

Review

Energy Efficiency and Sustainability of Additive Manufacturing as a Mass-Personalized Production Mode in Industry 5.0/6.0

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Abstract

This review article examines the role of additive manufacturing (AM) in increasing energy efficiency and sustainability within the evolving framework of Industry 5.0 and 6.0. This review highlights the unique ability of additive manufacturing to deliver mass-customized products while minimizing material waste and reducing energy consumption. The integration of smart technologies such as AI and IoT is explored to optimize AM processes and support decentralized, on-demand manufacturing. This article discusses different AM techniques and materials from an environmental and life-cycle perspective, identifying key benefits and constraints. This review also examines the potential of AM to support circular economy practices through local repair, remanufacturing, and material recycling. The net energy efficiency of AM depends on the type of process, part complexity, and production scale, but the energy savings per component can be significant if implemented strategically. AM significantly improves energy efficiency in certain manufacturing contexts, often reducing energy consumption by 25–50% compared to traditional subtractive methods. The results emphasize the importance of innovation in both hardware and software to overcome current energy and sustainability challenges. This review highlights AM as a key tool in achieving a human-centric, intelligent, and ecological manufacturing paradigm.

Keywords: energetic efficiency; reducing energy consumption; strategies; sustainability; additive manufacturing; AM; Industry 6.0; Industry 6.0



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1. Introduction

This review article examines the energy efficiency and sustainability of additive manufacturing (AM) as a transformative, mass-customized production mode in the context of Industry 5.0 and 6.0 [1]. The Industry 5.0 paradigm opposes total automation in favor of multi-level collaboration between humans and machines (collaborative robots), and a sustainable Industry 6.0 model has been proposed after the COVID-19 pandemic [2]. Industry 6.0 is characterized by intelligent, autonomous, and sustainable systems derived from previous generations of the industrial revolution [3]. Industry 6.0 combines solutions from the digital, physical, and biological domains, including the healthcare industry, where mechanization, robotics, brain–computer interfaces, advanced biotechnology, 6G networks, AI, and quantum computers will help make and implement medical decisions, improve patient outcomes, and optimize healthcare [4]. In this way, Industry 6.0 goes beyond the human–machine collaboration to focus on environmental sustainability, human well-being, and social responsibility, creating an industrial ecosystem that balances efficiency, ethics,

and sustainability [5]. Visionary leadership, digital investments and employee upskilling play a key role in the transformation processes to Industry 6.0, while automation and AI implementation serve to create new opportunities for employees [6]. As global industries evolve toward more human-centric, resilient, and sustainable models, additive manufacturing stands out for its ability to combine personalization with environmental responsibility [7]. The purpose of this article is to critically assess how AM contributes to energy savings, waste reduction, and resource optimization in decentralized and smart manufacturing ecosystems. This review highlights the intersection of emerging digital technologies such as AI and IoT with AM to increase the efficiency and responsiveness of manufacturing processes [8]. This review examines the environmental footprint of different AM methods and materials, comparing them with conventional manufacturing techniques [9,10]. This review also explores a life-cycle assessment (LCA) framework to assess the broader impact of AM across industries [11]. This article aims to identify current challenges, including high energy consumption in some processes, and propose paths for sustainable innovation [12]. By combining technological progress with sustainability metrics, the review is aligned with the goals of Industry 5.0 (human–machine collaboration) and Industry 6.0 (autonomous, intelligent systems) [13,14]. This review aims to provide a comprehensive reference for researchers, practitioners and policy makers focused on the future of green manufacturing [15]. This article contributes to shaping a vision of industrial progress that balances personalization, efficiency and ecological responsibility [16,17].

1.1. Genesis of the Issue

The genesis of energy efficiency and sustainability research in AM occurred as AM began to transition from prototyping to full-scale production. Early studies focused on comparing the energy consumption of additive and subtractive methods, revealing mixed results depending on materials and applications [18]. As the concept of mass customization gained popularity, researchers saw a need to assess how customization affected energy consumption and resource utilization [19]. The rise of Industry 5.0, with its goals of human-centric and sustainable production, has driven a shift from purely technical efficiency to environmental and social impact [20]. Interest in sustainability has grown due to growing concerns about the environmental impact of digital manufacturing ecosystems and the circular economy [21]. Initial studies showed that AM, while potentially reducing transportation and storage needs, often uses more energy per unit than traditional mass production. Interest has expanded with the emergence of Industry 6.0, where intelligent automation, AI integration, and green manufacturing are driving innovation priorities (Figure 1) [22].

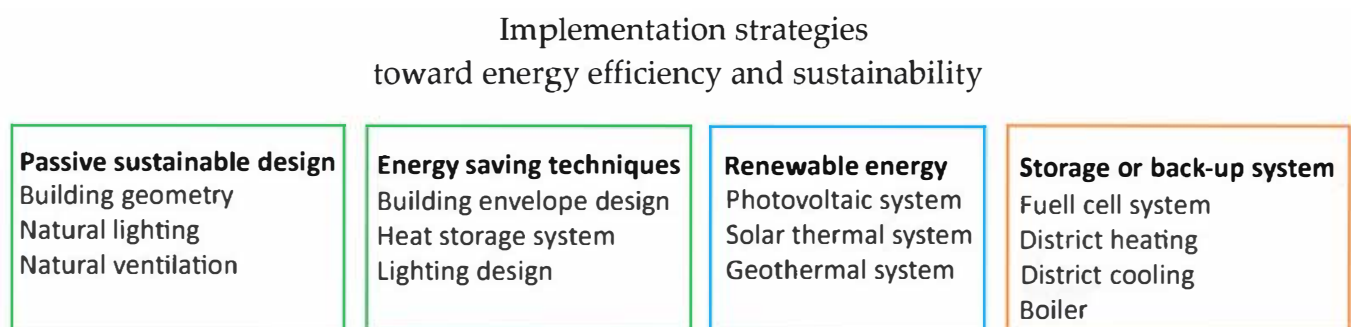


Figure 1. Selected current implementation strategies toward energy efficiency and sustainability (building case study, own elaboration).

AM in Industry 6.0 is transforming construction into a sustainable, decentralized, and highly adaptive process that is tailored to both environmental and user-specific goals. Additively manufactured building materials are key to the energy efficiency and sustainability goals of Industry 6.0, which emphasizes intelligent, adaptive, and mass-customized production systems. With 3D printing, materials such as bioconcrete, recycled polymers, and geopolymer cements are shaped layer by layer, enabling precise control of material placement and reducing waste by up to 60% compared to traditional construction. Topology-optimized designs enabled by AM reduce the volume of material required while maintaining structural integrity, thereby lowering both embodied energy and the overall carbon footprint. These materials often incorporate integrated insulation, passive ventilation ducts, and even embedded sensors, increasing the operational energy efficiency of buildings after construction. AM enables mass customization, tailoring walls, facades, and entire structural elements to specific climatic, cultural, or ergonomic needs without increasing production costs [23]. In Industry 6.0, cyber-physical systems and AI-based design algorithms enable real-time optimization of building material composition based on local environmental data, improving sustainability [24]. On-site 3D printing using locally sourced or recycled aggregates further reduces transportation emissions and supports circular economy practices. Already, homes are being 3D printed using earth-based or carbon-neutral materials, achieving near-zero energy use in construction. Life-cycle assessments show that AM in construction can reduce CO₂ emissions by up to 70% per square meter compared to conventional techniques. Governments, academia and industry have begun to invest in sustainability metrics, green certifications and life-cycle analyses specific to additive manufacturing [25–27]. The concept of energy-sensitive design and decentralized sustainable manufacturing has become key to adapting AM to future industrial paradigms. Today, the field continues to evolve, aiming to make AM not only innovative and flexible, but also measurably energy-efficient and sustainable in the context of mass personalized production [27].

1.2. Scientific and Economic Gaps

A significant research gap is the lack of standardized methodologies for assessing energy efficiency and sustainability across AM technologies and materials [28]. Comparative LCAs are often inconsistent or incomplete, making it difficult to compare AM with conventional manufacturing [29,30]. There is limited research on the energy implications of mass customization, particularly how high design variability affects production efficiency and environmental burden [31,32]. Data on material sustainability, especially for new raw materials such as composites and biopolymers, are sparse or fragmented, making informed material selection difficult [33]. Few studies have explored the integration of AI and IoT to optimize real-time energy use in distributed, personalized manufacturing networks [34–36]. On the economic side, cost-benefit analyses that include hidden energy and environmental costs are underdeveloped, limiting investment decisions [37]. The economic scalability of sustainable AM remains uncertain, particularly when balancing customization, production speed, and energy consumption [38,39]. Business models for decentralized, energy-efficient AM ecosystems are still immature, and the paths to profitability and sustainability are unclear [40,41]. There is insufficient policy and regulatory support to encourage green additive manufacturing, creating a gap between research capacity and industrial adoption [42]. There is a lack of interdisciplinary collaboration between engineers, economists, environmental scientists, and policy makers, which slows down overall progress in the field (Figure 2) [43,44].

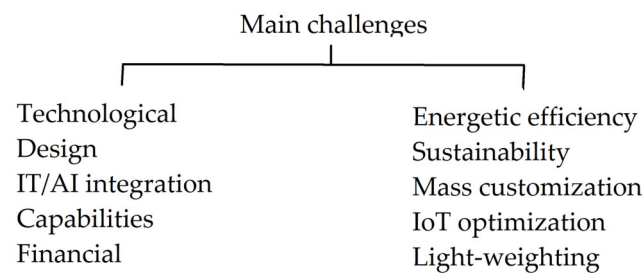


Figure 2. Main challenges for scientists, engineers, economists, and policy makers (own elaboration).

2. Materials and Methods

2.1. Dataset

This bibliometric analysis was conducted to examine the state of research and the state of knowledge and practice in the area of planning and implementing ML planning and implementation for optimizing AM materials and technologies. In order to efficiently carry out this, commonly known and used bibliometric methods were used to analyze current, recently published (i.e., up to 10 years ago) scientific publications with a global reach. This approach assumes formulating such research questions that, thanks to the answers to them, it is possible to identify key areas included in the current state of research, the origin of the publications (institutions, country, sources of research funding), the most influential authors (as leaders of research teams) and articles, and also—if possible—the evolution of research topics in recent times. This is important due to the observed dynamic changes in conducting and financing research in the area of AI, green technologies and sustainable development. In addition, when possible, an attempt was made to identify SDGs related to the publications included in the review, as part of the global transformation that prepares us for the world in 2030 with respect for the environment and future generations. This approach allows for a more comprehensive understanding of current research and economic and social trends, strategies, research and business practices based on ML in the development of AM. This approach provides the necessary understanding and planning of further development activities in this field and strengthening its potential in both the technological and regulatory areas. In the light of the paradigms of Industry 4.0 (automation, robotization, technical control throughout the production cycle) and Industry 5.0 (human and environment in the center of attention), it is necessary to understand and plan further development activities in this field and strengthen its potential. Such interpretation of current and relevant bibliometric data enriches current discussions and provides a solid basis for future research and similar reviews.

2.2. Methods

In this study, a deliberate and planned search of four bibliographic databases was used: Web of Science (WoS), Scopus, PubMed, and dblp. This combination resulted in a search covering the widest possible scope of studies and a wealth of data of global importance for the development of knowledge and its applications (Table 1). In order to quickly identify leading results, appropriate filters were applied so that further analyses could focus only on selected literature, narrowing the search scope to articles in English. After filtering, each article was manually reviewed again individually to ensure that it met the inclusion criteria, which, once performed, allowed the final sample size to be determined. Then, the main features of the dataset were analyzed, including the most frequent authors/research groups, institutions, countries, funding mode (if reported), scientific fields, and subject groups. This allowed us to map the main research achievements in the study area and identify emerging trends, which were not always in line with expectations. Where possible, we tracked temporal trends to monitor changes in the research area over time and grouped

publications into thematic clusters that showed relationships across different research areas. This process highlighted important themes and subfields within the research area, including emerging ones.

Table 1. Bibliometric analysis procedure (own approach).

Name of Stage	Tasks
Defining research goals	Defining exact goals of the bibliometric analysis
Selecting bibliometric databases	Choosing appropriate datasets and developing research queries according to the study goals
Data preprocessing/preparation	Removing duplicates and irrelevant records from the collected dataset, organizing the records to adapt them to the requirements of the ML training set
Bibliometric software selection	Selection of optimal tools from the area of bibliometric software for analysis
Data analysis	Description/keywords, type of publication, author, affiliation, area/topic, country, etc.
Analysis results/visualization(where possible)	Presentation of the results to emphasize insights
Interpretation of resultsand discussion	Interpreting results in the context of the research goals

In this study, selected elements of the PRISMA 2020 guidelines for bibliographic reviews were used to structure the research process and ensure its replication. The focus was on the following ten selected aspects of PRISMA 2020 presented in the Supplementary Materials:

- Item 3: justification,
- Item 4: objectives,
- Item 5: eligibility criteria,
- Item 6: information sources,
- Item 7: search strategy,
- Item 8: selection process,
- Item 9: data collection process,
- Item 13a: synthesis methods,
- Item 20b: synthesis results, and
- Item 23a: discussion.

For the bibliometric analysis, tools embedded in the Web of Science (WoS), Scopus, PubMed and dblp databases were directly used. The selected review methodology supports the replication of this study, enabling refinement of categorization by authors, affiliations, keywords, research areas, documents and sources standardized in the above-mentioned data bases. The results of the performed analyses are presented in a table to provide comprehensive and flexible analysis and visualization, adapted to the complexity of the topic.

3. Results

3.1. Data Sources

In order to refine the search in the selected databases, advanced queries were used using filters, limiting the results to articles in English. The search was performed as follows:

- In the WoS database, the “Subject” field (consisting of title, abstract, keywords plus and other keywords) was used;
- In the Scopus database, the article title, abstract and keywords were used;
- In PubMed and dblp databases: manual sets of keywords were used.

The databases were searched for articles using keywords such as “additive manufacturing” OR “AM”, “3D print” or “3D printing”, “Industry 5.0” AND/OR “Industry 6.0” AND “energy” AND/OR “sustainability” (Table 2).

Table 2. Detailed database search query (own version).

Parameter/Feature	Detailed Description
Inclusion criteria	Books, book chapters, articles (original, reviews, editorials), and conference proceedings, in English
Exclusion criteria	Articles, books, chapters older than 10 years, letters, conference abstracts without full text, other languages than English
Keywords used	Machine learning, climate change, energy optimization/optimization
Used field codes (WoS)	“Subject” field (consisting of title, abstract, keyword plus and other keywords)
Used fields (Sopus)	Article title, abstract and keywords
Used fields (PubMed)	Manually
Used fields (dblp)	Manually
Boolean operators used	No
Filters used	Results were refined by year of publication, document type (e.g., articles and reviews), and subject area (e.g., industry, engineering, computer science, and physics)
Iteration/validation option(s)	The query is used iteratively, refined in subsequent iterations based on the results, and verified by checking whether relevant publications appear among the top results
Wildcards and leverage truncation	Used symbol * for word variations (e.g., “energ*” for “energy” or “energetic”) and symbol ? for alternative spellings (e.g., “optimi?ation”)

The selected set of publications was then further refined by manually re-screening the articles and removing irrelevant publications and duplicates to determine the final sample size. A summary of the bibliographic analysis results is presented in Table 3 and Figures 3–7. Twenty eight articles (published 2021–2025) were reviewed (older articles were not observed).

Table 3. Summary of bibliographic analysis results (WoS, Scopus, PubMed, and dblp).

Parameter/Feature	Value
Leading types of publication	Article (91.20%)
Leading areas of science	Engineering (30.40%), Material science (30.40%), Physics and Astronomy (14.5%)
Leading countries	China, India, USA, Germany
Leading scientists	Asif, M.; Khalid, M.; Naeem, G.
Leading affiliations	Northwestern Polytechnical University, Huazhong University
Leading funders (where information available)	National Science Foundation of China

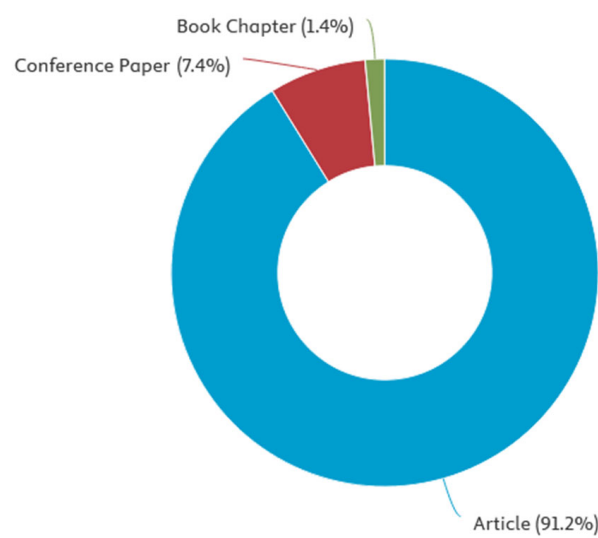


Figure 3. Results by type.

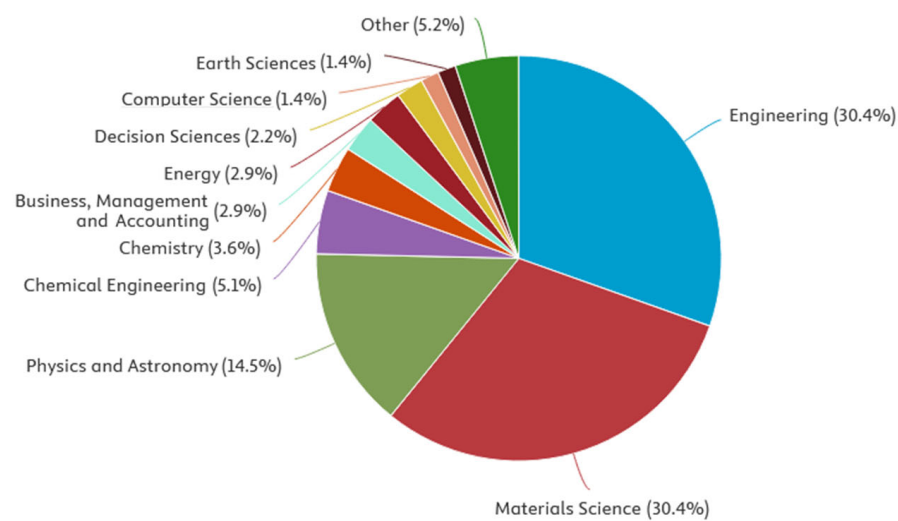


Figure 4. Results by area.

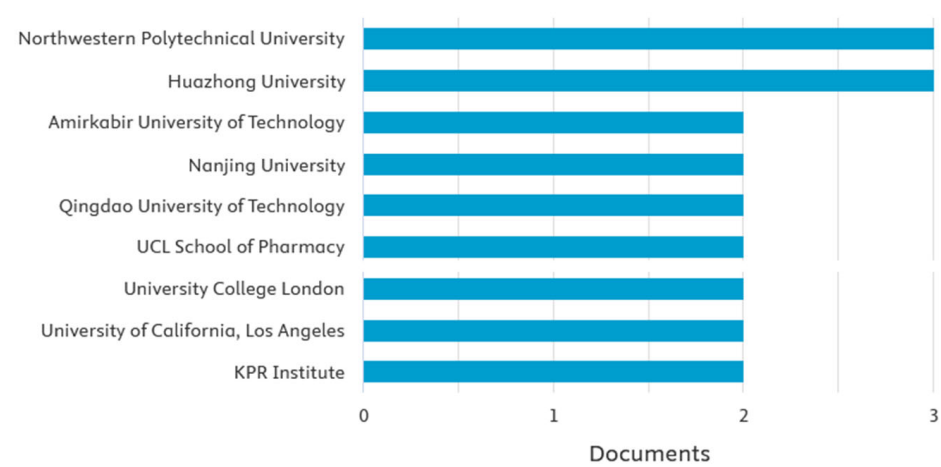


Figure 5. Results by affiliation.

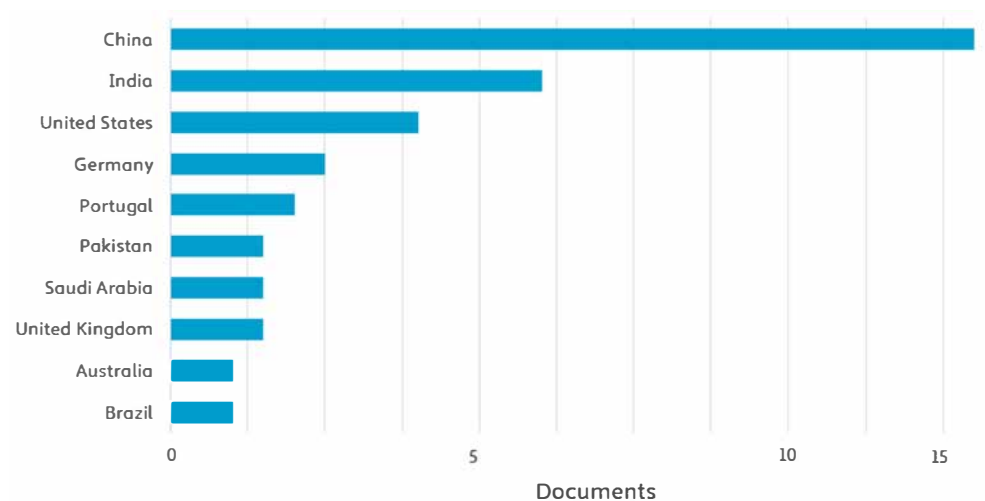


Figure 6. Results by country.

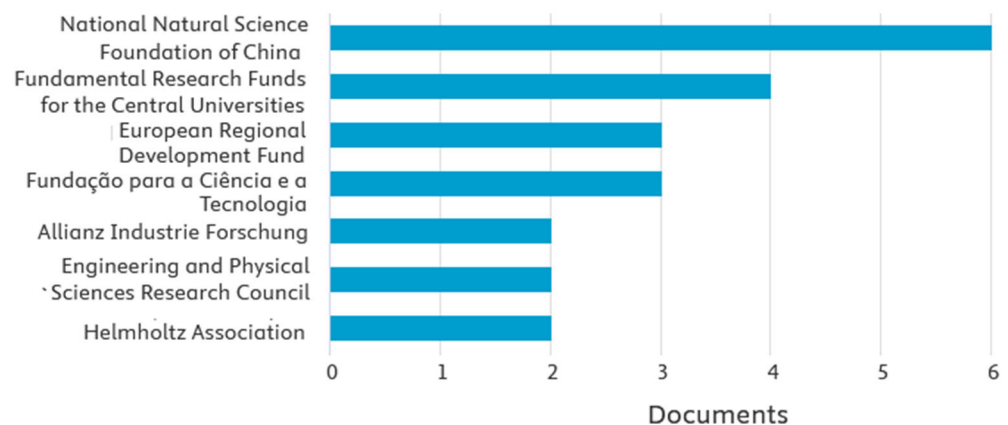


Figure 7. Result by funding sources.

3.2. Role of 3D Printing as a Mass-Personalized Production Mode in Industry 5.0/6.0

3D printing plays a key role in Industry 5.0 and 6.0, enabling mass-personalized production tailored to individual consumer needs without sacrificing efficiency. Unlike traditional manufacturing, it enables rapid production of customized items at scale, combining the advantages of mass production with personalization. In Industry 5.0, which emphasizes human–machine collaboration, AM enables designers and engineers to co-create customized solutions with customers [45]. Industry 5.0 reduces lead times and inventory costs by producing parts on demand, closer to the point of use [46–48]. The technology supports agile and decentralized production, increasing resilience and sustainability in supply chains [49,50]. In Industry 6.0, where hyper-automation and AI integration dominate, AM will become even more intelligent, self-optimizing, and responsive to real-time consumer data. Industry 6.0 supports the principles of the circular economy, co-creation, enabling the reuse of materials and local repair or remanufacturing [51,52]. From healthcare to aerospace, it facilitates the creation of complex, custom components that are difficult or impossible to make using conventional methods [53]. As consumer preferences shift toward personalized experiences, AM fits into the ethos of future industrial revolutions, transforming production from a rigid, centralized process to a flexible, user-centric ecosystem [54–58].

3.3. Circular Economy Enabling the Reuse of Materials and Local Repair/Remanufacturing

The circular economy is a key factor in the sustainability of AM, especially in the context of Industry 5.0 and 6.0, where waste reduction and resource efficiency are

paramount [59]. In contrast to the traditional linear model of production and disposal, the circular economy emphasizes the reuse, recycling, and regeneration of materials. AM supports this model by enabling local production and on-demand manufacturing, which significantly reduces overproduction and transportation-related emissions [60]. One of the main advantages is the ability to recycle used parts or failed prints into raw materials for new products, especially when using thermoplastics or composite materials [60]. By enabling local repairs and remanufacturing, AM extends the lifespan of products and components, reducing the need for complete replacement. This is particularly valuable in industries such as automotive, aerospace, and healthcare, where complex parts can be reprinted or repaired rather than thrown away [61,62]. The digital nature of AM means that products can be easily redesigned and adapted for reuse without the need for new tooling or molds. Integration with AI and IoT increases material traceability and predictive maintenance, ensuring components are repaired before failure occurs [63]. Energy efficiency is improved by reducing material consumption, minimizing waste, and shorter supply chains. In a circular economy, materials are viewed as assets rather than consumables, and AM facilitates their continued use [64]. Closed-loop systems can be created where waste is collected, reprocessed, and reintroduced into the production cycle. Additionally, decentralized manufacturing centers where AM is possible reduce the carbon footprint associated with centralized production and global logistics [65]. In Industry 6.0, where autonomous systems and real-time optimization dominate, AM can dynamically adjust production based on material availability and environmental impact. This supports zero-waste goals and increases the resilience of supply chains to disruptions [66]. Governments and industry are increasingly recognizing the role of AM in achieving circular economy goals. As sustainability regulations tighten, AM's ability to meet both economic and environmental goals becomes even more important [67]. Combining circular economy principles with advanced AM technologies offers a scalable path to a more sustainable and personalized industrial future (Figure 8) [68].

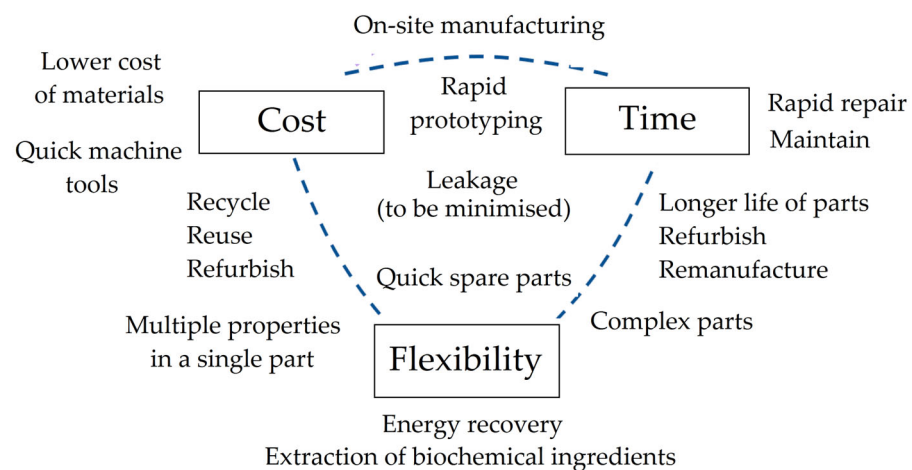


Figure 8. Circular economy of AM (own elaboration based on van Wijk's concept [69]).

3.4. Balancing Personalization, Efficiency and Ecological Responsibility

Balancing personalization, efficiency, and environmental responsibility is a major challenge and opportunity in the use of AM within Industry 5.0 and 6.0. AM is ideal for delivering highly personalized products without the inefficiencies of small-batch production. This enables customized solutions in sectors such as healthcare, fashion, and consumer goods, increasing user satisfaction while reducing waste from unsold inventory. At the same time, efficiency is maintained through digital workflows, rapid prototyping, and streamlined production chains [70]. AM eliminates the need for extensive tooling,

molds, and excessive material usage, leading to shorter lead times and reduced material consumption [71]. Environmental responsibility is further supported by local production, which minimizes transportation emissions and supports regional economies. The potential of using recycled or biodegradable materials in AM also contributes to a more sustainable life cycle. Intelligent technologies integrated with Industry 6.0, such as AI-driven design and predictive analytics, optimize energy consumption and minimize resource input in the printing process [72]. However, achieving this balance requires addressing challenges such as the high energy requirements of some AM methods and the limited recyclability of some materials. Careful material selection, energy-efficient hardware, and responsible end-of-life planning are key to closing the sustainability loop [73]. Human-centered design, a key feature of Industry 5.0, ensures that personalization does not come at the expense of environmental degradation. In addition, adaptive manufacturing systems enable just-in-time production, reducing overproduction and waste [74]. Standards and certifications can help measure and enforce eco-efficiency without limiting personalization. Governments and industries must work together to develop guidelines that align personalization with sustainability goals. the synergy of personalization, efficiency, and eco-responsibility positions AM as a cornerstone of the next industrial evolution [74,75].

From a make-to-order perspective, modern 3D printing methods are revolutionizing the production of human organs, implants, and some drugs [76]. The technology enables precise personalization tailored to the patient's needs, enabling medical solutions tailored to individual anatomical and physiological needs [77]. Bioprinting uses living cells and biomaterials to produce tissues and even functioning organs, offering an alternative to traditional organ transplants. In implant production, 3D printing creates lightweight, durable, and biocompatible components with complex geometry that were previously impossible to achieve [78]. Drugs can be printed with tailored doses and release profiles, increasing therapeutic efficacy and patient compliance. The additive nature of AM significantly reduces material waste, contributing to energy efficiency and reducing environmental impact compared to subtractive manufacturing methods. The process can be localized and on-demand, minimizing the carbon footprint associated with logistics and mass production. Importantly, the need for human donors is reduced, mitigating ethical and delivery concerns while eliminating the risk of immune rejection [79]. In addition, 3D printed models and tissues are increasingly replacing animal testing in research, which is a more humane and accurate approach [78–80]. Overall, the integration of 3D printing into medicine represents a shift towards sustainable, ethical, and highly personalized healthcare solutions [80].

3.5. Flexible, User-Centric Ecosystem

A flexible, user-centric ecosystem is the foundation for integrating AM into Industry 5.0 and 6.0, enabling energy-efficient and sustainable mass production of personalized products. This ecosystem prioritizes individual user needs while maintaining scalability and environmental responsibility [81]. AM allows users to co-design products via digital platforms, which fosters greater engagement and reduces the mismatch between production and demand. This co-creation approach minimizes waste and ensures that resources are used only for needed, valuable products. The ecosystem is inherently adaptable, able to switch between product designs and features without the need for major retooling, saving both time and energy [82]. Decentralized manufacturing centers powered by AM support local economies and reduce the carbon footprint associated with global logistics. These centers can respond quickly to changing user requirements, increasing supply chain resilience and reducing overproduction. Integration with AI and IoT further enhances this flexibility, enabling real-time monitoring, customization, and predictive maintenance [83]. Digital twins and cloud-based design repositories enable efficient collaboration across geographies

while reducing the need for physical prototypes. System modularity enables continuous upgrades and reuse of materials, contributing to a circular, low-waste production model. In this user-centric ecosystem, sustainability is not an afterthought, but a design principle built in from the start. Energy-efficient 3D printers and optimized material use reduce the environmental impact of manufacturing operations. The ability to repair, upgrade, or remanufacture items in-house extends product lifecycles and promotes responsible consumption. Regulatory frameworks and data standards ensure that personalization does not compromise environmental goals. The ecosystem empowers both consumers and producers by aligning technological innovation with human and ecological values. The ecosystem redefines industrial production as a responsive, intelligent and sustainable service that continuously adapts to the changing needs of people and the planet [84].

3.6. Energy Efficiency

The net energy efficiency of AM depends on the type of process, part complexity, and production scale, but the energy savings per component can be significant if implemented strategically [85]. AM significantly improves energy efficiency in certain manufacturing contexts, often reducing energy consumption by 25–50% compared to traditional subtractive methods. Laser-based AM uses approximately 38% less energy than traditional machining when producing complex aerospace components. Conventional manufacturing processes can require the removal of up to 90% of material, while AM often uses more than 90% of the input material, reducing both material waste (up to approximately 10%) and its associated embodied energy. In the automotive sector, redesigning parts from subtractive to AM can reduce weight by as much as 50–60%, resulting in improved fuel efficiency and indirect energy savings during product use. The AM-made aircraft engine nozzle is 25% lighter and consolidated from 20 parts into one, providing energy-efficient production and operation. For low-volume production, AM can reduce energy consumption per part by up to 50% by eliminating tooling and setup steps. In terms of absolute energy, some AM processes, such as Electron Beam Melting (EBM), use 0.2–0.5 kWh/cm³, while traditional CNC machining can use 2–3 kWh/cm³ for similar parts, up to 10 times more. AM also enables local, on-demand production, reducing shipping energy costs by up to 30%. Integrating a digital workflow into AM further increases efficiency by optimizing material layout and minimizing printing errors [85–89].

4. Discussion

The synergy of AM with digitization and AI paves the way for a sustainable, efficient, and highly personalized industrial future. As a key enabler of mass-personalized production in Industry 5.0 and 6.0, AM offers significant improvements in energy efficiency and sustainability. Unlike traditional subtractive manufacturing, it is an additive process that minimizes material waste, reducing both resource consumption and environmental impact. The digital nature of AM enables on-demand, local production, reducing emissions from long-distance transportation and centralized production centers. Customization at scale becomes possible without retooling, reducing the energy consumption associated with adjusting the production line. Advanced materials, including biodegradable and recycled polymers, are increasingly compatible with 3D printers, reinforcing circular economy practices. Intelligent sensors and AI integration in Industry 5.0 optimize energy consumption during the printing process, adapting to energy availability and demand in real time. In Industry 6.0, improved human–machine collaboration further improves operational sustainability by aligning production with ecological and social goals. In addition, AM supports lightweight designs and complex geometries that improve the energy efficiency

of final products. Energy-efficient, decentralized microfactories powered by renewable energy can be created, reducing the carbon footprint of production ecosystems.

3D printing offers significant energy and sustainability benefits over traditional methods such as casting and milling, especially in the context of mass-customized Industry 6.0 production. For example, manufacturing a complex aerospace bracket using CNC milling can waste up to 90% of the original material, while 3D printing the same part only uses the required 5–10% more than the final geometry, significantly reducing material waste and embodied energy. In terms of energy consumption, casting such a part can use 3–5 kWh/kg, CNC milling around 2–3 kWh/cm³, while metal 3D printing such as selective laser sintering (SLS) typically uses 0.5–1.5 kWh/cm³, with future low-energy variants aiming to reduce energy consumption [85–89]. Traditional casting and tooling lead times can take weeks, while 3D printing can produce fully functional, customized parts in hours or days, reducing logistical and operational energy costs. Cast surface quality often requires additional finishing, while AM can integrate complex geometries and even functional gradients into a single design with minimal post-processing. Lifecycle emissions of 3D-printed housing components have been shown to be up to 70% lower compared to concrete blocks using earth-based or recycled materials. In healthcare, custom prosthetics through traditional means can involve 5–7 process steps and significant waste, while AM provides a customized fit in a single step with near zero waste. AM also enables real-time design adaptation based on AI and environmental feedback, enabling energy optimization during both production and end-use. In the future factories of Industry 6.0, digital twins and cyber-physical systems will synchronize 3D printing processes with energy monitoring to continuously reduce consumption. These comparisons underscore how 3D printing is evolving into a cornerstone of sustainable, efficient, and customized production.

4.1. Scientific Consequences of Achievement

Achieving energy efficiency and sustainability in AM as a mass-customized production mode in Industry 5.0/6.0 has significant scientific implications. This enables the development of closed-loop production systems that reduce material waste and carbon emissions. The decentralized, on-demand nature of AM minimizes transportation needs, contributing to a smaller environmental footprint. Advances in materials science are driven by the demand for recyclable, biodegradable, and energy-efficient raw materials. These innovations are catalyzing new research in life-cycle analysis and sustainable design principles for additive manufacturing. Additionally, the integration of AI and digital twins in Industry 5.0/6.0 increases precision and resource optimization in real-time manufacturing processes. The scientific community is gaining new data and models to study human-machine collaboration and adaptive manufacturing ecosystems. This paradigm supports resilient, eco-friendly industrial systems aligned with global climate and sustainability goals [90–93].

4.2. Economic Consequences of Achievement

The economic implications of achieving energy efficiency and sustainability in AM within Industry 5.0/6.0 are transformational. Manufacturing costs are reduced by minimizing material waste, lower energy consumption, and reduced reliance on complex supply chains [94]. Decentralized production enables local manufacturing hubs, reducing transportation costs and supporting regional economic development. Mass customization allows companies to offer highly personalized products without the traditional costs of mass production, increasing customer value and market competitiveness [95]. Small and medium-sized enterprises (SMEs) can more easily enter high-tech markets with reduced capital requirements for flexible, scalable AM setups. Long-term operational savings result

from sustainable practices, creating more resilient business models that are less susceptible to resource price volatility. Job creation is shifting toward highly skilled roles in design, maintenance, data analysis, and sustainable innovation. Intellectual property is becoming a key economic asset as digital product files gain value relative to physical inventory. Circular economy models are gaining popularity, encouraging economic activity in recycling, remanufacturing and material recovery industries. Integrating energy-efficient and sustainable AM into Industry 5.0/6.0 therefore drives inclusive, innovation-driven economic growth (Figure 9) [96].

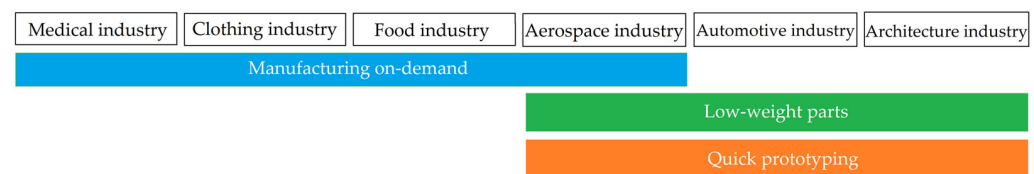


Figure 9. Key applications of circular economy of AM (own elaboration).

4.3. Societal Consequences of Achievement

The societal implications of achieving energy efficiency and sustainability in AM within Industry 5.0/6.0 are profound. This enables communities to produce locally, reducing dependence on global supply chains and increasing self-sufficiency. Consumers gain access to affordable, customized products that better meet individual needs, improving quality of life. The environmental benefits of reducing waste and emissions contribute to healthier living conditions, especially in urban areas. The shift toward sustainable production is fostering greater public awareness and commitment to ecological and ethical consumption. Education and training programs are evolving to equip workers with skills in design, digital manufacturing, and sustainable technologies, promoting lifelong learning and social mobility. High-tech, green job opportunities are supporting more equitable economic participation among diverse populations. Remote and underserved regions can benefit from digital manufacturing hubs, reducing regional disparities. Collaboration between humans and machines in manufacturing is encouraging a more human-centric and inclusive industrial culture. Sustainable AM supports societal resilience, well-being and alignment with broader goals such as the UN Sustainable Development Goals (SDGs) [97–99].

4.4. Limitations

The energy intensity of AM processes, especially for metal-based additive manufacturing, can be significantly higher than traditional methods, limiting overall energy efficiency [93]. The sustainability of materials used in AM is limited because many raw materials, such as thermoplastics and resins, are petroleum-based and difficult to recycle. AM often involves long print times and high energy consumption per part, which may not be scalable in mass-customized contexts [84]. Post-production steps (e.g., cleaning, curing, and surface finishing) add hidden energy costs and environmental burdens that are not immediately apparent at the printing stage. Limited recyclability of support structures and failed prints contributes to material waste, reducing the sustainability benefits often associated with AM [95]. Decentralization of the supply chain, while offering flexibility, can hinder centralized energy optimization and complicate sustainability tracking in Industry 5.0/6.0 networks. There is a lack of standardized sustainability metrics and energy efficiency benchmarks for AM across industries and materials [96]. The environmental impact of printer manufacturing and maintenance is often overlooked but has significant impacts throughout the equipment lifecycle. Many 3D printers lack the ability to use biodegradable or bio-based materials at scale, limiting sustainable material options. Digital infrastructure

requirements for mass customization (e.g., cloud storage and AI design tools) introduce indirect energy demands that offset some sustainability benefits [97].

4.5. Directions of Further Research

Future research should focus on developing low-energy 3D printing technologies, especially for metal and composite materials, to improve energy efficiency at scale. Research into sustainable, recyclable, and bio-based printable materials is essential to reduce the environmental footprint of mass-produced personalized products [98]. Life-cycle assessment (LCA) frameworks tailored to AM need to be improved to accurately measure energy consumption and sustainability at all stages. Research into intelligent energy management systems integrated with 3D printers can enable real-time energy monitoring and optimization in Industry 5.0/6.0 settings. Research should explore closed-loop material systems where waste and failed prints are recycled into new raw material with minimal energy consumption [99]. Further research is needed into eco-design and generative design algorithms that optimize material usage and reduce printing time without compromising personalization. Comparative studies of centralized and decentralized AM networks can reveal optimal models for sustainable and energy-efficient production. Development of hybrid manufacturing systems combining AM with traditional methods can provide better trade-offs between sustainability and efficiency [99]. Research on digital twin technology can improve predictive maintenance and energy forecasting, in line with the intelligent automation goals of Industry 6.0 [100]. Interdisciplinary research combining engineering, data science, and environmental science is needed to holistically assess and improve the sustainability of AM in mass-customized manufacturing [101].

Despite its advantages, AM can be energy-intensive, especially in metal-based processes such as selective laser melting (SLM), which limits its sustainability on an industrial scale. This challenge is being addressed by developing low-energy AM techniques such as binder jetting and cold spray methods that require less heat input. Future directions also include ML-based process optimization, reducing printing time and energy consumption by fine-tuning parameters in real time. Integration of renewable energy into AM facilities, including solar or wind-powered printers, is being explored to offset carbon intensity. Furthermore, switching to energy-efficient, recyclable raw materials and closed-loop material systems supports a more sustainable, mass-customized AM framework within Industry 6.0.

As Industry 5.0 and the emerging vision of Industry 6.0 shift manufacturing paradigms, AM is emerging as a transformative force, particularly in enabling mass, personalized production. In this advanced industrial framework, sustainability and energy efficiency are not secondary goals, but central principles—driving technologies to be not only smarter, but also more responsible and regenerative. From an energy efficiency perspective, AM offers significant benefits. Traditional subtractive manufacturing often wastes significant amounts of material and energy by cutting from larger blocks, while AM constructs objects layer by layer, using only the material needed. This material precision translates into lower energy consumption in both production and waste processing. Additionally, AM can localize production, drastically reducing the energy footprint associated with global logistics and inventory management. In the context of Industry 5.0—which emphasizes human-centric, resilient, and sustainable production—this decentralization is consistent with energy-conscious, on-demand, and customized production models. However, energy efficiency in AM varies depending on the technology (e.g., fused deposition modeling—FDM, selective laser sintering—SLS, and stereolithography—SLA) and materials (plastics, metals, ceramics). For example, metal 3D printing can be energy-intensive due to high-temperature sintering or laser fusion. Therefore, developing process optimization, energy recovery systems, and AI-based energy management becomes crucial to adapt AM to

the energy goals of Industry 6.0, which envisions hyper-connected, autonomous, and sustainable production ecosystems. From a sustainability perspective, AM supports the principles of the circular economy. This facilitates design for disassembly, easy repair, and recycling. Furthermore, AM enables the use of biodegradable or recycled materials and minimizes overproduction through mass customization. In Industry 5.0, where human values and environmental concerns converge, AM enhances ethical production by reducing waste, shortening supply chains, and supporting local economies. The development of bioprinting and sustainable biomaterials also opens new frontiers in green manufacturing. In Industry 6.0, the integration of quantum computing, advanced robotics, and real-time data ecosystems can further enhance the sustainability of AM. Predictive modeling can optimize material and energy use at unprecedented levels, while autonomous, self-correcting printers reduce errors and resource waste. In summary, AM has significant potential as a sustainable and energy-efficient enabler of mass, personalized manufacturing in Industry 5.0/6.0. Realization of this potential depends on continuous innovation in materials science, energy systems, and digital integration to address current constraints and scale responsibly.

5. Conclusions

In summary, AM has great promise as a sustainable and energy-efficient manufacturing method aligned with Industry 5.0 and 6.0 goals. Its ability to enable mass customization, minimal material waste, and local production supports more resilient and environmentally friendly supply chains. Integration of intelligent systems such as AI and IoT further optimizes processes and reduces energy consumption. However, challenges remain, particularly in the energy intensity of some AM techniques and the environmental impact of some materials. Further research and innovation are needed to improve equipment performance, expand the use of sustainable materials, and refine LCA methodologies. Policy makers and industry leaders must also support enabling frameworks that encourage the adoption of greener AM practices. AM is a key enabler for a more personalized, efficient, and sustainable industrial future.

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Abbreviations

The following abbreviations are used in this manuscript:

3D	Three dimensional
AI	Artificial intelligence
AM	Additive manufacturing
FDM	Fused deposition modeling
LCA	Life-cycle assessment
SLA	Stereolithography
SLS	Selective laser sintering

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