

ENERGY SECTOR

Creating a Collaborative Ecosystem for Additive Manufacturing Innovation in the Energy Sector

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Abstract

The potential of Additive Manufacturing (AM) goes beyond technological innovation and involves the interaction of several actors who co-create value across the innovation chain. The energy sector is extremely capital-intensive, technical, and risk-averse towards regulatory risks. AM offers flexibility in design, cost, and sustainability, which are increasingly important given the continued disruption and pressure on global supply chains to localise manufacturing. The pace and scale of adoption within the sector is, however, held back by fragmented actions, low levels of digital interoperability and limited inter-organisational coordination. The paper suggests a new model: a Collaborative Ecosystem of Additive Manufacturing in Energy Systems (CEAM-ES), which is designed to bring together actors, including Government, Industry, Academics, and Technology Facilitators under a shared set of standards, and mutual accountability.

The framework is based on the theory of business ecosystems, the theory of national innovation systems thinking, and analyses of AM collaboration from industry perspectives, and is conceived as a structured model of collective governance, digital integration, and trust-based partnership. It continues to encourage a systematic approach to accelerate the diffusion of AM in the U.S. energy sector through knowledge sharing, capability matching, cross-sector learning, and coordinated regulatory participation. The paper proposes a conceptual connection between ecosystem theory and practical challenges of implementing AM in the energy infrastructure, providing a basis for empirical testing and policy development.

Keywords: additive manufacturing (AM); collaborative ecosystem; energy systems; U.S. energy sector; business ecosystems; cross-sector collaboration; technology diffusion

1 Introduction

The United States is facing a period of unprecedented change in the energy sector, both in terms of digitalisation and sustainability as well as the reshaping of industrial policy. Flexibility, efficiency, and resilience are strategic technologies as the country moves toward decarbonization in various directions. The key enabler to this transformation is Additive Manufacturing (AM) or 3D printing. AM is a technique for making parts in layers using a digital model, which would be difficult to achieve with traditional manufacturing techniques (USD OE, 2015).

When applied to the energy industry, AM will help to transform the design and manufacture of turbines, fuel nozzles, heat exchangers, and nuclear reactor components. It can help to cut supply chains, reduce downtime, and improve lifecycle efficiency (European Commission, 2021). Industry-wide evaluations have all confirmed that AM is a now-established, broadly used production method rather than a new one that is only trying out various technologies (Wohlers Associates, 2021). Moreover, due to the disruptions of the world economy, such as the COVID-19 pandemic, identifying weaknesses in the most critical supply chains has become a reality, and the ability to produce

components locally, using AM, now has a new definition; a systematic literature review has confirmed that the use of AM has shown measurable improvements in supply chain resilience by minimising reliance on distant and centralised production networks, while giving rise to new vulnerabilities (Naghshineh & Carvalho, 2022).

Despite these benefits, however, there is a lack of coherence in the extent to which AM is implemented in the energy sector in the U.S. Research into AM has been spearheaded by national laboratories, but the inter-institutional cooperation and collaboration between the private sector, government institutions, and academia have been uneven and project-specific, with the Manufacturing Demonstration Facility at Oak Ridge National Laboratory being the DOE's main initiative to facilitate AM adoption in energy-related industrial applications (U.S. Department of Energy, 2025).

While technological innovation is important, as Heising et al. (2020) point out, it will not secure a lasting industrial transformation without accompanying factors. The enabling ecosystem, which consists of a network of actors, is crucial for the success of AM as it is necessary for cooperation to ensure the exchange of knowledge, standardisation, and co-evolution. The U.S. energy sector is complex and capital-intensive, and requires an ecosystemic approach to ensure innovation on both governmental and non-governmental levels is aligned. That is why the paper suggests the concept of Collaborative Ecosystem of Additive Manufacturing in Energy Systems (CEAM-ES) with the principles of cooperation, shared governance, and sustainability. This framework combines concepts from business ecosystem theory, AM industrial research, and policy analysis to develop a coherent framework that enables AM-related activities to align with national energy priorities. In a new paradigm of collaboration, CEAM-ES sees the technology as a key enabler in the energy transition and industrial resilience.

2 Conceptual and theoretical background

The notion of ecosystems as a way of thinking about industrial innovation has evolved. It is rooted in the initial definition of business ecosystems as “communities of interacting organizations” (Moore, 1996), which is a development of the previous formulation of firms as “co-evolving members of a shared competitive and cooperative environment” (Moore, 1993). Ecosystems are relational organisations that are highly interdependent, open to trust, and share a vision, whereas linear supply chains are more transactionally efficient. Value is co-produced and shared through interactions between several actors, including firms, regulators and knowledge institutions in these systems. Additive manufacturing ecosystems are particularly crucial in manufacturing industries where the technologies are both disruptive and capital intensive – which is the case with AM. The technological organization of AM is structured to merge rigid boundaries between firms: software developers work together with materials scientists, machine developers, and production engineers. As a result of these interactions, complex interdependencies emerge, which are not controllable by a single actor. For such ecosystems, Jacobides et al. (2018) assert that a fit between members’ contributions (complementarity) and between decision-making and value-sharing processes (alignment of governance) is needed. The idea of an ecosystem as a structure of interconnected actors has since been further developed by Adner (2017) who conceptualises an ecosystem as an alignment structure of partners that must align to create a value proposition; earlier work by Adner and Kapoor (2010) illustrates how the speed and success of technology adoption is closely linked to a firm’s position within this interdependent structure and this transfer of ideas applies directly to the way in which AM technologies are diffused across the energy value chain.

Collaborative value chain development; shared data and design standards; flexible regulation and the shift towards experimenting with the culture are all necessary for AM ecosystem development (Heising et al., 2020). In the energy industry, operational risk, long investment cycles, and safety requirements make coordination even more important. The need to use cross-sector collaboration to speed up AM adoption has been highlighted by both the U.S. Department of Energy (USDOE) and the National Science and Technology Council (NSTC) (USDOE, 2022; NSTC, 2022); however, there is still no integrated national mechanism. Hence, the CEAM-ES model developed in this paper is based on these theoretical and institutional frames, which have collaboration as the structural center of AM innovation in energy systems. Moreover, the ecosystem approach is also closely connected to the two approaches, National Innovation Systems (NIS) and Network Governance (Freeman, 1995; Lundvall, 2010), where the key characteristics of innovation are seen as a socially based process influenced by institutions and trust and as an interactive learning process.

The concept of systems of innovation is grounded in the work of Edquist (1997) who first presented this concept as the sum of economic, social, political, organizational and institutional elements that together influence the development, diffusion and utilization of innovations, and also in Nelson's (1993) comparison of the institutional configuration of countries and their ability to produce different innovation outcomes for the same technology. In the energy industry, therefore, it reflects that, in addition to technological readiness, the quality of the links among research institutions, policymakers, and private organizations plays a crucial role in the dissemination of AM technologies. A successful ecosystem leads to systemic alignment: knowledge is shared, regulation is aligned, and monetary rewards are aligned, with all aligned toward common innovation goals. The synergy of NIS knowledge with the idea of CEAM-ES reflects how AM can be effective in the energy environment of the United States only if collaborative governance and policy consistency prevail, not scientific and technical capacity.

3 The role of collaboration in AM innovation

AM collaboration is a catalyst and pathway for AM innovation. The design, testing, and validation of AM components is multidisciplinary in nature. For example, a 3-D printed turbine blade manufacturing process would require mechanical engineers, metallurgists, design engineers, and quality assurance specialists to communicate. The stakeholders have different fields of expertise, and innovation is a result of cross-fertilisation of these capabilities; recent ecosystem-level research shows that innovation is not just about the technology or end product, but that collaboration is structured differently within different manufacturing ecosystems than in software or platform ecosystems, where the findings do not transfer in the same way (Morar et al., 2024).

This collaboration is transindustry, spanning all the companies in the energy sector. The Energy, Equipment, Software, and Regulatory bodies should work together to establish Design guidelines, Safety and Test conditions. The USDOE-GE project for the production of turbine parts is one example of successful collaboration, which involved a significant reduction in the design process, a significant improvement in material behaviour, and benchmarking of AM at the industrial level (USDOE, 2022). But collaborative innovation comes with myriad challenges. While technical data barriers are typically identified as the main obstacles, empirical analysis of AM adoption determinants reveals that differences in organisational culture and fears about IP rights are also significant. The lack of interoperability between digital platforms is more likely to hinder the successful integration of AM into collaborative production networks in the firm than technical barriers alone (Oettmeier & Hof-

mann, 2017). Furthermore, it is not recommended to experiment openly in energy fields where risk aversion is a major concern (highly regulated sectors). These challenges require conscious ecosystem design, institution-building, incentives, and platforms to enable collaboration while maintaining competitive interests. Heising et al. (2020) indicate that in an “ecosystem of cooperation and competition in a trusted context with congruent incentives for all, additive manufacturing will thrive. It becomes possible, therefore, to think of collaboration as a form of interaction and as a paradigm of governance. This paradigm would make the technological development coincide with the goals of the nation.

Beyond organisational collaboration, the success of collaboration in AM is also determined by the digital and informational infrastructure on which it is supported. Cloud-based design archives, simulators, and additive assembling information interchanges enable actors spread out geographically to collaborate with one another in real-time to decrease redundancy and reduce innovation funnels. Emerging trust-assurance mechanisms, such as digital part-passport frameworks that record the provenance and lifecycle history of AM components, illustrate how digital infrastructure is increasingly being used to build the cross-border, cross-organisational trust that safety-critical sectors such as energy require before scaling collaborative production (National Additive Manufacturing Innovation Cluster, 2026). With these mediums, the interaction of collaboration is not a project-based interaction but a continuous learning system, where product, testing, and field performance data are provided back to research and design. In this regard, digital connectivity is the enabler of collaborative innovation, which brings together the stakeholders with transparency, shared metrics, and shared intelligence so as to add to the overall capacity of the ecosystem

4 The need for a collaborative ecosystem in the energy sector

The industry of the U.S. energy sector is structured into fossil, renewable, and nuclear subsectors, which present a challenge, as well as opportunities, to additive manufacturing. On the one hand, the innovation adoption is delayed due to the complexity and risk sensitivity of the sector. Its dependency on modular components, infrastructure that is expensive to maintain and geographically dispersed assets, on the other hand, are perfectly fitted to the AM decentralised production model. However, the existing AM programs in energy are still isolated. Large companies run proprietary AM initiatives, colleges conduct their own research, and federal agencies invest in short-term demonstration projects. Such a disjointed landscape leads to duplication of efforts, inconsistency in standards and lack of scalability. These inefficiencies could be solved via a collaborative ecosystem approach in three ways:

- **Knowledge Integration:** Knowledge flows can be bridged between academia and industry, and discovery and standardisation is sped up by knowledge infrastructure, and open-access databases.
- **Networked Investment:** The Joint R&D programs reduce the financial risk and synchronise the investment priorities between the public and the private stakeholders.
- **Innovation Diffusion:** Ecosystem structures can promote the transference of best practices between regions and industries and increase the AM application beyond pilot projects to a fully industrialised application.

5 The collaborative ecosystem model for additive manufacturing in energy (CEAM-ES)

The Collaborative Ecosystem of Additive Manufacturing in Energy Systems (CEAM-ES) is designed in the form of a multi-actor system that facilitates the diffusion of technology, development of capacity, and sustainability. It is based on the principles of collaboration that Heising et al. (2020) have identified and brings them to refer to the realities of the U.S. energy sector in terms of regulation and operation.

Table 1. Collaborative Ecosystem Model for Additive Manufacturing Innovation in the Energy Sector (CEAM-ES).

Domain	Core function	Key mechanisms
Knowledge and technology integration	Transfer the research outcomes to the practical energy application through open innovation.	Build online collaborative forums; establish national data and design repositories; form cross-laboratory testing standards.
Governance and policy alignment	Promote coherency among the federal agencies, industry, and regulatory bodies in AM policymaking.	Create a National Additive Manufacturing and Energy Council; streamline existing funding streams; mainstream AM within national energy roadmaps.
Industry-academic partnerships	Establish human resource and translational research.	Introduce joint doctoral courses and internships; subsidize research institutes in universities and energy companies.
Cross-sector collaboration and market connectivity	Facilitate cross-industry knowledge sharing and cross-industry infrastructure sharing.	Collaborate with aerospace, defence and automobile industry; co-location of certification laboratories; standardisation of quality assurance measures.
Sustainability and market incentives	Incorporate lifecycle assessment and circular economy concepts on AM implementation.	Promote recycling of powders and polymers; Green tax credit on AM used components; green AM in federal contracting.

6 Pathway to implementation

Building a collaborative ecosystem is not a straightforward process, but it is an evolutionary process and it is influenced by trust, coordination and shared learning. In the CEAM-ES framework, a three-phase process is followed that aims at maturing relationships, aligning capabilities and governing the system through systemic governance as opposed to strict policy schedules.

6.1 Stage One: Foundation and relationship building

The first stage focuses on mapping and the involvement of stakeholders. In collaboration with NTSC and national laboratories, the USDOE ought to undertake a national audit of AM actors in the energy sector, discovering capabilities, interests, and overlaps of resources. Information sharing and project matchmaking should be built on digital platforms to facilitate transparency and trust. At this stage, pilot partnerships, including USDOE-industry-university partnerships on small-scale turbine component printing, are confidence-building mechanisms.

6.2 Stage Two: Network expansion and capability

Once the basic relationships are established, the next focus is to strengthen the collaboration using formalised structures. There should be joint research centres in the main energy areas (e.g., Texas, Pennsylvania, and California), which should be co-funded by the state and federal government. Such

hubs would act as anchors of the ecosystem, where there would be shared testing facilities, certification labs and training. NSTC is well-qualified in metrology and standards, which ought to be used to develop shared quality criteria. SMEs and startups should also be part of the expansion of the network to make it inclusive and diverse in the market.

6.3 Stage Three: Institutionalization and governance maturity

The last phase involves embedding collaboration into institutional routines, and requires the creation of National AM-Energy Council that would facilitate interagency and sector coordination of strategy. This entity would oversee data governance, ecosystem health and performance in relation to the sustainability metrics. In the long run, CEAM-ES becomes self-governing and has the characteristics of trust-based collaborations, open data sharing, and unceasing innovation. This adaptive model reflects the logic of co-evolution of natural ecosystems when the mutual benefit and adaptation maintain the long-term balance (Jacobides et al., 2018).

7 Conclusion and future research directions

Additive Manufacturing is not just another technological revolution; it is a reinvention of the intersection of industrial cooperation, innovation and sustainability. In the U.S. energy industry, AM has limited transformative capacity due to institutional disaggregation and poor coordination across the sector. To bridge these gaps, the Collaborative Ecosystem of Additive Manufacturing in Energy Systems (CEAM-ES) proposed in this paper offers a strategic roadmap to the realisation of collateral collaboration, shared governance and relevant incentives.

Furthermore, CEAM-ES develops a vision of AM as a technological and social innovation that can bridge digitalisation, sustainability and energy security by instilling trust and co-creation among government agencies, the private industry and academia. Not only will its implementation help to make the countries more resilient, but it will also introduce the culture of innovation into the larger industrial layer.

However, the success of the framework relies on the ongoing investigation and change. Future studies ought to examine the effects of the ecosystem governance frameworks, including the data-sharing policies, intellectual property models, and value distribution mechanisms, on the outcome of innovation. Comparison of the U.S and global AM ecosystems would have enlightened us on the best practices in establishing openness as well as competitiveness. Hence, researchers should also consider how to develop digital trust technologies, such as blockchain, to be used in the design of security, the way to incorporate the principles of equity and workforce inclusion in AM networks.

Thus, creating an ecosystem of AM innovation is not a policy program that is run and done but a dynamic and changing process of reciprocity, institutional adjustment, and adaptive governance. When successfully implemented, CEAM-ES has the potential to turn AM into a proven industrial asset into an instrument of strategic enabler of the U.S. energy transition to achieve sustainable growth, technological sovereignty, and jointly make strides toward a cleaner and more resilient energy future.

Looking ahead, the formation of international AM collaboration platforms and the reconciliation of the U.S. industrial policy with international sustainability standards will play a major role. Enhanced transatlantic collaboration, data interoperability treaties, and congruent certification systems have the capacity to make the U.S. a global leader in additive manufacturing and energy innovation. Placing collaboration at the core of the modernisation of industries, the CEAM-ES framework reconfirms that

the next generation of energy transformation does not rely simply on high-technology and high-tech solutions but on how well the ecosystem of the ecosystem that supports their development cannot help but to succeed.

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