

ENERGY INDUSTRY

Harnessing the Potential of Additive Manufacturing to Drive Innovation and Sustainability in the U.S. Energy Industry

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Abstract

Additive manufacturing (AM), generally known as 3D printing, is changing the nature of industrial production and redefining the principles of innovation in various industries, including the energy industry. This paper examines how AM can be used effectively to drive innovation and sustainability in the U.S. energy industry. Drawing from the theoretical framework of the AM innovation system (Lavoie and Addis, 2018) and adopting the insights of sustainable manufacturing, the idea of the circular economy, and industrial ecology, this paper explores the role of AM in promoting low-carbon technologies, supply-chain optimisation, and design flexibility. It also discusses the technical, policy and infrastructural obstacles that limit AM adoption. The study establishes that AM can help to decrease the amount of waste, increase the performance of particular components, and decentralise production significantly, using the case examples of companies like Siemens Energy and the conclusions offered by the Department of Energy (DOE) AM Forward initiative. The paper concludes with policy and strategic recommendations on how AM can be incorporated in the transition to a sustainable and resilient future of energy in the U.S.

Keywords: additive manufacturing; 3D printing; innovation systems; sustainability; U.S. energy industry; circular economy; advanced manufacturing

1 Introduction

Rising global competition, pressure to decarbonise, and the need to increase supply chain resilience and constant innovation are all challenges currently facing the energy industry in the United States. As the country rapidly moves toward renewable and low-carbon energy systems, new manufacturing technologies are emerging as key facilitators of sustainability and competitiveness ([US Department of Energy, 2023](#)). Additive manufacturing (AM), which involves the construction of three-dimensional objects through layer deposition, is one of these and is revolutionizing the design, construction, and service of energy systems.

New strategies are needed for energy production to reduce waste, ensure optimum use of materials, and decentralise production to the local level due to the complexity of the energy infrastructure, its ageing, and disruption by climate change ([Orme, 2023](#)). But AM presents a special chance to overcome these obstacles, from design flexibility to material efficiency and digital integration. Besides, the AM process does not discard material like the subtractive methods used in the past, reduces production time, and can create geometrically complex parts that enhance system performance ([Lavoie and Addis, 2018](#)).

In addition to production efficiency, AM is now understood as a means to strengthen national energy security by enabling companies to quickly adapt to energy security challenges and lower reliance on

imported components (Attaran, 2017). Huang et al. (2013) suggest that the environmental and economic advantages of AM are throughout the product lifecycle, covering raw material extraction through to end-of-life recovery; energy is a capital-intensive industry where AM is particularly relevant. Gebler et al. (2014) also point out that the spread of 3D printing technologies has implications for global energy demand and industrial sustainability, and therefore the relevance of AM for the decarbonisation agenda of the U.S. energy industry.

Therefore, this paper delves into the strategic application of AM in the U.S. energy market for innovation and sustainability by synthesising findings from the innovation systems perspective, the circular economy theory, and empirical evidence from cases aimed at understanding how AM can transform product design, prototyping processes, and reduce the linkage between economic growth and material intensity.

More importantly, the paper explores the scope of AM within the context of the overall industry digitalisation and the Fourth Industrial Revolution (Industry 4.0). The integration of AM with artificial intelligence (AI), robotics, and smart sensors can optimise processes in real time and enable data-driven decision-making (Zhang et al., 2022). In this regard, AM can transform value generation, the business model, and the innovation context of the U.S. energy economy. In addition, these effects apply not only to operational efficiency but also to strategic resilience and national competitiveness in the global race for clean energy.

2 Theoretical and conceptual background

The three complementary viewpoints that underpin the current paper are the Additive Manufacturing Innovation System (Lavoie and Addis, 2018), the concepts of sustainable manufacturing and the circular economy (Geissdoerfer et al., 2020), and the concept of industrial ecology.

2.1 The additive manufacturing innovation system

Lavoie and Addis's (2018) conceptualization of AM assumes that AM is an innovation system consisting of a network of actors, firms, universities, research institutes, and government agencies involved in knowledge production, diffusion, and commercialization. From this systemic point of view, there is interdependence between the development of the technology, the market, and policy mechanisms in which AM is developed. This innovation environment is US-dominated, as the country published the greatest amount of AM research and publications in the world from 2011 to 2016 (Lavoie and Addis, 2018), suggesting it has the greatest capacity to extend AM influence to strategic areas such as energy.

In this model, entrepreneurial activities, academic, collective, and state-driven, are the enactments of the process of developing codified knowledge into market innovations. This is particularly the case in the energy sector, where partnerships between the state, businesses, and universities enable the transfer of technology and the creation of products (Mazzucato, 2020).

2.2 Sustainable manufacturing and circular economy

Three principles of the circular economy are targeted at achieving a circular economy: complete material cycles, recycling, remanufacturing, and disassembling designs (Ellen MacArthur Foundation, 2023). AM contributes to circularity by enabling the creation of lightweight components, increasing component lifespan, and making on-demand part replacement more convenient, thus reducing the volumes the company has to keep in inventory and emissions related to transportation (Ford & Des-

peisse, 2016). More importantly, digitization and localized manufacturing align well with sustainable manufacturing goals, as they minimise waste and maximise energy efficiency (Liu et al., 2020). Despeisse and Ford (2015) argue that the value added by AM is not in its use as a standalone manufacturing method, but when combined with other strategies to manage the lifecycle of products. Kellens et al. (2017) agree with this and observed that the energy use for printing with AM methods varied widely based on the material used and the type of AM machine in their environmental impact assessment of AM processes, which led them to believe that sustainability should not be assumed for AM and that it must be assessed on a case-by-case basis. Niaki and Nonino (2017) call AM management an emerging new discipline in its own right, saying that companies need to acquire new skills to leverage the benefits of AM in terms of sustainability: skills in supply chain design, quality assurance and workforce training. Combining these perspectives, it is clear that the theoretical potential of AM as an enabler of a circular economy is crucially dependent on the practical implementation of AM by organisations.

2.3 Industrial system integration and ecology

The transition from digital manufacturing to optimization of environmental performance can be seen from an industrial ecology perspective as the juncture of AM. It facilitates the incorporation of data-informed feedback into design, production, and maintenance. AM is linked to artificial intelligence (AI) and digital twins, which means that predictive maintenance and circular asset management are possible, which is crucial in energy infrastructures that are required to operate in dynamic environments (Zhang et al., 2022).

3 Additive manufacturing in the U.S. energy industry

There are a number of applications of AM in the energy sector including fossil fuel technologies, renewable energy systems, nuclear energy and new hydrogen technologies.

3.1 Adoption and use cases

The use of AM is also finding its way into the oil and gas sector to create better performance and minimise downtime, such as complex drilling components, impellers and flow control devices. In 2025, for instance, Siemens Energy is leveraging AM to perform rapid component repairs and prototyping of gas turbine parts, thus cutting down time for repair and improving the parts' reliability (Siemens Energy, 2025).

Having a flexible approach in developing specialized parts and structures, AM can help in the implementation of renewable energy systems, such as wind and solar energy. The 3D-printed moulds of wind turbines have reduced the production time by 40 per cent and the costs by 25 per cent, according to the National Renewable Energy Laboratory (NREL) (US Department of Energy, 2023). In the field of nuclear power, potential uses of AM could be to enhance metal printing to produce safety-critical components and heat exchangers, to provide superior performance and longer service life.

Continuing the trend of AM's increasing presence in the energy industry, Gao et al. (2015) emphasize the importance of metal AM with respect to the production of complex, high-performance turbine and heat exchanger components, in which traditional casting processes are too expensive to compete at low production volumes. In an influential NIST report, Thomas and Gilbert (2014) project that the economic value of AM is mainly due to the production of custom low volume parts and a reduction in material waste. Both of these are easily transferable to energy infrastructure projects that demand

custom, low volume parts. While this is true, [Chen et al. \(2015\)](#) warn that the environmental benefits of AM are dependent on the energy sources used for production and the utilisation rate of the machines required, and that improvements in material efficiency may not lead to a net reduction in emissions without using low carbon electricity.

3.2 Industry and research collaboration

An example of collaborative innovation is the AM Forward program of the U.S. Department of Energy (DOE), which was launched in 2022. It is bringing together small and medium-sized enterprises (SMEs) with the major manufacturers such as Honeywell, Lockheed Martin, and Raytheon to enhance the adoption of AM and upskilling their workforce. It fits into the idea that [Lavoie and Addis \(2018\)](#) highlight in their article on the concept of collective entrepreneurship that there is a cross-sectoral collaboration that also provides a mutual technological learning.

4 Driving innovation through additive manufacturing

AM is an innovation driver on a variety of levels, such as design, supply chain design, and product development.

4.1 Design and product innovation

The benefit of AM is that there is design freedom, allowing the engineers to design those structures that they would not be able to design in conventional manufacturing. This property enhances the thermal efficiency of energy turbines, battery casings, heat exchangers, etc. ([Thompson et al., 2016](#)). The design for additive manufacturing (DfAM) paradigm combines computational modelling and material science so that designs can be iterated and optimised continuously.

4.2 Supply chain agility and resilience

The COVID-19 pandemic highlighted the fragility of global supply chains, and AM enables greater decentralisation of production and local production, which helps to reduce such risk. This means that the companies will be able to print the spare parts when they are needed, rather than relying on companies in distant locations, and reduce carbon footprint as a result of logistics ([Kamble et al., 2019](#)). At the local level, this localisation has an added advantage of enhancing national resilience and connects to the policy aims for national manufacturing capacity building.

[Sasson and Johnson \(2016\)](#) assert that AM changes the nature of the supply chain: manufacturing is no longer a centralised process, but one where manufacturing hubs are dispersed across the country and are made possible on an as-needed basis. Building on this, [Mellor et al. \(2014\)](#) suggest a framework for structured implementation of AM, arguing that its successful integration is dependent on technology capabilities, organizational strategy and supply chain redesign, and not just on using AM as a manufacturing tool.

4.3 Collaborative R&D and knowledge spillovers

AM innovation is multidisciplinary. Thus, startups, energy firms and colleges can share similar digital settings and digital repositories. This partnership can create knowledge spillover which can speed up the diffusion of technology in the industry ([Lavoie and Addis, 2018](#)). An example is the Manufacturing Demonstration Facility (MDF) at Oak Ridge National Laboratory (ORNL), which works with industry partners to co-create AM solutions for clean energy components.

5 Advancing sustainability and circularity

It is essential that the energy sector be sustainable, in terms of minimising environmental impact and optimising the use of resources. AM supports these goals in several ways.

5.1 Material efficiency and waste reduction

It is estimated that, in traditional subtractive manufacturing, 70 per cent of the raw material is lost, and less than 10 per cent is lost in additive manufacturing, by producing the parts layer by layer (Ford & Despeisse, 2016). Besides, AM can recycle and reuse materials in the form of powder wastes to create new prints in a cyclic process. This is in line with the United Nations sustainable development goals (SDGs 9 and 12): industry, innovation and infrastructure, and responsible consumption and production.

5.2 Energy and lifecycle optimization

Although AM has high localised energy consumption, design efficiency, weight saving and shorter logistics chains can reduce its total lifecycle energy consumption (Mehroliya et al., 2021). One such application is lightweight turbine components created using AM which will improve the efficiency of the energy conversion process and reduce emissions in the process. Life Cycle Assessment (LCA) studies indicate that a 25–30% reduction in energy can be achieved when compared to traditional manufacturing (Kokare et al., 2023).

Faludi et al. (2015) did a comparison between the sustainability of AM and traditional machining methods, which showed AM to have the most significant advantages in the production of low volume, geometrically complicated parts that are often used in special energy components. This strengthens the case for AM's circularity advantages not being universal, but rather to be applied selectively to high value and/or customised parts, as opposed to mass-produced standard parts.

5.3 Decentralized production and localized circularity

The AM networks, which are decentralised, promote local sustainability by decreasing transportation needs and sustaining the local economies. “Glocalization”, local production serving global demand, mirrors Lavoie and Addis's (2018) vision of distributed innovation systems that transcend traditional supply hierarchies.

6 Challenges and policy implications

Despite its potential, AM adoption faces several barriers in the U.S. energy industry.

- **Technical and economic constraints:** Big capital requirements, a lack of material variety, and certification make large-scale implementation difficult. Components produced by AM are still time-consuming and expensive to qualify to be used in critical energy applications (US Department of Energy, 2023). Moreover, inconsistencies in printing parameters influence reproducibility and reliability.
- **Workforce and skills gap:** AM requires hybrid skills in materials science, data analytics, and digital design. Workforce training is also one of the enablers of sustainable AM integration, as outlined by the US Department of Energy (2023) and America Makes consortium. The innovation system can become bottlenecked without specific investments in education, as Lavoie and Addis (2018) found in the previous AM ecosystems.

- **Regulatory and policy environment:** The lack of standardised certification practices and environmental measurements hinders commercialisation. Mazza (2018) proposes the implementation of a mission-oriented innovation policy that would help in uniting federal investment, research funds, and industry standards. The U.S. government's Clean Energy Smart Manufacturing Innovation Institute is an example of such coordination where AM is being incorporated in national decarbonization efforts.

7 Conclusion and future directions

Additive manufacturing is a technological revolution and one of the opportunities that will help the sustainable transformation of the U.S. energy industry, as it facilitates economically and environmentally sustainable innovation by redesigning production systems based on the digital incorporation of materials, material circularity, and local production. However, the success of AM, according to Lavoie and Addis (2018), lies in the strength of the innovation system, whereby the university, industry and government co-create values.

Hence, future studies should focus on quantifying the net carbon benefits of AM in the various energy sub-sectors and come up with predictive models that can be used to relate design optimisation to the environment. On policy fronts, the U.S. needs to maintain mission-driven public-private partnerships, increase workforce development and develop lifecycle-based certification systems. When properly leveraged, AM will be able to speed up the process of transformation of the country to a cleaner, smarter and more sustainable energy future.

In conclusion, additive manufacturing is not just a technological breakthrough, but also a socio-technical system which embodies the concept of sustainability, inclusivity, and resilience. Its effective implementation in the U.S. energy environment will rely on the persistent learning, adaptive governance, as well as the entrepreneurial policy strategy that correlates industrial capacity with national sustainability targets. The intersection of AM and renewable energy technologies and digital innovation is on the verge of transforming the way energy is generated, transmitted, and used, and represents a key milestone in the process of the net-zero, innovation-driven U.S. economy.

References

- [1] Attaran M (2017). The rise of 3-D printing: The advantages of additive manufacturing over traditional manufacturing. *Business Horizons*, 60(5), 677–688.
- [2] Chen D, Heyer S, Ibbotson S, Salonitis K, Steingrímsson JG, Thiede S (2015). Direct digital manufacturing: definition, evolution, and sustainability implications. *Journal of Cleaner Production*, 107, 615–625.
- [3] Despeisse M, Ford S (2015). The role of additive manufacturing in improving resource efficiency and sustainability. In *IFIP International Conference on Advances in Production Management Systems* (pp. 129–136). Cham: Springer International Publishing.
- [4] Ellen MacArthur Foundation (2023). What is a circular economy? *Ellen MacArthur Foundation*. <https://www.ellenmacarthurfoundation.org/topics/circular-economy-introduction/overview>
- [5] Faludi J, Bayley C, Bhogal S, Iribarne M (2015). Comparing environmental impacts of additive manufacturing vs traditional machining via life-cycle assessment. *Rapid Prototyping Journal*, 21(1), 14–33.
- [6] Ford S, Despeisse M (2016). Additive manufacturing and sustainability: An exploratory study of the advantages and challenges. *Journal of Cleaner Production*, 137, 1573–1587. <https://doi.org/10.1016/j.jclepro.2016.04.150>
- [7] Gao W, Zhang Y, Ramanujan D, Ramani K, Chen Y, Williams CB, Wang CCL, Shin YC, Zhang S, Zavattieri PD (2015). The status, challenges, and future of additive manufacturing in engineering. *Computer-Aided Design*, 69, 65–89.

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- [8] Gebler M, Uiterkamp AJS, Visser C (2014). A global sustainability perspective on 3D printing technologies. *Energy Policy*, 74, 158–167.
- [9] Huang SH, Liu P, Mokasdar A, Hou L (2013). Additive manufacturing and its societal impact: a literature review. *The International Journal of Advanced Manufacturing Technology*, 67(5), 1191–1203.
- [10] Kamble S, Gunasekaran A, Gawankar S (2019). Achieving sustainable performance in a data-driven agriculture supply chain: A review for research and applications. *International Journal of Production Economics*, 219, 179–194. <https://doi.org/10.1016/j.ijpe.2019.05.022>
- [11] Kellens K, Mertens R, Paraskevas D, Dewulf W, Duflou JR (2017). Environmental impact of additive manufacturing processes: does AM contribute to a more sustainable way of part manufacturing? *Procedia CIRP*, 61, 582–587.
- [12] Kokare S, Oliveira JP, Godina R (2023). Life cycle assessment of additive manufacturing processes: A review. *Journal of Manufacturing Systems*, 68, 536–559. <https://doi.org/10.1016/j.jmsy.2023.05.007>
- [13] Lavoie M, Addis JL (2018). Harnessing the potential of additive manufacturing technologies: Challenges and opportunities for entrepreneurial strategies. *International Journal of Innovation Studies*, 2(4), 123–136. <https://doi.org/10.1016/j.ijis.2018.11.001>
- [14] Liu F, Li T, Jiang X, Jia Z, Xu Z, Wang L (2020). The effect of material mixing on interfacial stiffness and strength of multi-material additive manufacturing. *Additive Manufacturing*, 101502. <https://doi.org/10.1016/j.addma.2020.101502>
- [15] Mazzucato M (2020). The value of everything: Making and taking in the global economy (an excerpt). *Journal of Economic Sociology*, 21(5), 39–57. <https://doi.org/10.17323/1726-3247-2020-5-39-57>
- [16] Mehroliya S, Arya A, Mitra U, Paliwal P, Mundra P (2021). Comparative analysis of conventional technologies and emerging trends in wind turbine generators. *Proceedings of the 2021 IEEE International Conference on Electrical Power and Energy Systems (ICEPES)*, 1–6. <https://doi.org/10.1109/ICEPES52894.2021.9699538>
- [17] Mellor S, Hao L, Zhang D (2014). Additive manufacturing: A framework for implementation. *International Journal of Production Economics*, 149, 194–201.
- [18] Niaki MK, Nonino F (2017). Additive manufacturing management: A review and future research agenda. *International Journal of Production Research*, 55(5), 1419–1439.
- [19] Orme DM (2023). How 3D printing helps accelerate sustainable manufacturing. *World Economic Forum*. <https://www.weforum.org/stories/2023/06/how-3d-printing-helps-accelerate-sustainable-manufacturing/>
- [20] Sasson A, Johnson JC (2016). The 3D printing order: variability, supercenters and supply chain reconfigurations. *International Journal of Physical Distribution & Logistics Management*, 46(1), 82–94.
- [21] Siemens Energy (2025). Additive manufacturing at Siemens Energy: Innovation in every layer. <https://www.siemens-energy.com/global/en/company/innovation/additive-manufacturing.html>
- [22] Thomas DS, Gilbert SW (2014). Costs and cost effectiveness of additive manufacturing: A literature review and discussion (NIST Special Publication 1176). *National Institute of Standards and Technology*.
- [23] Thompson MK, Moroni G, Vaneker T, Fadel G, Campbell RI, Gibson I, Bernard A, Schulz J, Graf P, Ahuja B, Martina F (2016). Design for additive manufacturing: Trends, opportunities, considerations, and constraints. *CIRP Annals*, 65(2), 737–760. <https://doi.org/10.1016/j.cirp.2016.05.004>
- [24] US Department of Energy (2023). Supply chains progress report. *US Department of Energy*, Washington, DC. <https://www.energy.gov/policy/supply-chains-progress-report>
- [25] Zhang L, Zhou W, Chen X (2022). Digital twins and additive manufacturing. In *Advances in additive manufacturing technologies* (pp. 71–92). Springer. https://doi.org/10.1007/978-3-031-11401-4_4
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