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Energy Consumption in Additive Manufacturing Technologies: A Literature Review

KEYWORDS
Additive Manufacturing, Sustainable production, Sustainability, 3D Printing, Energy Conservation, Resource Efficiency, Energy consumption, Responsive Production

ABSTRACT
In an era where manufacturing drives global economic growth, Additive manufacturing (AM) is often celebrated for its potential to revolutionize sustainable manufacturing, yet its true potential for energy conservation stays under explored. This review critically examines the energy demands of various AM technologies, including laser powder bed fusion, material extrusion, binder jetting, and contrasting them with traditional manufacturing methods. The literature delves into AM's energy consumption patterns, highlighting its advantages in minimizing material waste, optimized light weight designs, enabling local and on-demand production and supporting a circular economy. While some AM process can be more energy intensive, the overall life cycle analysis reveals that AM often achieves significant energy savings. Case studies, particularly from the aerospace and automotive industries, suggest that AM can cut emissions better than traditional techniques. The review shows key strategies for improving energy efficiency in AM, including process optimization, material selection, and the integration of renewable energy sources. These insights provide a roadmap for researchers and industry to harness the full sustainability potential of AM, while addressing its current limitations

1. INTRODUCTION

Today speedily growing and competitive industry is asking for products with lower manufacturing time, higher sustainability, low energy consumption, low cost, environmentally friendly, value for money and much more. Many of such expectations can be fulfilled by Additively Manufactured components in future. AM components are manufactured by 3D-Printers are available in various technologies and with variation in printing material.

The manufacturing industry's rapid development significantly impacts the global economy by converting raw materials into consumable finished goods. However, it also depletes natural resources and generates waste and emissions, contributing to substantial adverse impacts on the environment and society. Most of the study emphasizes the increasing demand for sustainability in modern society due to factors such as climate change, diminishing natural resources, and stringent government regulations [1].

This review provides comprehensive overview of the energy consumption in AM technologies, potential benefits over traditional manufacturing technologies and multiple advantages of AM, including waste minimization, design optimization and circular economy. In cases where AM technologies (e.g., laser-based) are energy intensive, its overall sustainability benefits are discussed as a key tool for ecofriendly manufacturing. The main motivation for this review stems from the need to address the environmental and resource challenges in manufacturing industry and growing adoption of AM in aerospace and automotive industries, where conventional manufacturing consumes massive amounts of energy and materials [2]. Despite the fact thatAM offers advantages, there are still few studies that comprehensively evaluate the energy consumption of AM. This paper aims to bridge this gap and guide the future research and applications of AM technology; therefore, it will provide a comprehensive overview of the current state of AM and its potential for sustainable manufacturing.

2. TECHNOLOGIES IN ADDITIVE MANUFACTURING AND ENERGY EFFICIENCY

Assessing the energy efficiency of AM technology involves considering various factors. Whatever specific energy consumption values may vary based on machine design, process parameters and material utilization. In this section a general understanding of AM technology is provided.

Table 1. Evolution based classification of 3D printing technologies [3], [4], [5], [6]

Name	Material	Technique	Application	Year
Fused deposition modelling	Thermoplastic	Heating and extrusion of thermoplastic filament	End-use products, medical industry	1980s
Selective Laser Sintering	Polymers, ceramic, sand, metal	High powered lasers to fuse powder	Prototyping, end use products for aerospace, automotive and medical industry	1980s
Stereolithography	UV Photopolymer	Hardening of liquid plastic by UV laser	Prototyping	1986
Material Jetting	Photopolymer	Deposition of droplets onto a substrate	Prototyping, Medical, construction	1990s
Laminated Object Manufacturing	Paper, Plastic	Adhesive coated laminates by heat or pressure and cut by laser or knife	Prototyping	1991
Binder Jetting	Plastic, metal, ceramic, sand	Application of liquid binding agent to powder plane	Prototyping, Rapid tool making	1993
Electron Beam Melting	Metal	Electron beam to fuse metal powder	Aerospace area and medical implants	2000

2.1. Laser power bed fusion

Laser technology is used in LPBF to selectively melt and fuse layers of powdered material to build a three-dimensional object. The energy efficiency of LPBF depends on various parameters such as laser power, scanning speed, and powder bed preheating. LPBF typically requires high laser power for melting the powder, which can affect in relatively higher energy consumption [7].

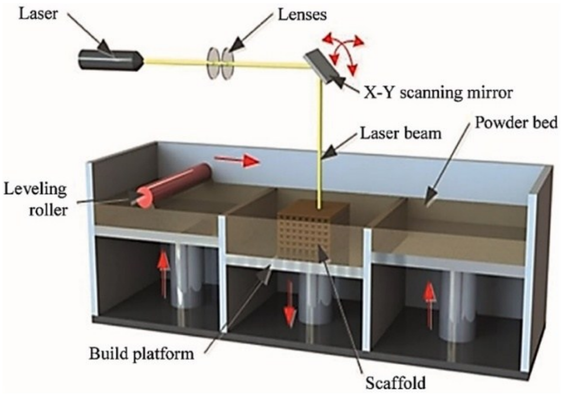

Figure 1. Schematic diagram of Laser Powder bed Fusion [8]

LPBF can be considered less energy-efficient compared to some other AM technologies. This is mainly due to the high-energy requirements of the laser used for melting of material. The laser power required to achieve material fusion and build complex geometries can lead to higher energy consumption [9].

Moreover, LPBF printing process often involves preheating the powder bed or using heated build platforms to maintain proper temperature during the printing process. These additional energy requirements contribute to the overall energy consumption of LPBF.

2.2. Binder jetting

Binder jetting is generally considered to be a more energy-efficient AM process compared to some other technologies, such as laser-based processes like laser powder bed fusion (LPBF). This is primarily because binder jetting does not require the use of high-energy lasers for material melting. In binder jetting, a binder agent is selectively applied to layers of powdered material, creating adhesion and forming the desired object. The process typically involves lower energy requirements since it does not involve the use of high-power lasers or intense heat sources for melting the material [10].

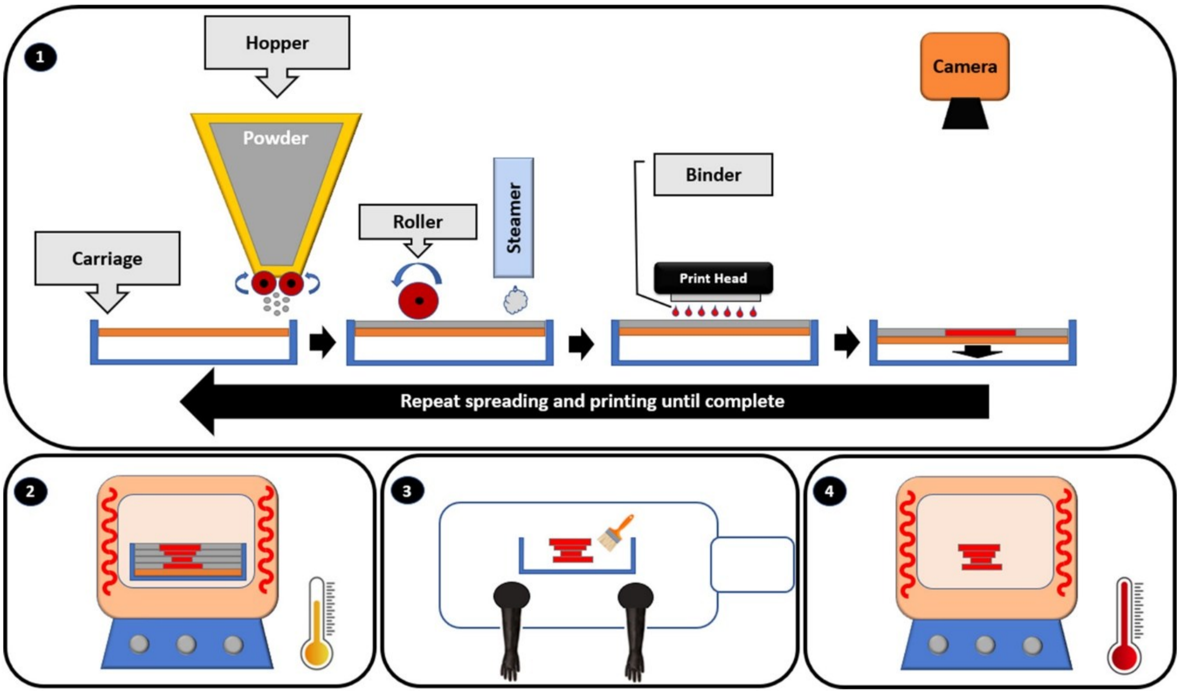

Figure 2. Schematic overview of manufacturing process for Binder Jetting Technology [10]

Moreover, binder jetting has the potential for efficient material utilization. The technology allows for the use of loose powder beds, which can be reused for subsequent builds, minimizing material waste and reducing overall energy requirements [5].

However, it is important to note that the energy efficiency of binder jetting can still vary depending on factors such as machine design, process optimization, and specific operational settings. Advances in technology, such as improved binder deposition systems and optimized process parameters, can further enhance the energy efficiency of binder jetting.

2.3. Direct energy deposition (ded)

Direct Energy Deposition (DED) is an additive manufacturing (AM) technology that includes the precise deposition of material using a focused energy source, such as a laser or an electron beam. DED processes can have variations in energy efficiency characteristics depending on the specific energy source used and the applications [11]. Here are some points to consider:

1. Laser-based DED:

In laser-based DED, a high-powered laser is used to melt and fuse the material while it is deposited. Laser-based processes generally require higher energy consumption due to the high energy levels needed for melting and bonding the material [12].

2. Electron Beam DED:

   In electron beam DED as an energy source utilizes an electron beam for material melting and deposition. In terms of energy conversion electron beams can be highly efficient, resulting in relatively lower energy consumption compared to laser-based DED processes [12].

3. Process Optimization:

Factors such as scanning strategies, layer thickness, and material utilization possibly can influence the energy efficiency of DED. Optimization of these parameters can help minimize energy waste and improve overall energy efficiency [12].

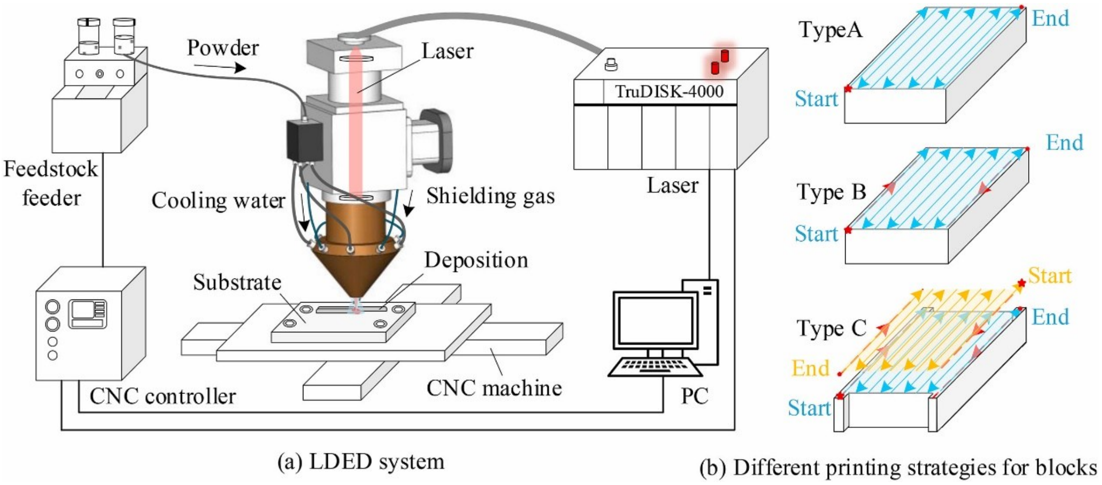

Figure 3. overview of Direct Energy Deposition additive manufacturing process [13]

2.4. Material extrusion

Material extrusion, also known as fused filament fabrication (FFF) or fused deposition modelling (FDM), which is an additive manufacturing (AM) technology that involves the extrusion of a melted thermoplastic filament to create three-dimensional structures. Material extrusion processes, such as FFF or FDM, are generally considered to be relatively energy-efficient compared to some other AM technologies. Some noticeable points relatable to energy efficiency is mentioned below [14]:

1. Lower Energy Consumption:
   Material extrusion processes typically require lower energy consumption compared to other AM technologies like laser-based processes. The energy requirements of material extrusion are mainly associated with heating and melting of the thermoplastic filament, which mostly involves lower energy levels compared to the high-powered lasers used in other AM technologies.
2. Energy Conservation:
   Material extrusion systems can be designed with such mechanisms that most of the energy is conserved. For example, some machines include energy-saving features such as heated build chambers or heated beds to improve adhesion and reduce the need for excessive energy input during the printing process.
3. Process Optimization:
   Process optimization factors such as print speed, layer thickness, and infill density can be used to influence energy efficiency in material extrusion. Optimizing these parameters can help decreasing energy waste and improve overall energy efficiency.

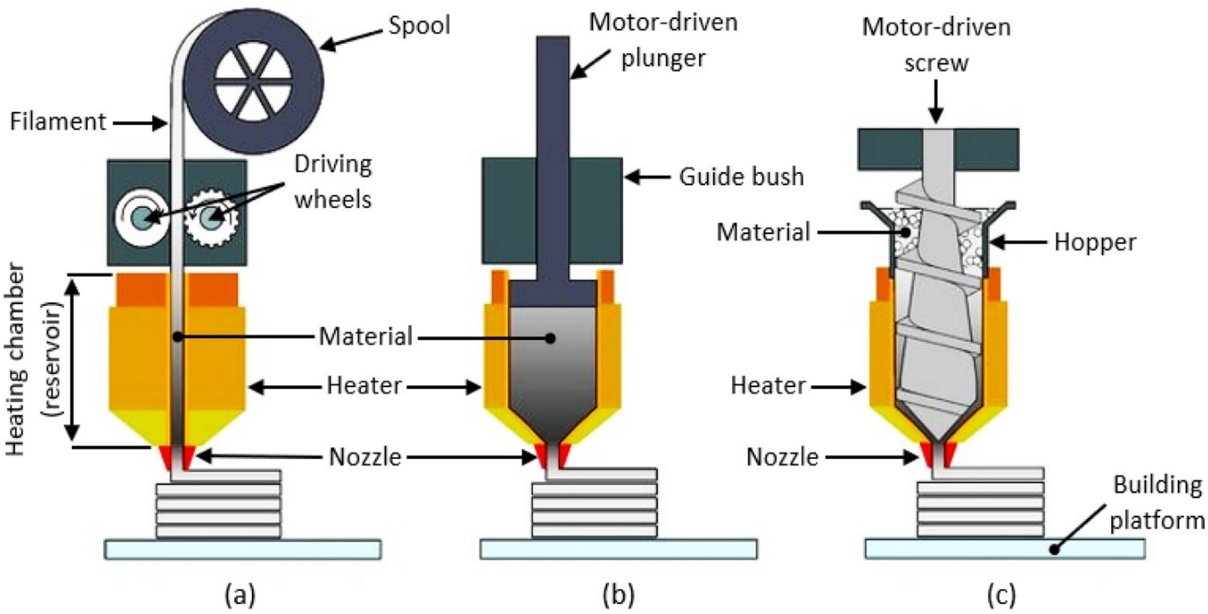

Figure 4. Three types of Material Extrusion based Additive manufacturing process (a) filament, (b) syringe and (c) screw [14]

2.5. Material jetting

Material jetting is an additive manufacturing (AM) technology that involves the precise deposition of droplets of liquid photopolymer or wax material onto a build platform, layer by layer, to create three-dimensional objects. Material jetting processes can have different energy efficiency characteristics depending on the specific system and materials used. Here are a few points to consider [15]:

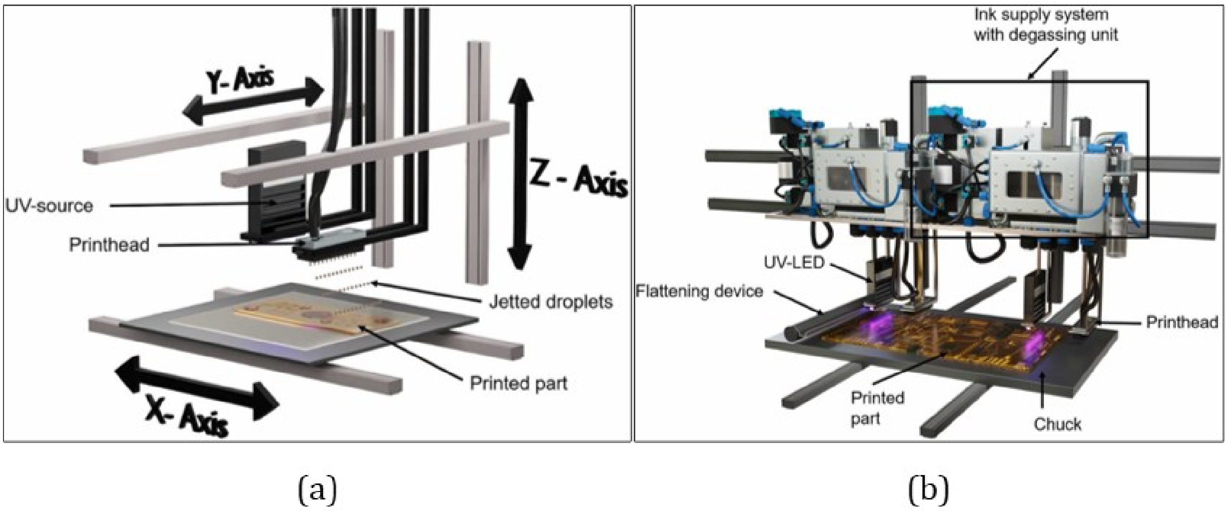

Figure 5. Schematic diagram of Material Jetting (a) printing process and (b) printing instrument [15]

1. Energy Requirements:
   Material jetting systems typically require energy for various components, such as the print-heads, curing systems, and temperature control mechanisms. The energy consumption can vary depending on the specific printer design, the number of print-heads, and the power requirements of the curing process.
2. Material Utilization:
   Material jetting technology allows for high material utilization since it deposits the exact amount of material needed for each layer. The ability to finely control the amount of material deposited can help minimize waste and improve overall energy efficiency.

3. Process Optimization:
   Energy efficiency in material jetting can be influenced by process optimization factors such as print speed, layer thickness, and curing settings. Optimizing these parameters can help reduce energy consumption and improve overall efficiency.

3. SUSTAINABILITY APPLICATIONS

Additive manufacturing (AM) has been studied extensively in terms of its sustainability. Several research articles have focused on evaluating and modelling the environmental impacts of AM, as well as its role in improving resource efficiency and sustainability. Studies have analysed the energy consumption, material usage, and environmental performance of AM processes, providing insights into the sustainability of this manufacturing method. Additionally, research has explored the potential of AM to contribute to a more sustainable way of part manufacturing, as well as its impact on energy and resource efficiency in manufacturing processes. Furthermore, the sustainability of AM has been assessed in comparison to traditional manufacturing methods, with studies examining the environmental impacts of AM versus traditional machining through life-cycle assessments [16].

Figure 6. Sustainability in Additive Manufacturing [17]

Additive manufacturing has the potential to provide several sustainability advantages across the product and material life cycles. These advantages incorporate producing less waste during manufacturing due to it being an additive process, optimizing geometries and creating lightweight components that reduce material consumption in manufacturing and energy consumption in use, reducing transportation in the supply chain, and reducing inventory waste due to the ability to create spare parts on-demand [18] [19].

Additionally, improvements can be realized in both production and use phases as manufacturing processes and products can be redesigned for AM, and extended product life can be achieved through technical approaches such as repair, remanufacture, and refurbishment, and more sustainable socio-economic patterns such as stronger person-product affinities and closer relationships between producers and consumers [20].

The advantages of additive manufacturing include:

- Economical attractive for small batches of customized products.
- No requirement for tools and moulds, so there are no switch-over costs.
- Simple sharing of digital files for modification and customization of components and products.
- Material investment funds because of the additive nature of the interaction and the capacity to reuse squander material.
- Capacity to make novel, complex designs that are not feasible with customary assembling strategies.
- Final parts have extremely low porosity.

3.1. Reduced material waste

Additive Manufacturing (AM) can be considered a promising sustainable manufacturing method due to its ability to eliminate excess material and reduce unnecessary waste [21]. By creating products layer-by-layer, additive manufacturing generates less waste compared to traditional subtractive methods. AM enables part optimization of geometries through generative design [22] and the creation of lightweight components, resulting in reduced material consumption during manufacturing, which is a key advantage over traditional manufacturing methods. The technology also offers benefits across the product and material life cycles, including in product and process redesign, material processing before input, make-to-order part and product production, and the closing of the loop [23]. These aspects contribute to the reduction of waste material and support the sustainability of additive manufacturing. The ability to reuse unused materials further contributes to material savings. Overall, additive manufacturing offers advantages in terms of reduced material waste and increased resource efficiency [24] [17].

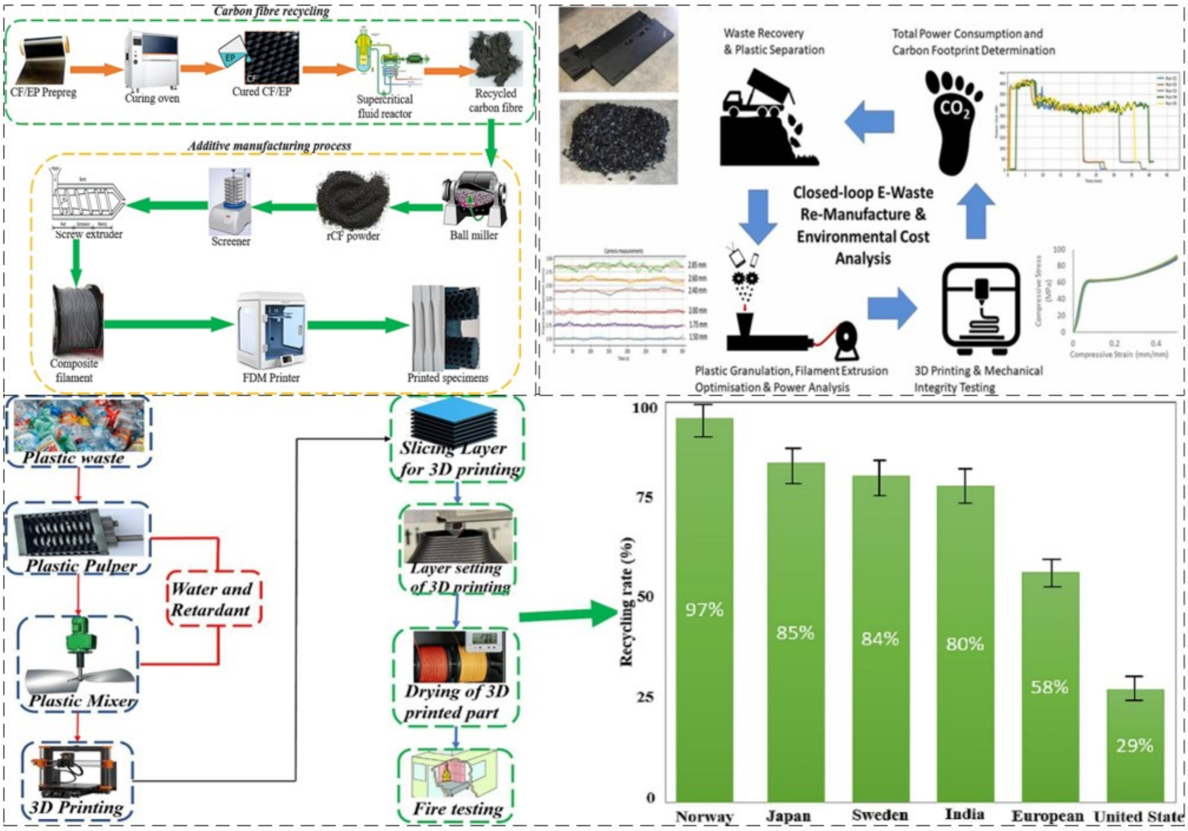

Figure 7. Pictorial representation of reduced waste and waste recovery by [25] and [26]

3.2. Energy efficiency

Additive manufacturing (AM) has been the subject of extensive research regarding its energy efficiency. Several studies have focused on evaluating the energy consumption of various AM processes (Section 5), to understand their sustainability [27]. Research has also compared the energy consumption of AM with traditional manufacturing methods, providing insights into the potential energy savings offered by AM.

Additive manufacturing, or 3D printing, presents both advantages and challenges in terms of energy efficiency. While it is generally found to be more energy-intensive per unit produced compared to traditional manufacturing methods, but there are factors that contribute to improved energy efficiency. In case of on-demand production, AM enables matching exact demand and reducing energy waste associated with excess inventory. As it allows for higher raw material utilization, many of the material processing steps utilized in subtractive or conventional manufacturing are absent, which further contributes to energy conservation. However, challenges such as energy consumption in feedstock production and limitations in material options affect overall energy efficiency. Further innovation and technological advancements are necessary to enhance energy efficiency in additive manufacturing, including the development of energy-efficient technologies and sustainable feedstocks. Addressing these challenges can lead to improved energy efficiency in the manufacturing industry [28].

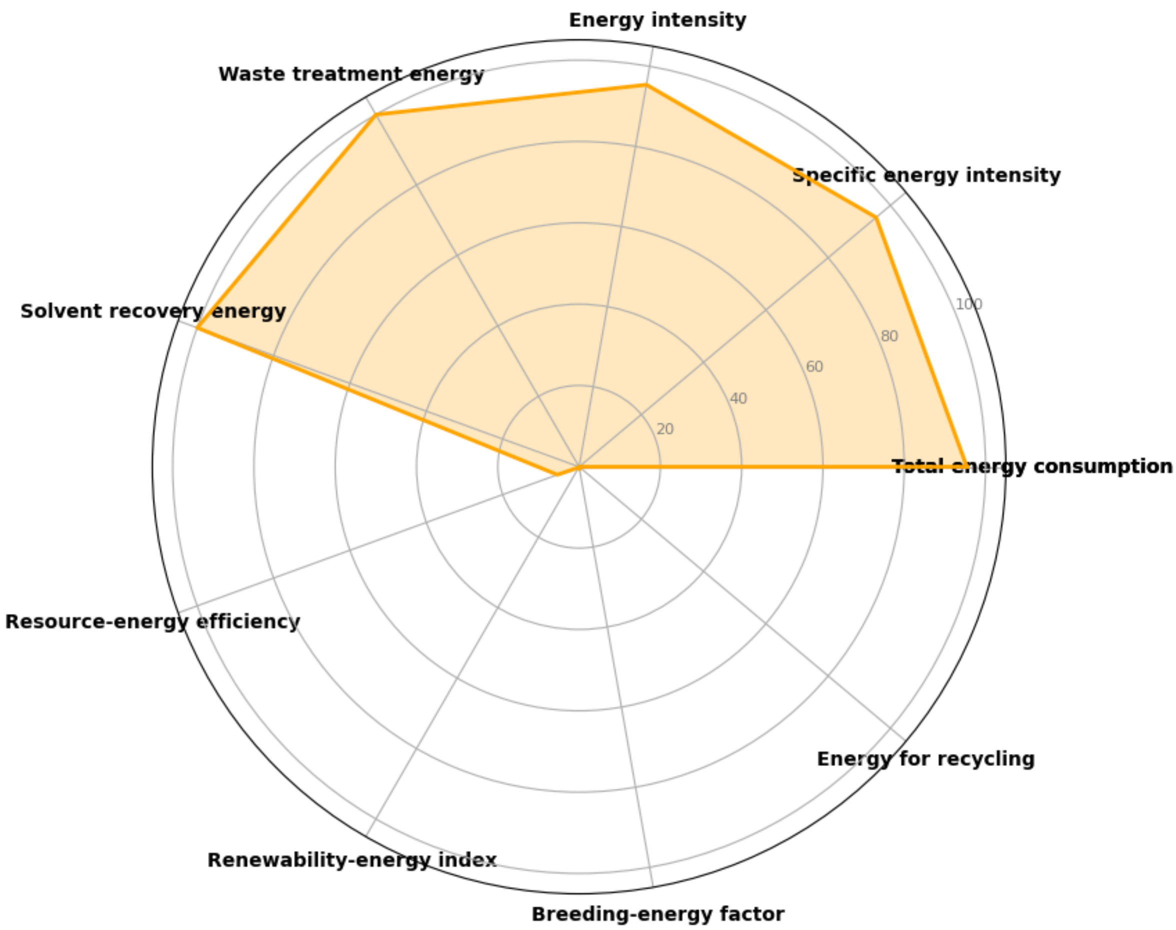

Figure 8. Radar chart of Energy indicators for AM material [29]

Researcher Chea et al. (2025) emphasized the importance of understanding the energy dynamics of manufacturing systems, indicating the significance of energy optimization in the manufacturing industry [29]. Furthermore, article suggests factors like material selection (biodegradable, easy to recycle, recycled material), transport optimization and inclusion of renewable energy has potential for developing efficiency by optimizing energy use in manufacturing methods. These examinations aggregately stress the critical role of energy management and optimization in additive manufacturing processes to achieve sustainability and cost-effectiveness.

3.3. Design optimization and light weighting

Utilizing the technology's unique capabilities to optimize the design for specific performance criteria is design optimization in additive manufacturing. Material usage, structural integrity, weight reduction, and functional integration are all part of this. AM-produced component's performance and efficiency can be enhanced using optimization methods [30] [31]. Topology optimization is particularly suitable for additive manufacturing, as it allows for the creation of optimized material layouts that meet specific structural requirements while minimizing weight. By exploring different design possibilities and material distributions, topology optimization can prompt to lightweight, structurally efficient components [32].

This manufacturing method allows for the creation of complex geometries and structures that are not achievable with traditional manufacturing techniques. Hence it provides an opportunity to designers to look for a design with minimal material and maximum operational strength, resulting into less material usage, less printing operation and less energy consumption.

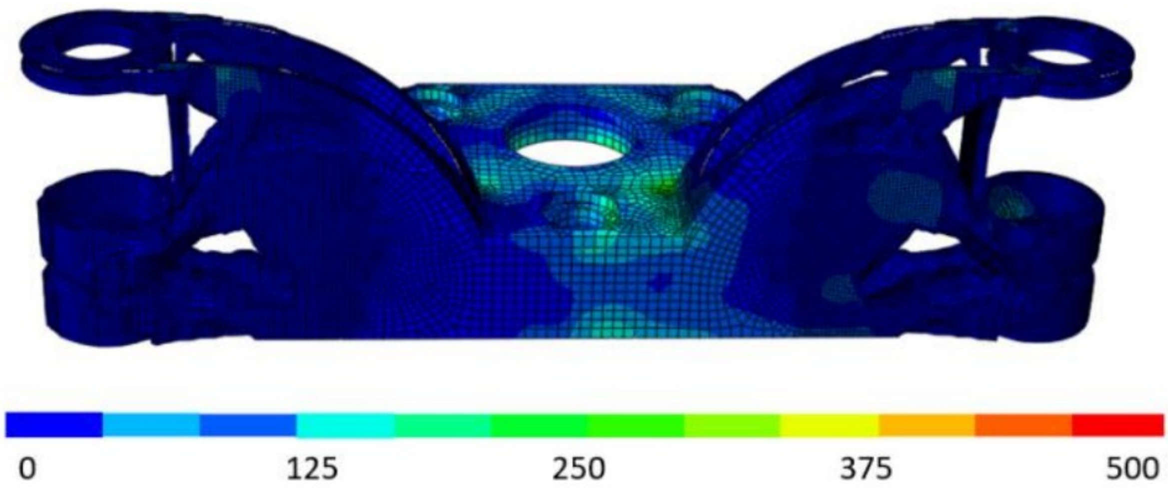

Figure 9. Von Mises Stress of additively manufactured light weight pelvic structure for a humanoid robot in MPa [33]

With topology optimization in additive manufacturing, components can be designed with intricate internal structures, such as lattice or honeycomb patterns, which support strength while reducing overall weight. This approach uses Finite Element method analysis to simulate part behaviour, and an algorithm minimizes material in low stress region [33]. This light weighing capability has numerous benefits, including improved energy efficiency, reduced material consumption, and enhanced performance in industries such as aerospace, automotive, and healthcare [34].

Furthermore, lightweight designs in additive manufacturing play a crucial role in reducing CO_2 emissions across a product's life cycle. In aviation industry weight reduction leads to significant energy efficiency improvements during the usage phase. Gebler et al. (2014) concluded that compared to conventional manufacturing methods, around 25% of the total CO_2 reduction comes from the manufacturing phase with additive manufacturing. Most emissions reductions occur during the product's operational life [34]. Lightweight designs enabled reduce fuel consumption, leading to greater energy efficiency and lower emissions over time. With AM technologies, a fuel nozzle for the leap jet engine with intricate structure manufactured as a single unit avoids the need for energy-intensive multiple part welding [35].

Moreover, automotive industry is using additive manufacturing techniques to produce parts with lower wear rate, less weight, less volume and higher stiffness leading to reduced power consumption. Aerospace and automotive industries use the AM manufactured prototypes to understand the aerodynamics of the design. This makes the product development cycle shorter and best design can be used for better energy efficiency, power density and resource efficiency [31].

3.4. Local manufacturing and on-demand production

Local manufacturing refers to the ability to produce goods closer to the point of consumption, dropping the need for long-distance transportation and reducing associated costs and environmental impacts. Additive manufacturing facilitates local manufacturing by enabling the production of products on-site or in proximity to the end-users. This decentralized approach reduces supply chain complexities and transportation requirements, leading to shorter lead times and increased flexibility in meeting customer demands [36]. Rinaldi et al. 2021 performed a study on the supply chain structures of Traditional Manufacturing (TM), AM centralized, and AM decentralized [37]. Based on the study a stimulation was proposed model to compare the aspects like supply chain lead time, total holding cost, total transport cost, capacity utilization and number of machines. Results for holding cost and transport cost shown in figure 5 shows decentralized supply chain structure for additive manufacturing is more economical and environment friendly compared to other two structures.

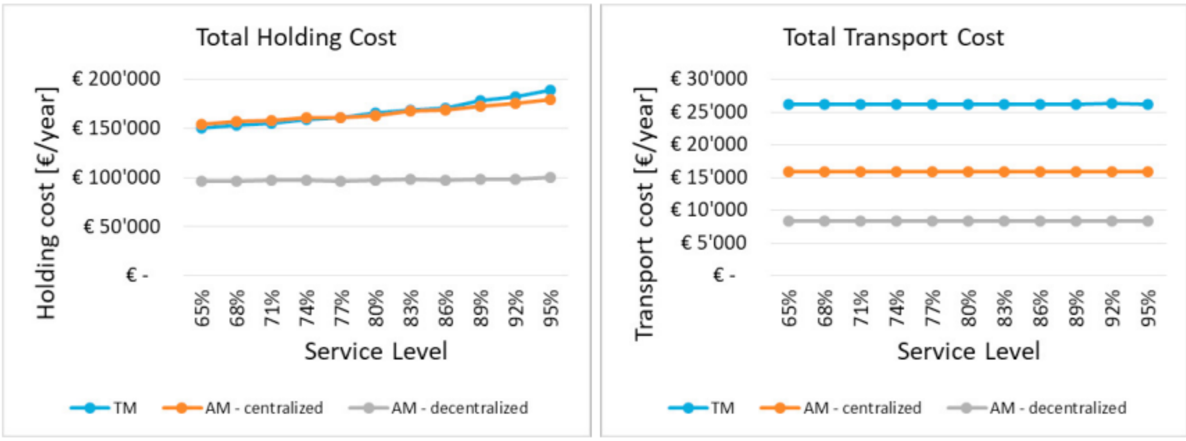

Figure 10. Comparison of Total holding cost and Total transport cost for three different supply chain structures [37]

On-demand production is another key benefit of additive manufacturing. Traditional manufacturing often relies on mass production and inventory storage, resulting in excess stock, waste, and high carrying costs. With additive manufacturing, products can be produced as needed, dropping the need for large inventories. This on-demand production model offers several advantages, including reduced inventory waste, lower storage costs, and the ability to quickly respond to changing market demands [38]. Chauhan et al., (2025) proposed AM-enabled supply chain model in which on-demand production plays a key role in reducing the energy expenses and consumption [39].

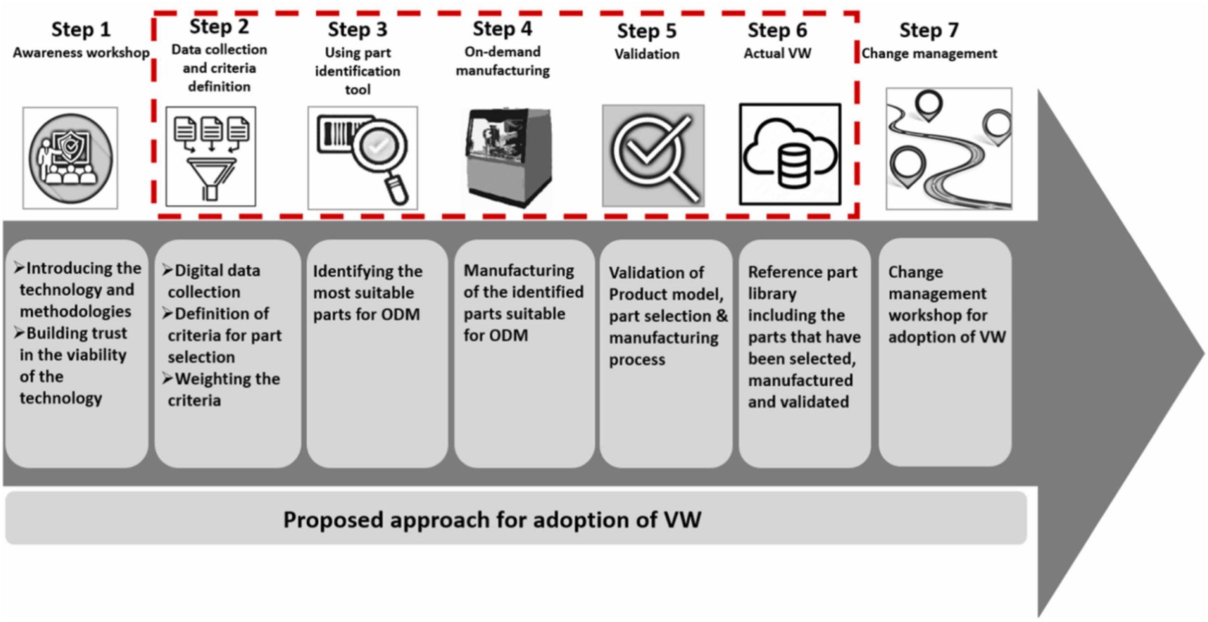

Figure 11. Virtual Warehousing proposed approach by to achieve on-demand production [40]

By combining local manufacturing and on-demand production, additive manufacturing enables a more agile and efficient manufacturing ecosystem. It allows customization, personalization, and the production of spare parts on-demand. This approach not only reduces waste but also improves resource efficiency, as materials are used more precisely, reducing overall material consumption.

Overall, additive manufacturing's capability for local manufacturing and on-demand production contributes to more sustainable and responsive manufacturing practices, leading to reduced costs, minimized waste, and increased customer satisfaction.

3.5. Recyclability and circular economy

AM offers opportunities for advancing the principles of the circular economy. The ability to reuse or recycle materials in AM processes can minimize waste and enhance resource efficiency. For instance, powders used in metal AM can be reclaimed and reused, reducing material waste and the need for virgin resources. Moreover, AM can facilitate the repair and refurbishment of components, extending their lifespan and reducing overall waste generation.

Recyclability in additive manufacturing involves the ability to recover and reuse materials, components, or products at the end of their lifecycle. This includes recycling of unused or excess material, the possibility of reprocessing printed parts, and the incorporation of recycled materials into the AM process [41].

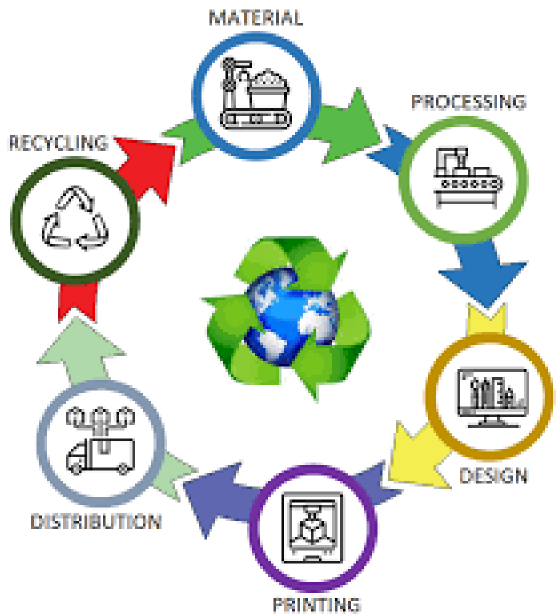

Figure 12. Circular Economy [42]

Selecting recyclable or biodegradable materials for AM manufacturing process is an important step. Also, implementing methods for revamping used powders or materials can help maintain their quality and enable their reuse, reduces waste generation [43]. Designing of the products with AM-specific considerations, such as modular or components which are easy to dissemble, facilitates easier material separation for recovering purposes. Design optimization techniques can also minimize material waste during the 3D-printing process [34].

3.6. Low energy consumption

Low energy consumption is an important aspect for sustainable manufacturing, including additive manufacturing (AM). Energy efficiency in additive manufacturing involves reducing the energy consumption associated with the entire manufacturing process, including preparation of material, printing, post-processing, and outside operation. This can be achieved through different strategies such as optimizing process parameters, improving equipment design, utilizing energy-efficient materials, and enforcing energy management systems [44].

By fine-tuning parameters such as layer thickness, printing speed, and laser power, it is possible to reduce energy consumption while maintaining product quality and integrity. Process simulation and modelling techniques can aid in identifying the optimal parameter settings [45]. The choice of materials in additive manufacturing can impact energy consumption. Selecting materials with lower energy requirements for processing and considering their recyclability or reusability can contribute to energy savings [46]. Chen et al., (2025) modified the surface of copper powder with from smooth to rough surface with Molybdenum particles via ball milling. This resulted in better laser energy absorption by material and improved energy efficiency in Laser based additive manufacturing technologies [47].

Designing energy-efficient AM equipment and optimizing facility layouts can contribute to reducing energy consumption. This includes utilizing energy-efficient components, implementing waste heat recovery systems, and optimizing the overall energy management of the manufacturing facility [48].

4. ENERGY EFFICIENCY AND ENVIRONMENTAL PERFORMANCE OF AM VERSUS CONVENTIONAL MANUFACTURING

A comparative analysis is needed to assess the energy and environmental impacts of AM and traditional manufacturing. By studying the existing literature, these two-manufacturing process can be evaluated by exploring and analysing the assessment methods and frameworks. The assessment can be based upon Life Cycle Assessment (LCA), process level energy and emissions analysis, supply chain and logistic analysis, multi-criteria decision analysis, case studies and applications-based research.

Life Cycle Assessment (LCA)
LCA is employed to evaluate the environmental impacts of different manufacturing processes, aiming to identify potential reductions in environmental burdens within the manufacturing industry.

Pusateri and Olsen (2024) conducted a study using a combination of LCA and Life cycle costing (LCC) to compare energy consumption, material utilization and environmental impacts between Wire Arc Additive manufacturing (WAAM) and conventional manufacturing methods [49]. Their results demonstrated a potential overall impact reduction of up to 54% with WAAM. Another study by Kokare et al. (2023) emphasized the importance of LCA in recognizing specific environmental impacts during various manufacturing stages, highlighting that AM can be more environmentally friendly than conventional methods due to better material utilization and lower material consumption, despite potentially higher energy consumption in some cases [50]. LCA performed by Ehmsen et al., (2025) provides a detailed and clear insights about the environmental impacts of powder production with gas atomization process and showed that the use of inert gas is the prime factor on environmental impact [51]. Such analysis helps to identify the opportunities to reduce the negative impact on sustainability.

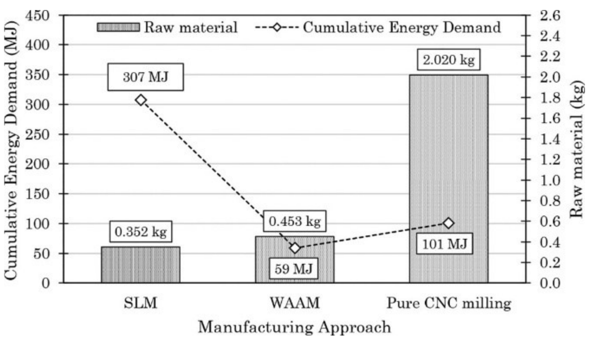

Figure 1. Comparison of energy demand and material usage across CNC, selective laser melting (SLM) and WAAM [50]

4.1. Process-level energy and emissions analysis

The process-level energy and emissions analysis compare the energy consumption and emissions associated with each stage of the manufacturing processes. Pusateri and Olsen (2024) collected process-level energy data for WAAM and conventional manufacturing methods, evaluating parameters such as material utilization, deposition rate and electricity use [49]. According to the study, WAAM has potential to drastically cut energy usage because it uses less material and electricity during manufacture. Such analysis helps to identify hotspots and inefficiencies of the manufacturing processes, showing how well WAAM performs in terms of resource efficiency and sustainability performance compared to conventional methods.

4.2. Supply chains and logistic analysis

The supply chain and logistics study help to look at how the industrial process's material transportation and logistics affect the environment. Considerations include material selection, transportation methods and logistical efficiency. In comparing AM to traditional manufacturing, Santiego-Herrera et al., (2024) noted that AM's ability to use less energy and resources might result in more effective supply chains and logistical systems [52]. This research underscores how crucial it is to improve logistical efficiency and material selection to enhance the overall sustainability of manufacturing operations.

4.3. Multi-criteria decision analysis

In multi-criteria decision analysis, manufacturing processes are evaluated according to a range of factors such as environmental impact, economic cost and social implications. The necessity of comprehensive sustainability evaluation that considers the social, economic and environmental aspects of AM processes was emphasized by [53]. By adopting a triple-bottom-line approach, stakeholders may make better judgements about the sustainability of various production techniques. This thorough assessment assists in determining the most environmentally friendly manufacturing solutions by balancing the benefits to the economy, society and environment.

4.4. Case studies and applications-based research

A comparative analysis was conducted by Pusateri and Olsen (2024), for two products- an injection moulding tool for optical fibre casings and a forging dye for automotive parts. The study demonstrated the potentials of WAAM above conventional techniques by showing notable reductions in environmental consequences [49]. Similar to this, Santiego-Herrera et al., (2024) investigated how AM technology affected the environment in comparison to traditional methods and found that well-optimized AM operations may cut emissions by as much as 94% [52]. These case studies provide the practical advantages and disadvantages of using AM technologies, offering valuable direction for future research and industrial applications.

Y. Wang et al., 2020 highlighten that high energy consumption of SLM process is most responsible for the environmental impact associated with SLM production [54].Analysis performed by Kokare et al., (2023) depicts selective laser melting (SLM) is the least energy efficient compared to pure CNC milling and wire arc additive manufacturing (WAAM) [50]. Energy demand of SLM was found to be 307 MJ, which is nearly five times higher than WAAM (59 MJ) and three times higher than pure CNC milling (101 MJ). Guarino et al., 2020 emphasizes that SLM uses a lot more energy than laser cutting, with a requirement of around 235.3 MJ, whereas laser cutting uses just 40.55 MJ [55].

5. CONCLUSION

AM emerges as a transformative force in advancing sustainability within the manufacturing sector. This review has shown that AM offers clear advantages over traditional method, particularly in reducing material waste, enabling lightweight and complex designs, and supporting localized, on-demand production. These advantages not only improve energy efficiency but also help conserve resources and improve overall product performance in industries like aerospace, automotive and healthcare. AM supports a more flexible and responsive manufacturing ecosystem. It contributes to lower emissions and more efficient supply chains by minimizing transportation and inventory needs. Its compatibility with circular economy principles and potential for using recycled or renewable materials further supports its role in sustainability. Some processes remain energy intensive shows AM is not without challenges. There is still work to be done in improving system efficiency, expanding material options and integrating renewable energy into production. Continued research and innovation will allow manufacturing industry to take benefits of AM's full potential. In short AM is not a complete solution, but it offers a promising path toward shaping a more sustainable industrial future.

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