for evaluating the life-cycle inventory of manufactured products, given that the production process for any product can be represented as a set of unit processes that convert plant inputs into product outputs. Following the unit process taxonomy [28, 29] each unit process step – such as drilling holes – is associated with input materials, energy required, losses of materials, machine and material variables, and output to the following processes. Process-specific calculations, such as the time, power, and energy to perform a given manufacturing operation, are presented as a reusable framework.

## 2.1 Overview

LCA studies have been applied to many AM processes, including powder bed fusion (PBF), directed energy deposition (DED), material extrusion (MEX), vat photopolymerization (VAT), and binder jetting (BJ) [30]. Among the literature on environmental analysis of AM processes, it was found that PBF and MEX had the highest volume of papers, and no ecological analyses of sheet lamination were found [31]. Of the 30 papers considered, all reported on energy consumption, while a subset of 15 papers reported on resource consumption, and 11 papers reported on process waste [31].

The energy consumption of AM processes is of high interest, as its quantification is critical for wider industrial adoption of AM. Compared to other inventories, such as consumables consumption, raw material usage, and material required for support structures, energy consumption has received closer attention in the literature [18]. Accordingly, this section compiles available data on energy consumption across processes, materials, and machines. Energy consumption can be expressed as specific energy consumption (SEC, in MJ/kg) or energy consumption rate (kWh/kg). For this section, all energy consumption rates have been converted to specific energy consumption. A graphical representation of reported SEC ranges across additive processes and materials is shown in Fig. 1

Notably, the SEC varies by process as well as material. Producing aluminum components with LPBF is associated with the highest SEC, likely due to the embodied energy of the feedstock material as well as the high electricity requirements for printing.

Gutowski et al. developed a framework for evaluating the energy requirements for manufacturing process equipment as a function of process rate (kg/hr) [33]. Conducting a meta-analysis of prior LCA studies shows that AM processes generally have lower process rates and higher specific energy use relative to conventional manufacturing (CM) processes [33].

In the following sections, we review key LCA studies across common AM processes that showcase novel applications or extensions of the LCA methodology. Many studies focus on process energy consumption, while others capture additional aspects of LCA, such as impact on human health and environmental systems. For each process discussed, SEC values across machines and materials are tabulated. The methods of BJ, DED, and sheet lamination are not considered.

## 2.2 Laser powder bed fusion

The primary LCA categories for LPBF include primary material production, feedstock material production, production phase, and post-processing operations. Primary material production encompasses the extraction of metals and their subsequent processing into ingots. Feedstock material production entails gas atomization and sieving of metal powder. The production phase entails warming the printer, printing through laser scanning, cooling the printer, cleaning the printer, and maintaining the printer. Post-processing operations vary but may include machining to remove parts from the build plate, heat treatment, support removal, and further post-processing. A comprehensive empirical study from Faludi et al. using the ReCiPe Endpoint H/A framework revealed that process electricity consumption dominated environmental impacts for LPBF [34]. Contributions from material waste, argon, machine transportation, and machine disposal were negligible [34].

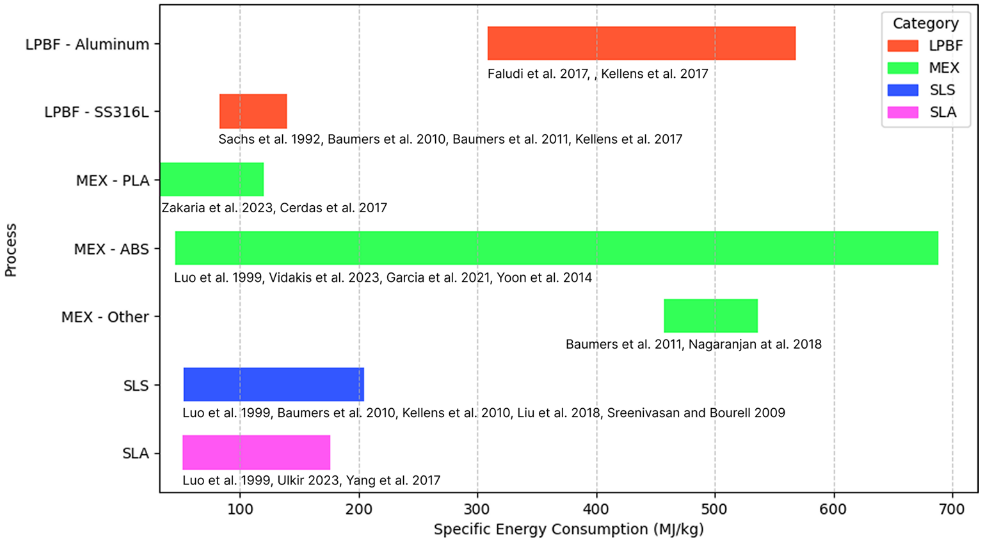


**Fig. 1** Specific energy consumption (MJ/kg) across AM processes and materials. Note that a specific energy consumption of 1247 MJ/kg as reported by Luo et al. [32] for the Stratasys FDM 1650, printing ABS is considered an outlier and is excluded from the MEX-ABS data. PLA: polylactic acid, ABS: acrylonitrile butadiene styrene, SLS: selective laser sintering, and SLA: stereolithography

**Table 2** Specific energy consumption for metallic components produced by AM

| Machine | Material | Specific energy consumption (MJ/kg) | Source | Year |
|---|---|---|---|---|
| Concept Laser M3 linear | SS 316 L | 96.8 | [35] | 1992 |
| MTT SLM 250 | SS 316 L | 111.6-139.5 | [36] | 2010 |
| MTT SLM 250 | SS 316 L | 83–106 | [37] | 2011 |
| Concept Laser M3 Linear | SS 316 L | 423–588 | [37] | 2011 |
| Concept Laser M3 | Stainless steel | 80.32 | [38] | 2011 |
| Concept Laser Mlab | Aluminum | 309.1–533 | [39] | 2017 |
| Renishaw AM250 | AlSi10Mg | 566.2 | [34] | 2017 |

The LCA data for LPBF is shown in Table 2. Specific energy consumption for LPBF ranges from 83 to 588 MJ/kg for steel and 309.1–568.5 MJ/kg for aluminum.

Compared to traditional manufacturing, literature suggests that AM is often less environmentally friendly, or conditionally more environmentally friendly, as measured by SEC and ReCiPe H/A Midpoint scores. Priarone et al. demonstrated that the SEC of LPBF-produced components is greater than that of those produced by traditional manufacturing (i.e., machining), even when components are redesigned for AM [40]. The design methodology used included Topology Optimization (TO), the design of support structures, and the design of allowances and features for post-AM finishing operations. However, considering the energy and carbon dioxide emission savings across the usez phase of the lightweight component, the predicted break-even point for using an AM-based manufacturing process occurred within a few months of component use as an aircraft bearing bracket [40]. An LCA comparison of PBF to casting, machining, BJ, and bound powder extrusion (a novel AM process) revealed that PBF was associated with 9.2% lower carbon dioxide ($CO_2$) emissions than casting when renewable energy was used as the primary source of energy, in part due to mass reduction [41]. Water usage (L/kg), energy consumption (MJ/kg), and $CO_2$ emissions (kg/kg) were reported for each process. In contrast, machining was the least environmentally friendly due to material waste given the initial feedstock size. However, when considering additional environmental impacts such as ecosystem quality, human health, and resource usage, LPBF may be more favorable. Peng et al. conducted a cradle-to-gate study comparing the environmental impact of LPBF to CM for an industrial hydraulic valve using the ReCiPe Midpoint H and Endpoint (H, A) methodologies (Fig. 2) [42]. Valve bodies produced by LPBF had 37% lower environmental impact than CM, and a further 10–23% reduction with LPBF-optimized designs, such as lightweighting and gradient processing. These results indicate that components with lightweight potential may be a compelling vector for reducing environmental impact in LPBF.

A summary of LCA studies comparing LPBF to CM is shown in Table 3.

In summary, LCA studies for LPBF indicate that the process can be environmentally favorable under certain conditions, especially when lightweighting and design optimization are feasible. The resultant material and energy savings, in addition to environmental savings during the use phase for transportation components, result in lower energy and carbon emissions for LPBF.

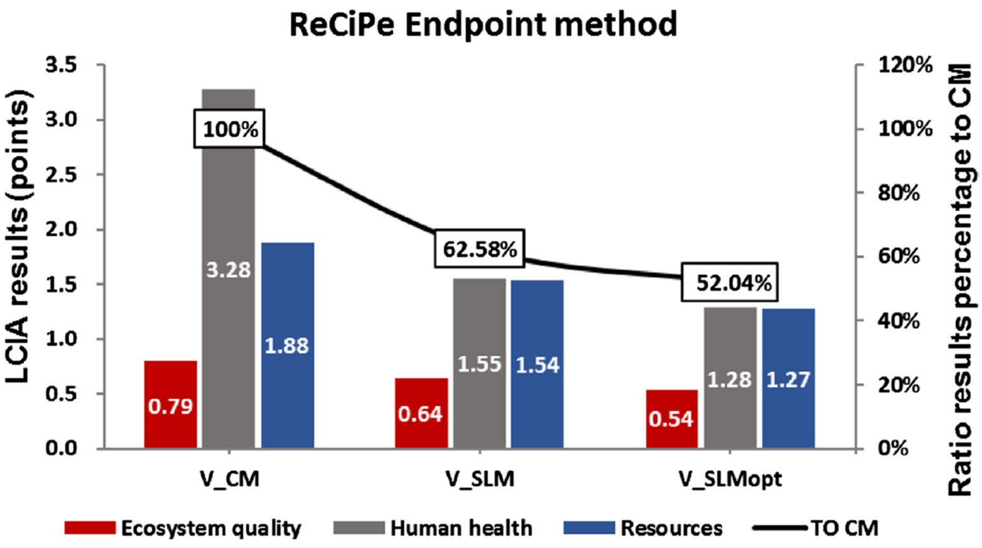


**Fig. 2** Life cycle impact assessment results for three components: V_CM, conventionally manufactured; V_SLM, produced by LPBF; and V_SLMopt, produced by LPBF with an optimized component design. Results show that LPBF has a lower environmental impact based on ecosystem quality, human health, and resources utilized [42]

**Table 3** Summary of LCA studies comparing LPBF to CM

| Comparative process | AM Machine | Material of the AM component | Part description | Key findings | Source |
|---|---|---|---|---|---|
| Subtractive manufacturing (milling) on Al7075 | N/A | AlSi10Mg | Airplane bearing bracket | AM is generally associated with higher energy demand per part. However, if all raw materials derive from primary production (i.e., material recycling is not considered), the AM-based approach consumes comparable or less energy than CM. Lightweighting reduces the environmental impact from material production and the use phase if the component is part of a transportation system and should be considered. | [43] |
| Casting and machining | RenAM 500Q | 17-4PH SS | Double cardan H-yoke (automotive) | PBF had the lowest associated $CO_2$ emissions when renewable energy was used | [41] |
| Casting + CNC milling | Renishaw AM 250 SLM | Stainless steel | Industrial hydraulic valve with complex inner geometry | LPBF had a lower impact by 37% (ReCiPe Midpoint H and Endpoint H, A), due to material and energy savings from lightweighting and design optimization | [44] |
| Investment casting | N/A | Inconel 718 | Aircraft engine turbine blade | 4% lesser carbon footprint for the SLM component due to slightly lower electricity consumption | [45] |
| Subtractive manufacturing | EOS M290 | Ti6Al4V | Femoral stem (medical prosthetic) | SLM had a lower environmental impact due to lower material wastage | [46] |

## 2.3 Material extrusion

For MEX-based AM processes, LCA studies include the preparation and drying of raw material in powder form, the fabrication of filament and its drying, and printing via extrusion of feedstock through a heated nozzle [47]. An original study from Zakaria et al. characterized the current, voltage, and power draw from the mainboard, LED lights, feeder, Z-axis motors, fans, nozzle, blower, and heated bed during the printing process using INA219 and ACS714 sensors. Results revealed that heating the bed accounted for 69% of total energy consumption across the printing process [48].

Vidakis et al. investigated the influence of printing parameters on overall energy printing consumption (MJ), specific printing energy (MJ/g), and specific printing power (kW/g) [47]. Printing parameters included infill raster density, raster deposition angle, nozzle temperature, fused filament printing speed, layer deposition thickness, and bed temperature, using a Taguchi L25 orthogonal array approach. Statistical analysis revealed that printing speed and layer thickness significantly affect specific printing energy, while deteriorating mechanical responses.

The SEC data for MEX is shown in Table 4. Specific energy consumption for MEX ranges from 32.23 to 1247.04 MJ/kg.

A comparative analysis between Fused Deposition Modelling (FDM) and injection molding revealed that FDM had

**Table 4** SEC data for MEX. Values marked with * have been converted from kWh/kg to MJ/kg

| Machine | Material | Specific energy consumption (MJ/kg) | Source | Year |
|---|---|---|---|---|
| Stacker S4 | PLA | 120 | [48] | 2023 |
| Replicator 5th Generation FDM 3D printer | PLA | 32.23–63.79 | [49] | 2017 |
| Intamsys Funmat HT | ABS | 51–679 | [47] | 2023 |
| GTMAX 3D CoreAB 400 | ABS | 45.4–49.46 | [50] | 2021 |
| Dimension 768 SST | ABS P400 | 688.68* | [51] | 2014 |
| Stratasys FDM 1650 | ABS | 1247.0*[a] | [32] | 1999 |
| Stratasys FDM 2000 | ABS | 414.7* | [32] | 1999 |
| Stratasys FDM 8000 | ABS | 83.1* | [32] | 1999 |
| Stratasys FDM Quantum | ABS | 587.1* | [32] | 1999 |
| Stratasys Fortus 400mc | ASA | 457.2 | [52] | 2018 |
| FDM 400 mc | Polycarbonate | 536.00* | [37] | 2011 |

*ASA* acrylonitrile styrene acrylate

[a] The high SEC reported by Luo et al. [32] for the Stratasys FDM 1650 may be partially explained by the low process productivity (0.00381 kg/h). It may therefore not be representative of typical production.

a lower environmental impact when the production batch size was below 14 components, as larger batch sizes amortize the energy consumption of the manufacturing process across more parts (printing ABS on GTMAX 3D CoreAB 400) [50].

Regarding novel applications of the LCA methodology, Winter et al. developed a software-based workflow for machine control, processing, and visualization of sensor signals, parameter variation, and reporting functions that automatically evaluates the product carbon footprint for MEX [53].

## 2.4 Selective laser sintering

Selective laser sintering (SLS) is an AM process for sintering fine polymer powders into solid components using a scanning laser. System boundaries for the environmental footprint of SLS encompass cleaning and preparing the SLS printer, preheating the SLS printer, recoating, laser sintering, cooling down the SLS printer, product breakout, powder filtering, powder replenishment, and powder storage [54]. For consumables, an inert process atmosphere for SLS is typically achieved by a continuous flow of nitrogen or argon. The process uses polymer powder as feedstock, such as the polyamide-based PA11 and PA12.

Kellens et al. conducted a unit process life cycle inventory for the EOSINT P760 machine. They found that laser exposure, recoating, and other productive modes of operation accounted for 87% of total production time, with machine tool cleaning, preheating, and cooling accounting for the remaining time. Applying the ReCiPe Endpoint H/A method, waste materials (powder production and end-of-life treatment) accounted for 41.4% of the environmental impact, while energy accounted for 33.7% [55].

The LCA data for SLS is shown in Table 5. Specific energy consumption for SLS ranges from 52.2 to 204.3 MJ/kg.

A comparative study between SLS (30 Systems ® Sinterstation® HiQ™ + HiS™ SLS machine) and injection molding (IM) found that SLS is energy-favorable for small production volumes, but will have equivalent energy consumption to IM for 150–300 parts, or one to two complete builds, depending on the material of the injection mold [58]. The energy crossover production volumes are smaller than the cost crossover production volume [58].

## 2.5 Vat photopolymerization

LCA studies of VAT include the energy consumption of the laser projector, motor, and computer board [59]. Environmental impacts consider the toxicity of the resins used, as well as liquid and gaseous waste produced during production and cleaning. Mele et al. developed a life-cycle model for a bottom-up SLA Form 2 printer, with Clear 04 resin, including the following equipment: a vat for cleaning parts with isopropyl alcohol, an ultraviolet curing oven, and auxiliary consumables such as resin cartridges, tanks, latex gloves, and plastic vats [60]. Midpoint indicators calculated by ReciPe v.1.1 from a hierarchist perspective (MidPoint H) revealed that the production phase of SLA strongly impacts the EndPoint index of human health. At the same time, ecosystem quality and resource availability are predominantly influenced by the transportation of equipment and consumables [60].

**Table 5** Specific energy consumption for products produced by selective laser sintering.

| Machine | Material | Specific energy consumption (MJ/kg) | Source | Year |
|---|---|---|---|---|
| Concept Laser M3 linear | SS316L | 96.8 | [56] | 2018 |
| EOSINT P760 | PA 2200 | 131.4–143.3 | [55] | 2010 |
| EOSINT P760 | PA 3200 GF | 94.7 | [55] | 2010 |
| EOSINT P760 | PA 3200 GF | 129.8 | [55] | 2010 |
| Sinter-station HiQ+HS | PA (Nylon-12) | 204.3 | [37] | 2011 |
| Van-guardTM HiQ+HS | PA (Nylon-12) | 52.2 | [57] | 2009 |
| Sintersta-tion DTM 2000 | Polymer | 144.3 | [32] | 1999 |

Simon et al. developed a unit-process life-cycle inventory model for VAT, accounting for the energy required to run the projector (i.e., to cure the resin), the motor (i.e., to move the build platform via a stepper motor), the computer, and the control board during production. Per-category energy consumption was measured during the production period and analytically modeled with an accuracy of 83–97%. Empirical results indicate that the projector, in both idling and printing phases, is the dominant power consumer, followed by the computer [59].

The LCA data for VAT is shown in Table 6. Specific energy consumption for VAT ranges from 51.74 to 175.95 MJ/kg.

Ulkir et al. examined the environmental impacts of the SLA process and FDM, including raw material extraction, manufacturing, and recycling [61]. Compared to ABS, PLA, and PETG, UV Resin was the most environmentally friendly material based on midpoint and endpoint indicators, with its recycling stage having the highest environmental impact [61]. Yang et al. developed and validated a mathematical model of SLA energy consumption across different print

**Table 6** Specific energy consumption data for vat photopolymerization

| Machine | Material | Specific energy consumption (MJ/kg) | Source | Year |
|---|---|---|---|---|
| Anycubic Photon Mono X | UV Resin | 51.74[b] | [61] | 2023 |
| Perfactory Micro EDU | LS600M | 175.95 | [62] | 2017 |
| 3D Systems SLA-250[c] | SLA 5170 Epoxy Resin | 116.89[d] | [32] | 1999 |
| 3D Systems SLA-3000 | SLA 5170 Epoxy Resin | 148.97 | [32] | 1999 |
| 3D Systems SLA-5000 | SLA 5170 Epoxy Resin | 74.52 | [32] | 1999 |

[b] As calculated based on a material consumption of 78.63g for UV Resin and a manufacturing energy consumption of 1.13 kWh (see Table 2).

[c] Although an EOM manufacturer is not directly cited in [32], the printer names correlate to legacy printers of the printer manufacturing company 3D Systems

[d] Values for Luo et al. 1999 [32] were converted from kWh/kg to MJ/kg using a conversion ratio of 1 kWh = 3.6 MJ

parameters [62]. Their specific energy consumption of 176 MJ/kg is relatively high compared to other values reported in the literature, in part due to the lower capacity utilization ratio and small layer thickness (0.025 mm) used in empirical experiments. Across all combinations of layer thickness, curing time for stable layers, curing time transition rate, and part orientation, surface roughness is within the 10 µm range, indicating that reductions in energy consumption are possible without compromising part surface quality [62].

## 3 Design strategies

Innovative design strategies are pivotal in maintaining sustainability in AM. Proper DfAM optimizes resource use, reduces the need for support structures, and enables complex geometries that minimize material waste. These strategies not only improve production efficiency but also promote lightweight designs that enhance product performance while reducing environmental impact. By embracing DfAM principles, manufacturers can harness AM's full potential for sustainable innovation.

DfAM is an engineering and design approach tailored to leverage the unique capabilities and advantages of AM technologies. Unlike traditional manufacturing, where designs are often constrained by the process limitations of machining or molding, DfAM focuses on creating components optimized for AM processes [6]. Aligned with the normative framework ISO/ASTM 52910:2018 [63], recent studies [64, 65] emphasize that DfAM not only enables functional integration and lightweighting but can also deliver measurable sustainability benefits such as reduced material use, lower energy demand, and minimized life-cycle impacts.

The incorporation of DfAM into AM techniques, which improve their sustainability, enables the design of lightweight, material-efficient structures. DfAM enables complex geometries and functional integration that reduce resource consumption, in contrast to traditional manufacturing techniques, where design is often constrained by tooling and machining limitations. Additionally, DfAM facilitates product modification to meet specific needs, reducing overproduction and promoting resource efficiency.

While DfAM clearly enables material efficiency, lightweighting, and energy savings, there remain research gaps in its integration with sustainability metrics. Current frameworks often neglect full life cycle perspectives, and comparative LCA data across different AM processes remain limited. Moreover, advanced approaches such as AI-driven generative design (A-DfAM) are still at an early stage, requiring further research to quantify their sustainability contributions and address computational scalability. These gaps highlight opportunities for future work in bridging design innovations with measurable sustainability outcomes.

### 3.1 Fundamentals and methodologies of DfAM

DfAM encompasses methods and tools that integrate AM's technological and geometrical capabilities into the design process [63]. DfAM methods are categorized into design-making, which guides the creation of designs, and design assessment, which evaluates acceptability based on criteria such as cost and manufacturability. These methodologies are crucial for optimizing product outcomes and contribute to sustainable development by minimizing material waste and improving process efficiency [66].

Three primary DfAM methodologies, opportunistic DfAM, restrictive DfAM, and dual DfAM, have been identified by Laverne, Anwer, Le Coq, and Segonds [66] to assist designers. These methodologies were derived from an analysis of 27 peer-reviewed publications on DfAM decision-making methods. Figure 3 illustrates these methodologies, with a pie chart showing their distribution among the reviewed papers. Opportunistic DfAM explores AM's potential for complex geometries and material distribution, enabling lightweight designs that reduce material use and energy consumption. Restrictive DfAM focuses on

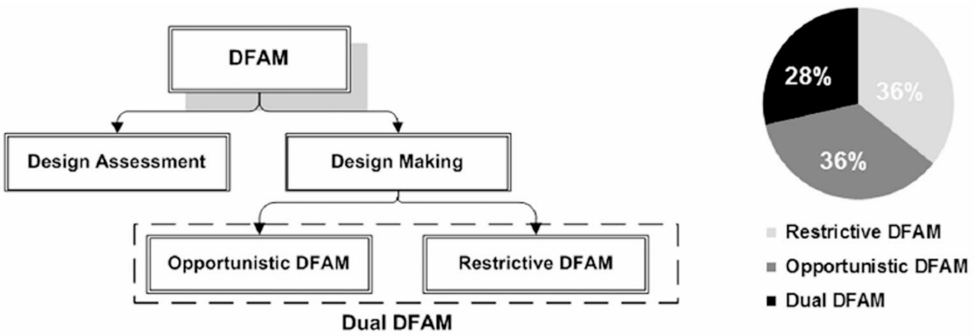


**Fig. 3** Methodologies and distribution of the DfAM practices [66]

the limitations of AM processes, ensuring designs adhere to material and machine constraints and minimizing waste while improving manufacturability. Dual DfAM combines both approaches, balancing creativity and sustainability by optimizing designs within realistic constraints, thereby fostering innovation while reducing environmental impact.

Dual DfAM can be further divided into component-based DfAM (C-DfAM) and assembly-based DfAM (A-DfAM), reflecting the systemic level of the targeted product. C-DfAM focuses on the design of individual components optimized for AM. Two distinct approaches are used: one based on functional features and assembly constraints, and another that starts with a geometric computer-aided design (CAD) model (Fig. 4). The first approach refines designs through topological or parametric optimization, minimizing material use while ensuring components meet functional and performance specifications. These optimized designs reduce material waste and energy consumption, making them inherently more sustainable. Similarly, CAD-based methods that use parametric lattice structures enable designers to minimize material use, thereby reducing environmental impact. While lattices may reduce overall strength, they can be optimized to maintain sufficient mechanical performance for specific applications. By enabling these resource-efficient designs, C-DfAM contributes directly to sustainable development in AM [66].

A-DfAM, on the other hand, focuses on assemblies, the collection of components that together form a complete product (Fig. 5). A key contribution of A-DfAM to sustainable development is the consolidation of components. Reducing the number of parts in an assembly can lead to simpler, more efficient manufacturing processes, less material waste, and faster production times. A-DfAM methods focus on optimizing the design of assemblies to minimize both the number of parts and their environmental footprint, contributing to the broader sustainability goals of AM. Although A-DfAM methods are less developed, accounting for only 12% of the examined publications, their potential to reduce resource consumption and streamline manufacturing processes makes them a critical avenue for promoting sustainable practices in AM.

## 3.2 Topology optimization

Topology Optimization (TO) is a cutting-edge design methodology that determines the most efficient material distribution within a given design space to meet performance goals under specific constraints. It minimizes material use while maintaining structural integrity, enabling the creation of lightweight, high-performance designs. The integration of TO with AM enhances this capability, as AM can fabricate the complex geometries generated by TO, including intricate lattice structures, which are key to achieving sustainability in engineering and manufacturing [67].

There is a distinction between Generative Design (GD) and TO. TO focuses on creating a single, optimized design that meets specific constraints and objectives, prioritizing structural integrity. It is typically used when the solution space is defined, and the goal is to make the design as lightweight as possible. In contrast, GD generates multiple design options in an evolutionary process and is used when the entire shape is unknown, allowing the program to explore various possibilities to find the best solution [68]. Lattice structures, characterized by networks of interconnected cells or struts, exemplify the synergy of TO and AM. These structures offer exceptional strength-to-weight ratios, thermal efficiency, and energy absorption capabilities, making them ideal for applications in aerospace, automotive, medical implants, and energy systems [67]. As illustrated in Fig. 6, TO and AM were utilized to design a cable mount for the front spar of the vertical stabilizer. This innovative approach replaced a traditional component comprising over 30 separate parts with a single integrated part, achieving a 30% weight reduction and significantly shortening construction and installation times [67]. Similarly, the antenna bracket for RUAG's Sentinel satellite (Fig. 7) serves as another notable example of the practical application of TO. The optimized component's weight was reduced from 1.6 kg to 940 g [67].

For instance, lattice-filled aerospace brackets reduce weight by up to 17% while improving dynamic response (Fig. 8), and medical implants mimic natural bone porosity

Fig. 4 Process Flow of C-DfAM [66]

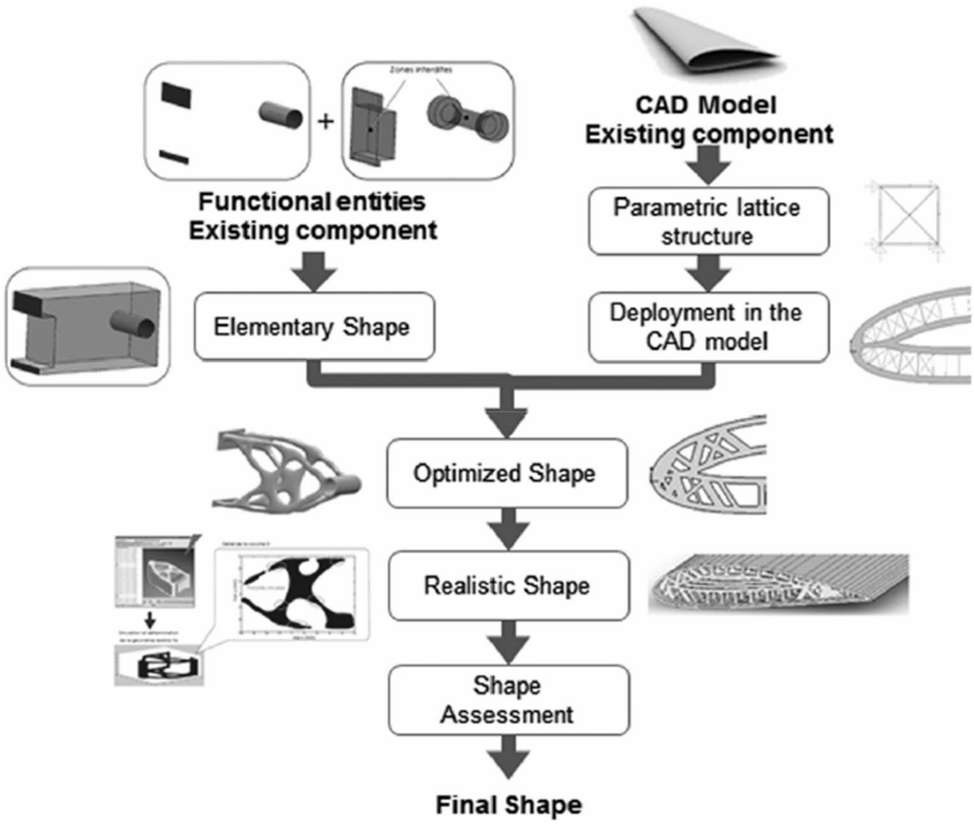
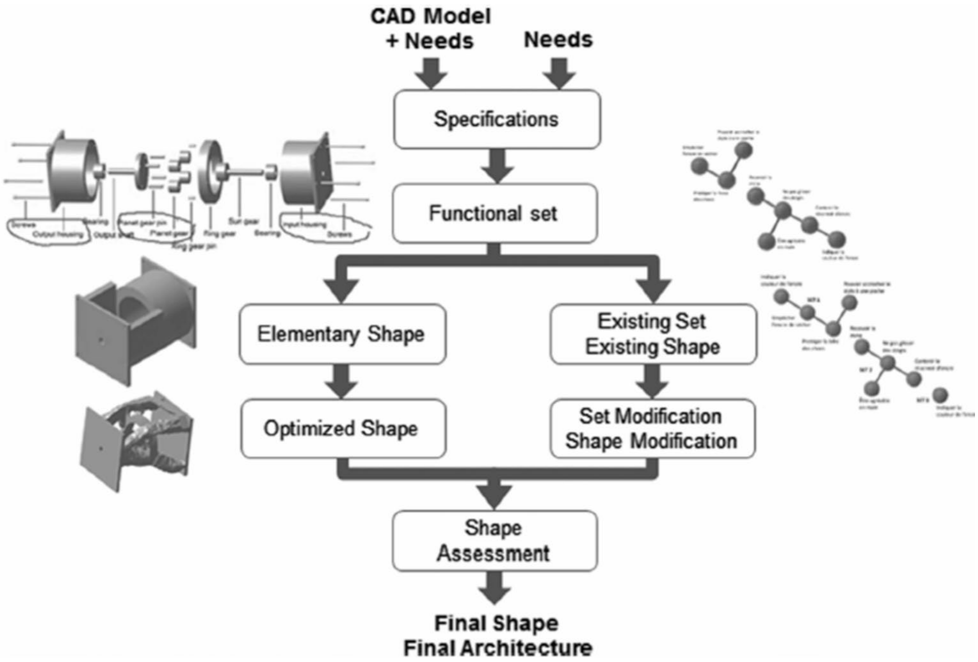


Fig. 5 Workflow of C-DfAM [66]



to enhance biocompatibility and patient-specific customization. In thermal applications, lattice structures are used to optimize heat transfer and energy dissipation, contributing to the efficiency of heat exchangers and vibration-damping systems [67].

The integration of TO, lattice structures, and AM directly supports sustainability by reducing material waste, energy consumption, and the carbon footprint of production processes. TO-driven designs minimize resource usage while maintaining or enhancing performance, leading to lighter

**Fig. 6** Airbus A350 cable mount [67]

vehicles and aircraft that consume less fuel, energy-efficient heat exchangers, and durable, customized medical implants that improve patient outcomes with minimal material input. Furthermore, AM eliminates the need for mold and tooling, reduces transportation requirements through localized production, and supports the use of recycled or renewable materials. Together, TO and AM offer a pathway to sustainable innovation that addresses the dual challenges of high-performance design and environmental responsibility. For example, Munk and Miller [69] applied density-based TO to a load-bearing aircraft component, achieving a 46% weight reduction (from approximately 17.9 kg to 9.7 kg) while maintaining a fatigue life of over 1.4 million cycles. This weight savings, enabled by AM-friendly geometry, directly supports fuel efficiency and reduced in-service emissions. Similarly, Liu et al. [70] demonstrated that a topology-optimized hinge arm produced via AM resulted in a 30% reduction in mass and a nearly 50% decrease in life-cycle $CO_2$ emissions compared to CM, emphasizing the long-term environmental benefits of TO-enabled lightweighting.

### 3.3 Generative design

The new generative DfAM (G-DfAM) method, designed to address research questions, combines the liberties and limitations of AM. It integrates existing DfAM methods, particularly C-DfAM, and shares similarities with the GD process. GD refers to technologies that suggest or optimize design options based on user-defined criteria [72], automating part of the design process to save time and allowing designers to focus on setting parameters. TO is a key tool in GD, optimizing material layout within a design space to achieve desired properties such as weight reduction or improved stiffness [73].

AM and GD exhibit significant synergy [74]. AM enhances GD's potential by enabling the production of parts with organic, complex shapes that are difficult to manufacture using traditional methods. An example of different GD options is shown in Fig. 9. Combining AM with GD leads to optimized parts that are faster and more cost-efficient to produce. Moreover, AM enables the consolidation of multiple components into a single part [76], simplifying production, reducing costs, and improving efficiency [73].

As a case study, GM and Autodesk engineers at GM's Tech Center in Michigan used GD to reimagine a seat bracket in Fig. 10. The software generated over 150 design options, leading to a new organic structure that is 40% lighter and 20% stronger than the original [75].

**Fig. 7** Three stages of the TO for the Antenna Bracket for RUAG's Sentinel Satellite [69]

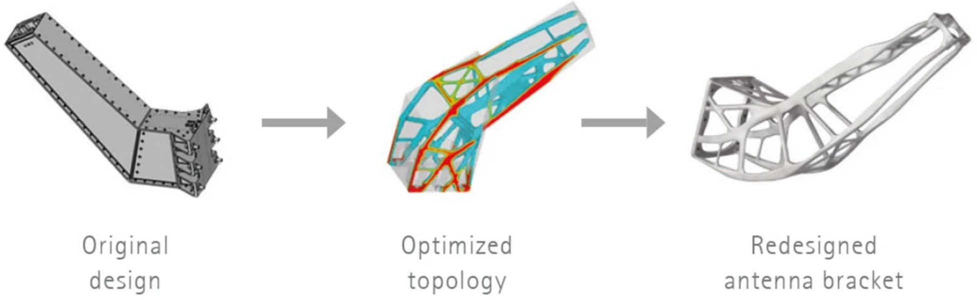


**Fig. 8** Lattice-filled Airbus A350 cable mount [67]

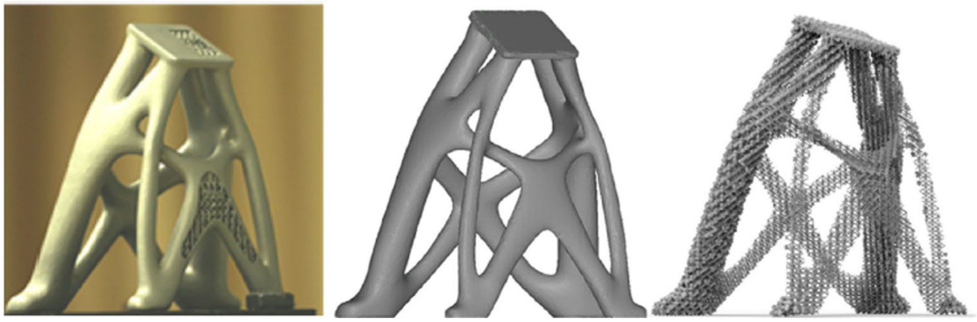


**Fig. 9** Various design alternatives for the same General Motors seat bracket, generated by Autodesk's GD tool [75]

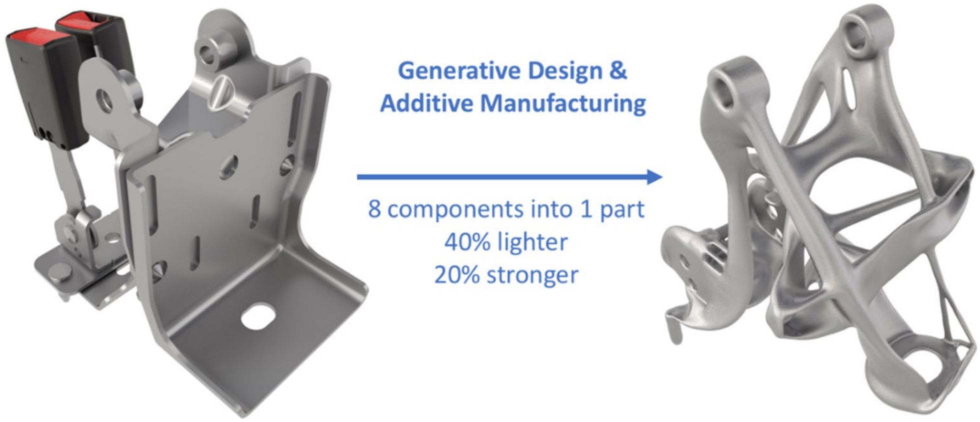


**Fig. 10** The seat bracket [75]

In 2014, a team led by Arup developed a process for 3D printing structural steel joints (Fig. 11) in collaboration with CRDM/3D Systems, WithinLab, and EOS. The prototypes, initially planned to be produced in stainless steel, were made using additive laser sintering in maraging steel, which offered higher strength than anticipated, enabling greater material reduction. The most efficient node used 75% less material than a traditionally manufactured one. While only scaled prototypes were printed, this project suggests future possibilities for 3D-printed structural components. The main limitation is machine size, but as demand grows, larger machines will likely be developed, reducing weight and costs in building elements, transportation, and installation [78].

### 3.4 DfAM tools

By eliminating iterative design reviews and increasing efficiency, the DfAM workflow is streamlined through the integration of CAD, computer-aided engineering (CAE), and computer-aided manufacturing (CAM) tools (Fig. 12). These tools help create lightweight, high-performance parts by supporting sophisticated techniques like TO and lattice infill optimization [5, 6]. AI-driven capabilities are being progressively added to contemporary software platforms, enabling real-time feedback on design modifications to enhance sustainability and manufacturability.

Several powerful DfAM tools have emerged, each offering specialized capabilities:

- nTopology provides field-driven design, lattice optimization, and reusable workflows ideal for architected materials in aerospace, biomedical, and energy sectors [79, 80].
- Autodesk Fusion integrates GD with simulation and CAM, offering manufacturability analysis and sustainability insights [81].
- Altair Inspire is widely used for conceptual design, enabling TO, motion simulation, and stress analysis within a user-friendly interface [82].

Another widely adopted platform in DfAM is Rhinoceros (Rhino), paired with its parametric design plugin Grasshopper. This combination enables designers to develop highly

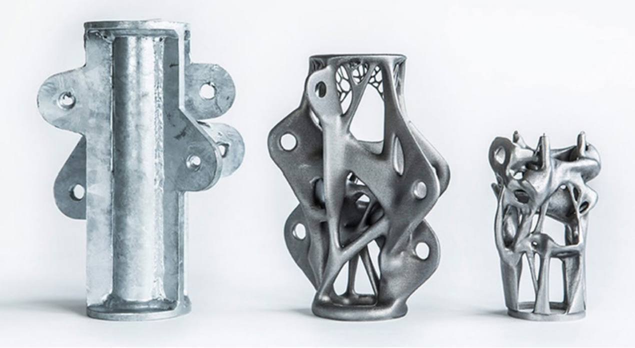


**Fig. 11** The three structural steel components depicted are each engineered to withstand the same loads and forces [77]

customized, complex geometries such as gradient lattices, gyroid structures, and metamaterials through algorithmic design logic. Grasshopper's visual programming interface supports rapid prototyping and design iterations, which is especially valuable when exploring spatially varying properties or simulating material behavior across complex domains [83].

Moreover, plugins such as Millipede, Kangaroo, and Crystallon extend Grasshopper's capabilities into areas like structural optimization, physics-based simulation, and lattice generation for AM. Rhino + Grasshopper is particularly suited for experimental and architectural AM parts, and is increasingly used in biomedical scaffold generation, aerospace structural components, and art-inspired engineering forms.

In summary, the integration of advanced DfAM tools, including TO and simulation platforms such as ANSYS and Altair Inspire, GD environments like nTopology and Fusion, and algorithmic modeling systems such as Rhino with Grasshopper, enables engineers to create high-performance, lightweight, and sustainable components. These tools streamline the AM workflow while supporting lifecycle assessment, process simulation, and real-time design feedback, making them critical for environmentally responsible and manufacturable product development.

The incorporation of DfAM into AM techniques, which improves their sustainability, enables the design of lightweight, material-efficient structures. Table 7 provides a comparative overview of DfAM methodologies, highlighting their applications across AM processes, associated benefits, limitations, and sustainability implications.

While this section highlights the sustainability advantages of DfAM, several limitations remain. First, quantitative sustainability metrics are inconsistent: although weight and material savings are frequently reported, energy consumption and carbon footprint reductions are rarely standardized across studies. Second, the integration of sustainability considerations into automated DfAM workflows

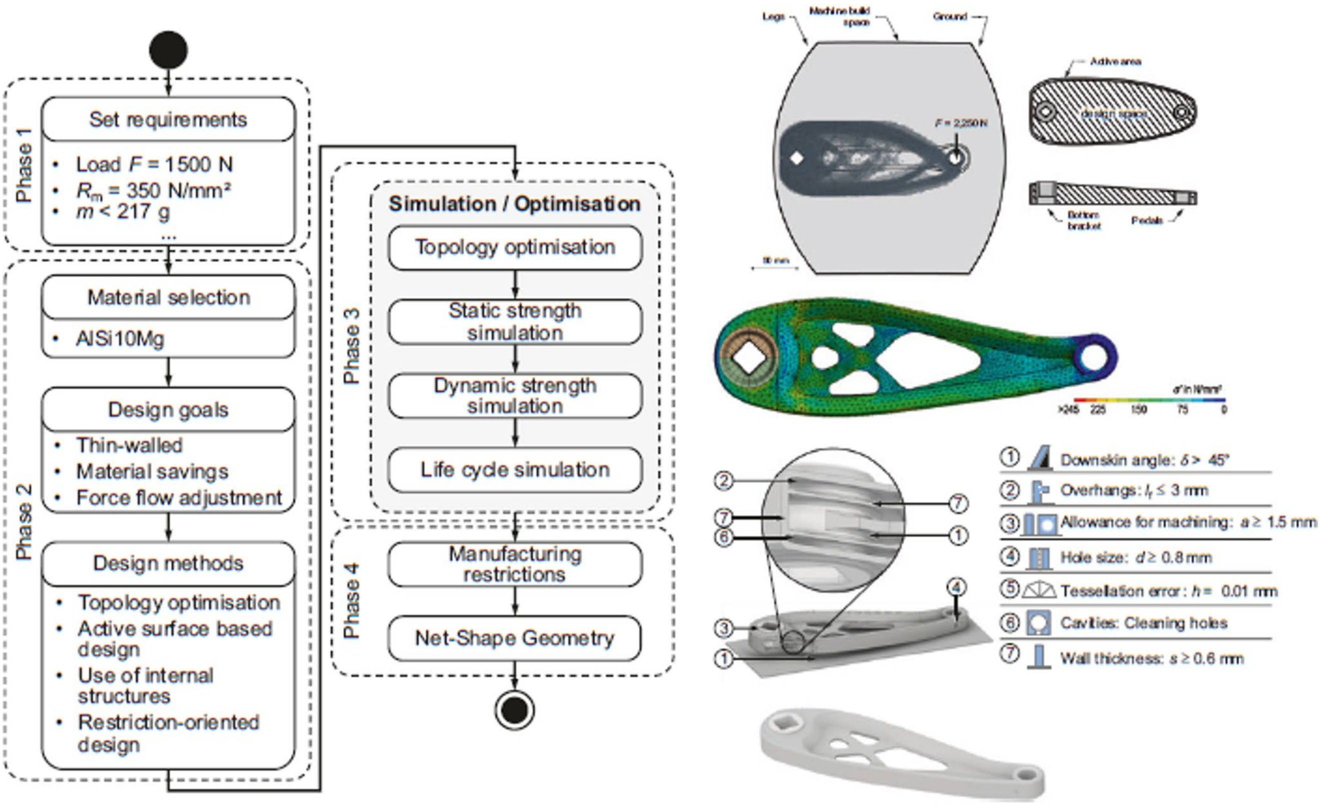


**Fig. 12** The structured approach to optimizing part geometry and process efficiency in AM [6]

**Table 7** Comparative overview of DfAM methodologies, applications, and sustainability implications

| Methodologies | Processes | Key Benefits | Limitations & Challenges | Sustainability Implications |
|---|---|---|---|---|
| **TO** | PBF, MEX | Reduces weight, enhances structural efficiency | High computational cost, manufacturability constraints | Up to 40–60% material savings; reduced $CO_2$ footprint |
| **GD** | PBF, BJ, MEX | Creates multiple design alternatives; improves performance | Requires advanced software; validation complexity | Lightweighting leads to 20–30% energy reduction |
| **Lattice & Cellular Structures** | PBF, VAT | Enables lightweight, high-strength components | Complex to model; limited standardization | Significant material savings (up to 50%) and recyclability improvements |
| **Support Structure Optimization** | PBF, DED | Reduces material waste, build time, and post-processing | Process-specific; not yet standardized | 20–30% reduction in material and energy consumption |
| **Multi-objective & Simulation-driven Optimization** | All processes | Balances strength, cost, and sustainability objectives | Requires advanced computational resources | Enhances overall efficiency and reduces overproduction |
| **A-DfAM** | Emerging across processes | Real-time adaptive design, predictive sustainability outcomes | Still in early development; data-intensive | Potential to integrate LCA metrics directly into design workflows |

remains limited, constraining scalability and broader industrial adoption. Third, comparative analyses across ASTM AM process categories are scarce, making it difficult to generalize conclusions beyond isolated case studies. Finally, the connection between DfAM approaches and life cycle assessment (LCA) frameworks remains fragmented, underscoring the need for standardized evaluation methodologies that capture environmental, economic, and social sustainability dimensions.

## 4 Material selection

The selection and configuration of materials are critical in optimizing AM processes. Using bio-based, recyclable, or energy-efficient materials can substantially minimize the environmental footprint of these processes [84]. Advancements in material science have facilitated the development of high-performance materials that offer both durability and environmental sustainability. Careful material selection further supports AM's contribution to a circular economy and the efficient use of resources. There has been growing concern about the environmental impact of traditional petroleum-based polymers, conventional metals, and resins used across different industries [85]. This section discusses the significance of material configuration in reducing environmental impact, improving material characterization, and addressing cost factors, as well as the non-toxic and safety perspectives of metals, polymers, resins, and composites, as shown in Fig. 13 [86]. The early innovation and industrialization of sustainable metals, polymers, resins, and composites provided researchers and practitioners with a strong foundation for developing environmentally responsible AM solutions. Understanding the life cycle of materials management and monitoring material consumption trends will provide information to determine how to satisfy material needs at acceptable economic and environmental costs, assisting both regionally and globally [87].

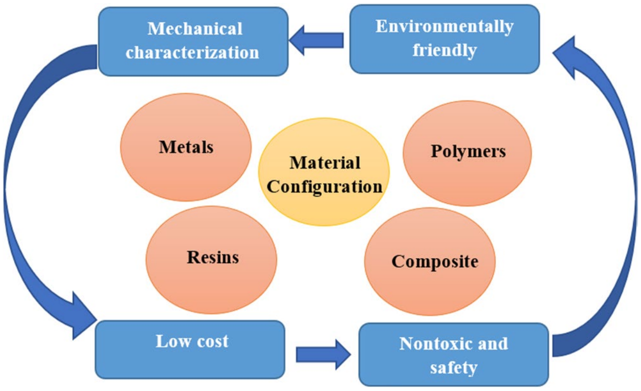


**Fig. 13** Material configuration

As the AM landscape evolves, the integration of composites and ceramics signifies demand for advanced, multifunctional materials tailored to meet diverse industrial demands [88]. Table 8 provides a summary of each material category, including its subcategories and primary applications, along with insights into how these materials contribute to sustainability.

### 4.1 Metals

Metals such as titanium and aluminum alloys, stainless steel, nickel-based superalloys, copper, and magnesium

**Table 8** Commonly used AM materials, their categories, and applications

| Material | Types | Subcategories | Application | Insights into material |
|---|---|---|---|---|
| Metals | Aluminum | AlSi10Mg | Automotive, aerospace | Sustainable metals 3D printing is an emerging, highly specialized application in AM, currently used mainly for medical applications such as temporary implants and devices [88]. |
| | Stainless Steel | 316 L, 17−4 PH | Tooling, medical devices | |
| | Nickel Alloys | Inconel 625, Inconel 718 | High-temperature applications | |
| | Cobalt-Chrome Alloys | CoCr | Dental and orthopedic implants | |
| Polymers | Thermoplastics | PLA, ABS, PETG | Prototyping, consumer goods | Protein–polymer conjugates are widely used in medicine, biotechnology, and nanotechnology [89]. |
| | High-performance Polymers | PEEK, Ultem | Aerospace, medical devices | |
| | Thermoplastic Elastomers | TPU, TPE | Flexible parts, wearable devices | |
| Resins | Photopolymers | Standard Resin, Tough Resin | Prototyping, dental models | Current innovations in sustainable resin use for 3D printing focus on enhancing biodegradability and recyclability, and on reducing the carbon footprint [90]. |
| | Castable Resins | Castable Wax Resin | Jewelry, dental casting | |
| | Engineering Resins | High Temp Resin, Durable Resin | Functional prototypes, tooling | |
| Composites | Fiber-reinforced Polymers | Carbon Fiber Reinforced Polymer (CFRP), Glass Fiber Reinforced Polymer (GFRP) | Automotive, aerospace | Carbon fiber-infused polymers possess a sophisticated structure that makes them highly suitable for high-performance thermal applications. Their unique composition allows them to withstand elevated temperatures while maintaining strength and durability. This capability makes them ideal for use in industries that require materials to perform under extreme conditions [91]. |
| | Metal Matrix Composites | Aluminum MMC, Titanium MMC | High-performance structural components | |
| | Ceramic Matrix Composites | Silicon Carbide (SiC) Composites | High-temperature applications | |

alloys are widely used in engineering due to their high performance and versatility in producing complex components with reduced material waste and enhanced design flexibility [92]. While these metals are mostly conventional materials for industrial use, they are reengineered and enhanced for AM processes to improve mechanical performance, corrosion resistance, and printability. This is not inherently low in environmental sustainability, for instance, titanium [84, 93]. It is an energy-intensive material to produce. Researchers are exploring sustainable pathways such as powder reuse, in-process recycling, and design for minimal material use to improve the overall sustainability profile in AM. Additionally, AM is rapidly advancing toward multi-material metal printing, enabling graded structures and enhanced functional integration. However, current research on bio-based and hybrid materials is primarily concentrated on polymer systems, with relatively limited exploration of metal–ceramic or metal-carbon combinations aimed at reducing weight and improving sustainability in load-bearing structural applications [94].

As illustrated in Fig. 14, sustainable metal 3D printing represents a significant advancement in AM. This innovative technology is primarily utilized in the medical sector for creating temporary implants and devices. Sustainable metals comprise magnesium, iron, and zinc-based alloys that offer significant benefits. Chua et al. highlight that steel alloys demonstrate approximately 10% higher tensile strength than magnesium and zinc alloys under identical mechanical loading conditions, underscoring their potential for improved performance in medical applications. Incorporating sustainable metals into 3D printing could transform the industry while advancing environmental sustainability [95]. Voet et al. reported that magnesium alloys have moderate mechanical properties but are suitable for applications requiring weight reduction. Zinc alloys offer good strength to corrosion resistance, with excellent recyclability and 20% lower energy consumption in processing over magnesium and iron alloys, and are also ideal for die casting of components [96]. Sezer et al. noted that iron alloys generally have a higher environmental impact due to their larger

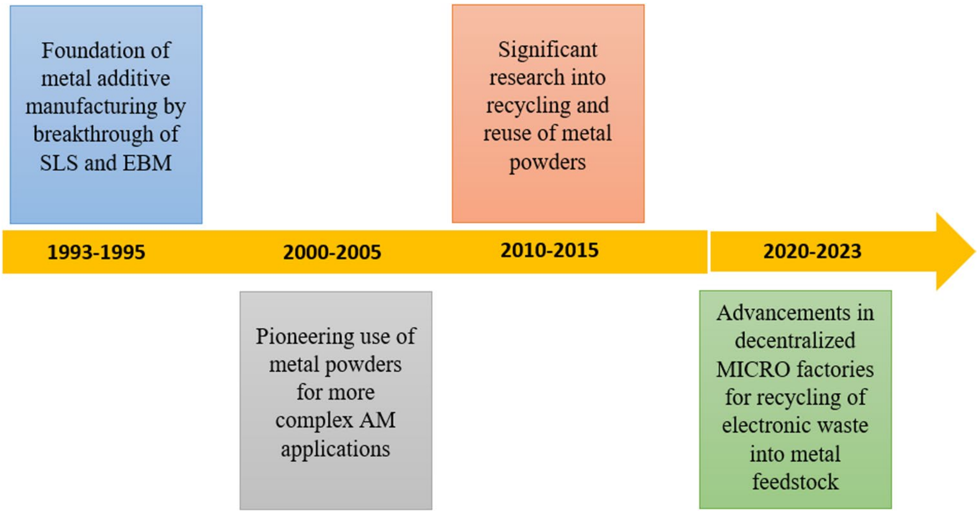


**Fig. 14** Timeline diagram of sustainable metals

carbon footprint compared to magnesium and zinc alloys. However, extensive recycling can significantly mitigate this impact, reducing the carbon footprint by up to 70% for iron alloys, 60% for magnesium alloys, and as much as 85% for zinc alloys. In terms of biodegradability, magnesium alloys are the most degradable, potentially losing 90–95% of their mass within a year under optimal conditions. Zinc alloys follow, with a mass loss of 50–70%, while iron alloys are the least biodegradable, degrading by only 10–30% over the same period. Environmental factors such as chloride exposure, high humidity, direct water contact, and acidity can further accelerate degradation and reduce the overall sustainability of these materials [97].

Li et al. suggested that, when evaluating the safety characterization of sustainable metals like zinc and iron alloys, several factors must be considered, including reactivity, handling hazards, and toxicity. Magnesium alloys are very reactive when finely divided or in powder form. Additionally, they ignite easily and burn rapidly with a white flame; hence, careful handling is required to avoid sparks and static electricity. Generally, magnesium is stored in a dry and cool environment away from oxidizing agents. Prolonged exposure to iron oxides and zinc powder can lead to siderosis, respiratory, and gastrointestinal issues; thus, proper safety precautions and respiratory protection should be recommended when handling these toxic metals [98]. Magnesium alloys have higher operating and processing costs than zinc and iron alloys, primarily due to their high energy demands, reactivity, handling challenges, and specialized production methods. Currently, biodegradable metals account for approximately 8% of all materials used in AM, with projections suggesting this could rise to 15% by 2030. Among these, magnesium and its alloys are the most used biodegradable metals in AM [99].

## 4.2 Polymers

Current innovations in sustainable polymer usage for AM focus on enhancing biodegradability, recyclability, and reducing carbon footprint [100]. Trends in the field include the development of bio-based polymers, such as PLA, polyhydroxyalkanoates (PHA), and polycaprolactone (PCL), which decompose naturally and minimize environmental impact. Moreover, advancements in polymer composites, incorporating recycled materials and reinforcing agents, support the production of sustainable yet robust 3D-printed products [101]. As sustainability gains traction across industries, the integration of these innovative polymers into AM signifies a shift towards greener, more responsible production practices [102].

Sustainable polymers are most likely to replace harmful conventional petroleum-based plastics, which have caused numerous environmental impacts, including pollution (marine, atmospheric, and soil) and global warming [103]. Zheo et al. noted that the tensile strength of organic-based polymers ranges from 50 to 70 MPa. In comparison, starch-based polymers have a tensile strength of 10 to 30 MPa, cellulose has a strength of 20 to 40 MPa, and protein-based polymers range from 5 to 30 MPa. Due to these mechanical characteristics, organic-based polymers have become increasingly popular in AM. Organic-based polymers have a hardness of 60–80 on the Shore D scale [104], which is higher than that of many other polymer materials. Among biodegradable plastics, PLA is widely available and can safely decompose after use, minimizing environmental pollution [105]. PLA is a polymer composed of repeating units of lactic acid, a naturally occurring organic compound. PLA is considered biodegradable under appropriate conditions, such as in composting facilities or anaerobic digestion systems [106].

### 4.3 Resins

In the evolving AM, sustainable resins, both thermoplastics and photopolymer-based, have become integral to advancing eco-manufacturing [107]. Sustainable resins are emerging as pivotal materials, driving a shift toward eco-conscious production. Sourced from renewable resources or recycled feedstocks, they combine environmental sustainability with high-performance outcomes [108]. Current innovations in sustainable resin use for AM focus on enhancing biodegradability and recyclability, and on reducing the carbon footprint. Trends in the field include the development of bio-based resins, such as plant-derived PLA and PHA, renowned for their biodegradability and minimal environmental impact [109].

Cellulose-based resins derived from plant fibers are recognized for their renewable, sustainable properties. Although these materials are still emerging within the AM market, their biocompatibility makes them promising candidates for medical and environmentally focused applications [110]. Starch-based resins are derived from natural starches (e.g., corn and potato) and are often blended with other biodegradable polymers to improve mechanical properties and printability [111].

### 4.4 Composites

Composites, formed by combining polymers, metals, or ceramics, are valued for their superior mechanical properties and customizable functionalities. Recent advances in 3D printing of composites emphasize the optimization of material combinations and process parameters to achieve greater strength, durability, and lightweight performance [90]. Concurrently, ceramics, known for their high-temperature resistance and excellent mechanical properties, are gaining traction in AM.

AM has opened up new integration of continuous fibers, nanoparticles, and reinforcement phases within polymer matrices to produce high-performance composites suitable for aerospace, automotive, and biomedical applications. Additionally, hybrid composites combining metals and ceramics are being researched to meet multifunctional requirements, such as electrical conductivity and thermal stability, using multi-material printing platforms [112]. Researchers are increasingly developing functionally structured composites with spatially tailored properties. Recent studies demonstrate that these next-generation composites can outperform traditional materials by offering enhanced structural performance alongside improved sustainability and resilience.

## 5 Applications of AM that promote sustainability and energy efficiency

AM has significant applications in renewable energy that directly support sustainability goals. By supporting localized, on-demand production, AM shortens supply chains, reduces transportation-related emissions, and minimizes material waste [9]. Across energy sectors, it enables the fabrication of complex, cost-effective, and customizable components that enhance performance and reduce production costs [113]. While these benefits are broadly applicable, the following subsections highlight sector-specific applications in wind, solar, hydropower, nuclear energy, and energy storage, where AM directly improves efficiency and cost reduction (Fig. 15) [113].

### 5.1 Wind turbines

AM can localize production, reduce supply chain length, and decrease transportation costs, offering significant supply chain and logistics benefits for the wind energy sector [114]. AM's potential applications in the wind industry include:

#### 5.1.1 Blade molds

The US Department of Energy and Oak Ridge National Laboratory (ORNL), in collaboration with TPI Composites, fabricated a 13-meter wind turbine blade mold using the big-area AM system (Fig. 16), cutting fabrication time from months to days and significantly reducing costs. The mold incorporated integrated heating channels, thereby improving composite curing efficiency [115].

#### 5.1.2 Nacelle covers

Nacelle structures gain significant advantages from AM-enabled features, including integrated wireways, airflow channels, and structural bases. The ORNL's AM Integrated Energy project showcased nacelle components with functionalized designs (Fig. 17), enhancing performance while reducing part count and manufacturing complexity [116].

#### 5.1.3 Towers

GE Renewable Energy, COBOD, and Holcim pioneered on-site 3D printing of concrete turbine tower bases (Fig. 18). This approach enables taller towers, reduces logistics challenges, and improves energy capture efficiency by accessing higher-altitude winds [117].

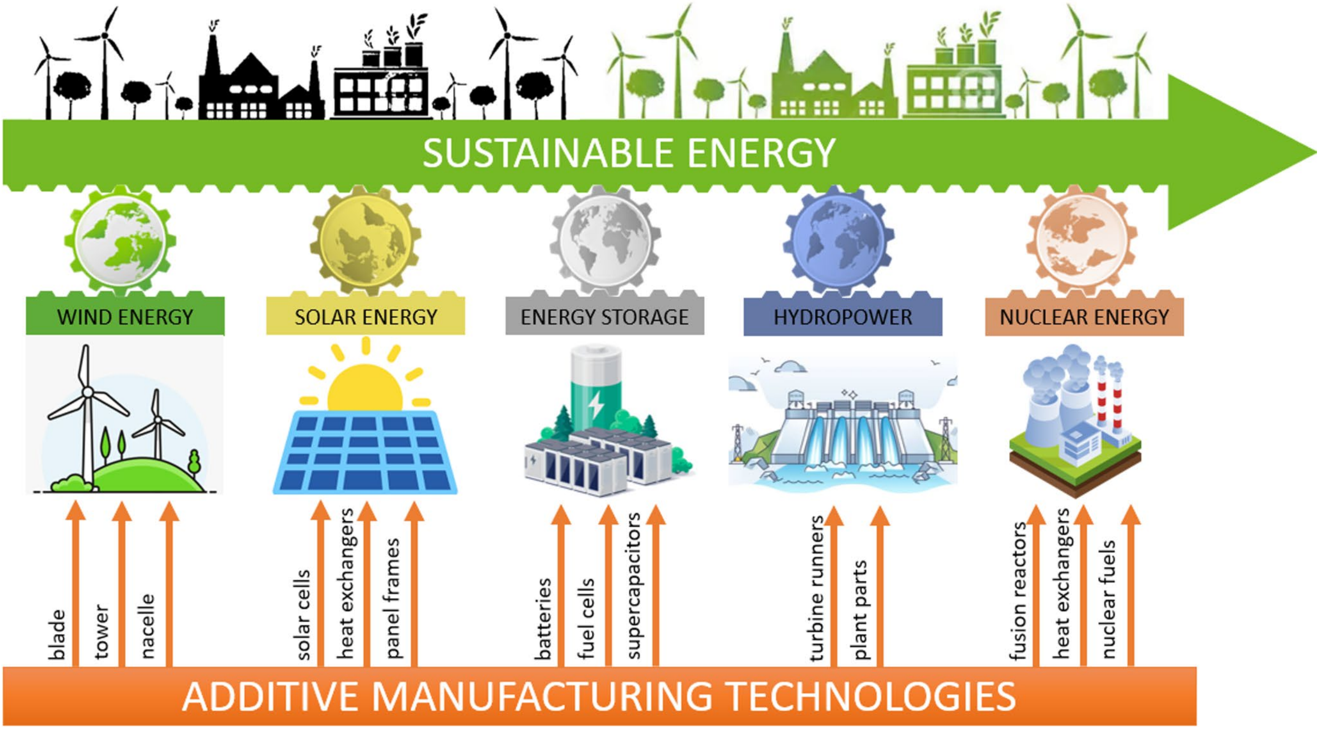


**Fig. 15** Integration of AM in Sustainable Energy

**Fig. 16** ORNL/TPI AM blade mold [115]

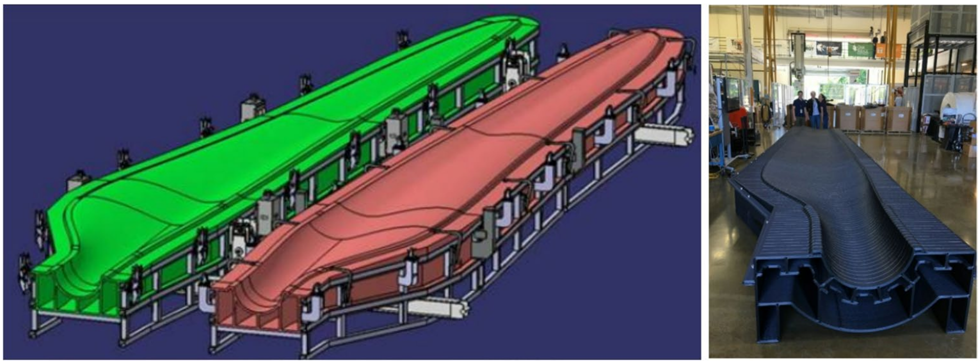


**Fig. 17** Nacelle Structure [116]

#### 5.1.4 Magnets

AM has also been applied to bonded magnet composites, in which magnetic powder is embedded in non-magnetic matrices (Fig. 19). This reduces the use of rare earth materials while maintaining magnetic performance, addressing supply risks in the wind sector [116].

While wind applications emphasize large-scale structural benefits, solar energy relies on micro- and nanoscale AM precision to improve efficiency.

### 5.2 Solar panels

In solar energy, AM enables precise deposition and microscale structuring of components to improve light absorption and reduce cost [9]. One of the key applications

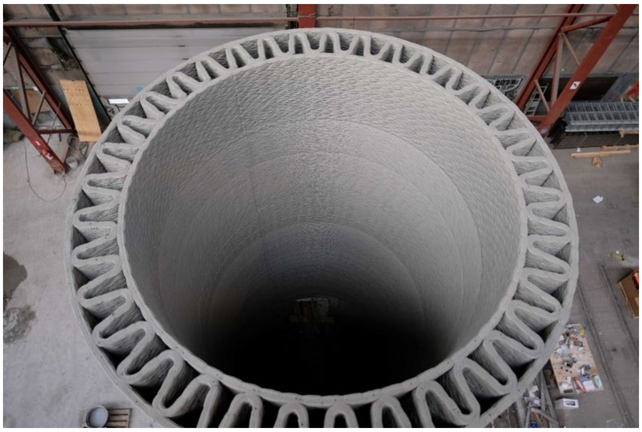


**Fig. 18** 3D printed wind tower base Sect [116].

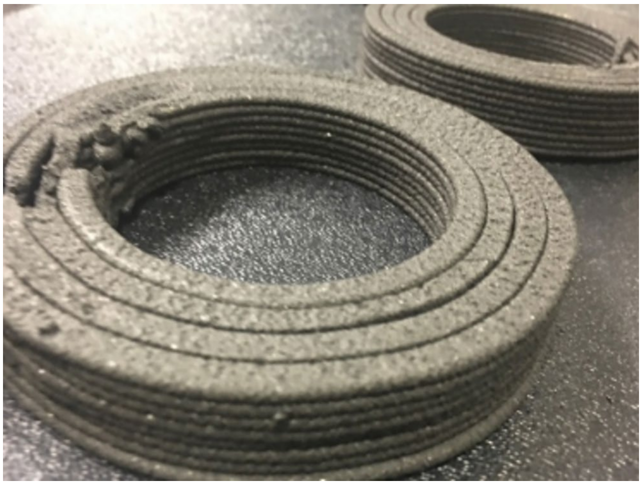


**Fig. 19** Printed Magnets [116]

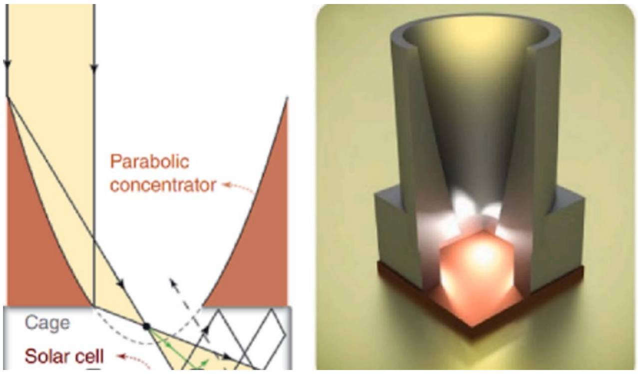


**Fig. 20** Schematic illustration of the external light trap [119]

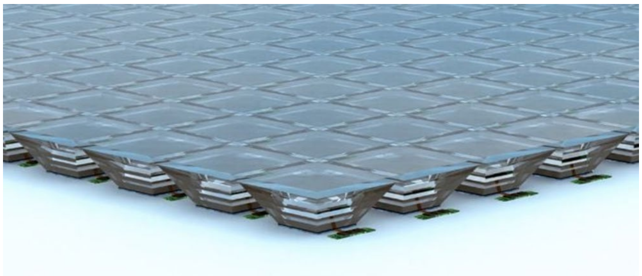


**Fig. 21** Inverted pyramid-shaped solar cells [121]

of 3D printing in solar energy is the production of solar cell parts [118] and light-trapping structures (Fig. 20) [119]. These structures enhance the efficiency of solar cells by improving their ability to capture and convert sunlight into electricity. Techniques such as micro/nanoscale 3D printing [4], including electrohydrodynamic printing (EHDP), Direct Ink Writing (DIW), two-photon lithography, and projection micro stereolithography (PμSL), have been employed to achieve high-resolution, complex geometries previously unattainable. These methods enable the creation of intricate designs that optimize light absorption and improve overall solar cell performance [9].

Moreover, 3D printing technology can be integrated with roll-to-roll (R2R) and sheet-to-sheet (S2S) manufacturing systems, enabling the mass production of solar cells on flexible substrates such as transparent plastics and metallic foils. This integration helps meet the growing demand for solar energy solutions while reducing manufacturing costs and material waste [9].

Stanford University developed a 3D-printed concentrator called the Axially Graded Index Lens (AGILE) [120], a pyramid-shaped optical device that collects sunlight from any angle without mechanical tracking (Fig. 21) [121]. This innovation simplifies system design while lowering production costs and improving solar panel efficiency [121].

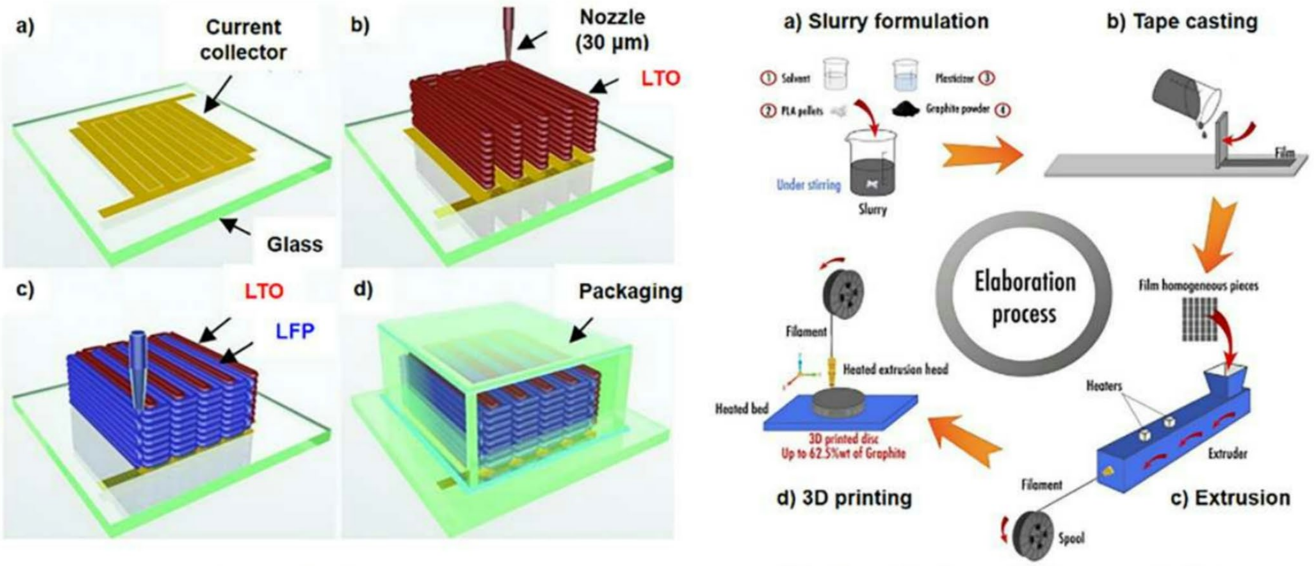
## 5.3 Energy storage

Beyond power generation, AM is also transforming energy storage technologies, enabling renewable energy to be managed and dispatched more effectively.

AM improves electrochemical and thermal storage devices by enabling 3D microstructures that enhance transport properties, power density, and life cycle. In lithium-ion batteries, techniques such as DIW [122], FDM [123], and Digital Light Processing (DLP) [124] have been used to fabricate interdigitated and bicontinuous electrodes (Fig. 22) [125]. These techniques reduce ion diffusion lengths and improve energy density.

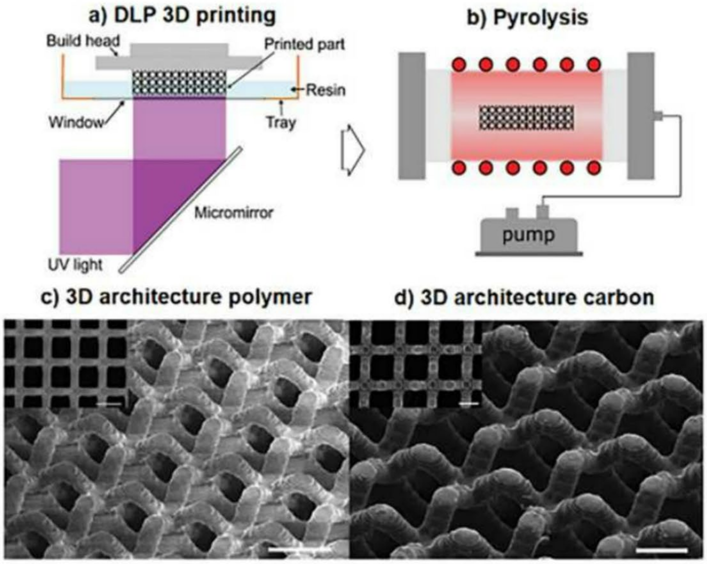
Fuel cells also benefit from AM through precise fabrication of thin-film electrolytes and bipolar plates, reducing costs while increasing power density. Techniques such as Inkjet Printing [126, 127], SLA, and SLS [128] are commonly used.

In supercapacitors, DIW-printed porous microstructures improve charge–discharge rates and energy density, enabling integration into applications such as wearable electronics [129]. In parallel with advancements in



(a) Direct ink writing

(b) Fused deposition modelling



(c) Digital light processing

**Fig. 22** AM techniques for lithium-ion battery manufacturing: (a) DIW, (b) FDM, (c) DLP [125]

electrochemical storage, hydropower facilities are leveraging AM for durable, large-scale, and cost-effective components [125].

### 5.4 Hydropower

AM also offers significant advantages for low-head hydropower [130]. Together, Oak Ridge National Laboratory (ORNL) and Cadens LLC evaluated the potential of AM for these systems at the Rome Mill plant in Wisconsin. A tube-turbine system was installed, incorporating AM-fabricated components, including the intake adapter, draft tube, and turbine housing (Fig. 23). Complex geometries were optimized during the design phase using computational fluid dynamics simulations.

They used the Large Format AM process to create significant components, such as the draft tube, which employed a clamshell design to eliminate the need for internal supports [131]. A DOE-funded project with ORNL and TVA is

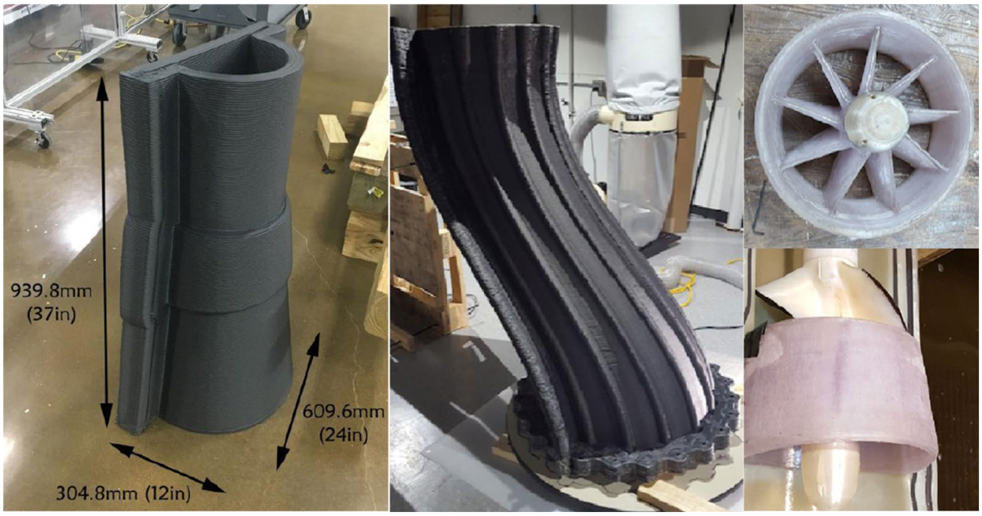


**Fig. 23** 3D printed hydropower plant parts [131]

**Fig. 24** Large-scale Francis runner concept [132]

**Fig. 25** Pelton turbine runner fabricated using Wire Arc AM [133, 134]

developing a hybrid AM process to print significant metal components directly, aiming to cut lead times by 50% for hydropower turbines (Fig. 24) [132].

Similarly, Wire Arc AM has been used to fabricate Pelton turbine runners at a significantly lower cost than traditional forging and machining (Fig. 25) [133, 134].

Beyond renewable systems, AM also contributes to nuclear energy, where reliability, safety, and rapid prototyping are essential.

### 5.5 Nuclear energy

AM enables fabrication of intricate nuclear components that reduce assembly complexity, improve material performance, and cut lead times [135].

The construction of nuclear reactor core structures may be improved by using various AM methods, including BJ, laser-directed energy deposition (L-DED), electron beam melting (EBM), and SLM. Although these techniques are not currently widely used to produce nuclear power plant components, they have the potential to reduce production time and costs drastically. Additionally, they can simplify complex assemblies into single components and enhance performance and safety by tailoring materials and refining designs to provide greater strength where it is most needed [136].

At ORNL, the Transformational Challenge Reactor project produced a 3D-printed reactor core prototype within 40 h at temperatures up to 1400 °C using DED (Fig. 26), demonstrating accelerated development of advanced reactor systems [137].

A French multinational company, Framatome, has developed and successfully installed a 3D-printed stainless-steel fuel assembly component (Fig. 27) at a Vattenfall nuclear power facility in Forsmark, Sweden. This is a significant accomplishment for Framatome, which created a top-end grid intended to retain fuel rods and keep large debris out of the assembly. The component, produced using 3D laser printing technology, represents a first for the company. However, specific details about the printing process have not been disclosed [138].

Using cutting-edge 3D printing techniques, USNC, a Seattle-based company, is creating novel designs that are tailored for special materials, including Fully Ceramic

**Fig. 26** 3D-printed Reactor Core by ORNL [137]

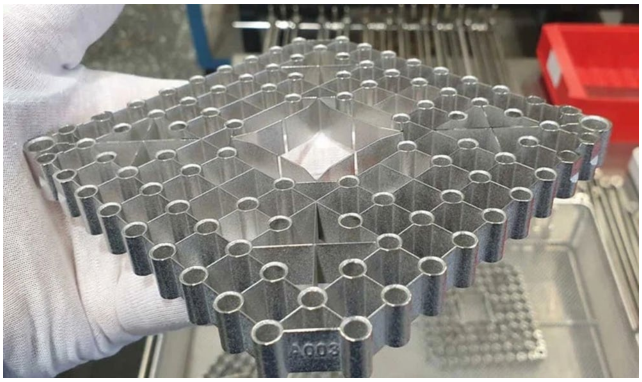


**Fig. 27** 3D-printed fuel assembly component by Framatome [138]

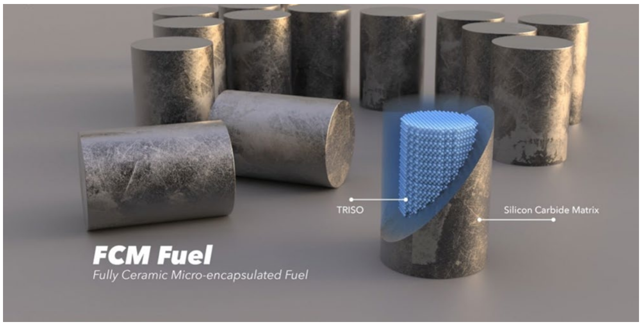


**Fig. 28** USNC's innovative FCM Fuel [139]

Micro-encapsulated (FCM) fuel (Fig. 28). USNC can produce ceramic particles that improve heat resistance by encasing conventional nuclear fuel using Desktop Metal's X-Series BJg 3D printers [139].

Across wind, solar, storage, hydropower, and nuclear sectors, AM delivers results that traditional methods cannot match. It enables faster blade mold fabrication, more efficient solar concentrators, higher-density batteries, durable hydropower components, and safer nuclear fuels. Together, these applications highlight AM's critical role in advancing sustainable energy infrastructure by reducing costs, enhancing performance, and minimizing environmental impact.

## 6 Sustainable infrastructure development for additive manufacturing operations

A practical operational framework for AM combines technological innovation with supply chain management. Utilizing big data analytics, AI, cybersecurity, Virtual Reality (VR)/Extended Reality (XR), and responsible supply chain practices improves resource efficiency, lowers environmental impact, and supports lifecycle assessments for ongoing improvement [140, 141].

### 6.1 IT innovations

An adequate AM infrastructure combines digital innovations with evidence-based supply chain strategies. While Big Data, AI, VR/XR, and blockchain offer promising ways to reduce energy use, waste, and emissions, their success relies on measurable metrics, lifecycle assessments, and transparent evaluation of trade-offs [142–145]. Cybersecurity measures, especially blockchain technology, safeguard design files such as G-code from tampering and unauthorized access. Zhangyue et al. reported a 40% reduction in cyberattacks when using blockchain, significantly improving trust and data integrity in AM systems [146]. Figure 29 illustrates how cyber-physical attacks can alter design parameters, highlighting the critical need for secure data infrastructures.

Throughout AM processes, AI and machine learning (ML), combined with data-driven monitoring, enhance defect detection, enable adaptive control, and support predictive maintenance, benefits consistently documented in recent reviews and case studies. In quality control, supervised ML models often achieve over 90% prediction

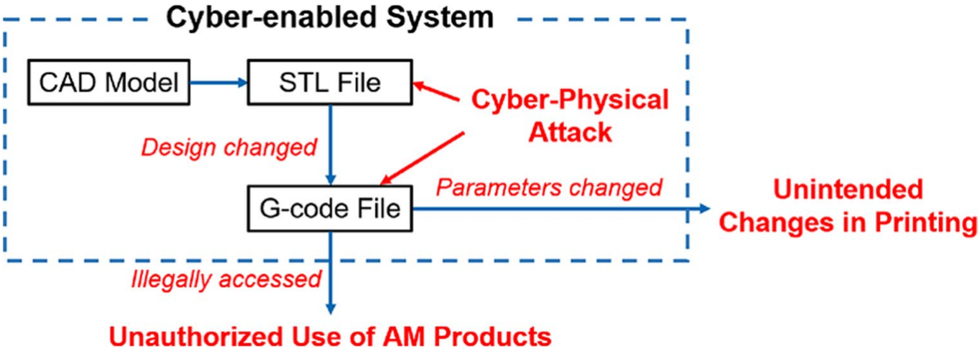


**Fig. 29** Demonstration of two common types of cyber-physical attacks in cyber-enabled AM [146]

accuracy, allowing earlier defect detection and reducing failed builds, particularly in laser-based metal AM [147]. These improvements typically result in reduced rework and scrap. However, many studies focus on model performance rather than plant-level reductions in scrap or energy use. Therefore, claims of specific percentage savings should only be made when supported by documented case studies [148]. A comparative LCA of FDM with recycled ABS versus injection molding reveals that for batch sizes below ~ 14 parts, FDM has a lower global warming potential (GWP); however, once batch size exceeds ~ 50 parts, injection molding becomes more environmentally favorable [50].

VR/XR combined with digital twins (DTs) improves sustainability in AM by reducing trial builds and enabling earlier defect correction. Chheang et al. [149] showed VR-based inspection enhances defect detection, Kos et al. [150] reported DTs use lowered product carbon footprints, and Xu et al. [151] introduced a defect-percentage metric for FDM that helps cut material waste. These tools strengthen quality monitoring and resource efficiency even though most studies emphasize qualitative rather than fully quantified outcomes.

While these digital tools can drive significant improvements, their effectiveness depends on factors such as infrastructure, energy sources, and implementation costs, making the benefits context-specific rather than universal [152–155].

### 6.2 Supply chain management

Sustainable Supply Chain Management (SSCM) ensures environmental, economic, and social sustainability from raw material sourcing to product end-of-life. Suppliers adopting eco-friendly materials and fair practices set the foundation for a sustainable chain [156]. Manufacturers contribute by reducing energy use and recycling, as noted by Feldmann et al. [157].

AM decentralizes production, minimizing transportation and emissions. Bhasin et al. highlight AM's ability to localize production, improving responsiveness and sustainability [158]. Decentralized production reduces transport emissions: for example, Kreiger & Pearce found that distributed 3D printing with PLA reduced cumulative energy demand by 41–64% (up to 55–74% if powered by solar PV) compared to conventional centralized production of polymer parts [159–161].

While SSCM can reduce impacts through localized production and sustainable materials, its advantages are dependent on production volume, energy mix, and material quality, making outcomes context-specific.

## 7 Organizational perspectives

Where possible, this review incorporates knowledge blocks and evidence-based data from industry sources such as Wohlers Associates, Additive Manufacturer Green Trade Association, and 3D Systems, highlighting operational practices, material savings, and documented environmental impacts. While space constraints prevent exhaustive reporting, key findings emphasize the distinction between reported corporate practices, literature-supported results, and projected trends, providing a critical assessment of feasibility, limitations, and measurable sustainability outcomes for sustainable AM strategies.

Achieving sustainability in AM requires alignment across organizational strategies, technological capabilities, and regulatory frameworks. Leading AM organizations emphasize the need for sustainable product design, materials optimization, energy-efficient processes, and life-cycle thinking. They advocate for DfAM, part consolidation, localized production, and digital workflows as key enablers for reducing material use, waste, and emissions. These shared themes reflect the broader shift toward resource efficiency and responsible manufacturing.

For example, a report by Wohlers Associates underscores the importance of DfAM in reducing energy and material waste through part consolidation [162]. The Additive Manufacturer Green Trade Association promotes collaborative research to quantify the sustainability benefits of AM and advocates for life-cycle assessments that extend beyond part-for-part comparisons [163]. Companies like 3D Systems, Nano Dimension, and Stratasys outline sustainability strategies on their resources, highlighting pillars such as responsible business practices, carbon footprint reduction, and digital supply chain transformation [164]. While many of these claims are marketing-driven, they illustrate the growing attention sustainability receives in industrial AM ecosystems.

## 8 Future perspectives and conclusion

This comprehensive review emphasizes the advancements in AM sustainability while highlighting areas for improvement. Future research should focus on developing a structured research agenda or roadmap that clearly identifies priority areas and measurable goals. Key directions include:

- Integration of circular economy principles through bio-based, recyclable, and biodegradable materials, along with refined LCA methodologies to better assess environmental impacts across technologies.
- Energy efficiency optimization, including AM process refinement, renewable energy adoption, and intelligent energy management systems. AI/ML can enable real-time monitoring, adaptive process control, and predictive maintenance, thereby reducing waste.
- Synergies with renewable energy systems, such as optimized components for wind, solar, and energy storage technologies, to advance decarbonization.
- Design innovations using GD, TO, and lightweighting to enhance resource and energy efficiency.
- Operational frameworks integrating big data analytics, cybersecurity, and virtual/augmented reality to support scalable, resilient, and sustainable AM applications aligned with global sustainability goals.

In conclusion, this review provides a comprehensive overview of the current state of AM, offering a multi-dimensional perspective that integrates environmental, economic, and operational frameworks with emerging technologies. Unlike previous reviews that focus on isolated aspects, this study highlights the interconnectedness of these factors, reinforcing its unique contribution to the field.

AM's ability to reduce material waste, enable localized production, and support digital workflows positions it as a pivotal enabler of sustainable manufacturing. Challenges such as energy-intensive processes, scalability, and material limitations remain. Targeted research addressing these challenges, along with standardization of sustainable practices and multi-stakeholder collaboration, will be critical to establishing a roadmap for AM sustainability. By adopting a holistic approach, AM can evolve into a cornerstone of a sustainable industrial ecosystem, demonstrating its strategic potential to advance resource efficiency, waste minimization, and innovative design.

**Acknowledgements** The authors sincerely thank their respective academic institutions for their support throughout this study.

**Author contributions** All seven authors, representing the three participating institutions, contributed equally to the preparation and writing of the manuscript.

**Funding** A.J.H. and K.G. acknowledge financial support from the MIT-Portugal Program. I. F. acknowledges the financial support from the Tennessee Tech-MET Program.

**Data availability** The data and materials presented in this study are available upon request to the corresponding author. All the data is presented within the manuscript.

## Declarations

**Conflict of interest** The authors declare no conflicts of interest related to this work.

## References

1. Winn Z (n.d.) Industrializing 3D printing. Available: https://news.mit.edu/2022/vulcanforms-printing-manufacturing-1128. Accessed 14 Dec 2025
2. Singh S, Mohanty RP, Mangla SK, Agrawal V (2023) Critical success factors of additive manufacturing for higher sustainable competitive advantage in supply chains. J Clean Prod 425:138908. https://doi.org/10.1016/J.JCLEPRO.2023.138908
3. Agnusdei L, Del Prete A (2022) Additive manufacturing for sustainability: a systematic literature review. Sustain Futures 4:100098. https://doi.org/10.1016/J.SFTR.2022.100098
4. Almeida H, Pei E, Vitorino L (2022) In: Sandhu K, Singh S, Prakash C, Subburaj K, Ramakrishna S (eds) Sustainability for 3D printing. Springer International Publishing, Cham, pp 1–13. https://doi.org/10.1007/978-3-030-75235-4_1
5. Sbrugnera Sotomayor NA, Caiazzo F, Alfieri V (2021) Enhancing design for additive manufacturing workflow: optimization, design and simulation tools. Appl Sci 11(14). https://doi.org/10.3390/app11146628
6. Lachmayer R, Ehlers T, Lippert RB (2024) Design for additive manufacturing. Springer-Verlag GmbH Germany
7. Alami AH et al (2023) Progress in 3D printing in wind energy and its role in achieving sustainability. Int J Thermofluids 20. https://doi.org/10.1016/j.ijft.2023.100496
8. Sun C, Wang Y, McMurtrey MD, Jerred ND, Liou F, Li J (2021) Additive manufacturing for energy: a review. Appl Energy 282. https://doi.org/10.1016/j.apenergy.2020.116041
9. Hunde BR, Woldeyohannes AD (2023) 3D printing and solar cell fabrication methods: A review of challenges, opportunities, and future prospects. Results Opt 11. https://doi.org/10.1016/j.rio.2023.100385
10. Yadav A, Garg RK, Sachdeva A, Qureshi MRNM (2025) Comparing environmental sustainability of additive manufacturing and investment casting: Life cycle assessment of aluminium LM04 (Al-Si5-Cu3). Mater Sci Eng A 923:147765. https://doi.org/10.1016/J.MSEA.2024.147765
11. Yadav A, Garg RK, Sachdeva A, Qureshi KM, Qureshi MRNM (2025) Strategic framework for additive manufacturing with smart polymer composites: a pathway to net-zero manufacturing. Polymers 17(10):1336. https://doi.org/10.3390/POLYM17101336

12. Qureshi KM et al (2025) Are polymer-based smart materials unlocking the path to sustainable manufacturing for a net-zero economy? Current trends and potential applications. IEEE Access 13:284–296. https://doi.org/10.1109/ACCESS.2024.3521944
13. Jayawardane H, Davies IJ, Gamage JR, John M, Biswas WK (2023) Sustainability perspectives – a review of additive and subtractive manufacturing. Sustainable Manufacturing and Service Economics (SMSE) 2:100015. https://doi.org/10.1016/J.SMSE.2023.100015
14. Ferreira BT, de Campos AA, Casati R, Gonçalves A, Leite M, Ribeiro I (2024) Technological capabilities and sustainability aspects of metal additive manufacturing. Prog Addit Manuf 9(6):1737–1773. https://doi.org/10.1007/S40964-023-00534-4
15. Shah HH, Tregambi C, Bareschino P, Pepe F (2024) Environmental and economic sustainability of additive manufacturing: A systematic literature review. Sustain Prod Consum 51:628–643. https://doi.org/10.1016/J.SPC.2024.10.012
16. Rahmani R, Bashiri B, Lopes SI, Hussain A, Maurya HS, Vilu R (2025) Sustainable additive manufacturing: an overview on life cycle impacts and cost efficiency of laser powder bed fusion. J Manuf Mater Process 9(1):18. https://doi.org/10.3390/JMMP9010018
17. Agrawal K, Bhat AR (2025) Advances in 3D printing with eco-friendly materials: a sustainable approach to manufacturing. RSC Sustain 3(6):2582–2604. https://doi.org/10.1039/D4SU00718B
18. Kokare S, Oliveira JP, Godina R (2023) Life cycle assessment of additive manufacturing processes: a review. J Manuf Syst 68:536–559. https://doi.org/10.1016/J.JMSY.2023.05.007
19. Singh G, Mehta A, Vasudev H (2024) Sustainability of additive manufacturing: a comprehensive review. Prog Addit Manuf 9(6):2249–2272. https://doi.org/10.1007/S40964-024-00579-Z
20. Saqib MA, Abbas MS, Tanaka H, Saqib MA, Abbas MS, Tanaka H (2024) Sustainability and innovation in 3D printing: Outlook and trends. Clean Technol Recycl 1(1):1–21. https://doi.org/10.3934/CTR.2024001
21. Bigliardi B, Bottani E, Gianatti E, Monferdini L, Pini B, Petroni A (2024) Sustainable additive manufacturing in the context of Industry 4.0: a literature review. Procedia Comput Sci 232:766–774. https://doi.org/10.1016/J.PROCS.2024.01.076
22. Mehta A, Vasudev H (2025) Sustainability of additive manufacturing: Using finite element models and 3D printing techniques. In: Advanced manufacturing processes: integration of sustainable approaches, pp 9–25. https://doi.org/10.1201/9781003476238-2
23. Bello KA, Maladzhi RW (2025) Innovative and best practices in sustainable strategies for waste reduction in additive manufacturing. Hybrid Advances 11:100527. https://doi.org/10.1016/J.HYBADV.2025.100527
24. Chea JD, Ruiz-Mercado GJ, Smith RL, Gonzalez MA, Meyer DE (2025) Sustainability assessment of additive manufacturing end-of-life material management. Next Sustainability 5:100085. https://doi.org/10.1016/J.NXSUST.2024.100085
25. Graziosi S et al (2024) A vision for sustainable additive manufacturing. Nat Sustain 7(6):698–705. https://doi.org/10.1038/s41893-024-01313-x
26. ISO (2006) ISO 14040:2006 - Environmental management — life cycle assessment — Principles and framework. Available https://www.iso.org/standard/37456.html. Accessed 14 Dec 2025
27. Goedkoop M, Heijungs R, Huijbregts M, De Schryver AM, Struijs J, Van Zelm R (2009) ReCiPe 2008: A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level
28. Todd RH, Allen DK, Alting L (1994) Manufacturing processes reference guide. Industrial Press, New York
29. Kalpakjian S, Schmid S (2013) Manufacturing engineering and technology, SI, 6th edn
30. Majeed A, Ahmed A, Lv J, Peng T, Muzamil M (2020) A state-of-the-art review on energy consumption and quality characteristics in metal additive manufacturing processes. J Braz Soc Mech Sci Eng 42(5). https://doi.org/10.1007/S40430-020-02323-4
31. Kellens K, Baumers M, Gutowski TG, Flanagan W, Lifset R, Duflou JR (2017) Environmental dimensions of additive manufacturing: mapping application domains and their environmental implications. J Ind Ecol 21:S49–S68. https://doi.org/10.1111/jiec.12629
32. Luo Y, Ji Z, Leu MC, Caudill R (1999) Environmental performance analysis of solid freeform fabrication processes. In: IEEE international symposium on electronics and the environment, pp 1–6. https://doi.org/10.1109/ISEE.1999.765837
33. Gutowski T et al (2017) Note on the rate and energy efficiency limits for additive manufacturing. J Ind Ecol 21(S1):S69–S79. https://doi.org/10.1111/jiec.12664
34. Faludi J, Baumers M, Maskery I, Hague R (2017) Environmental impacts of selective laser melting: do printer, powder, or power dominate? J Ind Ecol 21(S1):S144–S156. https://doi.org/10.1111/JIEC.12528
35. Sachs E, Cima M, Williams P, Brancazio D, Cornie J (1992) Three dimensional printing: rapid tooling and prototypes directly from a CAD model. J Eng Ind 114(4):481–488. https://doi.org/10.1115/1.2900701
36. Baumers M, Tuck C, Hague R, Ashcroft I, Wildman R (2010) A comparative study of metallic additive manufacturing power consumption. https://doi.org/10.26153/TSW/15198
37. Baumers M, Tuck C, Wildman R, Ashcroft I, Hague R (2011) Energy inputs to additive manufacturing: does capacity utilization matter? In: 22nd annual international solid freeform fabrication symposium - an additive manufacturing conference, SFF 2011, pp 30–40. https://doi.org/10.26153/tsw/15275
38. Kellens K, Rodrigues GC, Dewulf W, Duflou JR (2014) Energy and resource efficiency of laser cutting processes. In: Physics procedia, Austin, TX, pp 854–864. https://doi.org/10.1016/j.phpro.2014.08.104
39. Kellens K, Mertens R, Paraskevas D, Dewulf W, Duflou JR (2017) Environmental Impact of additive manufacturing processes: does am contribute to a more sustainable way of part manufacturing? Procedia CIRP 61:582–587. https://doi.org/10.1016/J.PROCIR.2016.11.153
40. Priarone PC, Lunetto V, Atzeni E, Salmi A (2018) Laser powder bed fusion (L-PBF) additive manufacturing: on the correlation between design choices and process sustainability. Procedia CIRP 78:85–90. https://doi.org/10.1016/J.PROCIR.2018.09.058
41. DeBoer B, Nguyen N, Diba F, Hosseini A (2021) Additive, subtractive, and formative manufacturing of metal components: a life cycle assessment comparison. Int J Adv Manuf Technol 115(1–2):413–432. https://doi.org/10.1007/S00170-021-07173-5
42. Peng T, Wang Y, Zhu Y, Yang Y, Yang Y, Tang R (2020) Life cycle assessment of selective-laser-melting-produced hydraulic valve body with integrated design and manufacturing optimization: A cradle-to-gate study. Addit Manuf 36:101530. https://doi.org/10.1016/J.ADDMA.2020.101530
43. Lunetto V, Priarone PC, Kara S, Settineri L (2021) A comparative LCA method for environmentally friendly manufacturing: Additive manufacturing versus Machining case. Procedia CIRP 98:406–411. https://doi.org/10.1016/J.PROCIR.2021.01.125
44. Peng T, Lv J, Majeed A, Liang X (2021) An experimental investigation on energy-effective additive manufacturing of aluminum parts via process parameter selection. J Clean Prod 279:123609. https://doi.org/10.1016/J.JCLEPRO.2020.123609
45. Torres-Carrillo S, Siller HR, Vila C, López C, Rodríguez CA (2020) Environmental analysis of selective laser melting in the manufacturing of aeronautical turbine blades. J Clean Prod 246:119068. https://doi.org/10.1016/J.JCLEPRO.2019.119068

46. Cappucci GM, Pini M, Neri P, Marassi M, Bassoli E, Ferrari AM (2020) Environmental sustainability of orthopedic devices produced with powder bed fusion. J Ind Ecol 24(3):681–694. https://doi.org/10.1111/JIEC.12968
47. Vidakis N, Kechagias JD, Petousis M, Vakouftsi F, Mountakis N (2023) The effects of FFF 3D printing parameters on energy consumption. Mater Manuf Process 38(8):915–932. https://doi.org/10.1080/10426914.2022.2105882
48. Zakaria S, Mativenga P, Ariff EARE (2023) An Investigation of energy consumption in fused deposition modelling using ESP32 IoT monitoring system. Procedia CIRP 116:263–268. https://doi.org/10.1016/J.PROCIR.2023.02.045
49. Cerdas F, Juraschek M, Thiede S, Herrmann C (2017) Life cycle assessment of 3d printed products in a distributed manufacturing system. J Ind Ecol 21(S1):S80–S93. https://doi.org/10.1111/JIEC.12618
50. Garcia FL et al (2021) Comparative LCA of conventional manufacturing vs. additive manufacturing: the case of injection moulding for recycled polymers. Int J Sustain Eng 14(6):1604–1622. https://doi.org/10.1080/19397038.2021.1990435
51. Yoon HS et al (2014) A comparison of energy consumption in bulk forming, subtractive, and additive processes: Review and case study. Int J Precis Eng Manuf-Green Technol 1(3):261–279. https://doi.org/10.1007/S40684-014-0033-0
52. Nagarajan HPN, Haapala KR (2018) Characterizing the influence of resource-energy-exergy factors on the environmental performance of additive manufacturing systems. J Manuf Syst 48:87–96. https://doi.org/10.1016/J.JMSY.2018.06.005
53. Winter S, Osterod JO, Schleich B (2024) Enabling product carbon footprint management in the material extrusion process. Procedia CIRP 122:31–36. https://doi.org/10.1016/J.PROCIR.2024.01.006
54. Kellens K, Renaldi R, Dewulf W, Kruth JP, Duflou JR (2014) Environmental impact modeling of selective laser sintering processes. Rapid Prototyp J 20(6):459–470. https://doi.org/10.1108/RPJ-02-2013-0018
55. K. Kellens, E. Yasa, W. Dewulf, and J. R. Duflou, "Environmental assessment of selective laser melting and selective laser sintering," Methodology, 4(January):5, 2010. Available: https://www.researchgate.net/publication/266450713_Environmental_assessment_of_selective_laser_melting_and_selective_laser_sintering. Accessed 14 Dec 2025
56. Liu ZY, Li C, Fang XY, Guo YB (2018) Energy consumption in additive manufacturing of metal parts. Procedia Manuf 26:834–845. https://doi.org/10.1016/J.PROMFG.2018.07.104
57. Sreenivasan R, Bourell DL (2009) Sustainability study in selective laser sintering-an energy perspective. SFF2009. https://doi.org/10.26153/tsw/15104
58. Telenko C, Seepersad C (2012) A comparison of the energy efficiency of selective laser sintering and injection molding of nylon parts. Rapid Prototyp J 18. https://doi.org/10.1108/13552541211272018
59. Simon T, Yang Y, Lee WJ, Zhao J, Li L, Zhao F (2019) Reusable unit process life cycle inventory for manufacturing: stereolithography. Prod Eng 13(6):675–684. https://doi.org/10.1007/S11740-019-00916-0
60. Mele M, Campana G, D'Avino G (2020) Life cycle impact assessment of desktop stereolithography. J Clean Prod 244:118743. https://doi.org/10.1016/J.JCLEPRO.2019.118743
61. Ulkir O (2023) Energy-consumption-based life cycle assessment of additive-manufactured product with different types of materials. Polymers 15(6):1466. https://doi.org/10.3390/POLYM15061466
62. Yang Y, Li L, Pan Y, Sun Z (2017) Energy consumption modeling of stereolithography-based additive manufacturing toward environmental sustainability. J Ind Ecol 21(S1):S168–S178. https://doi.org/10.1111/JIEC.12589
63. ISO/ASTM 52910:2018 - Additive manufacturing — Design — Requirements, guidelines and recommendations. Available: https://www.iso.org/standard/67289.html. Accessed 14 Dec 2025
64. Silva FJG, Pereira AB, Sousa VFC, Pinto AG (2024) Introduction and main principles in additive manufacturing. Additive Manufacturing Materials and Technology:1–30. https://doi.org/10.1016/B978-0-443-18462-8.00001-5
65. Thompson C, Volumetric JE, Thompson JE (2025) Volumetric additive manufacturing: ushering in a new era of fabrication. Hardware 3:2. https://doi.org/10.3390/HARDWARE3010002
66. Laverne F, Segonds F, Anwer N, Le Coq M (2015) Assembly based methods to support product innovation in design for additive manufacturing: an exploratory case study. J Mech Des 137(12). https://doi.org/10.1115/1.4031589
67. Zhu J, Zhou H, Wang C, Zhou L, Yuan S, Zhang W (2021) A review of topology optimization for additive manufacturing: Status and challenges. Chin J Aeronaut 34(1):91–110. https://doi.org/10.1016/J.CJA.2020.09.020
68. Ntintakis I, Stavroulakis G, Sfakianakis G, Fiotodimitrakis N (2022) Utilizing generative design for additive manufacturing, pp 977–989. https://doi.org/10.1007/978-981-16-7787-8_78
69. Khan N, Riccio A (2024) A systematic review of design for additive manufacturing of aerospace lattice structures: Current trends and future directions. Prog Aerosp Sci 149(4):101021. https://doi.org/10.1016/j.paerosci.2024.101021
70. Munk DJ, Miller JD (2021) Topology optimization of aircraft components for increased sustainability. AIAA Journal:1–16. https://doi.org/10.2514/1.J060259
71. Zou Y, Liu L, Li Q, Liu F. Title: Role of additive manufacturing technology in environmental sustainability: the case of aeronautical parts conflict of interest disclosure. Available: https://ssrn.com/abstract=5077665. Accessed 14 Dec 2025
72. Monica Schnitger (2018) Longitude media, "An introduction to generative design," Cadalyst. https://info.cadalyst.com/hubfs/Cadalyst_House_Assets/House-Asset-PDFs/GenerativeDesign-CadalystGuide-1638.pdf. Accessed 14 Dec 2025
73. Briard T, Segonds F, Zamariola N (2020) G-DfAM: a methodological proposal of generative design for additive manufacturing in the automotive industry. International Journal on Interactive Design and Manufacturing (IJIDeM):14. https://doi.org/10.1007/s12008-020-00669-6
74. Wu J, Qian X, Wang M (2019) Advances in generative design. Computer-Aided Design 116:102733. https://doi.org/10.1016/j.cad.2019.102733
75. Bill Danon, "GM is betting on generative design to make the vehicles of the future. Available: https://adsknews.autodesk.com/de/alternative-post/gm-autodesk-using-generative-design-vehicles-future/. Accessed 14 Dec 2025
76. Sossou G, Demoly F, Montavon G, Gomes S (2017) An additive manufacturing oriented design approach to mechanical assemblies. J Comput Des Eng 5. https://doi.org/10.1016/j.jcde.2017.11.005
77. Kurup P, Remo T, Cotrell J, Jenne SD, O'Connor P (2018) Analysis of supply chains and advanced manufacturing of small hydropower systems. National Renewable Energy Laboratory, Golden, CO, USA, Tech. Rep. NREL/TP-6A20-71511, [Online]. Available: https://www.nrel.gov/docs/fy18osti/71511.pdf
78. Donofrio M (2016) Topology optimization and advanced manufacturing as a means for the design of sustainable building components. Procedia Eng 145:638–645. https://doi.org/10.1016/J.PROENG.2016.04.054
79. nTopology, "nTopology lattice design software documentation. Available: https://www.ntopology.com/. Accessed 14 Dec 2025
80. nTopology Trevor Laughlin, "Introducing nTop 4: Realize the full potential of additive manufacturing. Available: https://www.ntop.com/resources/blog/introducing-ntop-4/. Accessed 14 Dec 2025

81. Autodesk "Achieve unmatched performance with topology optimization." Available: https://www.autodesk.com/solutions/topology-optimization?us_oa=dotcom-us&us_si=d799e709-c311-45a7-a97a-274805e89d06&us_st=Topology. Accessed 14 Dec 2025
82. Altair, "Transform Design and Manufacturing with Simulation-Driven Insights," 2025. [Online]. Available: https://altair.com/inspire. Accessed 14 Dec 2025
83. Perez C. Rhino3D, "Cutting-edge Level set optimization meets the flexibility of Grasshopper with FEA Simulation in the loop!". Available: https://blog.rhino3d.com/2024/12/levelopt-new-topology-optimization-tool.html. Accessed 14 Dec 2025
84. Agrawal R (2021) Sustainable material selection for additive manufacturing technologies: A critical analysis of rank reversal approach. J Clean Prod 296. https://doi.org/10.1016/j.jclepro.2021.126500
85. Ljungberg LY (2007) Materials selection and design for development of sustainable products. Mater Des 28(2). https://doi.org/10.1016/j.matdes.2005.09.006
86. Pakkanen J, Manfredi D, Minetola P, Iuliano L (2017) About the use of recycled or biodegradable filaments for sustainability of 3D printing. In: Smart innovation, systems and technologies, vol 68. https://doi.org/10.1007/978-3-319-57078-5_73
87. de León EHP, Valle-Pérez AU, Khan ZN, Hauser CAE (2023) Intelligent and smart biomaterials for sustainable 3D printing applications. https://doi.org/10.1016/j.cobme.2023.100450
88. Park S, Shou W, Makatura L, Matusik W, Fu K (2022) 3D printing of polymer composites: materials, processes, and applications. https://doi.org/10.1016/j.matt.2021.10.018
89. Jagadeesh D, Kanny K, Prashantha K (2017) A review on research and development of green composites from plant protein-based polymers. https://doi.org/10.1002/pc.23718
90. Kokkinis D, Schaffner M, Studart AR (2015) Multimaterial magnetically assisted 3D printing of composite materials. Nat Commun 6. https://doi.org/10.1038/ncomms9643
91. Cursaru LM et al (2021) Study of ZnO-CNT nanocomposites in high-pressure conditions. Materials 14(18). https://doi.org/10.3390/ma14185330
92. Alagha AN, Hussain S, Zaki W (2021) Additive manufacturing of shape memory alloys: A review with emphasis on powder bed systems. https://doi.org/10.1016/j.matdes.2021.109654
93. Marin E, Lanzutti A (2024) Biomedical applications of titanium alloys: a comprehensive review. https://doi.org/10.3390/ma17010114
94. Graf S, Thakkar D, Hansa I, Pandian SM, Adel SM (2023) 3D metal printing in orthodontics: current trends, biomaterials, workflows and clinical implications. Semin Orthod 29(1). https://doi.org/10.1053/j.sodo.2023.01.001
95. Chua K, Khan I, Malhotra R, Zhu D (2021) Additive manufacturing and 3D printing of metallic biomaterials. https://doi.org/10.1016/j.engreg.2021.11.002
96. Voet VSD, Guit J, Loos K (2021) Sustainable photopolymers in 3d printing: a review on biobased, biodegradable, and recyclable alternatives. https://doi.org/10.1002/marc.202000475
97. Sezer N, Evis Z, Koç M (2021) Additive manufacturing of biodegradable magnesium implants and scaffolds: Review of the recent advances and research trends. https://doi.org/10.1016/j.jma.2020.09.014
98. Li Y, Jahr H, Zhou J, Zadpoor AA (2020) Additively manufactured biodegradable porous metals. https://doi.org/10.1016/j.actbio.2020.08.018
99. Nocheseda CJC, Liza FP, Collera AKM, Caldona EB, Advincula RC (2021) 3D printing of metals using biodegradable cellulose hydrogel inks. Addit Manuf:48. https://doi.org/10.1016/j.addma.2021.102380
100. Fidan I, Naikwadi V, Alkunte S, Mishra R, Tantawi K (2024) Energy efficiency in additive manufacturing: condensed review. Technologies. https://doi.org/10.3390/technologies12020021
101. Naikwadi V, Fidan I (2025) Influence of post-processing on the mechanical and microstructural characteristics of nanomaterial-infused polymers in material extrusion. Int J Adv Manuf Technol. https://doi.org/10.1007/s00170-025-16220-4
102. Hunt EJ, Zhang C, Anzalone N, Pearce JM (2015) Polymer recycling codes for distributed manufacturing with 3-D printers. Resour Conserv Recycl 97:24–30. https://doi.org/10.1016/j.resconrec.2015.02.004
103. Naikwadi V, Fidan I, Ali MA, Mahmudov M, Gudavasov S, Hudson E (2024) Additive manufacturing of carbon nanotubes infused multi-materials and their mechanical characterization. University of Texas at Austin. https://doi.org/10.26153/tsw/58048
104. Mohamed MI, Aggag GA (2003) Uncertainty evaluation of shore hardness testers. Measurement (Lond) 33(3):251–257. https://doi.org/10.1016/S0263-2241(02)00087-8
105. Zhao X, Liu J, Li J, Liang X, Zhou W, Peng S (2022) Strategies and techniques for improving heat resistance and mechanical performances of poly(lactic acid) (PLA) biodegradable materials. https://doi.org/10.1016/j.ijbiomac.2022.07.091
106. Bhagia S et al (2021) Critical review of FDM 3D printing of PLA biocomposites filled with biomass resources, characterization, biodegradability, upcycling and opportunities for biorefineries. https://doi.org/10.1016/j.apmt.2021.101078
107. Liu J, Wang S, Peng Y, Zhu J, Zhao W, Liu X (2021) Advances in sustainable thermosetting resins: From renewable feedstock to high performance and recyclability. https://doi.org/10.1016/j.progpolymsci.2020.101353
108. Prasad V, Alliyankal Vijayakumar A, Jose T, George SC (2024) A comprehensive review of sustainability in natural-fiber-reinforced polymers. https://doi.org/10.3390/su16031223
109. Skliutas E, Kasetaite S, Jonušauskas L, Ostrauskaite J, Malinauskas M (2018) Photosensitive naturally derived resins toward optical 3-D printing. Opt Eng 57(4):041412. https://doi.org/10.1117/1.oe.57.4.041412
110. Chyr G, DeSimone JM (2022) Review of high-performance sustainable polymers in additive manufacturing. https://doi.org/10.1039/d2gc03474c
111. Pal S, Asha SK (2022) Biodegradable, solvent-free photocrosslinkable plla resin formulations for additive manufacturing. Macromol Chem Phys 223(22):2200139. https://doi.org/10.1002/macp.202200139
112. Maiti S, Islam MR, Uddin MA, Afroj S, Eichhorn SJ, Karim N (2022) Sustainable fiber-reinforced composites: a review. https://doi.org/10.1002/adsu.202200258
113. Mehrpouya M, Vosooghnia A, Dehghanghadikolaei A, Fotovvati B (2021) The benefits of additive manufacturing for sustainable design and production. Sustainable Manufacturing. https://doi.org/10.1016/B978-0-12-818115-7.00009-2
114. B. C. Kraynyk, D. W. Janzen. AI Rokkan, "Innovating the supply chain of wind energy through the application of additive manufacturing. Norwegian School of Economics 2017. Available: https://openaccess.nhh.no/nhh-xmlui/bitstream/handle/11250/2486943/masterthesis.PDF?sequence=1. Accessed 14 Dec 2025
115. Post BK et al (2017) Big area additive manufacturing application in wind turbine molds. In: Solid freeform fabrication 2017: proceedings of the 28th annual international solid freeform fabrication symposium - an additive manufacturing conference, SFF 2017. https://doi.org/10.26153/tsw/16964
116. Post B, Richardson B, Lloyd P, Love L, Nolet S, Hannan J (2017) Additivemanufacturing of wind turbine molds. Oak Ridge National Laboratory, Oak Ridge, TN, USA, Tech. Rep. ORNL/TM- 2017/290. https://doi.org/10.2172/1376487

117. GE Renewable Energy. Fit to print: GE is looking at 3D-printing wind turbine towers from concrete for more efficient wind farms. Available: https://www.ge.com/news/reports/fit-to-print-ge-is-looking-at-3d-printing-wind-turbine-towers-from-concrete-for-more-0. Accessed 14 Dec 2025
118. James S, Contractor R (2018) Study on nature-inspired fractal design-based flexible counter electrodes for dye-sensitized solar cells fabricated using additive manufacturing. Sci Rep 8(1):17032. https://doi.org/10.1038/s41598-018-35388-2
119. van Dijk L, Paetzold UW, Blab GA, Schropp REI, Di Vece M (2016) 3D-printed external light trap for solar cells. Progress Photovoltaics: Res Appl 24(5):623–633. https://doi.org/10.1002/pip.2702
120. Vaidya N, Solgaard O (2022) Immersion graded index optics: theory, design, and prototypes. Microsyst Nanoeng 8(1):69. https://doi.org/10.1038/s41378-022-00377-z
121. Clemens M.. Researchers From Stanford University introduce new 3D printed solar panels. Available: https://www.3dnatives.com/en/3d-printed-solar-panels-030820224/. Accessed 14 Dec 2025
122. Sun K, Wei TS, Ahn BY, Seo JY, Dillon SJ, Lewis JA (2013) 3D printing of interdigitated Li-ion microbattery architectures. Adv Mater 25(33). https://doi.org/10.1002/adma.201301036
123. Maurel A et al (2018) Highly loaded graphite-polylactic acid composite-based filaments for lithium-ion battery three-dimensional printing. Chem Mater 30(21). https://doi.org/10.1021/acs.chemmater.8b02062
124. Narita K, Citrin MA, Yang H, Xia X, Greer JR (2021) 3D architected carbon electrodes for energy storage. Adv Energy Mater 11(5):2002637. https://doi.org/10.1002/aenm.202002637
125. Liu Q, Ge R, Li C, Li Q, Gan Y (2023) Digital design and additive manufacturing of structural materials in electrochemical and thermal energy storage systems: a review. https://doi.org/10.1080/17452759.2023.2273949
126. Young D, Sukeshini AM, Cummins R, Xiao H, Rottmayer M, Reitz T (2008) Ink-jet printing of electrolyte and anode functional layer for solid oxide fuel cells. J Power Sources 184(1). https://doi.org/10.1016/j.jpowsour.2008.06.018
127. Li C, Shi H, Ran R, Su C, Shao Z (2013) Thermal inkjet printing of thin-film electrolytes and buffering layers for solid oxide fuel cells with improved performance. Int J Hydrogen Energy 38(22). https://doi.org/10.1016/j.ijhydene.2013.05.025
128. Guo N, Leu MC (2012) Effect of different graphite materials on the electrical conductivity and flexural strength of bipolar plates fabricated using selective laser sintering. Int J Hydrogen Energy 37(4). https://doi.org/10.1016/j.ijhydene.2011.11.058
129. Fieber L, Evans JD, Huang C, Grant PS (2019) Single-operation, multi-phase additive manufacture of electro-chemical double layer capacitor devices. Addit Manuf 28. https://doi.org/10.1016/j.addma.2019.05.001
130. Liu Q, Ge R, Li C, Li Q, Gan Y (2023) Digital design and additive manufacturing of structural materials in electrochemical and thermal energy storage systems: a review. https://doi.org/10.1080/17452759.2023.2273949
131. Roschli A et al (2023) Large format composite additive manufacturing for low-head hydropower. Addit Manuf Lett 7:100170. https://doi.org/10.1016/J.ADDLET.2023.100170
132. A. M. & M. T. O. Department of Energy. Innovative large parts manufacturing to revolutionize America's clean energy future. Available: https://www.energy.gov/eere/ammto/articles/innovative-large-parts-manufacturing-revolutionize-americas-clean-energy-future. Accessed 14 Dec 2025
133. Židonis A, Aggidis GA (2015) State of the art in numerical modelling of Pelton turbines. Renew Sustain Energy Rev 45:135–144. https://doi.org/10.1016/j.rser.2015.01.037
134. Appleyard D (2012) Welding Pelton runners. Renewable Energy World. [Online]. Available: https://www.renewableenergyworld.com/hydro-power/technology-equipment/welding-pelton-runners. Accessed 3 May 2026
135. Weller D. Will additive manufacturing power the evolution of nuclear energy?. Available https://amfg.ai/2024/01/18/will-additive-manufacturing-power-the-evolution-of-nuclear-energy/. Accessed 14 Dec 2025
136. Simpson J et al (2019) Considerations for application of additive manufacturing to nuclear reactor core components, vol. 1190. No. ORNL/TM-2019/1190. Oak Ridge National Laboratory. https://doi.org/10.2172/1564201
137. Huning AJ et al. 3D-printed nuclear reactor promises faster, more economical path to nuclear energy. Available: https://www.ornl.gov/news/3d-printed-nuclear-reactor-promises-faster-more-economical-path-nuclear-energy?page=1. Accessed 14 Dec 2025
138. Madeleine P. First 3D printed stainless steel fuel component installed at the Forsmark nuclear power plant. Available: https://www.3dnatives.com/en/framatome-nuclear-power-plant-270920224/. Accessed 14 Dec 2025
139. Sher D. Additive manufacturing is going nuclear. Available: https://www.voxelmatters.com/additive-manufacturing-is-going-nuclear/. Accessed 14 Dec 2025
140. Gopal M, Lemu HG, Gutema EM (2022) Sustainable additive manufacturing and environmental implications: literature review. Sustainability 15(1):504. https://doi.org/10.3390/SU15010504
141. Ribeiro I et al (2020) Framework for life cycle sustainability assessment of additive manufacturing. Sustainability 12(3):929. https://doi.org/10.3390/SU12030929
142. Majeed A, Lv J, Peng T (2019) A framework for big data driven process analysis and optimization for additive manufacturing. Rapid Prototyp J 25(2):308–321. https://doi.org/10.1108/RPJ-04-2017-0075
143. M. Perišić, D. Milenković, Y. Lu, A. Jones, N. Ivezić, and B. Kulvatunyou, "A data integration framework for additive manufacturing big data management. Available: https://doi.org/10.26153/tsw/17657. Accessed 14 Dec 2025
144. Chinchanikar S, Shaikh AA (2022) A review on machine learning, big data analytics, and design for additive manufacturing for aerospace applications. J Mater Eng Perform 31(8):6112–6130. https://doi.org/10.1007/S11665-022-07125-4
145. "GE Additive introduces Amp™ | Manufacturing Tomorrow. Available: https://www.manufacturingtomorrow.com/news/2021/11/16/ge-additive-introduces-amp/17908/. Accessed 14 Dec 2025
146. Shi Z, Kan C, Tian W, Liu C (2021) A blockchain-based G-code protection approach for cyber-physical security in additive manufacturing. J Comput Inf Sci Eng 21(4). https://doi.org/10.1115/1.4048966
147. Ng WL, Goh GL, Goh GD, Ten JSJ, Yeong WY (2024) Progress and opportunities for machine learning in materials and processes of additive manufacturing. Adv Mater 36(34):2310006. https://doi.org/10.1002/adma.202310006
148. Rahman MA et al (2023) Review of intelligence for additive and subtractive manufacturing: current status and future prospects. Micromachines 14(3):508. https://doi.org/10.3390/MI14030508
149. Chheang V et al (2024) Enabling additive manufacturing part inspection of digital twins via collaborative virtual reality. Sci Rep 14(1):29783. https://doi.org/10.1038/s41598-024-80541-9
150. Kos J, Schröder P, Trauer J, Endress F, Mörtl M, Zimmermann M (2024) Improving sustainability of additive manufacturing processes based on digital twins – a case study. Proc Des Soc 4:2089–2098. https://doi.org/10.1017/pds.2024.211
151. Xu C et al (2025) Digital twins for defect detection in FDM 3D printing process. Machines 13(6). https://doi.org/10.3390/machines13060448

152. Ostrander JK, Tucker CS, Simpson TW, Meisel NA (2020) Evaluating the use of virtual reality to teach introductory concepts of additive manufacturing. J Mech Des 142(5). https://doi.org/10.1115/1.4044006
153. Ho PT, Albajez JA, Santolaria J, Yagüe-Fabra JA (2022) Study of augmented reality based manufacturing for further integration of quality control 4.0: a systematic literature review. Appl Sci 2022 12(4):1961. https://doi.org/10.3390/APP12041961
154. Melo G, Ravi R, Jauer L, Schleifenbaum JH (2023) Exploring augmented reality for teaching design for additive manufacturing. In: Proceedings of 2022 international additive manufacturing conference, IAM 2022. https://doi.org/10.1115/IAM2022-94406
155. Lhachemi H, Malik A, Shorten R (2019) Augmented reality, cyber-physical systems, and feedback control for additive manufacturing: a review. IEEE Access 7:50119–50135. https://doi.org/10.1109/ACCESS.2019.2907287
156. Liu L, Zhang M, Ye W (2019) The adoption of sustainable practices: a supplier's perspective. J Environ Manag 232:692–701. https://doi.org/10.1016/J.JENVMAN.2018.11.067
157. Feldmann C, Delke V, Wasserman ME (2019) strategically aligning additive manufacturing supply chains for sustainability and effectiveness. IFAC-Papers OnLine 52(10):260–264. https://doi.org/10.1016/J.IFACOL.2019.10.034
158. Bhasin S, Singari RM, Arora PK, Kumar H (2022) Implications of additive manufacturing on supply chain management. https://doi.org/10.1142/S2424862221500299
159. Kreiger M, Pearce JM (2023) Environmental life cycle analysis of distributed three-dimensional printing and conventional manufacturing of polymer products. ACS Sustain Chem Eng 1(12):1511–1519. https://doi.org/10.1021/sc400093k
160. Hohn MM, Durach CF (2021) Additive manufacturing in the apparel supply chain — impact on supply chain governance and social sustainability. Int J Oper Prod Manag 41(7):1035–1059. https://doi.org/10.1108/IJOPM-09-2020-0654
161. Eyers DR (2017) Supply chain risk management for sustainable additive manufacturing. Smart Innovation, Systems and Technologies (SIST) 68:280–288. https://doi.org/10.1007/978-3-319-57078-5_28
162. Wohlers Associates. Available: https://wohlersassociates.com/. Accessed 14 Dec 2025
163. The Additive Manufacturer Green Trade Association. Available: https://amgta.org/. Accessed 14 Dec 2025
164. Nano Dimension. Available: https://www.nano-di.com/. Accessed 14 Dec 2025