

ENERGY SECTOR

Developing a National Framework for Additive Manufacturing in the U.S. Energy Sector

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Abstract

The layer-by-layer printing of components using digital models, known as Additive Manufacturing (AM), is transforming manufacturing environments around the world. AM presents a new opportunity to redefine energy infrastructure production and maintenance in the United States, where energy security, industrial resiliency, and sustainability are strategic imperatives. The technology's capabilities span supply chain optimization and lifecycle emissions reduction in energy systems. However, even with significant investment by the U.S. Department of Energy (USDOE), the National Science and Technology Council (NSTC), and private industry, the lack of a coherent national framework specific to the energy sector has impeded coordinated development. The paper suggests a National Additive Manufacturing Framework to the U.S. Energy Sector (NAMF-E), a broad policy and institutional framework, which would incorporate governance of innovation, standardisation, capacity building of the workforce, and alignment to sustainability. Based on international experience in the oil and gas sector (Africa) and findings of AM effects on the global energy demand, the study conceptualises a model to mainstream AM in the systems of energy production, distribution, and consumption. The framework focuses on the coordination of inter-agencies, the involvement of stakeholders, and long-term sustainability indicators, making AM a driver of national competitiveness and a clean energy shift.

Keywords: additive manufacturing (AM); U.S. energy sector; National Additive Manufacturing Framework (NAMF-E); energy infrastructure; energy security; supply chain resilience; sustainability; innovation governance; workforce development; clean energy transition

1 Introduction

Technology and policy are set to make a major difference in the U.S. energy industry. Driven by the dual challenges of decarbonisation and industrial competitiveness, the search for manufacturing methods that can revolutionise the design, operation, and maintenance of energy systems has intensified. One of the most disruptive is additive manufacturing (AM), or 3D printing technology. Instead of using traditional subtractive manufacturing, AM is a progressive layering of material propelled by digital design files that is redefining the production paradigm (U.S. Department of Energy [USDOE], 2015). Its ability to make highly complex geometries with minimal waste, use new alloys, and manufacture locally at the point of need has a broad impact on the resilience and sustainability of the energy sector.

In a large-scale manufacturing environment, AM has gained significant momentum, from prototyping to full production runs, in the aerospace, healthcare, and construction sectors (Tofail et al., 2018). GE has partnered with international companies like GE Aviation and Siemens Energy to produce turbine blades, fuel nozzles and pressure vessels with enhanced performance and lower weight in AM. For instance, GE's fuel nozzle for its LEAP engine is 25% lighter and has five times the durability of the previous, conventionally manufactured fuel nozzle (GE Aerospace, 2018). This design approach

is now spreading to power generation hardware: Liu et al. (2023) demonstrate that AM-based design and processing of gas turbine blades also enables the manufacture of internal cooling channel geometry and turbine blade profile that cannot be cast or forged, thereby directly enhancing the thermal efficiency and service life of the corresponding power generation plants. The results of this type of analysis are representative of the efficiency and carbon footprint reduction that can be achieved, as well as a more resilient supply chain under an AM approach to design freedom in energy-adjacent industries (Sun et al., 2021).

A more recent energy sector-specific synthesis by Ukoba et al. (2025) reaffirms this picture, one in which AM is emerging as a key enabler of the on-demand production of components and optimised designs within the wider context of a Fourth Industrial Revolution (4IR) as it meets the energy infrastructure sector, and particularly in the case of renewable energy hardware that inevitably experiences a high rate of design iteration. Notwithstanding this development, there is no consistent national strategy in the United States for incorporating AM into the National energy transition strategy or industrial innovation strategy. The current efforts, such as America Makes, the USDOE Advanced Manufacturing Office, and the standardization efforts coordinated under the National Science and Technology Council (NSTC), continue to be largely focused and with little deployment plan for energy applications more than a few years out (National Science and Technology Council [NSTC], 2022).

Thus, it is appropriate and essential to develop a National Framework for Additive Manufacturing in the U.S. Energy Sector. Such an approach would help fill existing gaps in institutions and regulations, strengthen the integration of AM in national energy plans, and accelerate innovation in selected sub-segments of the energy sector, including renewables, nuclear power, or hydrogen energy. Empirical modelling indicates that, at scale, global industrial energy demand could be meaningfully reduced through AM adoption by implementing shorter supply chains and designing lighter components (Verhoef et al., 2017). This paper puts forward a multi-agency framework, grounded in international evidence and models developed for metal AM adoption in other resource-constrained energy contexts, such as a structured approach to guide metal AM adoption in Africa's oil and gas industry (Umar et al., 2023).

2 Conceptual and literature background

Studies on AM present a duality: it is considered both a technological innovation and an agent of industrial transformation. In a conceptual sense, AM shifts the manufacturing paradigm from a centralised, mass-production model to a distributed, digital, demand-driven one. In this way, economies of scope rather than scale are realized, allowing for the production of custom-made parts that waste less and have lower logistical costs. The impact of this is modelled directly by Verhoef et al. (2017), and they estimate that in the aerospace and construction sectors alone, by 2050, the use of AM could decrease global energy use by 5% to 27% thanks to weight reduction and shorter, more concentrated supply chains.

Research efforts around AM materials and processes such as powder bed fusion, directed energy deposition, and binder jetting, as well as the versatility of these materials and processes, have also been a focus of international research. Each option has its own distinct benefits for energy applications and for producing high-performance metallic components that will endure extreme operating conditions. Sun et al. (2021) identify these capabilities as examples of components in which AM is already being used to create structures that are hard or even impossible to produce

using traditional subtractive manufacturing techniques, such as nuclear reactor internals, fuel cladding, and pressure vessel components. This principle is also illustrated in a parallel series of research on power-generation hardware: A fuel path with internal cooling structures and graded materials used in AM-produced gas turbines can massively enhance thermal tolerance while simultaneously minimizing material waste compared to conventionally cast gas turbines, directly relevant to fossil, hybrid, and future generation combustion turbine assets in the U.S. energy fleet, as described by Liu et al. (2023). These capabilities are critical to the U.S. goals of modernizing fossil fuel plants, expanding turbine manufacturing, and servicing aging nuclear infrastructure (USDOE, 2015). Future AM-enabled energy systems are also anticipated to include digital twins, robotics, and predictive analytics, elevating AM from a manufacturing tool to the core of future energy infrastructure (Tofail et al., 2018).

In this paper, the authors extend that literature by placing AM in the context of the broader Fourth Industrial Revolution, which highlights the key considerations of the technology such as the reduction of cost, compression of time-to-market, and design optimisation, which are becoming more prominent in the deployment of renewable energy, where the iteration of components is becoming more frequent and performance requirements are evolving more rapidly. In contrast, Umar et al. (2023) discuss a systematic model of the adoption of AM to solve structural problems in the African oil and gas industry, such as skill gaps in the workforce, high operating costs, and unreliable supply chains. Four phases technology assessment, workforce training, infrastructure preparedness, and continuous improvement—are equally relevant in the U.S. context, as the model shows. Still, they represent vastly different starting points in the U.S. context. The American energy system has a much more advanced industrial and regulatory ecosystem. Still, it has its own coordination challenge: a lack of interagency regulation, fractured governance, and a lack of common data and certification standards to facilitate scalable integration of AM (NSTC, 2022).

3 The U.S. energy sector and the need for additive manufacturing integration

The U.S. energy system comprises fossil fuels, renewables, and nuclear, and all are under increasing pressure to become more efficient, reliable, and sustainable; AM is already making headway in adjacent industrial sectors. One example of GE's AM work is the manufacture of fuel nozzles for its jet engines that were 25% lighter and five times more durable than their predecessors, and that were made from just 20 distinct parts before, down to one with AM (GE Aerospace, 2018). Similar efficiencies are possible in gas turbine components and wind power structures when applied to energy-sector applications; Liu et al. (2023) prove this directly, with their AM-processed turbine blades being able to withstand higher operating temperatures as well as lower use of raw material than forged or cast blades, which increases fuel efficiency and reduces maintenance cycles for energy-generating assets. AM's ability to create complex geometries enables optimised thermal performance, lower component weight and increased fuel efficiency, all leading to measurable energy savings throughout the value chain (Verhoef et al., 2017).

AM is also transforming manufacturing in the renewable energy sector, such as wind turbine blade components, energy storage, and specialty solar components. Generating replacement parts locally or on-site decreases logistical cost and equipment downtime, especially pertinent in renewable installations in remote and logistically limited sites where replacing parts is time-consuming and can leave generation capacity idle for significant periods. Ukoba et al. (2025) suggest that the ability to manufacture replacements locally or in the immediate vicinity also reduces replacement-part lead

times and equipment downtime. For nuclear energy, AM is at the forefront of being investigated for the creation of radiation-resistant alloys and the construction of components for the reactors' internals that can be easily serviced and potentially have a longer service life for the entire plant (Sun et al., 2021). AM's ability to rapidly produce key components through on-demand printing decreases reliance on long supply chains distributed across various parts of the world, a feature already being explored in the structured adoption model developed for the oil and gas industry in Africa (Umar et al., 2023).

Yet there are still significant integration issues to overcome. Unresolved cybersecurity challenges regarding digital part files and uneven technical readiness of the energy workforce are the greatest barriers (NSTC, 2022). Those cybersecurity concerns are far from theoretical: Gupta et al. (2020) describe AM as an inherently cyber-physical system where the digital thread that connects the design to the actual production adds new attack surfaces, such as design tampering, theft of intellectual property, and production of counterfeit parts, with correspondingly high consequences when the end product is a safety-critical component in the energy sector. The deployment of the material in energy infrastructure is further complicated by regulatory uncertainty regarding material quality assurance, operational safety and IP protection, since there are significantly greater safety and reliability impacts when components fail in energy infrastructure compared to other industries that are not considered to be as safety critical (Tofail et al., 2018). This is especially significant because energy infrastructure assets are likely to have a multi-decade lifetime, and the lack of harmonisation today is likely to limit AM uptake for years to come. A coordinated national framework that integrates these regulatory, technical, and human resources aspects is necessary to maximize the potential of AM to transform U.S. energy infrastructure, as it has already shown in other related industries.

4 Policy and institutional context

American policy-makers have a considerable and fragmented policy environment for advanced manufacturing. The CHIPS and Science Act (2022) provides substantial investment in building domestic manufacturing capacity and supply chain resilience, and the USDOE's Advanced Manufacturing Office funds AM research through the national laboratory system. The NSTC's Subcommittee on Advanced Manufacturing also coordinates the National Strategy for Advanced Manufacturing, which establishes national goals for technology development, workforce development, and supply chain resilience. It provides AM measurement science, data standards, and quality certification pathways (NSTC, 2022). However, efforts for standardisation within the industry have started filling some of these gaps: The 2023 AM Data Security and Supply Chain Standardisation Roadmap was released by the Additive Manufacturing Standardization Collaborative (AMSC), sponsored by America Makes and the American National Standards Institute (ANSI), and found that the existing general-purpose IT cybersecurity guidance is still applicable, while no standardised framework currently exists to address AM-specific security requirements (Additive Manufacturing Standardization Collaborative [AMSC], 2023). The discovery further supports the cyber-physical vulnerabilities Gupta et al. (2020) outlined and demonstrates the critical need for specific cybersecurity guidance for the energy sector when deploying AM. However, these are not inter-sectoral energy governance mechanisms, but they operate within their own institutional mandates and have very limited formal coordination among USDOE, NSTC, and DOD.

There are more integrated approaches in international approaches. Advanced manufacturing technologies, such as AM, are increasingly part of the architecture of the EU circular economy policy and are

being integrated directly into EU industrial policy (European Commission, 2021). A U.S.-national focus on energy could then be a coordinating mechanism, bringing together the work of USDOE, NSTC, the Department of Defense, and the private industry energy sector. This would prevent the country from investing in a technology that falls short of delivering productivity and sustainability benefits, instead becoming an array of isolated pilot projects, and provide the manufacturing industry with a single body to manage the lack of standardisation and cybersecurity that has been addressed over a series of disjointed efforts.

5 Additive manufacturing in energy: Proposed framework

Based on Umar et al. (2023), NAMF-Energy is structured into six connected pillars (Table 1)

Table 1. Core pillars of the proposed National Additive Manufacturing Framework for the U.S. Energy Sector (NAMF-Energy).

Pillar	Strategic focus	Key actions/policy measures
Research & innovation ecosystem	Foster discovery and invention	Funding research, consortia, testbeds established
Standards & certification	Ensure quality and interoperability	Develop standards, accredit facilities, certify products
Public-private partnerships	Leverage resources and expertise	Joint projects, shared facilities, funding programs
Workforce development	Cultivate skilled workforce	Education programs, apprenticeships, training initiatives
Sustainability & circular economy integration	Minimize environmental impact	Material reuse, lifecycle analysis, design optimization
Governance & interagency coordination	Align efforts and remove barriers	Policy alignment, data sharing, strategic planning

6 Policy implementation roadmap

Implementation of NAMF-Energy is considered to be an adaptive process that is to be carried out in phases. Short-term (1–3 years), the federal government should put in place interagency coordination and pilot projects. These may involve on-site repair of the USDOE power plants through the AM and the construction of wind turbine component prototyping. At the same time, training programs for the workforce should be initiated in the main industrial areas.

The medium term (3–7 years) should be devoted to the expansion of demonstration projects to commercial applications. In partnership with Oak Ridge and Sandia National Laboratories, some of the regional Energy AM Innovation Hubs can be created, combining private manufacturers and research institutions. Certification schemes designed by NSTC would initiate uniformity in testing components and quality checks.

However, the NAMF-Energy hopes that AM can become a standard constituent of U.S. energy infrastructure in the long run (7–15 years). The federal procurement systems would be made AM components, especially in the defence-energy initiatives. Additionally, AM efficiency indices should be included in the energy modelling platforms of the USDOE, e.g. Annual Energy Outlook, to monitor the national carbon reduction targets contribution.

7 Future directions and research implications

The introduction of AM into the energy ecosystem of the United States will create new research horizons. The use of AM in hydrogen systems of energy is one of the possible paths, as new materials can enhance fuel cells' efficiency and storage density. The other one is carbon capture and storage (CCS), in which case AM can create complex reactor structures that increase capture efficiency. Cybersecurity and digital integrity of AM supply chains studies are also important since the technology depends more and more on digital design files that can also be susceptible to manipulation.

Socioeconomically, further research should explore the impacts of AM on the employment of the region, gender inquiry into engineering, and the spread of the benefits of innovation to communities. Moreover, the life-cycle modelling, which Verhoef et al. (2017) highlight, should be integrated into the federal energy policy to measure the overall contribution of AM to the national energy saving. The joint international research on the U.S., EU, and emerging economies may also boost the spread of AM standards and best practices.

8 Conclusion

Additive manufacturing is a strategic requirement and economic possibility for the U.S. energy sector's development of a national framework. With the progress of energy systems that are in the direction of decentralisation and decarbonization, the skill to design, manufacture, and fix key infrastructure on a local scale will determine the national resilience. The additive manufacturing, with its own flexibility and efficiency, provides an unprecedented platform to achieve the objectives. However, lack of logical governance and policy congruency has retarded its systemic assimilation.

The proposed National Additive Manufacturing Framework of Energy (NAMF-Energy) is a roadmap for overcoming these obstacles. Its ability to conduct research, standardisation and workforce development activities in the federal agencies and between workers makes AM one of the key pillars in the industrial and energy re-awakening of America. The framework also places the U.S. in a discourse at the global level where additive manufacturing is seen as a technological revolution and a sustainability enforcer.

Finally, NAMF-Energy will only be successfully implemented with the help of careful cooperation, foresight, and long-term investment. With the world facing the complex issues of climate change and energy security, the United States can be at the forefront not only in the development of renewable energy but also in the transformation of the same processes that shape its energy future. Additive manufacturing is not merely a tool, but rather a basis of a new industrial ecology, based on the merging of innovation, sustainability, and resilience with the service of national progress.

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