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Framework for Adoption of Metal Additive Manufacturing in the Oil and Gas Industry in Africa

Al-Amin Barambu Umar[1]*, Muniru M Mai[1] and Devon Hagedorn-Hansen[2]

[1]Nigerian National Petroleum Company Limited (NNPC), Abuja, Nigeria

[2]HH Industries, Cape Town, South Africa

ABSTRACT

The oil and gas industry in Africa is under mounting pressure to elevate operational efficiency and curb costs, even as supply chain challenges stemming from the pandemic persist. Additive manufacturing (AM) emerges as a unique solution with the potential to free segments of the industry from conventional supply chains. This study introduces a framework tailored to the distinctive challenges and opportunities of the African oil and gas sector, aiming to facilitate the effective adoption of metal AM. Considering constraints such as supply chain limitations, unstable electricity supply, remote locations, and limited manufacturing facilities, this framework intends to guide stakeholders in leveraging the transformative potential of AM technology while overcoming potential barriers. Leveraging a literature review, expert insights, and real-world scenarios, the study assesses the current state of metal AM in the oil and gas sector. The framework's applicability is demonstrated through a case study of the Nigerian National Petroleum Company (NNPC) Limited, while acknowledging the specific African context. It uncovers the existing state of metal AM in Africa and identifies various facilities along with their constraints. Encompassing domains such as prototyping, customized tooling, complex component fabrication, and spare part production, the framework addresses challenges like cultural shifts, quality control, and facility sustainability. It offers key stages encompassing technology assessment, workforce training, and strategic planning to drive the transition toward additive manufacturing. The adoption of metal AM in Africa's oil and gas sector holds the potential to significantly enhance operational efficiency and competitiveness, yet it necessitates overcoming multifaceted challenges. The proposed framework presents a strategic roadmap for harnessing this technology's transformative potential. By embracing innovation and surmounting region-specific obstacles, Africa's oil and gas industry can attain enhanced efficiency, cost-effectiveness, and adaptability.

***Corresponding author**

Al-Amin Barambu Umar, Nigerian National Petroleum Company Limited (NNPC), Abuja, Nigeria. Tel: +234 806 287 5988.

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Introduction

In the oil and gas industry, the availability of spare parts when required stands as a critical factor for both sustaining seamless operations and managing costs effectively. The primary objective revolves around maintaining an uninterrupted supply of spare parts while ensuring financial viability [1]. To achieve this, the spare parts management system must swiftly respond to unforeseen demands, striking the delicate balance between expenses, stock levels, and prompt deliveries [2]. The consequences of unexpected downtime within the oil and gas sector can translate into substantial revenue losses, an impact further magnified by the convergence of aging equipment and supply chain disruptions.

Additive Manufacturing (AM), a process whereby components are manufactured layer by layer from three-dimensional (3D) model data, has gained prominence across various sectors. However, its incorporation in the oil and gas industry has been gradual, despite its substantial potential to yield economic benefits. Overcoming challenges, such as enhancing product performance, cost reduction, shorter lead times, and establishing a more flexible and decentralized supply chain, remains a pressing focus for the oil and gas sector, unattainable through traditional manufacturing techniques [3].

The Nigerian National Petroleum Company (NNPC) Limited holds a pivotal role in the global oil and gas landscape, serving as the state-owned entity responsible for managing Nigeria's extensive hydrocarbon resources. Established in 1977, NNPC is the central point for Nigeria's upstream and downstream petroleum endeavors, encompassing exploration, production, refining, marketing, and distribution of oil and gas resources. Its intricate functions include collaborations and partnerships with international oil companies, rendering NNPC a cornerstone of Nigeria's economy and a significant player on the global energy platform. This stewardship ensures optimal utilization of Nigeria's petroleum reserves and maximizes the returns from oil and gas exports. NNPC Limited also plays a crucial role in ensuring the accessibility and affordability of petroleum products to meet the energy requirements of the nation. The company oversees distribution networks, storage facilities, and retail outlets, guaranteeing the smooth dispersion of petroleum products throughout the country. Recognizing the potential of additive manufacturing, NNPC Limited has initiated projects to harness its benefits. Within the oil and gas sector, characterized by intricate supply chains, demanding operational conditions, and a crucial reliance on spare parts availability, additive manufacturing's disruptive potential holds immense promise. With a strategic commitment to metal additive manufacturing, NNPC's endeavors open a window to evaluate its current standing, challenges, and pathways for seamless integration of the technology.

To comprehend the landscape of metal additive manufacturing within the oil and gas sector, this study employs a systematic literature review. This review probes into existing studies to gauge the current status of metal additive manufacturing's integration in this industry. Additionally, the study investigates the hurdles encountered during the adoption process through the consolidation of established research, expert viewpoints, and real-world scenarios. Moreover, the study extends its focus by utilizing the implementation of a facility within the NNPC Limited as an appropriate case study. This approach is tailored to reflect the distinctive challenges of the African region, ensuring a comprehensive analysis.

The study spotlights the prevailing scenario of metal additive manufacturing in Africa, identifying diverse facilities along with their associated constraints. Delving the framework's exploration, it encompasses a range of domains, from prototyping and spare part production to customised tooling and intricate component fabrication. Amidst these explorations, the study uncovers an array of challenges hampering the seamless adoption of additive manufacturing. These include the necessity for a cultural paradigm shift, the establishment of rigorous quality control and certification protocols, as well as the sustainability of facilities and feedstock. Notably, the framework traverses’ key stages, encompassing a meticulous technology assessment to pinpoint suitable applications, comprehensive workforce training to nurture requisite expertise, and strategic blueprints to arrange an easy transition toward additive manufacturing implementation. Through this structured framework, the study aspires to provide an actionable pathway for the successful assimilation of metal additive manufacturing within the oil and gas sector, specifically considering the contextual backdrop of the African landscape.

Methodology

This study employs a comprehensive methodology that draws on three distinct approaches to shed light on the landscape of metal additive manufacturing (AM) within the African oil and gas sector. The methodology encompasses a systematic literature review, an analysis of published material pertaining to additive manufacturing research and development in Africa, and a case study focusing on the Nigerian National Petroleum Company (NNPC) Limited.

A systematic literature review was conducted to gauge the current state of metal additive manufacturing integration in the oil and gas sector within Africa. This review involved a meticulous search and extraction of relevant journal articles, conference proceedings, and monographs from the Scopus database. The keywords "additive manufacturing" and "3D printing" were strategically utilized to ensure comprehensive coverage. To ensure accuracy and minimize redundancy, the keywords within the title and abstract were carefully cross-referenced. Articles were selected based on their relevance to additive manufacturing in the oil and gas industry within the African context.

To provide a broader perspective on additive manufacturing research and development in Africa, an analysis of published material was conducted. This involved evaluating research articles, expert opinions, and collaborative efforts that shed light on the progress of additive manufacturing across various industries in the African region. Emphasis was placed on authors' affiliations, types of articles, domains of research, publication years, and national contributions. Only documents directly relevant to Africa were included in the analysis.

An adoption framework was then developed to structure the process of implementing AM for spare part production in an oil and gas company. This framework was validated against expert opinion and against a use case within NNPC Limited. The framework was utilised as a guide for the adoption process and to assist with determining the practical implementation of metal additive manufacturing within the NNPC. This involved an in-depth analysis of NNPC's initiatives, strategies, successes, and challenges in incorporating additive manufacturing technology. Information was gathered through interviews, documents, and available reports, aiming to provide a rich understanding of the adoption process, challenges faced, and outcomes achieved.

The findings from each of these three approaches were synthesized to provide a comprehensive overview of the status, challenges, and opportunities of metal additive manufacturing within the African oil and gas sector. By triangulating insights from the systematic literature review, the NNPC Limited case study, and the analysis of published material, this study aims to offer a multi-dimensional understanding of the role and potential of additive manufacturing in shaping the future of the African oil and gas industry.

Metal Additive Manufacturing and the Oil and Gas Industry in Africa

Challenges in the African Oil and Gas Sector

The African oil and gas industry faces several challenges, some of these challenges are briefly discussed below.

A. Supply Chain Limitations

One of the major challenges in the African oil and gas sector is the limitations within the supply chain. This includes inadequate infrastructure, such as ports, roads, and railways, which hampers the efficient movement of equipment, materials, and personnel. Insufficient logistics and storage capacities also contribute to delays and increased costs.

B. Unstable Electricity Supply

Unreliable and inadequate electricity supply is a persistent challenge in many African countries. This poses significant difficulties for oil and gas operations, particularly in remote areas where access to reliable power sources is limited. The reliance on fossil fuels for power generation further exacerbates the issue, leading to increased operational costs and environmental concerns.

C. Remote Locations

Many oil and gas reserves in Africa are located in remote and underdeveloped regions, far from major urban centers. This presents challenges in terms of accessibility, infrastructure development, and provision of basic amenities, making it more expensive and time-consuming to operate in these areas. Limited access to skilled labor and the need for extensive logistical planning further complicate operations.

D. Limited Manufacturing Facilities

The African oil and gas sector heavily relies on imported equipment and technology due to the limited presence of local manufacturing facilities. This dependency increases costs and delays, as well as hinders technology transfer and the development of local expertise.

E. Other Relevant Challenges

Several other challenges impact the African oil and gas sector, including political instability, regulatory uncertainties, inadequate access to financing, and environmental concerns. These factors can hinder investment, delay project approvals, and create a challenging business environment.

Additive Manufacturing in the Oil and Gas Industry

At the beginning of 2023, five oil and gas companies, such as ConocoPhillips, Equinor, Shell, TotalEnergies, and Vår Energi, inked an industry collaboration agreement. The goal of the two-year agreement is to pool resources in a bid to standardise the digital supply of spare parts, setting an industry standard for a digital inventory ecosystem. The digital ecosystem, which leverages additive manufacturing technology, will allow these companies to drastically reduce lead times, physical inventories, the total cost of ownership, and materials waste, whilst reducing shipping distances, and improving the overall environmental impact, efficiency, and security of the supply chain [4].

A number of companies are looking to additive manufacturing to improve supply chains and create new parts using the benefits of geometric freedom offered by certain AM technologies [5]. Tubing, piping, heat exchangers, and valves are some of the components that companies are looking to reproduce using AM technologies rather than conventional casting methods. Other companies like Vallourec and Total produced the first 3D-printed safety critical component in the oil & gas industry. The component was a waterbushing used in drilling operations to counteract the buildup of hydrocarbons in wells. The part was produced with Wire Arc Additive Manufacturing (WAAM) and can be observed in operation in Figure 1.

Figure 1: Waterbushing Manufactured with WAAM (Courtesy of Total Energies / Vallourec) [6]

In another notable development, Shell, a prominent industry leader, has emerged as a pioneer of additive manufacturing innovation in Europe. Collaborating with LRQA (formerly Lloyd's Register), Shell has achieved CE certification for a 3D-printed pressure vessel produced in-house. This accomplishment is the result of a four-year collaboration aimed at showcasing the potential of 3D printing within the energy sector. Shell's achievement is significant as it makes the company the first in Europe to secure CE certification for a part produced in-house using 3D printing. During this certification process, LRQA, acting as a Notified Body, officially categorised the printed vessel within the scope of the European Pressure Equipment Directive (PED), designating it as a Category III pressure vessel. This innovative vessel, carefully crafted using Powder Bed Fusion technology at the Shell Energy Transition Campus in Amsterdam, is engineered to operate safely under pressures of up to 220 bar. The CE certification marks a milestone for the energy industry, given the absence of dedicated legislation or global standards for 3D-printed pressure-retaining components. Consequently, 3D-printed pressure equipment has not been widely accepted within industrial assets worldwide. Shell's pioneering efforts have not only secured CE certification but have also laid the groundwork for enhancing industry trust in additive manufacturing as a technical solution for sourcing spare parts "just in time" instead of stockpiling them for extended durations. This certification represents a step forward in the industry's quest for efficiency and adaptability [7]. The pressure vessel printed on the Concept Laser M2 machine can be observed in Figure 2.

Figure 2: 3D Printed Pressure Vessel that Obtained CE Mark [7]

Metal Additive Manufacturing Technologies in the Oil and Gas Industry

AM produced parts in the oil and gas industry are often made of metals and their alloys due to the severe stress exerted on the part and occasionally the need for the part to resist corrosive environments. Due of this, the bulk of parts are produced utilizing metal additive manufacturing; nevertheless, non-metal AM processes are used to produce 3D prototypes. Stainless steel, *aluminium*, titanium, cobalt chrome, alloys based on nickel (like Inconel), and other alloys like super-duplex stainless steel are the most often used metals and alloys in the oil and gas sector [3]. The different technologies that use these and other materials to create metallic components are briefly discussed below.

Binder jetting is the joining process whereby thin layers of powdered material are selectively coated with a liquid bonding agent [8]. Metals, ceramics, composites, and polymers are among the materials that are employed in binder jetting. Binder jetting of metals is a sinter-based additive manufacturing (SBAM) technology whereby the metal green part is produced through the binder jetting process but needs to be sintered in a furnace to achieve the final part.

Material extrusion (ME) is a technology where the material is heated and continuously flowed through a nozzle at a constant pressure before being deposited layer by layer. As a part is created layer by layer, both the part platform and the nozzle move within the cartesian plane. This method is relatively inexpensive, and most desktop hobby machines are of the material extrusion type. Materials like plastics and polymers are mostly used in this technique. Numerous aspects may have an impact on the final product's quality, but with process monitoring and continuous feedback, high-quality goods can be produced [9]. Material extrusion technology such as fused filament fabrication (FFF) can also be utilised to manufacture metal components through Sinter Based Additive Manufacturing [8].

Powder Bed Fusion (PBF) technologies use either a laser or electron beam to melt materials that are primarily in the powdered state and fuse them together [10]. This technique is mainly used for metals. PBF techniques include electron beam melting (EBM), direct metal laser sintering (DMLS), and selective laser melting (SLM). In the case of EBM, parts are produced by melting metal powder in a high vacuum chamber layer by layer using an electron beam. DMLS and SLM are technically the same even though the one refers to sintering instead of melting. They both use lasers as their energy source. Steel, Cu alloys, Al alloys, and Ti alloy are the materials used in EBM and SLM [11].

Directed Energy Deposition (DED) is a technology that uses an energy source like a laser or electron beam that is directly focused on a small area of the substrate while concurrently melting the feedstock material (powder or wire) that is directed to the energy source focal point. Examples include laser-engineered net shaping (LENS) and directed metal deposition (DMD). High-performance superalloys can be processed using this technology [8]. After the laser beam moves, the molten material is then deposited, fused, and hardened into the melted substrate.

Laminated Object Manufacturing (LOM), commonly referred to as sheet lamination, is a process used to create 3D parts by stacking sheets of material together and bonding them. For metals, the process is also known as ultrasonic additive manufacturing (UAM). In the UAM process, metal sheets or ribbons are joined together by ultrasonic welding. In this method, a sheet of material is fused to the previous layer using ultrasonic welding before the layer is sliced into the required shape and the next layer is attached [12]. These steps are continued until the required 3D shape is obtained. To remove unbound metal that formed during the welding process from the completed product made through this procedure, additional CNC machining may be required. UAM uses a variety of metals, including titanium, stainless steel, copper, and aluminium.

Figure 3 summarizes global AM or 3D printing research, innovation, and development. China comes in second with a contribution of 11%, trailing the United States with 39% (Fig. 3a). The global market for AM technology is predicted to expand by 25–30% by 2025 and reach a value of US$ 40 billion. Figure 3b shows the overall contribution to market share for each year starting in 2016. At least 1.5 million 3D printers with high-quality features were distributed and in use by numerous sectors and academic institutions as of 2019 [13]. By 2027, the number is predicted to increase to approximately 8 million people. This set acceptance for the 3D industry's growing research and development as well as the benefits of 3D printing, which is additive in nature as opposed to the majority of subtractive manufacturing techniques. The advantages of AM over traditional subtractive processes are time, cost, product complexity, resource consumption, material quality and structural integrity, post-fabrication processing and treatment, waste, prototyping, and general applications.

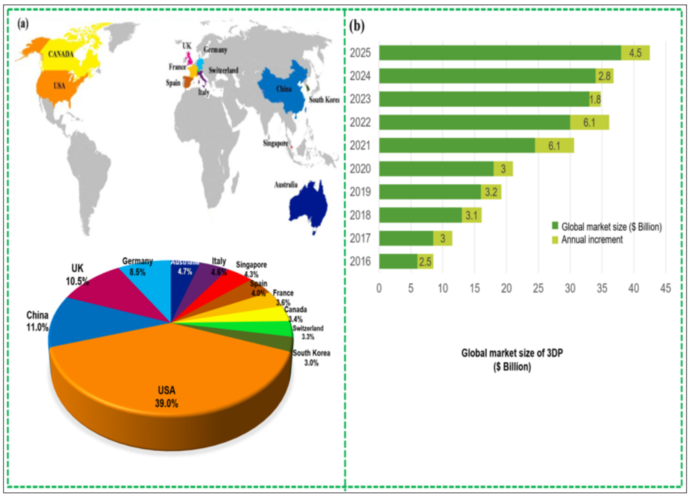


Figure 3: Global Outlook of AM Technologies showing: (a) Research intensive in developed countries, (b) Yearly distribution of milestones and global market share in US dollars [13]

Metal Additive Manufacturing in Africa

Currently, metal additive manufacturing adoption in Africa is limited to only a handful of countries. The map in Figure 4 shows the various metal additive manufacturing facilities located in Africa. Most of these facilities find their home in South Africa, while Nigeria, Morocco, and Egypt also mark their spots with metal additive manufacturing presence. These pins on the map spotlight the expanding reach of metal additive manufacturing, showcasing a blend of technological progress and regional collaboration.

Figure 4: Metal Additive Manufacturing facilities in Africa [14]

Presently there are roughly 23 metal additive manufacturing facilities in Africa. The facilities can be classed into 4 groups namely, government funded academic and research facilities, government facilities, large organization facilities, and small to medium enterprises facilities. These facilities have various types of metal additive manufacturing technologies with Laser Powder Bed Fusion being the most prominent technology (Table 1). Thus, LPBF technology was further investigated in this study, alongside the various parts that can be manufactured for the oil and gas industry. Most of the machines in Africa are located at government-funded academic and research facilities. In South Africa, government-funded, and academic facilities were the early adopters of AM technologies which led to a strong skill pool development and collaborations with industry [15].

Table 1: Metal Additive Manufacturing Technology Types Installed in Africa [14]

Location	LPBF	DED	Binder Jetting	Material Extrusion
Egypt	3	1	0	0
South Africa	21	8	2	3
Nigeria	1	0	0	0
Morocco	4	0	0	0

The adoption of metal additive manufacturing in Africa faces a range of challenges, as evidenced by insights from various sources [15-18]. A notable challenge is the technological lag that hinders the continent from keeping pace with global advancements in additive manufacturing. This lag poses a significant barrier to the effective integration of this transformative technology into African industries. In particular, the success factors observed in countries like South Africa, Morocco, and Egypt highlight the presence of underlying challenges related to visionary leadership, financial constraints, skills gaps, and limited interaction between academia and industry.

Furthermore, the importance of strong governmental support is emphasized, as exemplified by South Africa's experience, yet establishing consistent and long-term support from governments across Africa remains a challenge. The vision set forth in Egypt's Vision 2030 emphasizes the importance of new technologies, including 3D printing [17]. Such support is crucial for research funding, policy formulation, and the development of requisite infrastructure. Skill and workforce development emerge as another significant challenge, despite the lessons learned highlighting the importance of human resource enhancement through international partnerships. Formulating effective strategies to bridge the skills gap and create a proficient workforce capable of harnessing additive manufacturing's potential is imperative [15].

Effective industry-research networking and coordination, as demonstrated by South Africa's Rapid Product Development Association of South Africa (RAPDASA), is vital for preventing the duplication of efforts and pooling resources. However, the challenge remains in establishing such coordination mechanisms, encompassing institutional and logistical barriers. Aligning research priorities with local industrial needs, a key success factor for South Africa, poses a challenge across Africa. Overcoming this challenge involves understanding the unique demands of African industries and ensuring research efforts directly address these requirements [16].

The benefits of AM technology are more widely known and seen in research in Egypt. Numerous universities, research institutions, and regional manufacturing companies support this. The Additive Manufacturing Centennial Lab at the American University in Cairo, which focuses on wire-based AM technology, is one of these endeavours. In a similar vein, "PrintLab Egypt" also manages the AMTech business, which continues to advance AM product creation and research. Under the garb of the Fourth Industrial Revolution, this has led to the need to retool and reskill the next generation of workers in a time of overwhelming complexity, rapid change, and intense competition. This is done to put the country in a position to benefit from AM and Egypt to become a global player in this arena [19].

In Nigeria, there is little public-private collaboration in its manufacturing sector on 3D printing. For instance, the National Agency for Science and Engineering Infrastructure (NASENI) established the prototype engineering development institute (PEDI) and engineering materials development institute (EMDI) to further research on AM and other materials. There are currently 3D printers placed specifically for doing research and building sustainable AM capacity [20]. The NNPC through its Research, Technology & Innovation (RTI) division is currently establishing a metal AM and scanning facility that will serve as the centralized knowledge repository, actively engaging with different NNPC departments and establishing strategic partnerships with pertinent collaborators and other industry players. More details of this will be given in section 4.2.

Morocco has made advancements in additive manufacturing research and development. This can be linked to a number of private and public initiatives, including the inauguration of the Thales Industrial Competence Centre for Metal AM Research in 2017, the establishment of the Moroccan Association of Additive Manufacturing and 3D Printing, and a series of International Conferences on Additive Manufacturing, the first of which took place between November 19 and 20, 2020 [21]. These conferences served as a venue for regional and worldwide researchers working in a variety of Industry 4.0 and AM-related fields.

Moreover, fostering international partnerships for additive manufacturing development, as seen in Egypt, presents challenges in terms of aligning goals, navigating cultural differences, and establishing sustainable collaborations [17]. The burgeoning startup ecosystem in countries like Nigeria, South Africa, and Egypt could play a role in additive manufacturing adoption. Yet, startups face common challenges, including funding constraints, scalability issues, and the need for sustainable business models that could influence broader technology adoption. The additional challenge is that of access to stable power from the grid, as many countries in Africa suffer from unstable grids with power outages and fluctuations.

Cultivating a collaborative culture and driving innovation across institutions and sectors remains a challenge, even though South Africa's RAPDASA exemplifies the value of such efforts. Finally, the establishment of educational institutions and initiatives around additive manufacturing underscores ongoing awareness efforts. Overcoming the challenge of ensuring widespread awareness among stakeholders, potential users, and the general public is vital for the successful adoption of metal additive manufacturing in Africa. The experiences of South Africa, Morocco, and Egypt underscore the importance of collaborative endeavours, strategic planning, and capacity building to overcome these challenges and ensure additive manufacturing's growth on the continent.

Additive Manufacturing Adoption Framework

4.1. Introduction to the Adoption Framework

In the landscape of the African oil and gas industry, where cost-effectiveness, and adaptability are vital, the integration of metal additive manufacturing (AM) emerges as a transformative solution. This framework outlines a strategic structure for the successful adoption of AM within this industry, uniquely tailored to the challenges and opportunities specific to the African context. As the demand for operational uptime grows with aging infrastructure and alongside the complexities from supply chain disruptions and evolving market dynamics, the adoption of AM holds the promise of not only addressing these challenges but also ushering in a new era of production flexibility and component improvement. Grounded in a comprehensive approach, this framework navigates the complex journey from technological assessment to cultural acceptance, providing a structured roadmap that guides stakeholders toward harnessing the full potential of AM technology. Through a systematic consolidation of best practices, training, quality assurance, infrastructure development, and continuous improvement, this framework aids in improving the position of the oil and gas industry in Africa with respect to additive manufacturing adoption for spare part production.

Step 1: Technology Assessment

- **Objective:** Identify suitable applications for metal additive manufacturing (AM) in the African oil and gas industry.
- **Process:** Evaluate existing industry needs, challenges, and components where AM can add value, considering factors such as complexity, customization, and feasibility.
- **Outcome:** Compilation of potential applications where AM can provide significant advantages.

Step 2: Workforce Training and Expertise Development

- **Objective:** Build the necessary knowledge and skills within the workforce to effectively utilize AM technology.
- **Process:** Design and implement comprehensive training programs to familiarize employees with AM principles, operation, and maintenance.
- **Outcome:** Empowered workforce capable of harnessing the full potential of AM, contributing to successful adoption.

Step 3: Infrastructure and Facility Sustainability

- **Objective:** Establish a robust infrastructure to support the long-term implementation of AM technology.
- **Process:** Design and construct facilities equipped with the necessary equipment, power supply, and environmental controls to facilitate AM operations.
- **Outcome:** Sustainable facilities capable of consistent AM production and operation, minimizing downtime and disruptions.

Step 4: Quality Control and Certification Establishment

- **Objective:** Ensure the production of reliable, high-quality components through established quality control and certification processes.
- **Process:** Develop stringent quality control protocols tailored to AM, including material testing, component evaluation, and performance standards.
- **Outcome:** A verified and certified AM process, enhancing the industry's confidence in utilizing AM-produced components.

Step 5: Supply Chain Integration and Feedstock Management

- **Objective:** Integrate AM into the existing supply chain and ensure the availability of quality feedstock.
- **Process:** Collaborate with suppliers to provide appropriate raw materials for AM, establish efficient logistics, and integrate AM-produced components into the supply chain.
- **Outcome:** Seamlessly integrated AM process within the industry's supply chain, reducing lead times and enhancing component availability.

Step 6: Cultural Shift and Acceptance

- **Objective:** Cultivate a receptive organizational culture for AM adoption.
- **Process:** Conduct awareness campaigns, workshops, and educational initiatives to foster understanding, enthusiasm, and acceptance of AM among employees and stakeholders.
- **Outcome:** A shift in mindset where AM is embraced as a valuable tool rather than a disruption.

Step 7: Strategic Planning and Roadmap Development

- **Objective:** Develop a clear roadmap for the gradual integration of AM across different sectors of the oil and gas industry.
- **Process:** Formulate a comprehensive strategy detailing the gradual implementation of AM in various stages, considering budget allocation, timeline, and sector-specific requirements.
- **Outcome:** A well-defined roadmap guiding the adoption process, ensuring a systematic and phased approach.

Step 8: Monitoring and Continuous Improvement

- **Objective:** Ensure ongoing success and optimize the AM implementation.
- **Process:** Regularly assess the performance of AM applications, gather feedback, and continually refine processes to enhance efficiency and quality.
- **Outcome:** A dynamic and continuously improving AM ecosystem tailored to the evolving needs of the African oil and gas industry.

4.2. Case Study: Application of the Framework to NNPC Limited

The NNPC has actively undertaken to integrate additive manufacturing technologies into its operations. By using the adoption framework to streamline the process, the NNPC has demonstrated the benefits of the framework and slowly progressed through each stage while preparing for the latter stages during the adoption process. This section highlights some of the steps and how the NNPC is currently progressing through them.

Step 1: Technology Assessment

In this context, an exploration of high-impact use cases was carried out, in collaboration with subject matter experts, to assess the feasibility of various additive manufacturing technologies. The selection of these use cases aimed to maximize return on investment (ROI) while aligning with the unique challenges and opportunities specific to the NNPC's operations. By employing a multi-criteria decision analysis approach, a comprehensive evaluation of various parts was conducted to pinpoint those exhibiting a high potential for ROI. The selection process involved a careful consideration of factors such as part size, material characteristics, design intricacy, post-processing prerequisites, manufacturing time, and cost. Subsequently, the present cost and lead time for order fulfillment were seamlessly integrated into the ROI calculation. The analysis involved assigning greater weightage to parts characterized by elevated costs and extended lead times, effectively prioritizing them over readily accessible alternatives sourced from original equipment manufacturers.

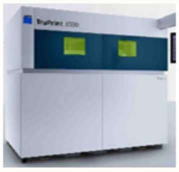
This systematic methodology seeks to not only evaluate the technical feasibility of integrating additive manufacturing but also to ensure economic viability within the context of NNPC's operations. The forthcoming sections delve into the strategic formulation of use cases, the intricate process of technology evaluation, and the vital role played by ROI calculations in driving the adoption of additive manufacturing technologies tailored to NNPC's specific needs.. Several components were identified with high ROI and ease of manufacturing with the specific AM technologies in the scope of the adoption project. These parts can be observed in table 2.

Table 2: Additive Manufacturing Use Case Development Results

Part Name	Use	Material	AM Technology
Shaft Coupling	To connect the rotating pump shaft with the drive shaft of the motor	Rubber	Material Extrusion or Vat Polymerisation
Shrouded Impeller	Pumping specific liquids	Brass, Stainless Steel,	Powder Bed Fusion
Unshrouded Impeller	Pumping specific liquids	Stainless Steel, PEEK	Powder Bed Fusion, Directed Energy Deposition, or Material Extrusion
Control Valve Trims	Control the flow of liquid and gas through a valve	Stainless Steel	Powder Bed Fusion
Choke Cage Valves	Throttle the flow of liquid in a valve	Stainless Steel	Powder Bed Fusion or Directed Energy Deposition
Burner Plugs	To plug an access hole in a burner	Inconel	Powder Bed Fusion or Directed Energy Deposition
Drill Bits	To create the hole	Steel with Tungsten Carbide Buttons	Powder Bed Fusion or Directed Energy Deposition
Stators	Direct fluid through to a rotor or direct flow type	Stainless Steel	Powder Bed Fusion

Once the potential use cases were pinpointed, an in-depth assessment of available technologies and hardware options was conducted. Among the additive manufacturing processes, laser powder bed fusion emerged as the optimal choice due to its practicality compared to the complexity of electron beam melting, which demanded additional facility considerations often challenging in the African context. A machine comparison was performed to check the various models available and their strengths and weaknesses or fundamental differences. The Direct Metal Laser Melting (DMLM) machine comparison can be observed in Table 3.

Table 3: Metal Laser Powder Bed Fusion Machine Comparison

DMLM Machine Compari-son					
Specification	**Concept Laser M2 Series 5**	**EOS M290**	**SLM 280 2.0**	**Trumpf TruPrint 3000**	**Renishaw Re-nAM 500S**
Build Volume	250 x 250 x 405 mm	250 x 250 x 350 mm	280 x 280 x 365 mm	300 mm diameter x 400 mm	250 x 250 x 350 mm
Support & Slic-ing	Materialise Magics or Autodesk Netfabb	Materialise Magics or Autodesk Netfabb	Materialise Magics or Autodesk Netfabb	Materialise Magics or Autodesk Netfabb	Materialise Magics or Autodesk Netfabb
Max Build Size with 50 mm Substrate	245 x 245 x 355 mm (heated)	250 x 250 x 300 mm	275 x 275 x 315 mm	300 mm diameter x 350 mm	245 x 245 x 300 mm
Layer thickness	25 – 120 µm	20 – 100 µm	20 – 90 µm	20 – 150 µm	20 – 100 µm
Laser Source Manufacturer	IPG	IPG	IPG	Trumpf	SPI/Trumpf
Laser focus diameter	70 µm	100 µm	80 µm	80 µm	80 µm
Dynamic 3D Laser Focus	Up to 500 µm	Optional	Up to 115 µm	NP	Up to 500 µm
Laser Configu-ration	Single Laser or Dual Laser	Single Laser	Single Laser or Dual Laser	Single Laser or Dual Laser	Single Laser or Quad Laser op-tions
Laser Power	400 W or 1 kW	400 W	400 W or 700 W	500 W	500 W
Inert Gas Consumption	5 l/min (Argon)	NP	8 l/min (Argon)	NP	1 l/min (Argon)
Power Input	400 V, 32 A, 5.5 kW up to 10.5 kW	400 V, 32 A, 8.5 kW	400 V, 63 A, 5.5 kW	400 V, 32 A, NP	400 V, 50 A, NP
Safety Glove Box	Standard	Optional	Optional	Optional	Optional
Heated Build Chamber	Optional	Optional	Optional	Standard	NP
Coating Quality Control	Optional	Optional	Optional	Optional	Optional
Source	[22]	[23]	[24]	[25]	[26]

*NP is information Not Published

The selection of a Concept Laser M2 Series 5 machine, provided by General Electric (GE) Additive, was driven by the machine's robust reputation for reliability on the African continent and the stringent quality prerequisites set by GE. Most of the machines had similar features without much variation in hardware options. The Concept Laser M2 was also selected due to the high focus of the machine’s architecture on safety. With the safety of staff and operators in mind, the Concept Laser M2 Series 5 was viewed as the best option as the glove box comes standard, so safety is not seen as an optional expense.

To facilitate industrial scanning of components, the Creaform HandyScan Black Elite was designated, primarily for its adherence to standards and the added advantage of a comprehensive digital training platform. All additive manufacturing and scanning equipment will be hosted within the NNPC RTI facility, accompanied by a skilled team proficient in their operation.

To affirm the practical applicability of the selected AM technologies for the earmarked use cases, specific components associated with these use cases were fabricated in collaboration with technology partners, solidifying the proof of concept. Images of these components can be observed in Figure 5.

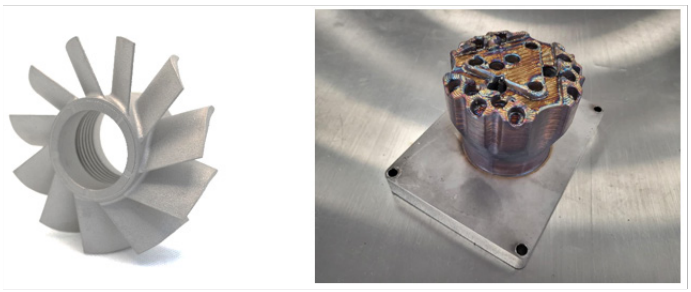


Figure 5: Proof of Concept Parts Manufactured by HH Industries/ RTI, NNPC Limited (Left) Inconel Drill Rig Stator, (Right) Steel Drill Bit without tungsten carbide buttons

Step 2: Workforce Training and Expertise Development

In order to ensure smooth, company-wide adoption, NNPC RTI will serve as the centralized knowledge repository, actively engaging with different NNPC departments and business units for knowledge dissemination via training, whitepapers, conferences, and publications. Establishing strategic partnerships with pertinent collaborators and other industry players will also be integral to the NNPC RTI team's scope. The various subject matter experts (SME's) can be observed receiving DMLM training in Figure 6.

Figure 6: Various NNPC Staff Receiving DMLM training with HH Industries

Step 3: Infrastructure and Facility Sustainability

The facility design phase encompassed the incorporation of cutting-edge AM equipment, ensuring that the facilities are technologically advanced and ready to meet the evolving needs of NNPC Limited. Attention was also devoted to power supply reliability, recognizing its critical role in sustaining uninterrupted AM operations. Moreover, environmental controls were integrated into the facility design to create an optimal production environment, aligning with NNPC Limited's commitment to sustainability. The entire facility was sourced and put together by HH Industries which streamlined the procurement process as well as standardized the training to utilize the equipment. The facility equipment ready to ship can be observed in Figure 7.

Figure 7: NNPC DMLM Facility Ready to Ship at HH Industries

The remaining steps of the framework are currently underway and various projects have already been initiated to achieve the objectives of the various framework stages.

Discussion

The presented study sheds light on the current status, challenges, and prospects of metal additive manufacturing (AM) adoption within the African oil and gas industry. The highlighting of the activities of the biggest oil and gas companies with regard to digital supply chains and additive manufacturing shows a paradigm shift in the industry towards AM technology and the need for certification for AM parts. The examination of metal AM facilities across Africa, as depicted in Figure 4 and Table 1, emphasizes the emerging yet promising nature of this technology's presence on the continent. The concentration of these facilities in South Africa, along with notable installations in Nigeria, Morocco, and Egypt, highlights the early strides being taken towards integrating AM into various sectors in several African nations. The expansion of metal AM facilities in these regions underscores a collaborative effort aimed at leveraging technological advancements to meet the continent's evolving demands.

The Additive Manufacturing Adoption Framework, as presented in Section 4.1, serves as a strategic guide to navigating the complexities of AM integration within the African oil and gas industry. This systematic approach, spanning from technology assessment to cultural shift, acknowledges the multifaceted nature of AM adoption. By addressing issues such as workforce training, quality control, and infrastructure development, the framework positions AM as a viable solution for enhancing operational efficiency and adaptability. The emphasis on continuous improvement underscores the dynamic nature of the oil and gas sector, ensuring that AM implementation remains agile and responsive to evolving industry demands.

The detailed case study of the NNPC in Section 4.2 provides valuable insights into the practical application of AM technologies. By assessing high-impact use cases, the NNPC exemplifies a proactive approach to maximizing return on investment (ROI) while aligning with operational necessities. The utilization of multi-criteria decision analysis offers a systematic method to select parts that exhibit the potential for significant ROI. The integration of cost and lead time into the ROI calculation exemplifies a comprehensive evaluation approach that considers both technical feasibility and economic viability.

The selection of laser powder bed fusion as the optimal AM technology within NNPC's context underscores the practical considerations involved in technology selection. The strategic choice of the Concept Laser M2 Series 5 machine and the Creaform HandyScan Black Elite scanner for component production and scanning, respectively, reflects a thorough evaluation of reliability, quality prerequisites, and training availability. The localization of equipment and knowledge within the NNPC Research, Technology, and Innovation Division positions the company to be a pivotal hub for fostering AM-related expertise within the African oil and gas landscape.

The validation of various stages of the framework through the NNPC case study was performed up to Step 3. While the remaining steps have not yet been concluded, the framework has aided in allowing the NNPC to plan for the next stages of adoption and to take a proactive approach to achieving the latter outcomes of the framework.

Conclusions

In conclusion, the outlined framework for the adoption of metal additive manufacturing in the African oil and gas industry presents a comprehensive blueprint to address the unique challenges and opportunities within this dynamic sector. By strategically addressing the diverse aspects ranging from technological assessment, workforce development, quality control, and supply chain integration to cultural transformation and continuous improvement, this framework offers a roadmap that ensures the successful integration of AM technology. As the industry strives to enhance operational efficiency, reduce costs, and navigate complex supply chain issues, the adoption of AM stands as a pivotal solution. By embracing this framework and fostering collaboration among stakeholders, the African oil and gas industry can effectively harness the transformative power of additive manufacturing, enhancing its competitiveness, resilience, and future readiness. This framework not only opens new avenues for innovation but also cements the industry's position as a pioneer in the realm of additive manufacturing, shaping the trajectory of its growth and evolution in the years to come.

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