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REVIEW ARTICLE

Additive manufacturing in the energy sector and the fourth industrial revolution

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Abstract

The advent of additive manufacturing, commonly known as 3D printing has opened new avenues for innovation in various industries, including the energy sector. This review focuses on the application of additive manufacturing in the energy sector and its determining parameters, stressing the new opportunities, and challenges the fourth industrial revolution (4IR) presents. The applications of additive manufacturing in producing on-demand components, spare parts, and optimized designs for improved energy efficiency are explored. Additive manufacturing's ability to reduce costs and time for energy machines and components to enhance efficiency will be crucial for renewable energy sources. A comprehensive analysis of previous studies was conducted to investigate the influence of additive manufacturing in various sectors. Findings from this review could facilitate an accelerated adoption of additive manufacturing in expanding the energy sector.

Keywords Additive manufacturing · Energy efficiency · Fourth industrial revolution · 3D printing

1 Introduction

The Fourth Industrial Revolution (4IR), characterized by the fusion of digital, biological, and physical innovations, is profoundly transforming industries, including the energy sector. Additive manufacturing (AM) or 3D printing, stands at the forefront of this revolution, offering transformative potential for designing, prototyping, and manufacturing. It has been progressively transforming various industries by enabling more flexible, cost-effective, and innovative production methods. This technology enables layer-by-layer construction of objects from digital models, providing unparalleled flexibility and efficiency in manufacturing processes. AM is a transformative technology driving innovations across various sectors including engineering, manufacturing, art, education, and medicine [1, 2]. Aerospace, automotive, and healthcare industries are at the forefront of adopting AM technologies. It is reported that the global market for AM in the energy sector is projected to grow from approximately $1.5 billion in 2020 to over $4 billion by 2025, with a compound annual growth rate (CAGR) of around 17% [3, 4].

AM involves various techniques such as stereolithography (SLA), selective laser sintering (SLS), and fused deposition modeling (FDM), each suitable for different materials and applications within the energy sector. AM printing has shown significant potential and growth in the energy sector. In wind energy, AM printing has been used to produce turbine blades with complex geometries that are lighter, yet durable, leading to an increase in energy efficiency by up to 10–15%. AM-printed solar panel components have been reported to reduce material costs by up to 25%, making

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solar energy systems more affordable and accessible. AM allows for the customization of parts on a per-project basis without additional costs, making the technology particularly beneficial for small-scale, bespoke renewable energy solutions [5, 6]. The flexibility of AM allows for the production of complex geometries that are otherwise challenging or impossible to achieve with traditional manufacturing methods [7, 8]. The ability of AM to accelerate the development and production of prototypes and functional parts reduces the time-to-market for new technological innovations in the energy sector by up to 50%. With advancements in AM technologies, materials used in energy applications now include high-performance polymers, metals, and composites, each providing unique properties such as heat resistance, mechanical strength, or corrosion resistance.

Extensive research has highlighted the advantages of AM in reducing waste, decreasing production time, and allowing for the customization of designs in real-time. Studies like those by Jones et al. [9] have demonstrated how AM can reduce the cost of producing wind turbine blades by up to 40%, presenting significant economic benefits. Despite these advancements, there remains a substantial gap in comprehensive studies that integrate AM with renewable energy applications, particularly in understanding its scalability for large components like wind turbine blades and solar panel infrastructures [10, 11]. Additionally, manufacturing advanced materials that can withstand the harsh environments of various energy setups is a current research need.

While previous reviews have primarily focused on the technical applications of additive manufacturing within specific subdomains of the energy sector, this review stands apart by integrating these insights within the broader context of the Fourth Industrial Revolution (4IR). By doing so, it provides a holistic view of AM's role not just as a manufacturing technology but as an integral part of the digital transformation occurring within the energy industry. The review examines how additive manufacturing complements emerging technologies like artificial intelligence, big data analytics, and the Internet of Things (IoT) within the energy sector. This perspective on AM's role in the 4IR ecosystem is often overlooked in previous reviews. While past studies have examined AM's impact on traditional energy sectors, this review emphasizes its potential for renewable energy by improving the efficiency, customization, and cost-effectiveness of components for solar, wind, and other clean energy technologies. The review does not only discuss the benefits of AM but also provides a critical analysis of the challenges that come with integrating AM in a 4IR-driven environment, such as cybersecurity, intellectual property concerns, and technological standardization, which have received less attention in previous reviews. Building on the comprehensive analysis of existing literature, this review proposes a framework for accelerating AM adoption in the energy sector. This framework includes practical insights into policy-making, industrial collaboration, and the role of government and private sector partnerships in fostering AM innovation. This review brings together the technical aspects of AM, the transformative potential of 4IR, and the strategic considerations for widespread adoption in the energy sector, thereby providing a fresh and unique perspective not extensively covered in prior literature.

This study aims to bridge these gaps by exploring the application of AM for large-scale renewable energy projects. By extension, assessing the material science innovations that enhance the durability and efficiency of 3D-printed energy components. The study also seeks to evaluate the integration of the Internet of Things (IoT) and Artificial Intelligence (AI) with AM processes to enhance the functionality and performance monitoring of energy systems. By filling these research gaps, this study contributes to a deeper understanding of AM's role in advancing the energy sector's efficiency and sustainability during the 4IR.

2 Methodology

The primary objective of this review is to analyze the current state, emerging trends, and prospects of additive manufacturing (AM) in the energy sector, particularly within the context of the 4IR. The review seeks to identify how AM technologies are being integrated into energy applications, the benefits they provide, and the challenges they face. Articles reviewed were published from 2015 onwards, focusing on the use of AM in energy applications. Articles discussing technological innovations, case studies, economic impacts, or policy implications of AM in the energy sector were considered. However, non-peer-reviewed articles, such as blog posts or news articles were excluded, including papers not written in English. Also, studies focusing solely on AM outside the context of energy applications were excluded. Searches were conducted in PubMed, Scopus, IEEE Xplore, and the Web of Science. Keywords and phrases like "additive manufacturing", "3D printing in energy applications", "renewable energy", and "Fourth Industrial Revolution" were used. The search strategy also involved a combination of keywords related to additive manufacturing and the energy sector: ("additive manufacturing" OR "3D printing") AND ("energy sector" OR "renewable energy") AND "Fourth Industrial Revolution". Authors independently screen titles and abstracts for eligibility, followed by full-text reviews of selected articles. Discrepancies were resolved through discussion or consultation among authors. Data were synthesized to highlight patterns, themes, and gaps in the literature. This study systematically consolidates existing research to provide a comprehensive overview of how AM is revolutionizing the energy sector under the umbrella of the 4IR, highlighting achievements and areas that need further exploration.

2.1 Additive manufacturing

Additive manufacturing (AM) represents a transformative approach to industrial production that enables the creation of lighter, stronger parts and systems. AM has been around but only started gaining ground (Fig. 1). AM process involves building items from the bottom up, layer by layer, and is distinctly different from traditional subtractive manufacturing methods Fu and Kaewunruen [12], [13]. The transformative nature of AM reduces costs, increases efficiency, and allows for innovation in design and material use that was impossible with traditional manufacturing methods. Additionally, it fosters sustainability by minimizing waste and energy use. This shift has significant implications for global supply chains, potentially reducing the need for large inventories as goods can be printed on demand close to the end-user. Figure 2 shows a plot of the market share of the application of AM.

AM is a rapidly evolving technology with vast potential across the aerospace, automotive, healthcare industries, and beyond. Approximately 60% of aerospace manufacturing companies are utilizing 3D printing technologies [14]. AM is being increasingly used in the aerospace and automotive industries for producing intricate components with advanced materials like aluminum alloys, titanium, and carbon nanofiber-reinforced composites [15–17]. These materials offer enhanced properties such as strength, lightness, and durability, making them ideal for critical applications in aerospace and automotive manufacturing [18, 19]. In the healthcare sector, AM is driving innovations in tissue engineering and bioprinting, offering new possibilities for creating customized implants, prosthetics, and even organs [1, 2]. The use of AM in healthcare is paving the way for personalized medicine and advanced clinical applications [1].

A study by the Department of Energy highlighted that AM could reduce energy use by up to 50% in manufacturing due to more efficient material usage and production processes [20]. AM customization capabilities without additional production costs are valuable in medical and dental applications where custom-fit devices are essential. Over 100,000 hip replacements have been manufactured using AM technologies, showcasing the impact in the medical field [5]. Furthermore, AM can enhance production speed by up to 300% compared to traditional methods, advantageous for the rapid prototyping of new products [12]. Moreover, the affordability of this technology is rapidly increasing, with 3D printers now available for as little as 250 USD for filament-based printers and 300 USD for resin-based ones. Additionally, the range of materials for 3D printing has expanded significantly, encompassing metals, polymers, rubber, resins, ceramics, cement, and more. AM encompasses a range of techniques that offer unique capabilities. In 2010, the International Organization for Standards differentiated AM into seven types as shown in Fig. 3.

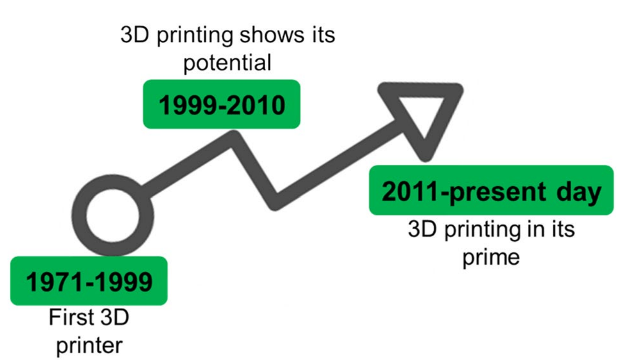

Fig. 1 History of 3D printing

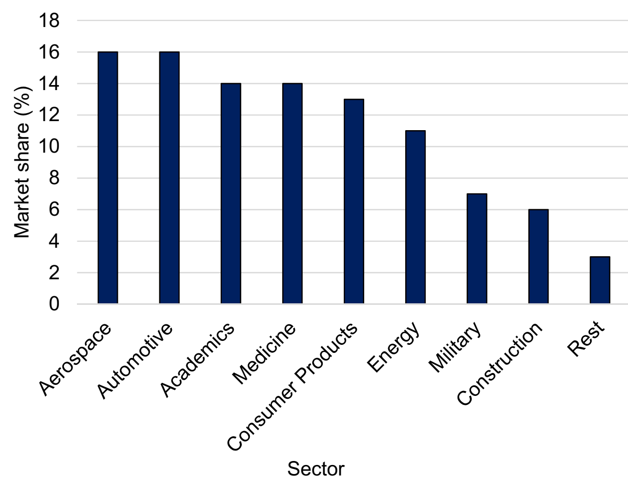

Fig. 2 A plot of the market share of the application of AM in various sectors

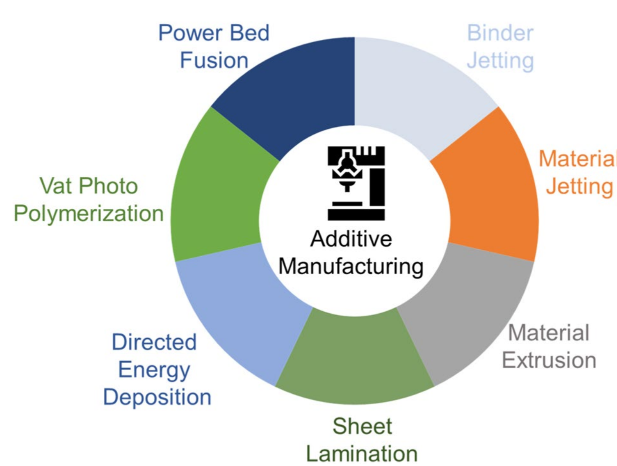

Fig. 3 Types of AM techniques

Powder bed fusion, fused filament fabrication (FFF), and metal additive manufacturing (MAM) methods like wire-arc additive, selective laser sintering, selective laser melting, electron beam melting, and laser-engineered net shaping are notable processes in AM [21–23]. MAM techniques, including ultrasonic additive manufacturing (UAM), friction stir additive manufacturing (FSAM), and friction-forging tubular additive manufacturing (FFTAM), have shown promise in producing parts with high accuracy and controlled porosity for applications like osseointegration in medical implants [24]. These methods also facilitate the creation of functionally graded materials, enhancing their utility across industries [25]. Moreover, AM techniques like wire arc additive manufacturing and fused deposition modeling are gaining prominence due to their scalability, cost-efficiency, and a wider range of material processability, especially in producing polymer-based materials [26, 27]. These techniques enable the creation of high-performance parts with improved mechanical properties and structural integrity [28, 29]. The integration of AM with traditional machining processes, known as hybrid manufacturing, is gaining traction for efficiently fabricating intricate components [30]. Post-processing methods play a crucial role in improving the surface finish of products manufactured through AM, further enhancing the quality of the final parts [31] as shown in Fig. 4. Additionally, the technology's flexibility allows for problem-specific production of parts, making it a versatile choice for various applications [30].

2.1.1 Merit and opportunities of additive manufacturing types

Additive manufacturing (AM) is gaining global acceptance due to its distinct benefits. Binder jetting, a key AM technique, minimizes dimensional distortion by operating at room temperature and offers one of the largest build volumes, up to 1.6 m^3. Although commonly used for sand-casting molds, metal and polymer binder jetting is limited to smaller build volumes (~ 0.3 m^3) with 100 µm layer heights. Metal binder jetting has been analyzed for process and material parameters, highlighting factors that impact results in both research and industrial applications.

Material jetting, similar to inkjet printing, deposits materials like polymers and waxes, solidifying them with ultraviolet light. Known for precision and accuracy, it can achieve 0.013 mm layers with a dimensional accuracy of ± 0.1% and a 14-micron resolution. Material jetting's multi-material capabilities are valuable for creating realistic prototypes, as shown in recent studies. Gulcan et al. [32] reviewed its efficiency in producing varied parts quickly, while Jabari et al. 2020 explored high-speed, electrically conductive 3D jetting using graphene-based ink.

Ultrasonic consolidation (UC) and laminated object manufacturing (LOM) are examples of sheet lamination methods. This method is cost-effective for non-functional prototypes, casting molds, and composites. It allows adaptable material to be used in builds, fitting applications requiring fast, manageable 3D printing. Sheet lamination is one of four primary AM metal methods, alongside binder jetting, direct energy deposition, and powder bed fusion, offering an economical approach for simple or composite parts.

Direct Energy Deposition (DED) entails delivering a feedstock substance in either powder or wire form, while simultaneously directing an energy source (such as an electron beam, laser beam, electric arc, or plasma) onto it, as illustrated in Fig. 5. DED is primarily used for fabricating metal components but can also be applied to polymer and ceramic components. It finds applications in various materials, including alloys, carbide-based and oxide ceramics, and high-temperature nitride-based and boride-based ceramics. DED is also utilized for producing small-sized or hard coatings on bulk ceramic components.

There are several printing techniques achievable with powder bed fusion (PBF), including selective laser melting (SLM), direct metal laser sintering (DMLS), selective heat sintering (SHS), selective laser sintering (SLS), and electron beam melting (EBM). SLS and DMLS are similar, but DMLS uses metals alone not plastic. SHS differs from

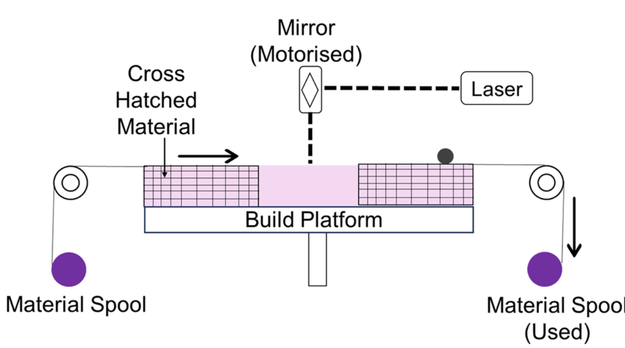

Fig. 4 The sheet lamination technique

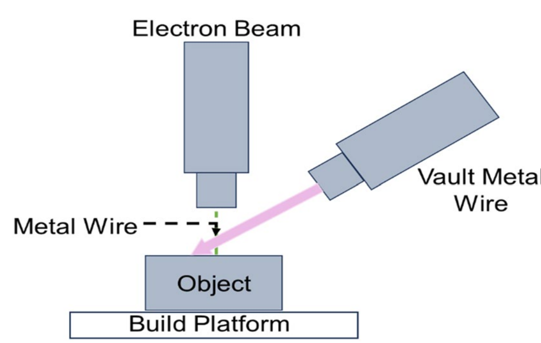

Fig. 5 Direct energy deposition schematic

other PBF techniques in that the thermal print head needs heating. A vacuum is needed and often used with alloys and metals in EBM. The powder bed fusion process involves spreading about 0.1 mm thick powder on the build platform shown in Fig. 6.

Powder Bed Fusion (PBF) offers several benefits, including cost-effectiveness, versatility with visual and prototype applications, and compatibility with a range of materials, utilizing powder for integrated support. However, it has drawbacks: PBF is energy-intensive, and issues like powder grain size, slow build speed, and limited product dimensions can impact outcomes. Narasimha Raju et al. [33] reviewed the laser PBF of steels, examining processing methods, microstructure, defects, control techniques, and mechanical properties, as well as current challenges and future trends. [34] and Chowdhury et al. [35] have also contributed detailed reviews, discussing the properties, materials, and numerical modeling for laser PBF.

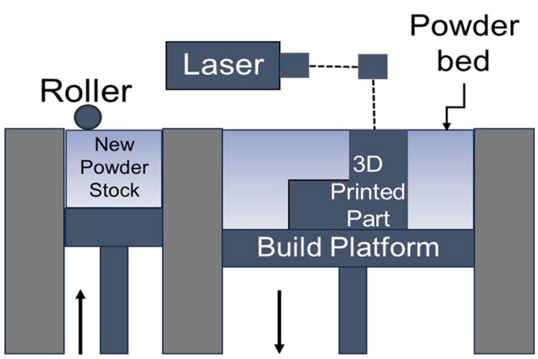

Fig. 6 A schematic of the powder bed fusion (PBF)

Vat photopolymerization is used in the jewelry industry where an exquisite finish with a smooth finish is required. The process is fast, precise, accurate, and of fine quality although it is expensive, warping, not strong, and durable. The first patented AM process called stereolithography is a Vat photopolymerization technique. The other types of Vat photopolymerization are digital light processing (DLP) and continuous digital light processing (CDLP). DLP is faster than stereolithography (SLA) since DLP layers are exposed at once.

Metal 3D printing material is available in different formats to accommodate various metal 3D printing procedures. Powder, wire, and filament are the most frequent. Metal 3D printing resin and metal sheets for lamination-based 3D printers are also available as shown in Fig. 7. In addition, AM can be categorized according to the state of the material utilized for the processing, including solid material processing, liquid material processing, and powder material processing, as depicted in Fig. 8. Figure 9 presents the classification of materials used for 3D printing. The 17 types of filaments used in 3D printing are summarized in Table 1. Table 2 presents a compilation of the different metals employed in 3D printing, their distinct properties, applications, and the specific type of 3D printing utilized for each material. Figure 10 displays a distribution of metal 3D printers. Powder bed fusion has a huge 54% with binder jetting coming next with 16%. DED, material extrusion, and sheet lamination followed behind. A summarized description

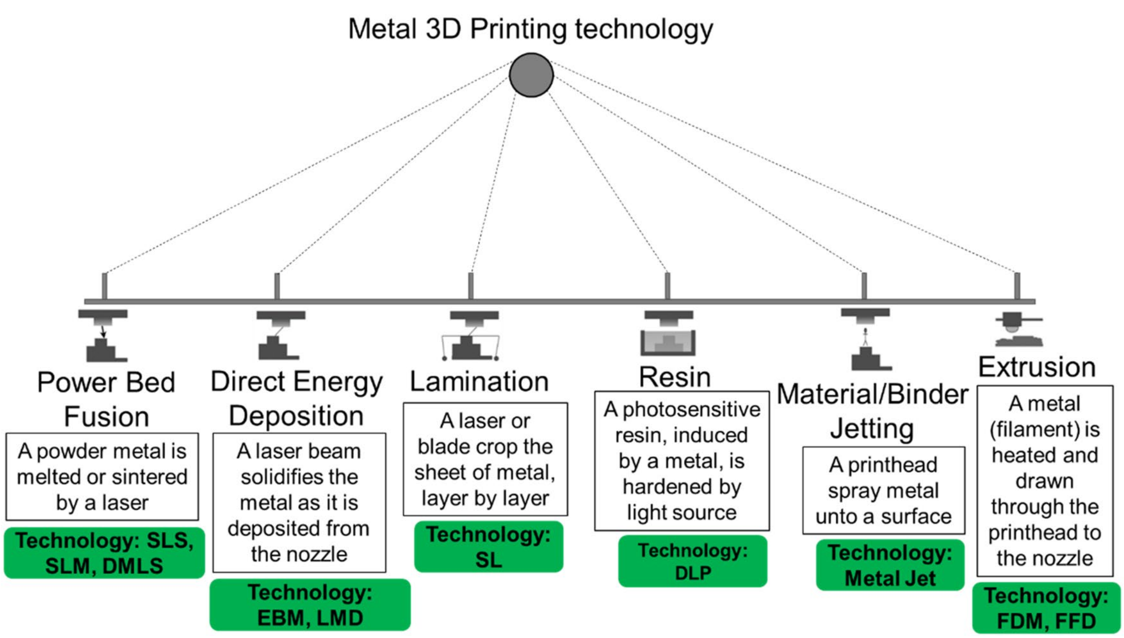

Fig. 7 Summary of metal 3D printing technology

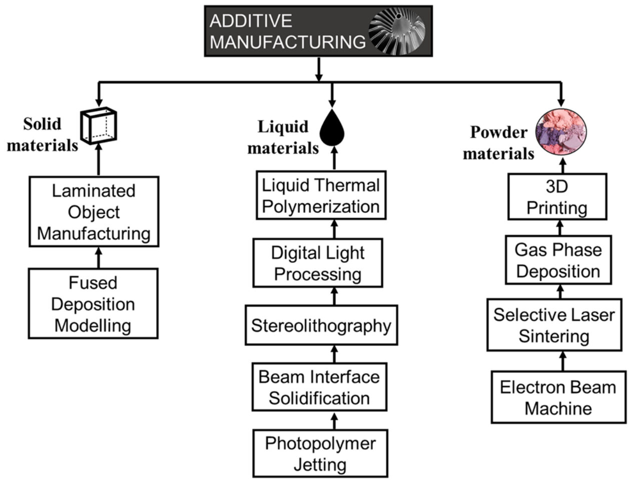

Fig. 8 Classification of AM based on material processing technique

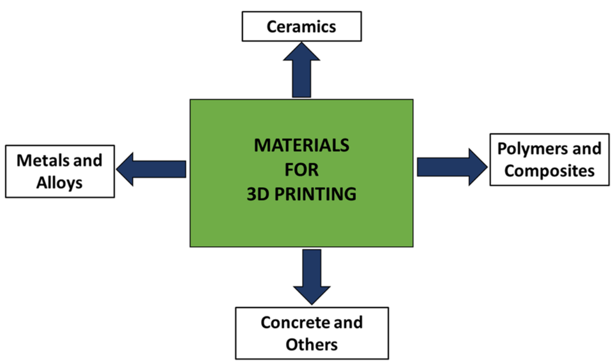

Fig. 9 Classification of materials used for 3D printing

of the top-performing ceramic 3D printers with their manufacturers, technology used, pricing, and cost of origin is shown in Table 3.

2.1.2 Case studies showing the impact of AM on cost, efficiency, and performance improvements

One notable case study is GE Renewable Energy's collaboration with Oak Ridge National Laboratory, where AM was used to produce blade molds [36]. This reduced mold manufacturing time by up to 35%, significantly cutting costs and improving the production speed of large-scale blades [37]. Additionally, AM allows for customized blade designs that are optimized for different wind conditions, leading to performance gains in energy efficiency. Another example is the Sandia National Laboratories' development of 3D-printed blade structures with complex internal geometries that reduce weight while maintaining strength [38]. This enables the production of longer blades, which capture more wind energy and result in a substantial boost in overall turbine efficiency.

A leading case study involves the use of AM by SunPower Corporation, which employed 3D-printed connectors and interconnects in its solar modules [39]. This innovation not only reduced material waste but also improved energy capture efficiency by 20% due to the enhanced precision in the placement of photovoltaic cells. Additionally, Heliatek has explored AM to produce organic solar films, a flexible and lightweight alternative to traditional panels [40]. Their use of AM has demonstrated a 30% reduction in production costs while improving the efficiency of solar energy conversion for flexible and portable applications [41]. These case studies will illustrate the tangible benefits of AM in terms of cost reduction, improved production speed, and enhanced performance for both wind turbine blades and solar panels. Incorporating these real-world examples will further strengthen the manuscript's discussion of the transformative impact of additive manufacturing in the energy sector.

2.1.3 Limitations of additive manufacturing in the energy sector

Additive Manufacturing (AM), while transformative, faces notable challenges in the energy sector, especially concerning scalability, material durability, and costs in large-scale renewable projects. Scalability is limited by slower production speeds compared to traditional methods like CNC machining, which can mass-produce parts more efficiently. Material durability is also a concern, as some 3D-printed materials lack the long-term resilience required for energy infrastructure, such as wind turbines or solar power systems, where harsh environmental conditions demand high-strength, wear-resistant materials. Additionally, AM's cost structure can become prohibitive for large-scale applications due to the expensive raw materials and equipment involved. In contrast, CNC machining offers a more established solution for producing robust, durable components at scale, though with greater material wastage. For example, Siemens has implemented AM for turbine blade repair, enhancing efficiency and reducing waste, but CNC is still preferred for mass production of large components in offshore wind farms due to its precision and cost-effectiveness over long runs [42].

2.2 Additive manufacturing in energy applications

Energy plays a vital role in human life, particularly in the context of the 4th Industrial Revolution (4IR) realization. It can be classified into two main categories: renewable and fossil-based energy sources. There is a growing emphasis on transitioning towards clean energy to mitigate greenhouse gas emissions. This has led to an increased focus on

Table 1 Different types of filaments and key features

Filament	Properties	Strength	Uses	Density	Durability	Flexibility	Print temperature (^{o}C)	Printing bed temperature	Cost (USD)
ABS	Durable, tough, impact resistant, lightweight easy to extrude	Medium	Functional parts by professionals and amateurs	1010	High	Medium	210–250 (high)	50–100	20 for 1.75 mm, 1 kg spool
Polyethylene Terephthalate (PET)	Durable, more flexible than ABS or PLA	Medium	All	1270	High	High	210–230 (high)	Not needed	24.99 for 1.75 mm, 1 kg spool
Polylactic Acid (PLA)	Biodegradable in some environments, easy to extrude	Medium	Consumer products	1240	Medium	Low	180–230	Not needed	24.99 for 1.75 mm, 1 kg spool
PEI	Strong, heat-resistant	High	Functional parts	1270	High	Medium	340–380	180–200	
PC-ABS	Durable, rigid, resilient, impact resistant, and deflecting heat	Medium	Functional parts		High	Low	260–280	120	
Wax	melts away	Low	Lost wax casting for patternmaking	–	Low	Low	170–180	Not needed	–
Nylon	Strong, flexible durable	High	All	1020	High	High	215–260	50–100	39.99 for 1.75 mm, 1 kg spool
PVA	Water soluble, biodegradable, dissolvable, oil resistant	High	When using PLA or ABS, support structure on a dual extrusion printer	–	Medium	Low	180–230	Not needed	35.99 for 1.75 mm, 0.5 kg spool
Lignin (bioFila)	Stronger than PLA, and biodegradable	Medium	–	–	Medium	Low	190–225	55	–
PP	Chemical resistance, flexible	Medium	Flexible parts	1040	Medium	High	210–230	120–150	
Polycarbonate	Flexible, transparent, durable, very strong, heat resistant	High	Functional parts	1180–1200	High	High	270–310	90–105	
ASA	Weather resistant, rigid, durable	Medium	Outdoor	–	High	Low	240–260	100–120	
PMMA, Acrylic	Transparent, durable, impact resistant, rigid	Medium	Light diffusers	–	High	Low	235–250	100–120	
Dark glowing plastic	Phosphorescence	Medium	Fun, entertainment		Medium	Medium	180–240	Not needed	18 for 1.75 mm, 1 kg spool
POM, acetal	Resilient, slow friction, rigid	High	Functional parts		Medium	Low	210–225	130	
Wood	Wood-like finish	Medium	Home decoration	1400	Medium	Medium	195–260	Not needed	30 for 1.75 mm, 1 kg spool

Table 1 (continued)

Filament	Properties	Strength	Uses	Density	Durability	Flexibility	Print temperature (°C)	Printing bed temperature	Cost (USD)
TPE/TPU	Rubber-like (extremely flexible)	Low	Elastic parts, wearable	–	Medium	High	225–235	40 for TPE, not needed for TPU	32 for 1.75 mm, 1 kg spool
Sandstone (PLA + Brick) aka LayBrick	Stone-like color and texture (smooth, rough, and in-between)	Low	Architecture	–	Low	Low	165–210	Not needed	32 for 1.75 mm, 0.25 kg spool

renewable energy sources. Some examples of renewable energy sources include hydroelectric power, solar energy, wind power, geothermal energy, and ocean currents. Research has shown that innovation in the energy sector, particularly renewable innovation, has a significant impact on energy intensity. Therefore, the renewable energy sector stands to benefit significantly from the research and implementation of additive manufacturing (AM) for several reasons. AM enables the production of custom-made parts, facilitating the repair and replication of complex components or machinery. The design flexibility offered by AM allows for innovative solutions in energy-related applications. Furthermore, the technology allows for scalable and improved component testing and evaluation, leading to enhanced efficiency and performance in the energy sector.

AM plays a pivotal role in transforming various energy industry sectors, from oil and gas to renewable energy sources such as wind and solar power [43, 44]. The global market for AM in the energy sector is projected to experience significant growth, with estimates indicating an annual increase of over 25%, reaching $600 million by 2025 [45]. Specifically, in wind energy, the utilization of 3D printing technology has the potential to reduce the cost of manufacturing turbine blades by up to 40% [46]. This cost reduction is attributed to the adaptability of AM in quickly customizing models to suit specific requirements [47]. Furthermore, the application of AM in building integrated photovoltaics (BIPV) is expected to result in a notable 50% reduction in material costs within the next decade [48]. This cost reduction is anticipated to be driven by the advantages offered by AM technology, such as mass customization, waste reduction, and faster time-to-market [48]. The adoption of AM in the energy sector, particularly in wind turbine blade manufacturing, is gaining momentum due to its ability to provide design optimization and material advancements tailored for this specific application [46]. Developing AM technology for wind turbines is a promising approach to enhancing electric power generation efficiency [49]. The integration of AM in the energy industry, especially in wind energy and BIPV, is poised to transform manufacturing processes, leading to cost savings, improved efficiency, and innovative design possibilities.

The ability of AM technology to produce complex geometries with high precision and speed makes it especially suitable for the demands of energy sector applications, including rapid prototyping, the manufacture of spare parts, and production components. For example, in the wind energy sector, AM is used to prototype parts such as turbine blades and components of the nacelle. The speed of innovation plays a critical role in advancing new technologies in the energy sector. Hence, AM has emerged as a key enabler in accelerating the developmental process by facilitating rapid prototyping of novel energy device designs. This capability

Table 2 Summary of the different metals used as filaments in 3D printing

Name of metal	Property	Application	Printing method
Stainless steel (316L)	Excellent corrosion resistance	Water, steam, etc	DMLS, PBF, SLM
Bronze	Aesthetics	Pump impellers and marine propellers, fittings, vase	DMLS
Nickel and alloy	Durability	Turbine engine, coins	SLS, PBF
Aluminum and alloy	Lightness	Aircraft parts	SLM, PBF
Titanium (mainly Ti-6Al-4 V)	Precision, high performance, lightweight, and robustness	Medical implants, aerospace, etc	SLM, EBM, PBF
Gold	Aesthetics	Jewelry	PBF
Cobalt	Lightweight	Defense and aviation	EBM
Steel (austenitic stainless steel, maraging, tool, and precipitation hardenable stainless steel)	Corrosion resistance, ductility	Simple to complex parts	DMLS, Powder Bed Fusion

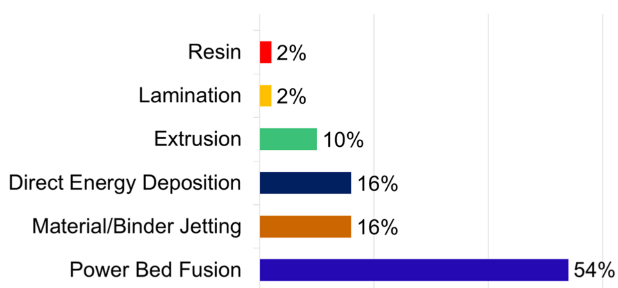

Fig. 10 Distribution of metal 3D printer for 2019

allows for the swiftly developing prototypes, often within days, a feat not achievable through traditional manufacturing methods [50]. Studies analyzing various industrial sectors across OECD countries have highlighted the role of green innovation in influencing energy intensity levels. This underscores the importance of innovative practices in shaping energy consumption patterns [51]. Moreover, the introduction of innovative technologies in the energy sector is crucial for decarbonizing the economy. By integrating innovative solutions, such as Industry 4.0 technologies, economies can drive sustainable development and reduce carbon emissions. This shift towards innovative mechanisms in the energy sector is essential for achieving long-term environmental goals [52].

Furthermore, the systemic modernization paradigm in the Russian energy sector emphasizes the need for innovation strategies to be internally driven. By fostering innovation and industrial ecosystems within the energy sector, countries can enhance their technological development and promote sustainable practices. This approach positions the energy sector as a pivotal infrastructure framework that unifies various sectors of the economy [53]. The integration of innovative technologies in the energy sector is paramount for driving sustainable development, reducing carbon emissions, and enhancing energy efficiency. AM, green innovation, and Industry 4.0 technologies are instrumental in accelerating the development of energy devices, improving energy intensity levels, and fostering systemic modernization within the energy sector. This rapid turnaround is critical for testing and refining designs before full-scale production begins.

AM is increasingly being adopted by energy companies for various applications, including prototyping and spare parts production. Approximately 35% of energy companies utilizing AM are leveraging it for prototyping purposes [22]. Swiftly producing spare parts on demand can significantly reduce downtime and inventory costs [22]. 3D printing technology has proven to be highly beneficial

Table 3 Some top-performing ceramic 3D printers

Product	Manufacturer	Country	Cost (USD)	Dimension (mm)	Technology
DeltaBots 3D PotterBot	DeltaBots	United States	3,250–27,950	490 × 490 × 710	Extrusion
Delta WASP 2040 & 40100 Clay	WASP	Italy	10,000	Ø400 × 200 × 0.5	Extrusion
StoneFlower 3.0	Maximo Soalheiro	Germany	3850	500 × 500 × 800	Extrusion
Cerambot Eazao & Delta	Eazao	China		370 × 390 × 470	Extrusion
VormVrij 3D Lutum (Lutum 4 M and 5 M)	VormVrij 3D	Netherland	3,700–7,400	430 × 450 × 500	Extrusion
FORM 3	FORMLAB	USA	3,499	125 × 125 × 165	SLA

SLA Stereolithography

in remote locations, such as offshore oil platforms, where the logistics of spare parts delivery can be challenging and costly. The Shell Technology Center in Houston experienced a significant 70% reduction in inventory costs for specific components due to the implementation of on-site 3D printing capabilities [54]. This advancement in AM is not only limited to prototyping or spare parts but is also increasingly utilized for producing critical components essential for energy systems [55]. The integration of 3D printing technology on offshore oil and gas platforms has been a subject of research, with a focus on optimizing energy systems and production processes. Studies have explored the modeling of integrated energy systems on offshore platforms, considering the coupling between energy supply systems and oil and gas production systems [56, 57]. Additionally, the application of AM has extended to the design and fabrication of surgical instruments, prosthetic hands, and custom-made prostheses, showcasing the versatility and impact of this technology across various fields, including medicine and manufacturing engineering [58–60].

The use of AM technology on offshore platforms aligns with the broader trend of digital transformation and automation in various industries. Research has highlighted the convergence of digital design, robotics, and the built environment, emphasizing the potential for autonomous architecture and innovative manufacturing processes [61]. Additionally, the development of new technologies, such as wind-storage-turbine bundled technology and waste heat recovery units, has deepened the energy flow coupling relationships within offshore energy systems, contributing to sustainable energy development [57, 62]. The application of AM technology on offshore oil platforms has demonstrated significant cost savings, operational efficiencies, and enhanced capabilities for producing critical components. This technology addresses logistical challenges and opens up opportunities for innovation and optimization within energy systems and manufacturing processes in remote and demanding environments.

In the nuclear sector, AM technologies are being explored for creating parts capable of withstanding extreme conditions within reactors. Siemens has conducted successful tests on 3D-printed gas turbine blades that exhibit full functionality under high-pressure conditions, showcasing the potential of AM to produce intricate and high-strength components. These blades have been proven to endure temperatures exceeding 1,250 °C and the high-pressure environments typical in turbine applications [63]. The advancements in 3D printing have led to its integration in various sectors beyond nuclear applications. This technology has gained significant traction in aerospace, construction, industry, art, education, protection, security, and medical fields due to its ability to fabricate complex structures efficiently [19]. Moreover, the construction sector has embraced AM technology, becoming an established method complete with accepted standards after a decade of research and development [64]. Furthermore, the potential of AM extends to energy and environmental applications. Studies have been dedicated to developing AM technologies for creating functional parts and devices tailored for energy and environmental purposes [65]. As the technology evolves, precision improves, and surface roughness enhances, AM is increasingly investigated for developing radio frequency components and advanced payloads, indicating its growing significance in various industries [66]. The utilization of AM in the nuclear sector and beyond demonstrates the technology's versatility and potential to revolutionize manufacturing processes across different fields. The successful testing of AM-printed components in extreme conditions underscores its capability to produce high-strength parts, paving the way for innovative applications in diverse industries.

The main barriers to scaling additive manufacturing (AM) for large components like wind turbine blades include limitations in printer size, production speed, material availability, and cost [67]. Most current AM technologies are designed for smaller-scale production, and producing large components such as turbine blades would require significantly larger machines and longer print times, which is not yet feasible for mass production. Additionally, the materials commonly used in AM for small parts may lack the durability and strength required for large, load-bearing structures like wind turbines.

To overcome these challenges, advancements in large-format 3D printing technologies are necessary. Research into stronger, lightweight composite materials specifically suited for AM could enhance durability and scalability. Moreover, hybrid manufacturing approaches, combining traditional manufacturing techniques with AM, could address production speed and cost concerns by using AM for complex or custom parts and traditional methods for simpler, larger sections. For instance, companies like GE and Siemens are exploring AM for producing smaller, highly optimized parts for turbines, and scaling this technology further could be a key step in overcoming current limitations. Developing more efficient and automated AM systems would also help reduce production times and costs, making the technology more viable for large-scale renewable energy projects.

2.3 Case studies of countries and organizations leveraging additive manufacturing in the energy sector

Additive manufacturing (AM) has been revolutionizing various industries by enabling the creation of complex geometries, reducing material waste, and shortening production times. The energy sector, in particular, has seen significant advancements due to the adoption of AM technologies. The following case studies from different countries and organizations have effectively leveraged AM in the energy sector, highlighting key sectors, major projects, and statistics that demonstrate its growing significance.

2.3.1 United States

AM has become a transformative force in various industries across the United States. Its applications span from aerospace and automotive to healthcare and energy, offering numerous benefits such as cost savings, reduced material waste, and enhanced design flexibility. General Electric (GE) has initiated AM into its energy sector operations, particularly in producing gas turbines and other critical components. AM was used in developing the GE9X jet engine which includes 19 3D-printed fuel nozzles. The 3D-printed nozzles are 25% lighter than their conventionally manufactured counterparts. AM reduced the production time of the nozzles by 30%. The nozzles are made with less material waste, reducing material usage by up to 50%. The GE9X engine is expected to be 10% more fuel-efficient than previous models. GE anticipates saving up to $3 million per engine in production costs due to the efficiencies gained through AM. The aerospace industry was one of the earliest adopters of AM in the USA, leveraging its capabilities to produce complex and lightweight components. GE Aviation has been a leader in using AM for jet engine components. The GE9X engine, for instance, features 19 3D-printed fuel nozzles that are 25% lighter and five times more durable than traditionally manufactured parts. Boeing uses AM to produce over 60,000 parts for various aircraft, including the 787 Dreamliner. These parts range from interior components to structural elements. The aerospace AM market in the USA was valued at approximately $1.4 billion in 2022 and is expected to grow at a compound annual growth rate (CAGR) of 20% over the next five years. AM components have contributed to a 20% reduction in aircraft weight, leading to significant fuel savings and lower CO_2 emissions.

The automotive industry in the USA has embraced AM for prototyping, tooling, and production of end-use parts, resulting in shorter development cycles and cost efficiencies. Ford uses AM to produce prototype parts and custom tools, significantly reducing the time and cost associated with product development. The company has also started using 3D-printed parts in its vehicles, such as the Ford GT. General Motors (GM) employs AM for producing lightweight components and complex geometries that would be challenging to manufacture using traditional methods. AM has reduced prototyping costs by up to 90% and lead times by 60% for automotive companies. The use of 3D printing in tooling has improved production efficiency by 20%.

In the healthcare sector, AM is revolutionizing the production of medical devices, prosthetics, and even bio-printed tissues and organs. Companies like Stratasys and 3D Systems produce custom prosthetics and implants tailored to individual patients, improving comfort and functionality. Surgeons use 3D-printed models of patients' anatomy for pre-surgical planning, leading to better outcomes and reduced operation times. The medical AM market in the USA was valued at $1.2 billion in 2022 and is projected to reach $3.5 billion by 2027. The use of 3D-printed surgical models has been shown to reduce operation times by 30% and improve surgical accuracy.

The energy sector in the USA is increasingly adopting AM to produce components for oil and gas, renewable energy, and power generation applications. GE Renewable Energy uses AM to manufacture parts for wind turbines, such as turbine blades and generator components, enhancing efficiency and reducing costs. Siemens employs AM to produce components for gas turbines, including burner tips and fuel nozzles, which improve performance and reduce emissions. AM has led to a 15% increase in the efficiency of gas turbines and a 20% reduction in production costs for wind turbine components. The use of AM in the energy sector has contributed to a 25% reduction in material waste and a significant decrease in CO_2 emissions.

The defense and space sectors are leveraging AM for rapid prototyping, producing mission-critical components, and reducing logistical challenges. NASA uses AM to produce rocket engine parts, satellite components, and tools for the International Space Station (ISS). The agency's Perseverance Rover on Mars features 11 3D-printed parts. The U.S. Department of Defense (DoD) employs AM for producing lightweight and robust components for military vehicles, aircraft, and weapon systems. AM has reduced the time required to develop and test aerospace components by 50%, contributing to more successful missions. AM has reduced the need for large inventories and enabled on-demand production of critical parts, enhancing operational readiness.

AM is playing a pivotal role in transforming industries across the United States. AM offers substantial benefits in terms of cost savings, efficiency, and innovation from aerospace and automotive to healthcare and energy. As the technology continues to evolve, its impact on the U.S. economy and industrial capabilities is expected to grow, solidifying the nation's position as a leader in AM.

2.3.2 Africa

Additive Manufacturing (AM) is progressively being adopted across Africa, transforming various sectors by providing innovative solutions and fostering local production. In Africa, the healthcare sector is one of the primary beneficiaries of AM in producing medical devices, prosthetics, and anatomical models, addressing the challenges of accessibility and cost. Organizations like the Enable Community Foundation and Robohand utilize 3D printing to produce affordable prosthetic limbs for amputees, particularly in South Africa and Kenya. AM has been instrumental during the COVID-19 pandemic in producing face shields, masks, and ventilator parts by local manufacturers. The 3D LifePrints organization in Nigeria, produced personal protective equipment (PPE) using 3D printing. 3D-printed prosthetics can be produced for as little as $50, compared to traditional prosthetics that cost upwards of $5,000. In Kenya, the adoption of 3D printing has reduced the waiting time for prosthetic limbs from several months to a few weeks. AM is also making significant strides in education and research across Africa. Universities and research institutions are incorporating 3D printing into their curricula and research projects to foster innovation and skills development. Institutions like the University of Pretoria in South Africa and Ashesi University in Ghana have integrated 3D printing into their engineering and design programs, enabling students to create prototypes and conduct research. The African Biomedical Engineering Consortium (ABEC) uses 3D printing to develop medical devices and educational models, promoting hands-on learning and innovation. Over 50 universities across Africa have incorporated 3D printing into their programs, benefiting more than 10,000 students annually. Research projects involving 3D printing have resulted in the publication of numerous papers, advancing knowledge in fields such as biomedical engineering and materials science.

The manufacturing sector in Africa is leveraging AM to improve production processes, reduce costs, and enhance the quality of products. Companies like the South African startup, Roboze, use 3D printing to produce industrial components, reducing reliance on imported goods and fostering local manufacturing capabilities. 3D printing service providers in Nigeria like CAD Works are helping local businesses develop prototypes and custom tools, accelerating product development cycles. Local production using 3D printing has reduced manufacturing costs by up to 30%, particularly for small-scale businesses and startups. The use of AM for tooling and prototyping has shortened development times by 50%, enabling faster time-to-market for new products. The energy sector in Africa is beginning to explore the potential of AM for producing parts and components for renewable energy systems and oil and gas operations. 3D printing is used to produce components for solar panels and wind turbines. Researchers in South Africa are developing 3D-printed parts for small-scale wind turbines to provide off-grid energy solutions. In Nigeria, companies are investigating the use of 3D printing to produce spare parts for oil rigs and pipelines, reducing downtime and improving operational efficiency. 3D printing has led to a 15% increase in the efficiency of renewable energy systems by enabling the production of optimized components. In the oil and gas sector, AM has reduced maintenance costs by 20% through on-demand production of spare parts.

AM is being explored as a solution to address housing shortages and improve construction efficiency in Africa. Organizations like the African Centre for Rapid Prototyping and Manufacturing (CRPM) in South Africa are developing 3D-printed housing solutions to provide affordable and sustainable homes. 3D-printed building components such as bricks, walls, and decorative elements, reduce material waste and construction time. 3D-printed homes can be built at 20–30% lower costs compared to traditional construction methods. The use of 3D printing has reduced the construction time for housing units by 50%, enabling quicker deployment of affordable housing solutions. AM is making a significant impact across various sectors in Africa, offering innovative solutions to long-standing challenges. The adoption of AM is driving economic growth from healthcare and education to manufacturing and energy, fostering local production, and improving the quality of life for many Africans. As technology continues to evolve and become more accessible, its potential to transform industries and contribute to sustainable development across the continent is immense.

2.3.3 India

Bharat Heavy Electricals Limited (BHEL), a prominent state-owned engineering and manufacturing enterprise in India, has been at the forefront of adopting additive manufacturing (AM) technologies to enhance its energy infrastructure capabilities. The integration of AM allows BHEL to produce complex components for gas turbines, boilers, and other critical energy equipment, thereby significantly reducing lead times and minimizing material waste in the energy sector. This is particularly important in the energy sector, where efficiency and reliability are paramount. BHEL's use of 3D printing technology has enabled the production of components with enhanced thermal and mechanical properties, which are essential for the demanding operational conditions of gas turbines [68]. Furthermore, the ability to rapidly prototype and manufacture parts has facilitated quick repairs of critical components, thereby minimizing downtime and reducing operational costs [68].

2.3.4 China

In the context of China, the State Grid Corporation of China (SGCC) exemplifies the successful integration of additive manufacturing into the energy sector. As the largest utility company globally, SGCC has leveraged AM to improve the reliability and efficiency of its energy distribution systems. The company utilizes 3D printing to manufacture components such as high-voltage insulators and connectors, which are vital for maintaining grid stability and performance [69]. The rapid prototyping capabilities of AM allow SGCC to produce custom parts tailored to specific requirements, addressing the challenges posed by heavy loads on the energy grid and the increasing demand for efficient and sustainable energy solutions [69]. The strategic application of AM technologies in SGCC not only enhances operational efficiency but also supports the broader goals of sustainability and innovation within the energy sector [69].

Overall, the adoption of additive manufacturing by both BHEL in India and SGCC in China highlights the transformative potential of this technology in the energy sector. By enabling the production of complex components with improved performance characteristics and facilitating rapid prototyping, AM contributes to enhanced operational efficiency and sustainability in energy infrastructure development [68, 69].

2.3.5 Europe

Additive Manufacturing (AM) is profoundly impacting industries across Europe, fostering innovation, reducing costs, and enabling complex designs that were previously impossible with traditional manufacturing techniques. Europe's aerospace industry has been at the forefront of adopting AM, utilizing its capabilities to produce lightweight and complex components that enhance performance and reduce costs. Airbus has integrated AM into its production processes to manufacture parts for its A350 XWB aircraft. The company uses 3D printing for over 1,000 parts, including structural components and cabin parts. The French aerospace manufacturer uses AM to produce parts for jet engines, such as turbine blades and fuel nozzles. Safran's LEAP engine, used in Boeing and Airbus aircraft, features several 3D-printed components. AM has enabled Airbus to reduce the weight of certain aircraft parts by up to 55%, leading to significant fuel savings and reduced CO_2 emissions. Safran estimates that using AM has reduced the production cost of some components by 30%. The automotive sector in Europe is leveraging AM for prototyping, tooling, and producing end-use parts, resulting in enhanced design flexibility and reduced lead times. The German automaker uses AM to produce custom tools, fixtures, and prototypes, significantly shortening development cycles and reducing costs. Volkswagen has also begun integrating 3D-printed parts into its production vehicles. BMW employs AM to produce metal and plastic parts for its vehicles. The company has developed a new production line that uses 3D printing to manufacture parts for its i8 Roadster. AM has reduced prototyping lead times by up to 90% for European automotive manufacturers. 3D printing for tooling and fixtures has led to cost reductions of approximately 58% for companies like Volkswagen.

AM is transforming healthcare in Europe by enabling the production of custom medical devices, implants, and anatomical models, improving patient outcomes and reducing costs. The Belgian company specializes in 3D printing for the medical sector, producing patient-specific implants, surgical guides, and anatomical models. Materialise's technology is used in complex surgeries, including orthopedic and cranio-maxillofacial procedures. This German company uses AM to produce custom cardiovascular implants and medical devices, enhancing the precision and effectiveness of treatments. 3D-printed surgical guides and models have improved surgical accuracy by 40%, improving better patient outcomes. Custom implants produced using AM can be up to 70% less expensive than traditional implants. The energy sector in Europe is adopting AM to produce parts for renewable energy systems, oil and gas operations, and power generation equipment. Siemens uses AM to produce parts for gas turbines, including burner tips and fuel nozzles, which enhance performance and reduce emissions. Siemens has also used 3D printing to produce wind turbine components. The Danish wind turbine manufacturer uses 3D printing to create prototypes and production parts for its wind turbines, improving efficiency and reducing costs. The use of AM has increased the efficiency of gas turbines by 15% and reduced production costs for wind turbine components by 20%. 3D printing has led to a 25% reduction in material waste in the energy sector.

AM is being explored in Europe as a solution to enhance construction efficiency, reduce costs, and enable innovative architectural designs. ICON and BIG (Bjarke Ingels Group) partnership is exploring 3D printing for building residential structures. Their project in Copenhagen involves the construction of 3D-printed homes that are sustainable and affordable. XtreeE, a French company specializes in 3D printing for construction, producing elements like concrete walls and structural components. XtreeE's technology has been used in several innovative projects across Europe. 3D printing has reduced construction times by up to 50% for residential and commercial buildings. Constructing 3D-printed homes cost 20–30% lower than traditional methods. Research institutions and universities in Europe are integrating AM into their programs to foster innovation and equip students with advanced skills.

This Swiss university is a leader in AM research, developing new materials and processes for 3D printing applications across various industries. The German research organization conducts extensive research in AM, focusing on industrial applications and advancing technology. Over 100 universities in Europe have integrated AM into their curricula, benefiting thousands of students and fostering a new generation of skilled professionals. European research institutions have published hundreds of papers on AM, contributing significantly to the global knowledge base. AM is making significant strides across various industries in Europe, offering numerous benefits such as cost savings, increased efficiency, and enhanced design flexibility. From aerospace and automotive to healthcare and energy, the adoption of AM is driving innovation and economic growth across the continent. As the technology continues to advance, its impact on European industries is expected to expand, solidifying Europe's position as a global leader in AM.

Siemens has been utilizing AM to enhance the performance and reliability of its gas turbines and other energy-related equipment. Production of burner components for SGT-A65 gas turbines. AM reduced the lead time for burner component production by 75%. The 3D-printed components have increased the operational efficiency of the turbines by 1.5%. The improved efficiency translates to a reduction of approximately 10,000 tons of CO2 emissions per turbine per year. Siemens estimates a cost reduction of 30% in the production of these components. Equinor, a multinational energy company based in Norway, has been leveraging AM to enhance its offshore oil and gas operations. Development and deployment of 3D-printed parts for offshore platforms. AM has reduced maintenance costs by 20%. The production time for critical components has been cut by 60%. Improved component quality and reduced production times have enhanced the safety and reliability of offshore operations. Equinor has also seen a reduction in material waste, contributing to its sustainability goals.

2.3.6 Saudi Arabia

Additive Manufacturing (AM) is increasingly being adopted in Saudi Arabia as part of the country's efforts to diversify its economy and promote technological innovation. This section examines the usage of AM in Saudi Arabia, focusing on key sectors, major projects, and the impact of this technology on the Kingdom's economic and industrial landscape.

The healthcare sector in Saudi Arabia is leveraging AM to improve patient care, reduce costs, and enhance medical training. King Abdulaziz City for Science and Technology (KACST) has been at the forefront of AM research and application in healthcare, producing custom prosthetics, implants, and medical devices. Hospitals like King Faisal Specialist Hospital and Research Centre use 3D printing to create patient-specific implants and surgical guides, improving surgical outcomes and reducing recovery times. Custom 3D-printed implants have reduced the cost of surgeries by up to 30%. 3D-printed surgical guides have improved surgical accuracy and reduced operation times by 20%.

Saudi Arabia is exploring AM to revolutionize its construction and infrastructure sectors, aiming to address housing shortages and promote sustainable building practices. The Ministry of Housing has partnered with international and local companies to develop 3D-printed homes, aiming to construct affordable and sustainable housing units quickly and efficiently. ICON, a construction technology company, has been involved in pilot projects to create 3D-printed homes in Riyadh, demonstrating the potential of AM in large-scale housing development. 3D printing technology has reduced the construction time for homes by 50%. The cost of constructing 3D-printed homes can be up to 30% lower than traditional construction methods.

The energy sector in Saudi Arabia, particularly the oil and gas industry, is adopting AM to improve the efficiency and reliability of operations. Saudi Aramco, the world's largest oil producer, uses AM to produce spare parts and components for its oil rigs and refineries. This includes complex parts that are difficult to manufacture using traditional methods. The Kingdom is also exploring the use of AM in producing components for solar and wind energy systems, aiming to enhance performance and reduce the costs of renewable energy projects. Saudi Aramco, one of the world's largest oil producers, has successfully integrated AM into its operations within the oil and gas sector, specifically to enhance maintenance and production processes. By utilizing 3D printing technology to produce spare parts and components for oil rigs and refineries, Saudi Aramco has achieved significant improvements. The implementation of AM has led to a 50% reduction in spare parts inventory and a 40% decrease in lead time for critical spare parts acquisition. This ability to manufacture parts on demand has resulted in minimized downtime and enhanced operational efficiency, ultimately leading to an estimated annual savings of $2 million for Saudi Aramco. Moreover, the use of 3D-printed parts has increased the operational efficiency of oil rigs and refineries by 15% and reduced maintenance costs by 20% through the on-demand production of spare parts [70, 71]. The adoption of scalable manufacturing technology, such as AM, in the oil and gas industry has transformed the design, production, and distribution of high-quality 3D objects. This shift has reduced costs and accelerated the innovation process, providing enhanced functionality. Market analysts identified the oil and gas industry as the fastest-growing user of 3D printing due to its ability to deliver cost-effective, rapid, and improved solutions [70, 71]. The incorporation of AM has revolutionized the operational efficiency of Saudi Aramco in the oil and gas sector. The ability to produce spare parts on demand has significantly reduced inventory, lead times, maintenance costs, and downtime, leading to substantial annual savings and increased operational efficiency. AM is being integrated into various manufacturing processes in Saudi Arabia, enhancing production capabilities and reducing reliance on imported goods. Companies like SABIC (Saudi Basic Industries Corporation) use AM to produce industrial components and prototypes, fostering local manufacturing capabilities. 3D printing service providers in Saudi Arabia are helping local businesses develop prototypes and custom tools, accelerating product development cycles. AM has shortened development times by 50% for local manufacturers and has led to a 25% reduction in material waste in manufacturing processes.

Saudi Arabia is investing in AM education and research to build a skilled workforce and foster innovation. Institutions like King Saud University and King Abdullah University of Science and Technology (KAUST) are integrating 3D printing into their curricula and research projects, promoting hands-on learning and technological advancements. The Saudi government supports various initiatives to promote AM research and development. This includes funding for research projects and collaborations with international partners. Over 20 universities in Saudi Arabia have incorporated AM into their programs, benefiting thousands of students. Saudi research institutions have published numerous papers on AM, contributing to global advancements in the field.

The defense and aerospace sectors in Saudi Arabia are exploring AM to produce complex parts, reduce costs, and enhance operational capabilities. The Saudi Arabian Military Industries (SAMI) is investigating the use of AM to produce components for military vehicles, aircraft, and equipment, aiming to improve performance and reduce lead times. Collaboration with international aerospace companies to develop 3D-printed parts for aircraft and satellite components, enhancing the Kingdom's aerospace capabilities.

AM has reduced the lead time for producing aerospace and defense components by 40%. The use of 3D printing has led to cost savings of approximately 30% in the production of complex parts. AM is making significant strides across various sectors in Saudi Arabia, offering numerous benefits such as cost savings, increased efficiency, and enhanced innovation. From healthcare and construction to energy and manufacturing, the adoption of AM is driving economic growth and technological advancement in the Kingdom. As Saudi Arabia continues to invest in AM technology and infrastructure, its impact on the nation's industrial capabilities and economic diversification efforts is expected to grow, solidifying its position as a leader in AM in the Middle East.

2.3.7 United Kingdom

EDF Energy has been utilizing AM to improve the performance and lifespan of its nuclear power plant components, and production of 3D-printed pump impellers and heat exchanger parts. The lifespan of 3D-printed components has increased by 30%. The cost of producing these components has been reduced by 25%. The improved durability of components has led to fewer shutdowns and maintenance interventions. EDF Energy estimates annual savings of £1.5 million due to the enhanced durability and reduced production costs. AM is significantly transforming the energy sector by improving efficiency, reducing costs, and enhancing the sustainability of operations. These case studies demonstrate the potential of AM technologies to drive innovation and operational excellence across various segments of the energy industry. The integration of AM supports the production of high-performance components and aligns with global efforts to achieve more sustainable and resilient energy systems.

2.4 Opportunities and challenges of additive manufacturing for energy in the 4IR

The 4IR, characterized by the fusion of digital, biological, and physical technologies, is transforming industries and societies worldwide. Additive manufacturing (AM) is a cornerstone of this revolution, offering innovative solutions across various sectors.

The integration of additive manufacturing (AM) in the energy sector aligns closely with Fourth Industrial Revolution (4IR) technologies by leveraging advanced digitalization, automation, and smart manufacturing processes. 4IR technologies, such as artificial intelligence (AI), Internet of Things (IoT), and big data analytics (BDA), enhance AM by enabling more precise design optimization, real-time monitoring, and predictive maintenance in energy systems. For example, AI-driven design tools allow for the creation of lightweight, efficient components for renewable energy projects, such as wind turbine blades or solar panel mounts, improving overall performance and reducing material waste [72]. IoT sensors integrated into 3D-printed parts can enable real-time data collection and remote monitoring, optimizing maintenance schedules for critical energy infrastructure, such as oil rigs or power plants. A real-world example is GE's use of AM for producing highly efficient gas turbine components, which have been combined with digital twins (a 4IR technology) to simulate and optimize turbine performance in real-time. This synergy of AM with 4IR technologies is transforming energy production, increasing efficiency, and reducing environmental impact.

Integrating additive manufacturing (AM) with IoT and AI for performance monitoring in energy systems is a growing trend, with several successful examples already in place. One notable project is General Electric's (GE) use of AM to produce gas turbine components, which are equipped with IoT sensors for real-time performance monitoring [73]. These sensors collect data on temperature, pressure, and stress levels during turbine operation, which AI algorithms analyze to predict maintenance needs and optimize performance. This integration allows GE to enhance the efficiency and lifespan of their turbines by enabling predictive maintenance, reducing downtime, and improving fuel efficiency. Another example is Siemens, which uses AM to manufacture parts for its energy systems while integrating IoT and AI to monitor the performance of these parts in real-time. Siemens' AM-produced gas turbine blades are equipped with sensors that communicate with AI-driven software to provide feedback on operational conditions [74]. This combination of

AM, IoT, and AI has enabled Siemens to improve energy efficiency and maintenance schedules while reducing operational costs. These examples demonstrate how the integration of AM with IoT and AI can enhance the performance, reliability, and efficiency of energy systems by enabling data-driven insights and advanced monitoring capabilities.

2.4.1 Opportunities and challenges

AM enables the creation of complex and intricate designs that are difficult or impossible to achieve with traditional manufacturing methods. Products can be tailored to meet specific customer requirements, from medical implants to consumer goods, enhancing personalization. Custom prosthetics and implants are designed to fit individual patients perfectly, improving outcomes and comfort [75, 76]. AM allows for quick development and testing of prototypes, significantly shortening product development cycles. Companies can produce parts and products as needed, reducing inventory costs and increasing responsiveness to market changes. Manufacturers like Volkswagen use AM for rapid prototyping, accelerating the development of new vehicle models. AM uses only the material necessary for the part being produced, minimizing waste and reducing material costs. Eliminates the need for expensive molds and tooling, lowering initial production costs. GE's use of AM for jet engine components reduces material waste and production costs while improving performance. AM can be used to produce parts and products locally, reducing the need for complex global supply chains and decreasing transportation costs. Digital designs can be stored and printed on demand, reducing physical inventory requirements. Military applications of AM include producing spare parts on-site and minimizing supply chain disruptions in remote or conflict areas. AM processes can be more energy-efficient compared to traditional manufacturing.

Several studies highlight the environmental benefits of additive manufacturing (AM) in energy production, particularly in reducing waste and improving energy efficiency compared to traditional manufacturing methods [77–79]. AM's layer-by-layer construction process significantly minimizes material waste, as only the necessary amount of material is used, unlike subtractive methods like CNC machining, which can waste up to 90% of raw material. A study by Oak Ridge National Laboratory found that AM can reduce energy consumption in production processes by up to 50% compared to conventional manufacturing techniques, AM allows for the creation of optimized, lightweight designs, particularly in energy components like turbine blades or heat exchangers, which reduces material usage and energy consumption during operation. For example, GE's 3D-printed fuel nozzles for jet engines are 25% lighter and more fuel-efficient than traditionally manufactured counterparts [80, 81]. Such AM's potential to reduce carbon footprints and drive sustainability in energy production by lowering material waste, enhancing energy efficiency, and cutting operational costs.

The cost of advanced AM equipment and high-quality materials can be prohibitive for small and medium-sized enterprises (SMEs). Significant investment in training and skill development is needed to effectively utilize AM technologies. SMEs may struggle to afford the high upfront costs of adopting AM, limiting their ability to compete with larger companies [82, 83]. Ensuring consistent quality across batches of 3D-printed parts can be challenging. The lack of standardized protocols for AM processes and materials hinders widespread adoption and integration into existing manufacturing systems. Ensuring the consistent quality and reliability of 3D-printed medical devices is crucial but challenging due to the variability in AM processes.

Digital designs are vulnerable to unauthorized replication and distribution, posing risks to intellectual property rights. The digital nature of AM exposes it to potential cybersecurity threats, including data breaches and design tampering. Protecting proprietary designs and manufacturing processes from cyber threats is critical for maintaining competitive advantage. While AM has made significant advancements, the range of materials that can be effectively 3D printed is still limited compared to traditional manufacturing [84, 85]. Achieving the desired material properties, such as strength and durability, can be difficult with some AM materials Chen et al. [86]. Ensuring that 3D-printed components meet the stringent material performance standards required for aerospace applications remains a challenge. The regulatory framework for AM technologies is still evolving, and navigating the regulatory landscape can be complex and time-consuming. Obtaining certification for 3D-printed parts and products, particularly in highly regulated industries like aerospace and healthcare, can be challenging. The process of certifying 3D-printed medical implants to meet regulatory standards can be lengthy and complex, delaying market entry.

In additive manufacturing (AM) for the energy sector, a range of advanced materials is being researched and applied for their specific properties suited to demanding conditions. Metals like titanium alloys, nickel-based superalloys, and stainless steel are favored for their exceptional strength, corrosion resistance, and ability to withstand high temperatures, making them ideal for components such as gas turbine blades [87, 88]. For instance, Siemens uses nickel-based superalloys in 3D-printed turbine blades that operate in extreme heat, improving efficiency. Polymers and composite materials, known for their lightweight and flexible properties, are increasingly used in renewable energy applications like wind turbine blades and solar panels [89]. Ceramics are also being explored for their high heat resistance, particularly in energy systems requiring thermal stability, such as in heat exchangers. These materials help enhance durability, reduce energy losses, and improve overall system performance across the energy sector.

AM holds immense potential in the Fourth Industrial Revolution, offering transformative benefits such as design flexibility, reduced time to market, cost efficiency, and sustainability. However, challenges such as high initial costs, quality control, intellectual property concerns, material limitations, and regulatory hurdles must be addressed to realize its full potential. As technology advances and more industries embrace AM, overcoming these challenges will be crucial for driving innovation and economic growth in the era of digital transformation.

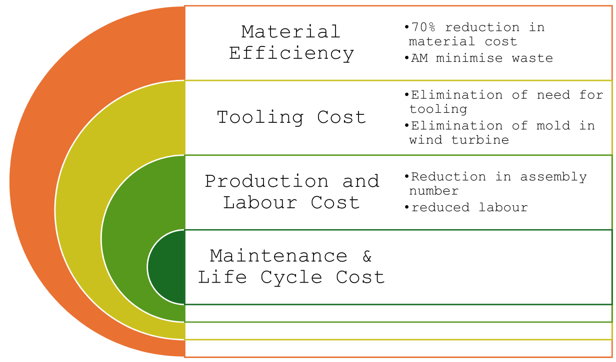

Fig. 11 A cost comparison model of additive manufacturing in energy

2.4.2 Cost comparisons between traditional and additive manufacturing methods

AM reduces material waste by using only the material needed to build the part layer-by-layer, while traditional methods like CNC machining typically result in significant material loss. For instance, in CNC, up to 90% of the raw material can be wasted, especially when creating complex geometries. In contrast, AM minimizes waste, leading to material cost savings [90]. A study by Deloitte estimated that AM can reduce material costs by up to 70% in some applications. Traditional manufacturing requires expensive molds, dies, and tools, which can add substantial costs, especially for small production runs or custom parts. AM eliminates the need for tooling, offering cost advantages in producing complex or customized components. For example, in wind turbine production, the elimination of molds can save hundreds of thousands of dollars per production cycle. AM can shorten the production cycle, particularly for complex geometries, because it reduces the number of assembly steps required. This also translates into lower labor costs. In traditional manufacturing, more time and manual labor are needed for assembly, especially for intricate parts with multiple components. By producing lighter, more efficient components, AM can extend the operational life of energy systems and reduce maintenance costs. For example, GE's 3D-printed fuel nozzles for jet engines, which are lighter and more durable, offer a 25% improvement in fuel efficiency and reduce the frequency of part replacement, contributing to long-term cost savings.

Figure 11 shows the summary of the A cost comparison model. Including specific case studies—like GE's AM-produced fuel nozzles and Siemens' 3D-printed turbine blades—alongside economic models showing these cost savings would provide clearer evidence of AM's cost efficiency compared to traditional methods.

2.5 Emerging trends, technological advancements, and prospects for additive manufacturing in energy applications

Additive manufacturing (AM) is transforming the energy sector by enabling customized, efficient component production across applications. AM allows for specialized designs like wind turbine blades and complex heat exchangers that surpass traditional manufacturing capabilities. In solar energy, 3D printing supports building-integrated photovoltaic (BIPV) systems, reducing material costs and enhancing adoption by integrating solar technology into architecture. For remote energy projects, such as offshore wind or rural solar, AM enables on-site production and repairs, minimizing downtime and logistics costs.

Key advancements in metal 3D printing technologies, like selective laser melting (SLM) and electron beam melting (EBM), allow for high-strength parts suited for harsh environments, including offshore and nuclear settings [91, 92]. Companies like GE Renewable Energy and Honeywell UOP are exploring large-scale applications, including a 3D-printed wind turbine base that could double the current size limits. Integrating AM with the Internet of Things (IoT) and artificial intelligence (AI) further enhances energy solutions by embedding sensors during production for real-time monitoring, which supports predictive maintenance.

Research into durable, high-performance printable materials is expanding AM's potential in extreme environments like geothermal and nuclear energy [93–95]. AM also promotes local energy solutions by enabling decentralized production, allowing communities to create renewable systems independently, and reducing reliance on large energy grids. Together, these advances in AM point to a future of more efficient, customized, and sustainable energy production.

2.6 Conclusion and recommendation

Additive manufacturing (AM) is revolutionizing the energy sector, offering enhanced efficiency in design, production, and maintenance, especially within the framework of the Fourth Industrial Revolution (4IR). By enabling the creation of complex geometries, streamlining supply chains, and allowing for rapid prototyping, AM helps energy companies reduce costs, improve system performance, and minimize production downtime through on-site part manufacturing. Its integration with digital tools like digital twins, IoT, and AI further enhances its capabilities, allowing for advanced data analysis and process optimization to improve manufactured parts' efficiency and performance.

Despite its benefits, there still exist some challenges in scaling AM for large components, ensuring material durability, and addressing high costs and regulatory gaps. Current limitations include insufficient capacity for large-scale production, the need for more resilient materials for harsh energy environments, and high initial investment costs. Additionally, the lack of standardized industry protocols for AM parts raises concerns about safety and reliability. Future research should focus on developing large-format AM technologies, cost optimization, and certification standards to accelerate AM adoption in energy applications.

Investment in R&D is essential for advancing additive manufacturing (AM) in the energy sector. Companies should focus on materials and techniques that endure extreme conditions and create robust regulatory frameworks for quality and safety. Developing a skilled workforce proficient in AM and digital tools is crucial; energy firms should invest in training and partner with academic institutions to cultivate talent. Collaboration between energy companies, AM providers, and researchers can drive innovation and address industry-specific challenges. Sustainability should also be prioritized by using recyclable materials, optimizing designs, and integrating renewable energy. Rigorous testing and real-time monitoring will ensure the reliability of AM components in critical applications, enabling the energy sector to harness AM's full potential for a sustainable future.

Declarations

Conflict of interest The authors declare no conflict of interest to the publication of this manuscript.

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