



3D PRINTING TECHNOLOGY FOR ENERGY GENERATION IN AFRICA: A REVIEW

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Abstract

Africa grapples with a profound energy challenge affecting over 600 million people without electricity access. This scarcity impedes economic growth, restricts healthcare services, and limits educational opportunities. Traditional energy solutions prove to be costly, unreliable, and environmentally unsustainable. In response to this challenge, 3D printing technology emerges as a transformative force, potentially revolutionizing energy generation across the continent. Drawing on interdisciplinary insights from mechanical engineering, renewable energy systems, and socio-economic development, the review synthesizes literature on the application of additive manufacturing in solar PV systems, wind turbines, micro-hydro power, and energy storage innovations. It highlights global examples and African case studies such as the Open-Source Micro-Hydro Power Project and the 3D-Printed Solar Kiosk, demonstrating how 3D printing can localize production, reduce costs, and empower communities. The methodology involved a comprehensive search of peer-reviewed literature from 2010 to 2025, resulting in the thematic analysis of 49 studies. Key findings reveal that 3D printing enables the fabrication of energy components using diverse materials such as polymers, metals, ceramics, and nanomaterials tailored to Africa's resource constraints. It supports decentralized renewable energy systems, enhances energy storage through custom lithium-ion batteries, and contributes to smart grid infrastructure. The review also examines the socio-economic impacts of 3D printing, including job creation, community empowerment, and environmental sustainability. It identifies barriers such as infrastructure gaps, material accessibility, and skills shortages, and proposes strategic solutions including FabLabs, vocational training, and policy innovation. A SWOT analysis and policy recommendations underscore the need for collaborative governance and investment to scale 3D printing in Africa's energy sector. Ultimately, this study positions 3D printing as a catalyst for sustainable energy innovation in Africa, offering a pathway toward inclusive development, climate resilience, and technological self-reliance.

Keyword: 3D printing, Energy generation, Decentralized energy, Renewable energy, Economic development

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1.0 INTRODUCTION

Africa, home to over 600 million people without access to electricity, confronts a profound energy challenge that reverberates across the continent's socioeconomic landscape (Munro et al., 2020). The absence of reliable energy impedes economic development and severely constrains healthcare services, educational opportunities, and overall quality of life. Despite efforts to expand traditional energy infrastructure, these solutions remain prohibitively expensive, environmentally unsustainable, and logistically impractical for remote and underserved communities (Arent et al., 2020). In this challenging context, 3D printing technology emerges as a promising tool, offering a glimmer of hope to address Africa's energy needs and pave the way for a sustainable future (Tabassum & Mir, 2023). The staggering figure of over six hundred million people without access to electricity in Africa is a stark reminder of the gravity of the energy challenge. This deficiency permeates every aspect of life, hindering economic growth and perpetuating cycles of poverty. Businesses struggle to operate without reliable energy, and entrepreneurs find their ambitions stifled (Ayuk, 2020). The lack of electricity in homes curtails the ability to engage in basic activities, limiting productivity and compromising overall well-being. Moreover, the impact extends to critical sectors such as healthcare and education.

Traditional energy solutions, which often rely on fossil fuels, present challenges that exacerbate existing problems (Kalair et al., 2021). The expense of establishing and maintaining conventional energy infrastructure poses a significant barrier, particularly in regions with limited financial resources. Moreover, the unreliability of these systems results in frequent

power outages, hindering the consistent provision of energy to homes, businesses, and essential services. The environmental impact of traditional energy sources is another critical concern (Sayed et al., 2021). Fossil fuels contribute to air pollution and climate change, leading to adverse effects on public health and exacerbating the challenges faced by vulnerable and underserved communities. The urgency to transition to more sustainable and eco-friendly energy solutions becomes increasingly apparent as the consequences of climate change manifest across the globe (Devi et al., 2023). In this challenging landscape, 3D printing technology emerges as a transformative and potentially revolutionary solution to Africa's energy woes. The unique capabilities of 3D printing, also known as additive manufacturing, allow for the creation of three-dimensional objects layer by layer based on digital models. This technology has demonstrated versatility in various industries such as manufacturing and healthcare and its application to energy generation holds immense promise for Africa yet unexplored (Yasli et al., 2023).

This review addresses a critical research gap in the lack of comprehensive analysis of how additive manufacturing can be strategically leveraged to overcome Africa's energy challenges. Unlike existing literature that focuses narrowly on isolated applications, this study adopts an interdisciplinary approach, integrating insights from mechanical engineering, renewable energy systems, and socio-economic development. It critically examines how 3D printing can enhance solar, wind, and micro-hydro technologies, improve energy storage through customized lithium-ion batteries, and support smart grid infrastructure globally (Table 1).

Table 1: Global Applications of 3d Printing in Energy Development

Sector	Application	Regional Examples	References
Solar Energy	3D-printed photovoltaic cells and panels	USA, Germany	Tarancón et al., 2022; Ukoba et al., 2023
Wind Energy	Customized turbine components	Denmark, China	Rouway et al., 2021; Tarancón et al., 2022
Hydro Energy	Micro-hydro turbine parts	Nepal, Canada	Svigir et al., 2019
Energy Storage	3D-printed lithium-ion battery casings	South Korea, USA	Chang et al., 2019; Browne et al., 2020

Smart Grids	Sensor housing and IoT device enclosures	Japan, Netherlands	Rathor & Saxena, 2020; Tsaramirsis et al., 2022
Bioenergy	Bioreactor components for biofuel production	Brazil, India	Saadi et al., 2022; de Oliveira et al., 2023

The originality of this scoping review lies in its holistic evaluation of 3D printing as a catalyst for energy innovation in Africa. It not only consolidates emerging research and practical initiatives but also proposes a strategic framework for stakeholders, governments, researchers, and communities to adopt and scale these technologies. By identifying barriers such as infrastructure limitations, material availability, and skill gaps, the study offers actionable recommendations for capacity building and innovation. This scoping review calls for a change in basic assumptions in how energy solutions are designed, produced, and deployed across the continent. It argues that strategic investments in infrastructure, education, and collaborative innovation are essential to unlock the full potential of 3D printing in Africa's pursuit of a sustainable and equitable energy future.

While 3D printing has gained traction in manufacturing and healthcare, its application in energy generation particularly within the African context remains underexplored. Therefore, this review introduces 3D printing technology as a novel and transformative approach to energy generation in Africa, offering decentralized, customizable, and cost-effective alternatives to conventional systems. This research addresses a critical gap in the lack of comprehensive analysis on how additive manufacturing can be leveraged to overcome Africa's energy challenges. This study further combined interdisciplinary insights from mechanical engineering, renewable energy, and socio-economic development to evaluate the feasibility and impact of 3D printing in energy systems. It critically examines how 3D printing can enhance solar, wind, and micro-hydro technologies, improve energy storage through customized lithium-ion batteries, and support smart grid infrastructure. Furthermore, it explores the socio-economic implications, including job creation, community empowerment, and environmental sustainability.

2.0. Methodology

Search Strategy

A comprehensive literature search was conducted to identify relevant studies on the application of 3D printing technology in energy generation within the African context. The databases searched included Scopus, Web of Science, IEEE Xplore, and Google Scholar. The search covered publications from 2018 to 2025, using combinations of keywords such as “3D printing”, “additive manufacturing”, “energy generation”, “renewable energy”, and “Africa”. Boolean operators (AND, OR) were used to refine the search. We outline the criteria for studies on 3D printing or additive manufacturing technologies specifically applied to energy generation, such as solar, wind, and bioenergy, in the context of African countries. Studies published in peer-reviewed journals from 2018 to 2025 and written in English were included. Exclusions are noted for studies that focus solely on non-energy applications, do not pertain to the African context, or are editorials, commentaries, or non-peer-reviewed sources.

Study Selection

The initial search yielded 1,200 records. After removing duplicates, 950 records remained. Titles and abstracts were screened, resulting in the exclusion of 800 records. The full texts of 150 articles were assessed for eligibility, and 100 were excluded for not meeting the inclusion criteria. 49 studies were included in the qualitative synthesis.

Data Extraction and Analysis

Data extraction was conducted using a standardized form that documented several key elements: the author(s) and year of publication, the country where the study was conducted, the type of 3D printing technology employed, the area of energy application, and the key findings and outcomes of the research.

3.0. Key findings and outcomes

The extracted data were synthesized thematically for qualitative analysis using descriptive statistics to identify trends in technology adoption, energy output, and regional focus and were further discussed as follows:

3.1. Potential Applications of 3D Printing for Energy Generation in Africa

Africa has the lowest electrification rate in the world, with around 600 million people still needing access to modern energy services. To meet the rising demand and close the access gap, Africa needs to diversify and expand its energy generation mix, which relies heavily on fossil fuels, especially natural gas and coal. These sources account for 60% of Africa's electricity output, while renewable sources, such as hydropower, wind, solar, geothermal, and bioenergy, account for 18% (Bishoge et al., 2020). Fossil fuels are a significant source of greenhouse gas emissions and expose Africa to the volatility and uncertainty of global energy markets and the risks of stranded assets in a net-zero world.

On the other hand, renewable energy offers a promising and cost-effective alternative for Africa's future energy needs. Renewable energy sources are abundant, indigenous and widely distributed across the continent and can provide electricity at competitive prices, especially as technology costs continue to decline (Ukoba et al., 2018). Renewable energy can also enhance energy security, create jobs, and support

local development, especially in rural and remote areas. Moreover, renewable energy can help Africa achieve its climate goals, as many African countries have committed to reducing their emissions and reaching net zero by mid-century.

However, renewable energy deployment in Africa faces many barriers and challenges, such as inadequate infrastructure, regulatory uncertainty, financing gaps, technical skills shortages, and social acceptance issues (Jabeen et al., 2023). To overcome these obstacles, Africa must adopt coherent policies and strategies and mobilize domestic and international resources and partnerships. The IEA estimates that Africa needs to invest around \$120 billion per year in its energy sector by 2040, of which 40% should go to renewable energy (Roche, 2023). This requires a significant increase in public and private funding and improved governance and transparency.

Energy generation in Africa is a complex and dynamic issue with multiple dimensions and implications. Africa can become a global leader in renewable energy but also faces many challenges and trade-offs. Africa's choices today will shape its energy future and development prospects for decades. Figure 1 displays the installed capacity of renewable energy in a few African nations (Ukoba et al., 2023). 3D printing can accelerate this transition by enabling localized production of components for solar, wind, and hydro systems. It supports decentralized energy solutions tailored to regional needs, helping overcome logistical and financial barriers to traditional infrastructure.

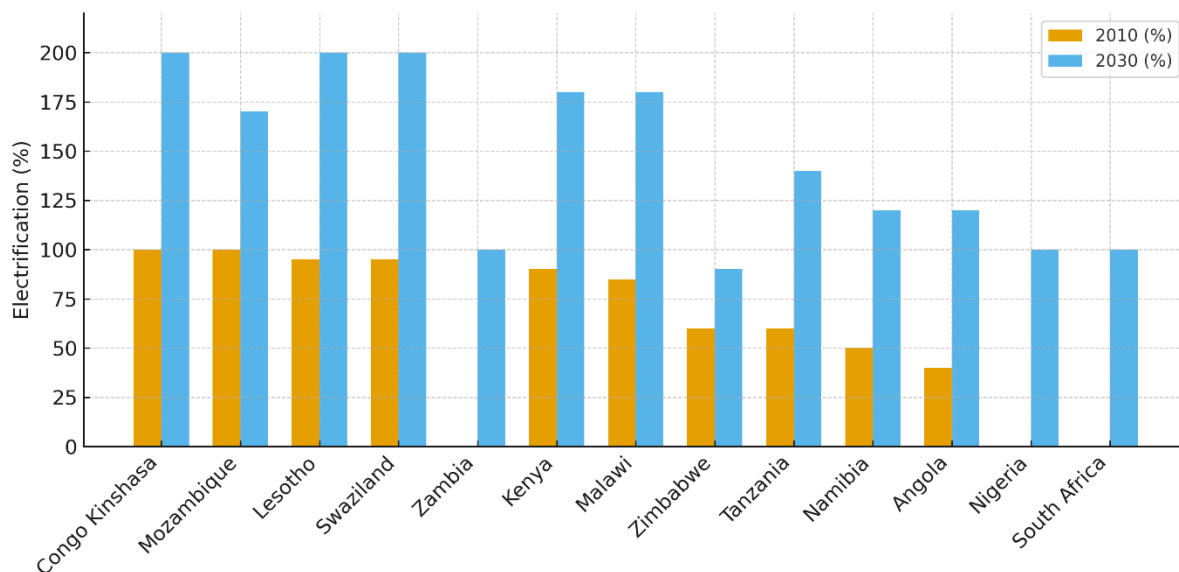


Figure 1. Data on the installed capacity of Renewable-based generation in total electricity generation in Africa adapted from Ukoba et al., 2023

Energy from the sun is referred to as solar energy. This energy can be obtained through heating or photons that excite electrons in a photoelectric substance to create a current. Egypt experienced the most tremendous growth, with 581 MW of solar energy in Africa, according to data supplied by the International Renewable Energy Agency (IRENA). With 373 MW, South Africa ranked second in Africa. With a 2.5 GW capacity, South Africa boasts the most extensive market-operated solar system. With an expected 55 MW added to the installed solar capacity, Kenya ranked third in 2018. Namibia's installed solar power reached 79 MW in 2018 after adding 33 MW. Ghana added 25 MW to bring its installed capacity to 64 MW, making it the sixth largest, as shown in Figure 2.

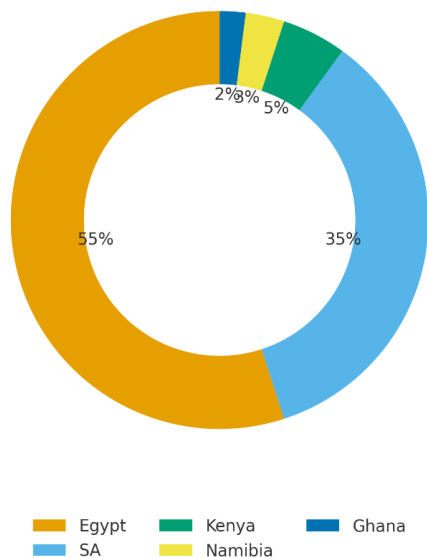


Figure 2. A chart of Africa's top 5 installed solar energy capacity countries in 2018 adapted from Ukoba et al., 2023.

According to a breakdown of installed solar capacity in South Africa, concentrated solar power accounts for 600 MW and photovoltaics for 2321 MW. Africa produces about 130 TWh yearly from its 37 GW installed hydropower producing capacity (Ukoba et al., 2023). The energy deficit in Africa has spurred a quest for innovative solutions that can address the challenges associated with traditional energy sources. In this pursuit, 3D printing technology emerges as a versatile and transformative tool, offering multifaceted applications across decentralized renewable energy, energy storage and transmission, energy-efficient devices, and research and development (Saadi et al., 2022).

As seen in Figure 3, a variety of cutting-edge 3D printing techniques, including binder jetting, Laminated Object Manufacturing (LOM), Fused Deposition Modeling (FDM), Inkjet Printing (IJP), Direct Ink Writing (DIW) and Stereolithography (SLA), have been used to create micro-sized Electrochemical Energy Storage (EES) devices with excellent compatibility and flexibility, as well as a small overall footprint, well-designed patterns, and controllable electrode thickness (Chang et al., 2019). As seen in Figure 3, a variety of innovative 3D printing techniques have been employed to create micro-sized Electrochemical Energy Storage (EES) devices with excellent compatibility and flexibility. These include:

- **Binder Jetting:** A method where a liquid binding agent is selectively deposited to join powder particles.
- **Laminated Object Manufacturing (LOM):** A technique that layers sheets of material, bonding them with heat and pressure, and cutting them into shape with a laser or blade.
- **Stereolithography (SLA):** A process that uses a laser to cure liquid resin into hardened plastic in a layer-by-layer fashion.
- **Fused Deposition Modeling (FDM):** A widely used method where thermoplastic material is extruded layer by layer to build an object.
- **Inkjet Printing (IJP):** A technique that deposits droplets of material, often conductive inks or polymers, to build structures.
- **Direct Ink Writing (DIW):** An extrusion-based method that uses viscoelastic inks to create complex structures with fine resolution.

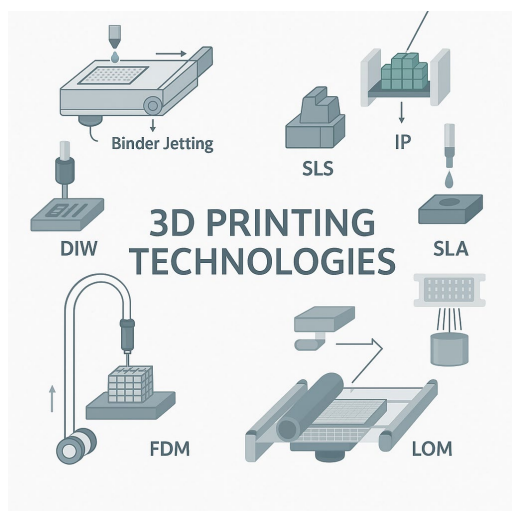


Figure 3. Overview of common 3D printing technologies (Binder Jetting, SLS, IJP, SLA, DIW, FDM, and LOM) for energy storage applications adapted from Chang et al., (2019).

These techniques enable the fabrication of EES devices with small overall footprints, well-designed patterns, and controllable electrode thickness. Compared to traditional subtractive processes, 3D printing offers a bottom-up manufacturing approach that allows for rapid construction of intricate 3D-structured energy storage systems at reduced costs. Table 2 also outlines the materials and methods used in the fabrication of energy generation components through 3D printing. The selection of materials was based on their mechanical, thermal, and electrical properties, as well as their availability and cost-effectiveness in the African context.

Table 2: Common Materials Used in 3D Printing for Energy Applications

Material Type	Examples	Application Area
Polymers	PLA, ABS, PVDF, Nylon	Structural components, piezoelectric devices
Metals	Titanium, Aluminum, Copper	Conductive parts, fuel cell components
Composites	Carbon fiber-reinforced polymers	Lightweight, strong structural elements
Ceramics	Alumina, Zirconia	High-temperature components, insulators
Nanomaterials	Graphene, Carbon nanotubes, BaTiO ₃ nanoparticles	Energy harvesting, supercapacitors
Printable Inks	Graphene-based, carbon aerogels	Electrodes for batteries and capacitors

3D printing offers a whole new bottom-up manufacturing approach to quickly construct 3D-structured EES devices with intricate structures and affordable prices compared to traditional subtractive processes.

3.2. Decentralized Renewable Energy

The decentralization of renewable energy sources is a crucial strategy for addressing energy poverty in remote and underserved areas of Africa (Zalengera et al., 2020). 3D printing plays a pivotal role in this domain by facilitating the creation of customized components for various renewable energy systems. One of the primary applications of 3D printing in decentralized renewable energy is fabricating solar PV system components (Tarancón et al., 2022).

Traditional solar panels, trackers, and mounting structures can be cumbersome and expensive to transport to remote locations. 3D printing offers a solution by enabling the on-site production of lightweight and efficient components. This empowers communities in remote areas to establish self-contained solar energy systems tailored to their specific needs. 3D printing technology introduces a level of customization in the production of wind turbine blades that was previously challenging to achieve. Wind conditions vary across different regions, and 3D printing allows for creating turbine blades specifically designed to harness the unique characteristics of local winds (Rouway et al., 2021). This customization maximizes energy output and efficiency, making wind energy more accessible and practical for communities in diverse geographical

settings. In regions with access to water resources, micro-hydro power systems can provide a sustainable source of electricity for rural villages. 3D printing facilitates the development of small-scale hydro turbines with components tailored to local water conditions. This approach harnesses the power of local water resources to generate electricity, offering a dependable and environmentally friendly energy solution for communities residing near rivers or streams. Figure 4 summarizes the application of 3D printing in the energy sector.

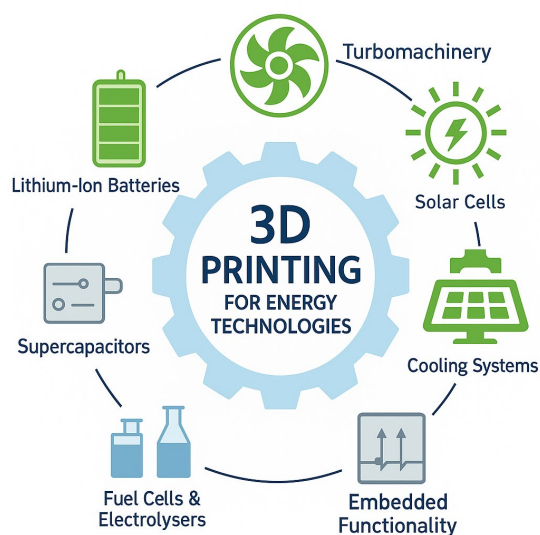


Figure 4. Schematic of 3D printing for energy applications (turbomachinery, solar cells, cooling systems, embedded functionality, fuel cells & electrolysers, supercapacitors, lithiumion batteries)

3.3. Energy Storage and Transmission

Efficient energy storage and transmission are critical components of a robust and reliable energy infrastructure. 3D printing contributes to advancements in this domain by offering innovative solutions for lithium-ion batteries and smart grid infrastructure (Tsaramirsis et al., 2022). Energy storage technologies, particularly lithium-ion batteries, are essential for storing excess energy generated from renewable sources for later use. 3D printing can revolutionize the production of lithium-ion batteries by allowing the creation of custom casings and internal components. This customization enhances the efficiency of batteries and reduces their weight, making them more suitable for off-grid and

decentralized energy systems. Smart grids play a crucial role in efficient energy management and distribution. 3D printing can be employed to manufacture sensors and communication devices essential for developing innovative smart grid infrastructure (Rathor & Saxena, 2020). These 3D-printed components contribute to the creation of a more responsive and interconnected energy grid, optimizing energy distribution and reducing wastage.

3.4. Energy-Efficient Devices

3D printing technology extends its influence on the development of energy-efficient devices that contribute to sustainable living practices. Customization and adaptability are key advantages offered by 3D printing in this domain (Cui et al., 2022). Traditional cooking stoves often contribute to deforestation and indoor air pollution. 3D printing allows for the creation of customized cookstoves designed for optimal efficiency. These 3D-printed stoves can reduce fuel consumption, mitigate deforestation, and improve indoor air quality, addressing health and environmental concerns in communities relying on solid fuels for cooking. Access to clean water is a fundamental requirement for rural communities. 3D printing enables the production of water pumps powered by renewable energy sources (Andres, 2021). These 3D-printed pumps can be tailored to local water conditions and energy availability, providing a sustainable drinking water and irrigation solution in rural areas.

3.5. Research and Development

The rapid prototyping capabilities of 3D printing offer significant advantages in the realm of research and development for sustainable energy solutions (Wang et al., 2021). This application accelerates the innovation cycle and facilitates education and training in the renewable energy sector. 3D printing expedites the development of prototypes for new energy technologies. Innovators can quickly and cost-effectively create physical models of their concepts, allowing for testing and refinement before large-scale implementation. This iterative process accelerates the deployment of sustainable energy solutions by reducing development timelines. 3D printing technology is a valuable tool for education and training in the renewable energy sector. Educational models and training tools can be created using 3D printing, providing direct learning experiences for students and professionals (Günther et al., 2020). This approach fosters the dissemination of knowledge and skills related to renewable energy technologies,

contributing to the growth of a skilled workforce in the energy sector.

4.0 Research and Development Initiatives

The pressing energy challenges facing Africa have spurred a wave of innovative initiatives leveraging 3D printing technology to transform the continent's energy landscape. These ongoing research and development endeavors demonstrate the potential of 3D printing to address energy poverty, promote sustainability, and empower local communities. This exploration delves into three notable initiatives:

4.1. Open-Source 3D Printed Micro-Hydro Power Project

The Open-Source 3D Printed Micro-Hydro Power Project is at the forefront of harnessing 3D printing for sustainable energy solutions in Africa. This initiative is driven by the vision of developing a low-cost micro-hydropower system that integrates easily replicable 3D printed components. The project recognizes the potential of micro-hydro power as a dependable and environmentally friendly energy source, particularly for rural areas with access to water resources (Svagir et al., 2019;). The primary objective of the Open-Source 3D Printed Micro-Hydro Power Project is to democratize access to clean energy by creating an open-source blueprint for a micro-hydropower system. By utilizing 3D printing technology, the project aims to reduce costs associated with manufacturing and increase the accessibility of this renewable energy solution. The easily replicable 3D-printed components are crucial to the scalability and widespread adoption of the micro-hydropower system. Its commitment to open-source principles sets this initiative apart, promoting collaboration and knowledge-sharing. 3D printing for critical components such as turbine blades and casing allows for customization based on local conditions, enhancing the efficiency of the micro-hydropower system. By making the design open source, the project encourages communities and researchers to adapt and improve the technology, fostering a collaborative approach to sustainable energy development. While the Open-Source 3D Printed Micro-Hydro Power Project represents a significant leap toward sustainable energy, it also faces challenges (Brown et al., 2020). Ensuring the reliability and durability of 3D-printed components in varying environmental conditions is a crucial consideration. The project's success hinges on overcoming these challenges and establishing a model that can be replicated and adapted in diverse settings across the continent.

4.2. 3D Printed Solar Kiosk Project

The 3DPrinted Solar Kiosk Project is a pioneering initiative that explores the intersection of 3D printing, solar energy, and digital services. This project centers on developing 3D-printable solar kiosks to provide clean energy solutions while offering digital services to rural communities (Diehl et al., 2023). The convergence of renewable energy and digital connectivity exemplifies the integrated approach needed for sustainable development. The 3DPrinted Solar Kiosk Project's primary goal is to address energy and digital connectivity challenges in remote areas. By harnessing solar energy through 3D-printed components, the project aims to establish solar kiosks that serve as energy hubs (Arabi et al., 2023). These kiosks provide clean and reliable energy and facilitate access to digital services such as internet connectivity, digital education, and telemedicine. The 3D-printable nature of the kiosks enhances scalability and adaptability to different contexts. This initiative stands out for integrating energy and digital services, recognizing the interconnected nature of modern development. The 3D-printed solar kiosks serve as a multifunctional solution, addressing energy poverty and bridging the digital divide (Li et al., 2023). By offering digital services, the project empowers communities with tools for education, healthcare, and economic opportunities. The 3D-Printed Solar Kiosk Project faces challenges related to integrating complex technologies and ensuring the sustainability of digital services in remote areas. The project's success hinges on effective community engagement, ensuring that the solar kiosks meet the specific needs of the communities they serve. As the initiative progresses, it can be a model for comprehensive energy and digital inclusion.

4.3. Makerspace for Sustainable Energy Project

The Makerspace for Sustainable Energy Project takes a grassroots approach, establishing makerspaces equipped with 3D printers in African communities (Mounde, 2020). This initiative recognizes the power of local innovation and community-driven solutions in sustainable energy. By providing access to 3D printing technology, the project empowers communities to design, prototype, and manufacture their energy solutions. The central objective of the Makerspace for Sustainable Energy Project is to democratize the innovation process. By establishing makerspaces equipped with 3D printers, the project seeks to create hubs of creativity where local communities can actively participate in developing their energy solutions. The makerspaces serve as collaborative environments where community members, including

entrepreneurs and students, can experiment with 3D printing technology for sustainable energy applications (Beltagui et al., 2021). This initiative embodies the spirit of community-driven innovation. By placing the tools of 3D printing in the hands of residents, the project catalyzes a bottom-up approach to sustainable energy development. Communities can design and iterate solutions tailored to their energy needs, fostering a sense of ownership and self-reliance. The project has the potential to address immediate energy challenges and stimulate local economies through entrepreneurship and skill development (Majid, 2020). The success of the Makerspace for Sustainable Energy Project depends on overcoming barriers related to access to technology, skills development, and the scalability of local solutions. Collaborative partnerships with educational institutions, businesses, and government entities can play a crucial role in sustaining and expanding the impact of makerspaces. The project's emphasis on local empowerment positions it as a catalyst for community resilience and sustainability.

4.4. Interdisciplinary Research Opportunities

The integration of 3D printing and materials science has the potential to revolutionize energy production in Africa. Advanced printable materials, such as conductive polymers and bio-based filaments, enable enhancements in solar cells, battery electrodes, and turbine components. Research by Chang et al. (2019) highlights techniques like Direct Ink Writing, Fused Deposition Modeling, and Stereolithography for developing micro-sized electrochemical energy storage devices. Collaborative efforts among mechanical engineers, materials scientists, and energy technologists can lead to significant advancements in thermal conductivity, electrochemical stability, and structural resilience, which are crucial for improving energy systems. Studies by Tarancón et al. (2022) and Browne et al. (2020) underscore the benefits of an interdisciplinary approach in creating sustainable and adaptable energy solutions.

5.0. Challenges and Limitations of Implementing 3D Printing for Energy Generation in Africa

Integrating 3D printing technology into Africa's energy landscape holds immense promise but has its share of challenges and limitations (Tabassum & Mir, 2023). Addressing these obstacles is crucial to realizing the full potential of 3D printing for

sustainable energy solutions on the continent. One of the primary challenges hindering the effective implementation of 3D printing technology for energy generation in Africa is the limited infrastructure (Signé, 2023). Access to electricity, a prerequisite for operating 3D printers, remains a significant hurdle in many African communities, particularly remote or underserved areas. Without a reliable power supply, the seamless integration of 3D printing into the energy generation process becomes challenging. Moreover, the requirement for reliable internet connectivity poses an additional layer of complexity. Many 3D printing processes involve accessing and transmitting digital designs, necessitating a stable internet connection. However, in regions with inadequate connectivity, the potential of 3D printing may be hampered, limiting the ability to share designs, access online resources, and benefit from collaborative initiatives (Rodríguez-Espíndola, 2020).

The availability of affordable and high-quality materials for 3D printing poses a critical limitation in Africa. The success of 3D printing relies heavily on the availability of suitable materials that meet specific criteria for strength, durability, and environmental sustainability. While advancements in material science have expanded the range of printable materials, ensuring their accessibility in Africa remains a challenge (Murphy, 2020). Affordability is a key consideration, as the cost of 3D printing materials can impact the feasibility of widespread adoption. Localized production and sourcing materials are essential to mitigate costs, but establishing reliable supply chains for these materials can be challenging in certain regions (Bazli et al., 2023). The need to import specialized materials can drive up expenses, making 3D printing less economically viable for communities facing financial constraints. Table 5 highlights some of the challenges and proposed solutions for 3D printing in energy generation in Africa. The success of 3D printing relies heavily on the availability of suitable materials that meet specific criteria for strength, durability, and environmental sustainability. Ensuring standardized testing and certification is essential (IEEE Industry Applications Society, 2024).

TABLE 5: CHALLENGES AND PROPOSED SOLUTIONS FOR 3D PRINTING IN ENERGY GENERATION IN AFRICA

Focus Area	Challenge	Proposed Solution
Material Accessibility	Limited access to suitable 3D printing materials; excessive costs and reliance on imports	Promote local material production through R&D and entrepreneurship; use recycled and sustainable materials
Infrastructure Gaps	Lack of reliable electricity and internet connectivity in rural areas	Deploy off-grid renewable energy systems (solar microgrids); expand rural broadband and mobile networks
Skills Shortage	Shortage of trained personnel for design, operation, and maintenance of 3D printing technologies	Implement training programs via vocational centers and universities; integrate 3D printing into STEM education
Durability & Standards	Printed components face durability issues in harsh conditions; lack of standardized testing	Develop region-specific design standards; conduct field trials; use hybrid materials and protective coatings
Policy & Governance	Absence of clear policies and regulatory frameworks for 3D-printed energy components	Establish supportive policies, incentives, and regulatory standards to encourage adoption and scaling
Environmental Concerns	Improper disposal of failed prints and non-biodegradable materials poses environmental hazards	Encourage use of recycled and biodegradable materials; promote circular economy principles

Table 6 further presents a SWOT analysis of the role of 3D printing in energy production in Africa, including expanded Opportunities and Threats with relevant case studies and examples.

TABLE 6: SWOT ANALYSIS: 3D PRINTING IN ENERGY PRODUCTION IN AFRICA

Category	Details
Strengths	<ul style="list-style-type: none"> - Enables decentralized and localized energy component production - Reduces manufacturing and transportation costs - Accelerates innovation via rapid prototyping - Supports diverse materials - Promotes job creation and community empowerment
Weaknesses	<ul style="list-style-type: none"> - Requires reliable electricity and internet, often lacking in rural areas - Limited access to affordable, high-quality materials - Shortage of skilled personnel - Durability concerns in harsh environments
Opportunities	<ul style="list-style-type: none"> - Accelerated Renewable Energy Deployment: 3D printing enables localized production of components for solar, wind, and hydro systems. Example: Open-Source 3D Printed Micro-Hydro Power Project. - Smart Grid Development: Supports creation of sensor housings and IoT enclosures. Example: Smart grid projects in Japan and the Netherlands. - Digital & Energy Inclusion: Combines energy access with digital services. Example: 3D Printed Solar Kiosk Project.

	<ul style="list-style-type: none"> - Circular Economy & Sustainability: Promotes use of recycled materials. Example: Makerspaces in Kenya and South Africa. - Educational & Vocational Training: Enhances STEM learning. Example: Makerspace for Sustainable Energy Project. - Policy Innovation: Supports new regulatory frameworks. Example: University-government collaborations in South Africa.
Threats	<ul style="list-style-type: none"> - Policy & Regulatory Gaps: Lack of standards may hinder adoption. Example: Open-Source Micro-Hydro Project lacks formal certification. - Environmental Risks: Disposal of failed prints poses hazards. Example: Waste challenges in Kenyan and South African makerspaces. - Economic Constraints: High costs deter adoption. Example: Makerspace for Sustainable Energy Project notes affordability issues. - Technological Obsolescence: Rapid tech evolution outpaces local capacity. Example: FabLabs struggle with outdated hardware. - Infrastructure Deficiencies: Unreliable electricity and internet disrupt operations. Example: Solar Kiosk Project faces power instability in rural areas.

5.1. Policy innovation and regulatory support

As 3D printing technology keeps getting better and shows how it could change how energy is made in Africa, the need for new policies is becoming increasingly important. To use additive manufacturing in energy systems, especially in areas that are decentralized and do not get enough attention, the rules need to be able to keep up with how quickly technology is changing. Without clear rules, standards, and rewards, people may be hesitant to use 3D-printed energy parts because they are unsure of what will happen and how risky it is (Rodríguez-Espíndola et al., 2020; IEEE IRDS, 2024; IEEE Technology Summit, 2025). Not only do supportive policies help keep printed parts safe and dependable, but they also encourage investment, collaboration, and the growth of successful projects. Partnerships between universities and governments, like the ones that are starting to happen in South Africa, show how policy frameworks can be created together to make sure that technological advances are in line with national development goals. By proactively addressing regulatory gaps and encouraging inclusive governance, African nations can fully utilize 3D printing as a driver of sustainable energy innovation.

5.2 Building Skills and Capacity for 3D Printing in African Energy Generation

Realizing the transformative potential of 3D printing technology for energy generation in Africa necessitates a strategic focus on building skills and

enhancing capacity within local communities. The multifaceted approach involves comprehensive training programs, the establishment of fabrication laboratories (FabLabs) and maker spaces, and the fostering of collaborative partnerships between universities, research institutions, and communities (Sharma & Halder, 2023). This concerted effort aims to empower individuals and communities to adopt 3D printing for energy solutions and innovate and tailor these solutions to their specific needs. Collaborative partnerships with educational institutions, businesses, and government entities can play a crucial role in sustaining and expanding the impact of makerspaces (IEEE SPEC, 2025).

5.2.1. Training Programs

Developing design expertise within local communities is central to the successful implementation of 3D printing. Training programs should focus on equipping individuals with the skills to create 3D models relevant to energy generation components. This includes understanding design principles, optimizing structures for efficiency, and adapting designs to local environmental conditions. Empowering individuals with design proficiency enables them to conceptualize and bring to life customized solutions that cater to the unique energy challenges faced by their communities. Beyond design, proficiency in operating and maintaining 3D printing technology is paramount. Training programs should cover the operation of 3D printers, including calibration, troubleshooting, and routine maintenance. This ensures the sustained

functionality of 3D printing equipment, reducing downtime and enhancing the reliability of the technology. Building local expertise in operation and maintenance contributes to the long-term sustainability of 3D printing initiatives for energy generation.

5.2.2. FabLabs and Makerspaces

Establishing FabLabs and makerspaces equipped with 3D printers creates hubs for innovation and direct learning. These spaces serve as communal workshops where community members, entrepreneurs, and students can access 3D printing technology. FabLabs offers a comprehensive array of fabrication tools, providing an environment conducive to experimentation and prototyping. By integrating 3D printers into these spaces, communities gain the resources to design, refine, and manufacture their energy solutions. The accessibility of FabLabs and makerspaces democratizes access to 3D printing technology, ensuring that even individuals without extensive technical backgrounds can engage with the technology (Beltagui et al., 2021). These spaces become centers for skill development, fostering a culture of innovation and collaboration. Moreover, FabLabs can serve as focal points for community-driven projects, encouraging collective problem-solving and co-creating sustainable energy solutions.

5.2.3. Collaboration with Universities and Research Institutions

Collaboration between universities, research institutions, and local communities facilitates a valuable exchange of knowledge and resources. Academic institutions can contribute their research expertise, technical knowledge, and access to innovative technology. In return, local communities provide contextual insights, practical challenges, and a deep understanding of the specific energy needs of their regions. This constructive interaction creates a dynamic environment for collaborative problem-solving and innovation. Universities and research institutions are pivotal in tailoring 3D-printed energy solutions to local needs. Researchers can co-create technologies that align with the cultural, social, and environmental context by engaging with communities. This collaborative approach ensures that 3D-printed energy solutions are technically viable and socially and economically sustainable (Khan & McNally, 2023). It also fosters a sense of ownership within communities, as they actively contribute to developing and implementing solutions that directly impact their lives. Collaboration extends to research and development initiatives that advance 3D printing applications for energy in Africa (Klenam et al., 2022).

Joint projects can explore innovative materials, optimize designs for local conditions, and address specific community challenges. By leveraging the expertise of academic institutions and the practical knowledge of communities, these initiatives can accelerate the development of sustainable and contextually relevant 3D-printed energy solutions.

5.3. Socio-Economic Impacts of Adopting 3D Printing for Energy Generation in Africa

Integrating 3D printing technology into energy generation in Africa goes beyond technological advancements; it holds the promise of significant socio-economic impacts. Adopting 3D printing for energy solutions is a catalyst for positive change, influencing economic development, job creation, community empowerment, and environmental sustainability (de Oliveira et al., 2023).

5.3.1. Increased Access to Energy

Decentralized renewable energy systems, empowered by 3D printed components, enhance African energy access. Communities can establish self-contained energy solutions by leveraging 3D printing to fabricate critical components such as solar panels, wind turbine blades, and hydropower systems. This increased access to reliable and sustainable energy is transformative, impacting daily life. The correlation between energy access and economic development is well-established. With reliable energy sources, communities can power small businesses, engage in productive agricultural practices, and operate essential services. 3D-printed energy solutions enable the creation of micro-grids and localized power systems, unlocking economic opportunities in remote and underserved areas (Stecula et al., 2023). The ability to establish and sustain economic activities contributes to poverty alleviation and fosters overall economic growth. Access to energy is intricately linked to the quality of life. It facilitates better healthcare services, enables educational initiatives, and enhances overall well-being. In regions where traditional energy sources are scarce or unreliable, 3D-printed energy solutions offer a lifeline. Clean and sustainable energy sources power essential services, such as healthcare clinics and educational facilities, improving living standards and creating a foundation for socio-economic advancement.

5.3.2. Job Creation and Economic Growth

The burgeoning 3D printing industry, driven by its applications in energy generation, has become a source of employment and economic growth. Jobs are

created at various 3D printing value chain stages, from manufacturing components to installing and maintaining energy systems. The production of 3D-printed components for energy systems generates employment opportunities in manufacturing (Sun et al., 2021). Local industries produce solar panels, wind turbine blades, and other energy-related components that witness growth, creating a skilled workforce. This localized manufacturing not only meets the energy needs of communities but also contributes to economic resilience. As 3D-printed energy solutions become prevalent, a demand for skilled technicians for installation and maintenance emerges. Communities benefit from job creation in these essential areas, creating a sustainable employment cycle. The need for ongoing maintenance fosters the development of a skilled workforce, ensuring the longevity and efficiency of 3D-printed energy systems.

5.3.3. Community Empowerment and Self-Reliance

A distinctive feature of 3D printing in energy generation is its ability to empower local communities. By enabling communities to design, prototype, and manufacture their own energy solutions, 3D printing fosters local ownership and participation. This empowerment goes beyond providing energy; it cultivates a sense of self-reliance, resilience, and community-driven innovation. Communities actively engaged in designing and creating their energy solutions become stakeholders in the development process. This sense of ownership enhances the sustainability of energy projects, as communities are more likely to invest in and maintain solutions that they actively contribute to creating. 3D printing for energy solutions enhances community resilience by providing tools to adapt to local challenges (Tomlinson, 2023). Communities can iterate and modify energy systems based on evolving needs and environmental conditions. This adaptability contributes to resilience in changing economic, climatic, or social circumstances.

5.3.4. Environmental Benefits

The environmental impact of 3D printing in energy generation cannot be overstated. By facilitating the development and deployment of renewable energy technologies, 3D printing reduces reliance on fossil fuels (Ju et al., 2023). This shift towards cleaner energy sources has far-reaching environmental benefits, including improved air quality and a reduced carbon footprint.

Conclusion

3D printing technology has the potential to revolutionize Africa's energy landscape by enabling decentralized, affordable, and customized energy solutions. This review is the first to comprehensively demonstrate that 3D printing, though widely applied in manufacturing and healthcare, represents a transformative and underutilized solution for renewable energy generation in Africa. It offers scalable, low-cost, and locally adaptable alternatives to traditional energy systems, particularly in remote and underserved communities. The transformative potential of 3D printing extends beyond energy provision to catalyze economic development, improve healthcare and education, and enhance overall societal well-being. Its affordability and capacity for customization make it especially suitable for addressing the financial and infrastructural constraints that hinder energy access across the continent.

To fully harness this potential, a collaborative and strategic approach is essential. Infrastructure development must address limited access to electricity and internet connectivity, while investments in reliable power sources and broadband expansion can mitigate operational challenges. Building skills and capacity within local communities is equally critical. Comprehensive training programs in design, operation, and maintenance of 3D printing technologies will empower individuals to actively participate in deploying and tailoring energy solutions. Establishing FabLabs and makerspaces can further foster a culture of innovation and local empowerment.

Finally, innovation must remain at the core of this transformation. Research and development initiatives, supported by partnerships between universities, research institutions, and communities, are vital to advancing 3D printing applications in energy. By weaving together infrastructure, capacity building, and innovation, Africa can position 3D printing as a cornerstone in its pursuit of a sustainable, inclusive, and resilient energy future.

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