

# Technology Development Programme

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Technology Mapping  
2025 Series

## Additive Manufacturing



# Technology Development Programme

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## Advanced Manufacturing Mapping Workshop

September 2025



## Version history

VERSION	DATE	CHANGES
0.0	16/01/2026	First issue
1.0	02/03/2026	Comments from participants implemented

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# Foreword

Additive manufacturing (AM) stands at the forefront of innovation for fusion energy and advanced engineering sectors. Its unique ability to produce highly complex, custom-designed components with unprecedented precision and efficiency makes it an essential tool for tackling the demanding requirements of fusion devices.

These systems often involve intricate geometries, advanced materials, and must endure extreme environments and challenges that traditional manufacturing methods struggle to address. AM enables rapid prototyping and iterative design, allowing researchers and engineers to test new ideas and refine solutions much faster than before. This agility is particularly valuable in fusion, where the pace of discovery and the need for tailored solutions are both high.

However, the transformative potential of additive manufacturing can only be fully realized through strong collaboration. Fusion research is inherently multidisciplinary, drawing on expertise from physics, materials science, engineering, and industry. By fostering open collaboration among these diverse stakeholders, the community can share knowledge, pool resources, and develop common standards for quality and safety. Such cooperation accelerates the qualification of new materials, the development of robust manufacturing processes, and the creation of reliable, high-performance components.

The workshop itself exemplified this collaborative spirit, bringing together experts from different organizations to collectively map out technology needs, set priorities, and define actionable steps for advancing AM in fusion.

Additive manufacturing and collaboration go hand in hand; by working together and sharing knowledge, we can make even greater advances in fusion energy than we could alone. This teamwork helps turn the promise of fusion into a practical and sustainable reality.

There are already several components, such as divertor elements, first-wall cooling structures, and plasma-heating subassemblies, for which additive manufacturing can significantly simplify existing design solutions. By leveraging the transformative synergy between design and manufacturing, AM can enhance overall component performance, particularly for plasma-facing and plasma-heating elements that demand complex internal geometries and efficient thermal management.

Depending on the system boundary definitions, some may fall or not inside the strict scope of nuclear safety-classified components. Nevertheless, AM offers performance and manufacturability advantages that are relevant regardless of safety classification.

As additive manufacturing moves toward applications in fusion-relevant systems, the parallel development of dedicated codes and standards becomes essential to ensure quality, qualification, and safe integration.

Delivery time and cost might be improved because of reduction of manufacturing steps, less involvement of indirect operators and, actual numbers, are already indicating business opportunity.

## Executive Summary

This report provides a comprehensive overview of the current state, challenges, and opportunities for additive manufacturing (AM) technologies, with a focus on their application to fusion and other advanced sectors. The analysis, based on the workshop outcomes, creating a detailed mapping of technologies, processes, materials, facilities, and ecosystem actors.

## Key Findings

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### 1.1.1 Technology Landscape

- The AM ecosystem encompasses a wide range of processes, including metal and ceramic AM, hybrid and multi-material manufacturing, and advanced design and simulation tools.
- Technology readiness levels (TRLs) vary: while some processes (e.g., design guidelines, certain ceramics) are mature (TRL 7–8), many fusion-relevant technologies remain at early to intermediate stages (TRL 3–6).

*It should be noted that these TRLs may defer between nuclear and non-nuclear applications. For nuclear-classified components, TRLs are typically lower because the corresponding design and construction codes are not yet established.*

### 1.1.2 Strengths and Opportunities

- AM enables unprecedented design freedom, rapid prototyping, and material efficiency, supporting the creation of complex, high-performance components.
- There is strong cross-sector potential, with AM advances in fusion also benefiting aerospace, automotive, energy, and medical industries.
- Ongoing R&D is driving progress in hybrid manufacturing, large-scale part production, advanced materials (e.g., ductile tungsten), and digital integration (AI, simulation, digital twins).

### 1.1.3 Main Gaps and Challenges

- **Material Data & Qualification:** There are significant gaps in material property data, especially for fusion-relevant materials under irradiation. Qualification protocols and standardized databases are still under development.
- **Process Control & Monitoring:** Robust, real-time monitoring and control systems are not yet universally available, limiting quality assurance and repeatability. The accuracy and validation of simulation is relevant to the prediction of part distortion and potential process failures.
- **Equipment & Facilities:** Some AM processes require specialized, costly equipment and post-processing capabilities that are not widely accessible.
- **Supply Chain:** Limited suppliers for critical materials (e.g., Eurofer97 wires, advanced ceramics) and economic barriers to scaling up production remain.
- **Standardization:** Industry-wide standards and NDE protocols for AM in fusion are lagging, slowing qualification and adoption.
- **Human Capital & Digital Integration:** There is a shortage of specialized training and fragmented digital tools, hindering knowledge transfer and interoperability.

### 1.1.4 Test Facilities and Ecosystem

- Europe hosts a robust network of R&D institutes, universities, and pilot facilities (e.g., Fraunhofer, KIT, CEA, CEIT, UPC CIM, Chalmers, AIT, Rise, Additure), with advanced capabilities in process development, material testing, and non-destructive evaluation.
- Specialized facilities for X-ray and neutron imaging, large-scale casting, and irradiation testing are critical assets, though some gaps remain for fusion-specific needs.
- International collaboration, including with partners outside Europe, is vital for advancing AM technologies.

### 1.1.5 Roadmap and Recommendations

- The report proposes a phased roadmap:
  - **Phase 1:** Foundation—data gathering, standardization, and collaboration.
  - **Phase 2:** Technology development— Design rules, process control, simulation, and pilot demonstrations.
  - **Phase 3:** Qualification and industrialization—certification, supply chain development, and scaling up.
  - **Phase 4:** Continuous improvement—innovation, expansion, and regular updates.

Addressing ecosystem gaps will require coordinated action across industry, academia, and research organizations, with a focus on data sharing, qualification, supply chain robustness, and digital integration.

## Introduction

### Context

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In 2024, Fusion for Energy launched a Technology Development Programme (TDP) as part of the implementation actions of its Industrial Policy. This TDP is dedicated to building and reinforcing European Fusion Supply chain capabilities for technologies that are deemed to be critical for the future of commercial fusion. The programme requires the identification of key technologies to direct R&D contracts to European contractors.

Prioritizing and allocating funding opportunities across the supply chain requires a comprehensive review of the involved technologies on each major fusion technical domain. Doing this exercise in a collaborative way will enable stakeholders to identify which technologies are fundamentally needed (technology mapping) and when are they needed (technology road mapping). A roadmap built through consensus of key stakeholders in the field can also serve as a powerful argument when seeking additional funding from national and international public and private investors.

The outcome of this exercise will serve all stakeholders to guide their action in their respective domains, allowing an effective investment of resources. Given the fast evolution of technology, a periodical follow-up of the workshop outcome shall be assured in subsequent technology mapping exercises.

## Workshop Objectives

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The main objectives of the Additive Manufacturing Mapping Workshop were to:

**1. Map Relevant Technologies**

- Identify and list all additive manufacturing technologies that are important for fusion and advanced sectors.
- Create a comprehensive and agreed-upon breakdown of these technologies as a foundation for future development.

**2. Characterize and Prioritize Technologies**

- Evaluate each technology for its current status, readiness level, market- and spin-off potential, added value, and major challenges.
- Establish priorities among the technologies to focus efforts on those with the greatest impact or urgency.

**3. Define Technology Development Actions (TDAs)**

- Propose specific actions needed to advance priority technologies, such as analysis, prototyping, testing, and planning for industrialization.
- Characterize each TDA by assessing available expertise, likelihood of success, implementation timeline, and estimated costs.

**4. Facilitate Collaboration and Information Sharing**

- Bring together experts, organizers, and facilitators from different organizations to share knowledge and perspectives.
- Use interactive tools (like Slido and Power BI) to gather input, encourage engagement, and support collaborative decision-making.

**5. Set the Roadmap for Future Work**

- Define clear next steps for research and development based on the prioritized TDAs.
- Ensure ongoing collaboration and follow-up to implement and continuously improve the identified actions.

In summary, the workshop aimed to systematically map, evaluate, and prioritize additive manufacturing technologies, define actionable steps for their development, and foster collaboration among stakeholders to accelerate progress in fusion and related fields.

## Technology Mapping Process

### Input Report

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In preparation of the exercise, staff from Fusion for Energy prepared a draft technology breakdown with input from other organizations and Industry colleagues, listing technologies of interest and grouping them functionally.

## 1.1.6 Preparation Steps

### 1.1.6.1 Defining Workshop Goals and Structure

- The organizing team set the objectives: to map out relevant additive manufacturing technologies for fusion and advanced sectors, and to identify priority areas for development.
- The agenda was planned, with sessions dedicated to key topics such as design, materials, fabrication and qualification.

### 1.1.6.2 Assembling the Team

- Chairs, co-chairs, hosts, and facilitators were selected from leading organizations (e.g., Fraunhofer IWS, F4E, KIT, CEIT, UPC).
- Roles were assigned: chairs led sessions and reported conclusions, hosts managed group work, and facilitators supported logistics and methodology.

### 1.1.6.3 Preparing Materials and Tools

- Presentations were created to introduce the Technology Development Program (TDP), workshop goals, and examples of fusion applications.
- Interactive tools like Slido and Power BI were set up to enable information sharing, polling, and collaborative mapping.

### 1.1.6.4 Organizing Participants

- Experts, organizers, and facilitators were registered for the event, with a wide and representative attendance.
- Participants were grouped by expertise for breakout discussions.

### 1.1.6.5 Setting the Scope

- Initial presentations established the background and scope for the workshop, ensuring everyone understood the context and objectives.
- The chair presentations provided a comprehensive overview of each session's focus.

## Initial Technology Breakdown

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The initial technology breakdown was structured around four main areas:

1. **Materials**

- Focused on the types of materials used in additive manufacturing, their properties, and suitability for fusion applications.
- 2. **Design & Applications**
  - Covered design principles, simulation tools, and how additive manufacturing can be applied to complex engineering challenges.
- 3. **Fabrication & Processes**
  - Examined the various additive manufacturing processes, including methods for producing and finishing components.
- 4. **NDE, Codes & Qualification**
  - Addressed non-destructive evaluation techniques, relevant codes and standards, and qualification procedures for manufactured parts.

#### **Process for Technology Breakdown:**

- Chairs and co-chairs presented an initial list of technologies within each area.
- Participants discussed and refined this list in breakout groups, characterizing each technology by its readiness level, market potential, added value, challenges, and alternatives.
- The agreed-upon breakdown formed the foundation for further mapping and prioritization during the workshop.

## **Online Workshop**

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The online session of the Additive Manufacturing Mapping Workshop was designed to kick off the collaborative process and set the foundation for technology mapping. It brought together participants virtually to introduce the workshop's goals, structure, and key topics.

#### **Highlights from the Online Session:**

- **Welcome and Introduction:** The session began with an overview of the Technology Development Program (TDP) and the objectives of the workshop.
- **Agenda:** The first session included presentations on the state of additive manufacturing, design and simulation, processes and fabrication, materials, and NDE (Non-Destructive Evaluation), codes, and qualifications.
- **Breakout Groups:** In a second session, participants joined breakout rooms focused on four main areas: Materials, Design & Applications, Fabrication & Processes, and NDE, Codes & Qualification. Each group was led by a chair and co-chair, with facilitators supporting logistics and methodology.
- **Interactive Tools:** Tools such as Slido were used to gather feedback, and support technology mapping.
- **Main Outcome:** The session produced a comprehensive list of relevant technologies, agreed upon by all participants, which formed the basis for further mapping and prioritization.

## In-Person Workshop

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The in-person session built on the basis laid during the online meeting, enabling deeper discussion, networking, and collaborative evaluation of technologies and development actions.

### Highlights from the In-Person Session:

- **Opening and Welcome:** The session started with a recap of the workshop's goals and organization.
- **Working Groups:** Participants engaged in focused breakout sessions to evaluate the current Technology Readiness Level (TRL) of each technology, its market potential, added value, and major challenges.
- **Networking:** group activities provided opportunities for informal discussion and networking.
- **Technology Development Actions (TDAs):** The groups proposed and characterized TDAs, assessing expertise availability, probability of success, implementation time, and cost for next steps.
- **Prioritization and Delivery:** The session included ranking of potential TDAs and outlining the top proposals, with forms completed for the most promising actions.
- **Outcome Presentation:** Results were presented to all participants, summarizing the prioritized TDAs and next steps for research and development.

## Final Report

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After the in-person workshop, the outcome was compiled into this final report. The report includes an overview of European capabilities in the field as well as the proposed technology roadmaps detailing and prioritizing possible actions for the period until the next review (typically 2 to 3 years).

This report is the result of a collective effort, with many participants providing valuable comments before the final version of the report is published.

## Additive Manufacturing Overview

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Additive Manufacturing (AM), commonly known as 3D printing, is a transformative suite of technologies that enables the creation of three-dimensional objects by building them layer-by-layer directly from digital models. Unlike traditional subtractive or formative manufacturing, which removes or shapes material from a bulk form, AM constructs parts by adding material only where needed, unlocking unprecedented design freedom and efficiency.

### 1.1.7 Key Principles and Process Chain

At its core, AM encompasses a digital-to-physical workflow:

- **Design & Digital Preparation:** The process begins with the creation of a 3D model using computer-aided design (CAD) software or 3D scanning. Temporary fabrication support structures are added for complex parts. The model is then converted into a standard file format (such as STL or AMF) and digitally sliced into layers.

- **Machine Setup & Build:** The sliced data is transferred to an AM machine, where materials—metals, polymers, ceramics, or composites—are selectively deposited and fused layer by layer using energy sources such as lasers, electron beams, or extruders.
- **Postprocessing & Validation:** After the building, parts typically undergo postprocessing steps (e.g., heat treatment, machining, surface finishing) and rigorous inspection (including nondestructive testing “NDE”) to ensure they meet functional and quality requirements.
- **Deployment:** The finished part is integrated into its intended application, whether as a prototype, end-use component, or tool.

This digital thread enables traceability, rapid iteration, and seamless integration with advanced data management systems, including digital twins and blockchain for supply chain security.

### 1.1.8 Unique Advantages

AM offers several compelling advantages over conventional manufacturing:

- **Design Freedom:** Complex geometries, internal channels, lattice structures, and topology-optimized forms can be produced without the constraints of tooling or traditional fabrication methods.
- Heat exchangers are a particularly promising example, as AM enables highly compact and high-performance internal channel networks. However, achieving the required geometric accuracy and surface quality inside these channels often depends on delicate and carefully controlled post-processing.
- **Customization & On-Demand Production:** Parts can be tailored to individual requirements and produced as needed, reducing inventory and enabling mass customization.
- **Material Efficiency:** By adding material only where necessary, AM minimizes waste and can reduce the environmental footprint of manufacturing.
- **Part Consolidation:** Multiple components can be integrated into a single, optimized part, reducing assembly steps, potential failure points, and supply chain complexity.
- **Rapid Prototyping to Production:** AM accelerates the product development cycle, from concept to prototype to low- and high-volume production, supporting agile innovation.

### 1.1.9 Technology Landscape

AM technologies are diverse, with the most prominent categories including:

- **Powder Bed Fusion (PBF):** Uses lasers or electron beams to selectively fuse powder particles, enabling high-resolution metal and polymer parts.
- **Directed Energy Deposition (DED):** Deposits material (often metal wire or powder) and fuses it with a focused energy source, suitable for large parts and repairs.
- **Binder Jetting:** Selectively deposits a liquid binder onto a powder bed, followed by postprocessing to achieve final properties.

- **Material Jetting:** offers unique capabilities for polymers, composites, and even construction-scale applications

### 1.1.10 Applications and Impact

AM is now widely adopted across industries such as aerospace, automotive, energy, healthcare, and construction. It enables:

- Lightweight, high-performance components (e.g., aerospace brackets, medical implants)
- Rapid tooling and spare parts
- Complex, architected materials for energy absorption, heat exchange, biomedical applications, etc.
- Large-scale complex structures.

### 1.1.11 Challenges and Future Directions

Despite its advantages, AM faces challenges including:

- Process repeatability and quality assurance
- Material property variability and certification
- Integration with existing manufacturing systems
- Workforce skills and digital infrastructure

Ongoing research and standardization efforts are addressing these challenges, paving the way for AM to become a cornerstone of digital, sustainable, and resilient manufacturing.

## Technical Breakdown

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### 1.1.12 The AM Process Chain

As explained in section 5.6.1, the typical AM process chain includes:

**Design & Digital Preparation:** Creation of a 3D model (CAD), conversion to a printable file (e.g., STL), and slicing into layers.

**Machine Setup & Build:** Layer-by-layer deposition and fusion of material, with process parameters (e.g., laser power, scan speed, layer thickness, etc) tailored to the material and geometry.

**Postprocessing:** Removal from the build plate, support structures removal, heat treatment, machining, surface finishing, and inspection (including NDT).

**Validation & Application:** Quality assurance, certification, and integration into the final application.

As described in section above the Additive manufacturing breakdown can be done in the following categories:

- **AM Processes:** Powder Bed Fusion (PBF), Directed Energy Deposition (DED), Binder Jetting, Material Extrusion, Material Jetting, other

- Materials: Metals, Polymers, Ceramics, Composites, Architected Materials
- Design for AM: DfAM Principles, Topology Optimization, Generative Design, Part Consolidation, Design Rules
- Process Control & QA: In-situ Monitoring, Thermography, X-ray Imaging, Metrology, NDT
- Postprocessing: Heat Treatment, Surface Finishing, Machining, HIP, etc

However, each category is interconnected and cannot be treated fully isolated and needs to be evaluation in conjunction:

- AM Processes are influenced by Materials, Design, QA, and Postprocessing.
- Materials selection impacts process, design and postprocessing.
- Design for AM must account for process/material constraints and postprocessing needs.
- Process Control & QA provides feedback to design, process, and postprocessing.
- Postprocessing is determined by process/material/design and feeds back into QA.

## 1.1.13 Interdependencies

### 1.1.13.1 AM Processes

- Materials: The choice of process determines which materials can be used (e.g., PBF for metals/polymers, DED for metals).
- Design for AM: Each process has unique design constraints (e.g., overhangs, minimum feature size).
- Process Control & QA: Each process requires specific monitoring and quality assurance methods.
- Postprocessing: The process affects the type and extent of postprocessing needed (e.g., support removal, heat treatment).

### 1.1.13.2 Materials

- AM Processes: Material properties (e.g., flowability, melting point, thermal conductivity) affect process selection and parameterization.
- Design for AM: Material characteristics influence design rules, achievable geometries, and performance.
- Postprocessing: Material type determines suitable postprocessing (e.g., heat treatments for metals, annealing for polymers).

### 1.1.13.3 Design for AM

- AM Processes: Design choices must align with process capabilities and constraints.
- Materials: Design may require specific materials for performance or manufacturability.
- Process Control & QA: Complex designs may need advanced monitoring and inspection.
- Postprocessing: Design decisions affect ease of support removal, finishing, and assembly.

#### 1.1.13.4 Process Control & QA

- AM Processes: Real-time monitoring and feedback improve process reliability.
- Design for AM: Data from QA can inform design improvements and DfAM guidelines.
- Postprocessing: Inspection results determine postprocessing needs and acceptance.

#### 1.1.13.5 Postprocessing

- AM Processes: Feedback from postprocessing can drive process optimization.
- Materials: Postprocessing methods are material-dependent.
- Design for AM: Design for postprocessing (DfX) ensures manufacturability and quality.
- Process Control & QA: Postprocessing steps are validated by QA.

## Map of Individual Technologies

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The purpose of this section is to provide a brief overview of the technologies used in the Additive Manufacturing and to explain their functions in simple terms, allowing non-expert readers to gain a basic understanding of their applications. Detailed information about each technology including development needs and list of actors is included in the dashboards.

### 1.1.14 AM Processes

AM processes are the different ways to built 3D objects layer by layer. Each process uses different materials and methods to create parts.

#### Main types:

- **Powder Bed Fusion (PBF):** A thin layer of powder (for example, metal alloy powder) is spread over a platform. A laser or electron beam melts the powder in specific areas to form each layer. Used for strong, complex parts in aerospace, medical, and automotive.
- **Directed Energy Deposition (DED):** Material (usually metal powder or wire) is fed into a focused energy source (like a laser), which melts it as it's deposited. It is good for repairing parts or making large components.
- **Binder Jetting:** A print head deposits a liquid binder (like a wax) onto a powder bed, sticking the powder together. The part is then sintered and may need further processing. Used for metal and ceramic parts.
- **Material Extrusion (FDM/FFF):** Plastic filament is melted and extruded through a nozzle, building up the part layer by layer. Common for prototypes and functional plastic parts. Can also be applied for metal powder mixed with binder (jet injection moulding) followed by sintering (needs compensation for shrinking).
- **Material Jetting:** Tiny droplets of liquid plastic or wax are jetted and hardened by light. Used for high-detail models and multi-material/color parts.

## 1.1.15 AM Materials

These are the raw materials used in AM processes. The choice of material affects the part's strength, appearance, and use.

### Main types:

- **Metals:** For strong, durable parts (e.g., titanium, tungsten, steel, aluminum, nickel alloys, CuCrZr). Used in aerospace, automotive, defense applications and medical implants.
- **Polymers (Plastics):** For prototypes, models, and some end-use parts. Includes ABS, PLA, nylon, and more.
- **Ceramics:** For high-temperature or wear-resistant parts. Used in medical and industrial applications.
- **Composites:** Combine two or more materials for improved properties (e.g., carbon fiber-reinforced plastics).
- **Architected Materials (Lattices):** Special designs with repeating patterns to make parts lightweight but strong.

## 1.1.16 Design for AM (DfAM)

Design for AM means creating parts that take advantage of what AM can do—like making complex shapes, combining parts, or reducing weight.

### Key concepts:

- **Topology Optimization:** Software removes unnecessary material, creating lightweight, strong parts.
- **Generative Design:** AI-driven tools suggest new shapes based on performance needs.
- **Part Consolidation:** Combines several parts into one, reducing assembly and potential failure points.
- **Design Rules:** Guidelines for making parts that print well (e.g., minimum wall thickness, support for overhangs). Beyond enabling manufacturability, design rules are also essential inputs for the development of design and construction codes such as ASME and RCC-MRx, which will ultimately govern the qualification of AM components. Coupled with these rules, advanced simulation tools help minimise part distortion and internal stresses, improving both quality and predictability.

## 1.1.17 Postprocessing

Postprocessing includes all the steps taken after printing to make the part ready for use.

### Common steps:

- **Heat Treatment:** Improves strength and durability.
- **Surface Finishing:** Polishes or smooths the part for better appearance or function.
- **Machining:** Cuts or drills the part to achieve precise dimensions.
- **Hot Isostatic Pressing (HIP):** Uses heat and pressure to reduce porosity and improve strength.
- **Support Removal:** Takes away temporary structures used during printing.

## 1.1.18 Process Control & Quality Assurance

These are methods and tools to make sure AM parts are built correctly and meet quality standards.

### Key elements:

- **In-situ Monitoring:** Cameras and sensors watch the build process in real time, detecting problems early.
- **Thermography & X-ray Imaging:** Measure temperature and look inside parts for hidden defects.
- **Metrology & Nondestructive Testing (NDT):** Use tools like CT scanning or ultrasound to check part dimensions and internal quality without damaging the part.
- **Quality Assurance (QA):** Ensures every part meets safety and performance requirements, and supports the certification of components where stringent qualification and documentation are required.

# Summary of the Workshop

In total, 80 people registered for participation to the 2025 Additive Manufacturing Technology Mapping workshop representing 51 entities.

Here below the **statistical summary** of the 51 entities:

### Breakdown by Entity Type

Entity Type	Count	Percentage
Private Companies	28	55%
Research & Tech Centres	12	23%
Public/Government Agencies	6	12%
Universities	4	8%

Assoc. / NGOs

1

2%

**Primary Industrial Focus**

- Nuclear & Fusion Energy (35%)
- Advanced Manufacturing (25%)
- Aerospace & Engineering (20%)
- Cross-Sector Tech & Innovation (20%)

**Geographical Presence**

The list is **98% European-centric**, with the highest concentration in **Spain (approx. 25%)**, followed by **Germany** and **Italy**.

**List of companies and institutions represented in the workshop:***Amentum**AMCM GmbH**ANI – Agência Nacional de Inovação**BJS Ceramics GmbH**BJS Composites GmbH**Bureau Veritas**Cadinox S.A.**CATEC – Centro Avanzado de Tecnologías Aeroespaciales**CDTI – Centro para el Desarrollo Tecnológico y la Innovación**CEA – Commissariat à l'énergie atomique et aux énergies alternatives**CEIT – Centro de Estudios e Investigaciones Técnicas**CIEMAT – Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas**CIM-UPC – Centre de Fabricació Additiva i Digital (UPC)*

*CITD Engineering & Technologies*  
*CNR–ISTP – Istituto di Scienza e Tecnologie per il Plasma (CNR)*  
*CREATE - Consorzio di Ricerca per l'Energia, l'Automazione e le Tecnologie dell'Elettromagnetismo*  
*DAES – Desarrollo de Aplicaciones Energéticas Sostenibles*  
*Danish Technological Institute*  
*DTT – Divertor Tokamak Test Facility*  
*Dynext S.r.l.*  
*EFA – European Fusion Association*  
*European Commission (EC)*  
*Eurecat – Centre Tecnològic de Catalunya*  
*Freemelt AB*  
*Framatome*  
*Fraunhofer-Gesellschaft (IGCV, IWS, ILT Institutes)*  
*HP – Hewlett-Packard*  
*Hypermetal*  
*IPP – Max-Planck-Institut für Plasmaphysik*  
*IPP CAS – Institute of Plasma Physics, Czech Academy of Sciences*  
*ISQ – Instituto de Soldadura e Qualidade*  
*KIT – Karlsruhe Institute of Technology*  
*Leading Management Solutions*  
*Mondaic GmbH*  
*MWB Industries*  
*newcleo*  
*Pangea Aerospace S.L.*  
*Pangea Propulsion*  
*Partille Scoutkår*  
*pro-beam Group*  
*RHP Technology GmbH*  
*Rosswag Engineering*  
*SIMIC S.p.A.*  
*SUPSI – Scuola Universitaria Professionale della Svizzera Italiana*  
*Tecnalia Research & Innovation*  
*Tecnocampus Mataró*  
*Tekniker – Fundación Tekniker*  
*The Steel Printers*  
*Treccani Engineering*  
*UKAEA – United Kingdom Atomic Energy Authority*  
*UPC – Universitat Politècnica de Catalunya*  
*Universidad de Sevilla*

Fusion for Energy wish to thank all participants for their inputs during and after the workshop.



# Outcome: Technology Road-Mapping

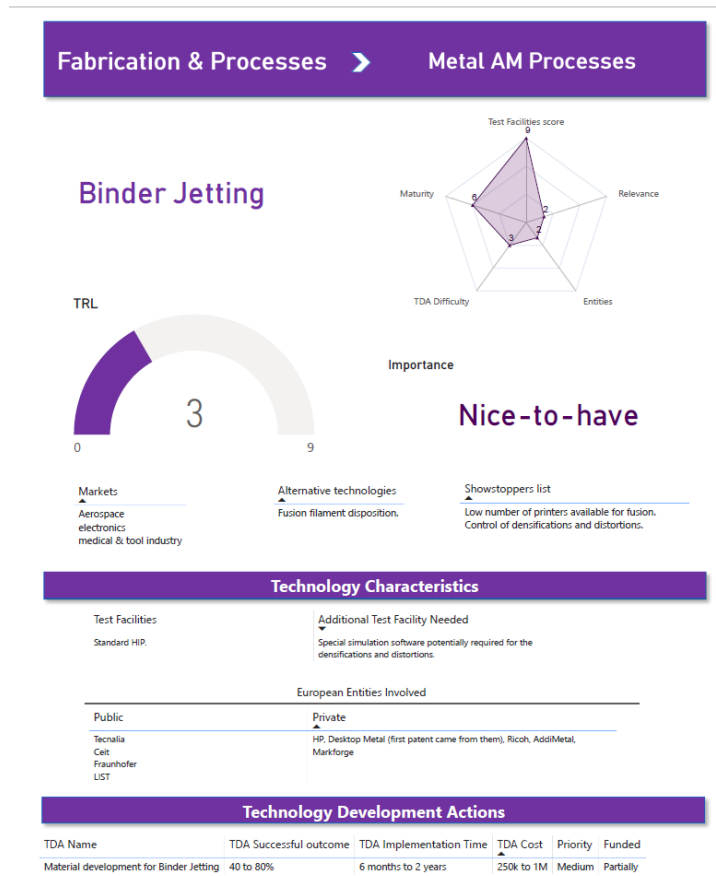
## Technology Dashboards

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During the in-person workshop and in the process of preparing this report, a lot of valuable data was collected into a database. For each technology, the following data is now available:

- TRL\*
- Criticality
- Other fields of application
- Alternative technologies
- Potential showstoppers
- Existing and needed test facilities
- European entities involved
- Technology development actions

This data has been arranged into a dashboard for each of the technologies:



*Typical technology*

All technology dashboards are available in Appendix 3: Technology dashboards. The dashboards are a view of the database at the time of publishing this document. The database will be updated regularly, and Appendix 3 may be re-published as necessary.

*\*It should also be noted that TRLs are application-dependent. A technology that reaches a high TRL in sectors such as aerospace or automotive may still be considered at a lower TRL for nuclear applications, where additional qualification, codes, and safety requirements apply.*

## SWOT Analysis

### 1.1.19 Strengths

- **Design Freedom & Complexity:** AM enables the creation of complex geometries, internal channels, and multi-material parts that are impossible or very costly with traditional manufacturing.
- **Rapid Prototyping & Customization:** Fast iteration cycles and the ability to tailor parts for specific applications (e.g., repair, lifecycle considerations).
- **Material Efficiency:** Potential for reduced waste due to near net shape manufacturing and optimized use of expensive or rare materials.
- **Growing Ecosystem:** Increasing number of R&D entities, suppliers, and collaborative projects in Europe and globally.

- **Cross-Sector Potential:** Technologies and know-how developed for fusion are also relevant for aerospace, automotive, energy, and medical sectors, broadening market potential.
- **Advances in Simulation & AI:** Integration of advanced simulation, AI, and process monitoring improves design, quality, and predictability.

### 1.1.20 Weaknesses

- **Data Gaps:** Lack of comprehensive material property data, especially for fusion-relevant materials under irradiation and extreme conditions.
- **Process Control Challenges:** Ensuring repeatability, quality, and in-process monitoring remains difficult, especially for large or complex parts.
- **Equipment & Facility Needs:** Some AM processes require specialized, costly equipment not widely available for fusion applications.
- **Standardization Lag:** Industry standards and qualification protocols for AM in fusion are still under development, slowing adoption.
- **Supply Chain Limitations:** Limited suppliers for certain critical materials (e.g., tungsten wires), and economic barriers to scaling up.
- **Post-Processing Demands:** AM parts may require extensive post-processing depending on application and end use (e.g., heat treatment, surface finishing, powder removal), adding time and cost. However still less than conventional casting.
- **Economic competitiveness:** Another challenge lies in the difficulty of establishing when additive manufacturing becomes economically competitive compared to traditional manufacturing methods. While conventional fabrication routes have well-defined and widely benchmarked unit costs (or cost ranges), this level of cost transparency is not yet fully available for AM. As a result, manufacturers may hesitate to adopt AM unless a clear technical benefit exists—such as enabling an otherwise unattainable design—or unless the potential cost savings are substantial enough to justify the uncertainty.

### 1.1.21 Opportunities

- **Filling Data & Qualification Gaps:** Centralizing material data, developing qualification protocols, and benchmarking processes will accelerate adoption.
- **Hybrid & Multi-Material Manufacturing:** Combining AM with traditional methods or using multiple materials in a single part can unlock new functionalities.
- **Large-Scale & Complex Components:** Advancing AM for bigger, more intricate parts (e.g., with internal cooling channels) for fusion and other high-value sectors.
- **Advanced NDE & Digital Twins:** Improving non-destructive evaluation (NDE) and integrating digital twins for real-time monitoring and predictive maintenance.
- **Sustainability:** Potential for recycling powders, reducing waste, and optimizing energy use.

- **International Collaboration:** Leveraging global expertise and facilities to accelerate R&D and standardization.

## 1.1.22 Threats

- **Economic Barriers:** High costs for equipment, materials, and qualification may limit industrialization and supply chain robustness.
- **Technological Uncertainty:** Some processes and materials (e.g., ductile tungsten, functionally graded materials) are still at low TRL and may face unforeseen technical hurdles.
- **Regulatory & Qualification Delays:** Slow progress in developing and harmonizing standards could delay market entry and acceptance.
- **Supply Chain Risks:** Dependence on a few suppliers for critical materials or equipment could create bottlenecks or vulnerabilities.
- **Competition from Traditional Methods:** In some cases, traditional manufacturing may remain more cost-effective or reliable, especially for high-volume or less complex parts.

## Main Test Facilities

---

### 1.1.23 Material and Process Testing Facilities

- **Fraunhofer Institutes (Germany):** Multiple branches (e.g., IGCV, IWS) active in AM process development, material testing, and large-scale part production.
- **CEIT (Spain):** Involved in process qualification, material development, and simulation for AM.
- **KIT (Karlsruhe Institute of Technology, Germany):** Focus on process simulation, material testing (including tungsten), and AM process benchmarking.
- **CEA (France):** AM platforms for metals special alloys ceramics and composites, AM process simulation and qualification (LPBF, DED, MBJ)
- **UPC CIM (Spain):** Material development and process demonstration, especially for ceramics and composites.
- **Chalmers (Sweden):** Powder metallurgy qualification and piloting AM development. Coordination of international AM R&D projects.
- **RHP (Austria):** Materials and AM process development.
- **RISE (Sweden):** Application center for AM and support to increase TRL level of AM products.
- **TWI (UK):** Metal additive manufacturing and support to supply chain in different technical disciplines.
- **University of Udine (Italy):** Materials and prototypes for nuclear fusion applications
- **Dynext srl (Italy):** LPBF and DED process and materials development, process simulation, product design and large-scale prototypes

### 1.1.24 Non-Destructive Evaluation (NDE) & Imaging Facilities

- **X-ray and Neutron Imaging:**
  - **CEA List (Saclay, France), ISQ (Portugal), SOLEIL (Saclay), ESRF (Grenoble), MAX-IV (Lund), Diamond (Oxford):** Advanced X-ray and neutron imaging for internal inspection of AM parts, including large and complex geometries.
  - **ESS (Lund, Sweden), ILL (Grenoble, France), DAES (Geneva):** Neutron scanning and activation analysis for deep inspection and material characterization.
- **Ultrasonic and Acoustic Testing:**
  - **University of Madrid, Fraunhofer, University of Hamburg:** Expertise in ultrasonic testing, acoustic resonance, and validation of new NDE techniques for AM.

### 1.1.25 Special Equipment and Pilot Facilities

- **Large-Scale Foundries and AM Pilot Lines:**
  - **Fraunhofer IGCV, Voestalpine, Voxeljet:** Facilities for large-scale casting, sand printing, and post-processing of AM parts.
  - **Gersthofen, Bayreuth (Germany):** Fiber production and ceramic AM pilot lines.
  - **CEA (France):** AM pilot lines for wire and powder processes
- **Specialized Equipment:**
  - **Induction systems, gas-filled chambers, CVI reactors, and large chambers with dust extraction:** Used for specific AM processes (e.g., DED, cold spray, ceramic extrusion).
  - **Freemelt,** facilities for series production of high-density refractory materials as tungsten.

### 1.1.26 Irradiation and Qualification Facilities

- **Neutron Irradiation:**
  - **FRM II (Garching), ILL (Grenoble), CEA (LLB), ESS (Lund):** Facilities for neutron activation analysis and irradiation testing of AM materials.
- **Material Qualification:**
  - **Centralized testing and database creation:** Multiple actors produce and test AM samples under standardized conditions to build qualification databases.

### 1.1.27 International and Non-European Facilities

- **USA:** National labs (e.g., ORNL), companies (e.g., Exone, Meltio), and research consortia contribute to AM process and equipment development.
- **Japan:** Ube, NGS—active in fiber and ceramic AM.
- **Israel:** Tiritone—monopoly manufacturer for certain ceramic AM technologies.

### 1.1.28 Key Insights

- **Collaboration is essential:** Many facilities work in partnership across Europe and internationally, combining expertise in materials, processes, and testing.
- **Specialization matters:** Some facilities focus on unique capabilities (e.g., neutron imaging, large-scale casting, ceramic AM), making them critical for advancing specific AM technologies.
- **Gaps remain:** While there is strong coverage for many AM processes, some specialized equipment (especially for fusion applications) is still under development or not widely available.

## Gaps in the Ecosystem

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### 1.1.29 Material Data and Qualification

- **Lack of Comprehensive Material Data:** There are significant gaps in material property data, especially for fusion-relevant materials (e.g., EUROFER, CuCrZr, tungsten, vanadium alloys) under irradiation and extreme conditions.
- **Qualification Protocols:** Standardized qualification procedures for AM materials and parts are still under development, making certification for critical applications challenging.
- **Proprietary and Fragmented Databases:** Much of the existing data is proprietary or scattered, limiting access and cross-comparison.
- **Limited Accuracy and Validation for Simulation:** Many commercial finite-element (FE) and Multiphysics tools were originally developed for formed or cast materials and rely on homogenized, isotropic material models. These assumptions do not always hold for AM parts, where anisotropy, porosity, and microstructural gradients can significantly influence performance. As a result, simulation outputs may not yet be as trustworthy as those applied to components manufactured through conventional methods. Robust physics-based simulation tools are needed.
- **Uncertainty in Safety Factors and Design Margins:** Because AM-specific material data remains incomplete—particularly under irradiation, cyclic loading, or extreme thermal gradients—design factors derived from simulations may carry higher uncertainty. This raises the question of whether current safety factors used for conventional materials can be directly applied to AM parts, or whether new, AM-specific design margins must be defined.

### 1.1.30 Process Control and Monitoring

- **Limited In-Process Monitoring:** Not all AM processes have robust, real-time monitoring and control systems, which are essential for ensuring quality and repeatability.
- **Process Parameter Standardization:** There is a lack of standardized process parameters and benchmarks, especially for new or hybrid AM processes.

### 1.1.31 Equipment and Facility Availability

- **Specialized Equipment Shortage:** Some AM processes require unique or costly equipment (e.g., for large-scale parts, ceramics, or advanced NDE) that is not widely available, especially for fusion-specific needs.
- **Post-Processing Capabilities:** Facilities for critical post-processing steps (e.g., heat treatment, powder removal, surface finishing) are not always accessible or optimized for AM parts.

### 1.1.32 Supply Chain and Industrialization

- **Limited Suppliers:** There are few suppliers for certain critical materials (e.g., tungsten wires, advanced ceramics), and economic barriers to scaling up production.
- **Raw Material Availability:** Some feedstocks (e.g., pure irregular powders, wires) are not yet commercially available or are only produced in small quantities. Some high-quality metal powders, particularly those required for fusion-relevant or high-performance applications, remain available only from a very limited number of suppliers and at significantly elevated prices. This restricted supplier base, combined with high production and purification costs, creates a bottleneck that limits broader industrial adoption and raises the economic barrier for scaling up AM processes.
- **Recycling and Sustainability:** Systems for recycling powders and wires, and for assessing the environmental impact of AM, are still underdeveloped.

### 1.1.33 Standardization and Codes

- **Slow Progress on Standards:** Industry-wide standards for AM in fusion and nuclear applications are lagging, which slows down qualification and adoption.
- **NDE and Inspection Protocols:** Non-destructive evaluation methods for complex AM parts are still being validated and standardized.

### 1.1.34 Human Capital and Training

- **Need for Specialized Training:** There is a shortage of skilled personnel trained in AM process control, simulation, and qualification, especially for large-scale and complex parts.
- **Knowledge Transfer:** Best practices and lessons learned are not always effectively shared across organizations and sectors.

### 1.1.35 Digital Integration

- **Fragmented Digital Tools:** Integration between design, simulation, manufacturing, and quality control tools is incomplete, limiting the benefits of digital twins and AI-driven optimization.
- **Data Sharing and Interoperability:** Lack of common platforms for sharing process and material data across the ecosystem.

#### Summary Table: Key Gaps

Area	Main Gaps Identified
Material Data & Qualification	Data gaps, lack of protocols, proprietary databases
Process Control & Monitoring	Limited real-time monitoring, lack of parameter standards
Equipment & Facilities	Shortage of specialized equipment, post-processing gaps
Supply Chain & Industrialization	Few suppliers, raw material limits, recycling issues
Standardization & Codes	Slow standards progress, NDE protocol gaps
Human Capital & Training	Skills shortage, limited knowledge transfer
Digital Integration	Fragmented tools, poor data interoperability

## Roadmaps

In this section it proposed a roadmap for advancing additive manufacturing (AM) technologies, based on the mapping and challenges identified during the workshop. The roadmap is structured in phases, that addresses technology development, qualification, and industrialization for fusion and related sectors.

### 1.1.36 Phase 1: Foundation & Data Gathering (0–2 Years)

#### Objectives:

- Fill critical data gaps, establish standards, and build collaboration networks.

#### Key Actions:

- Gather and centralize material data for AM, especially for fusion-relevant materials (e.g., EUROFER, CuCrZr, tungsten, 316 LN IG).

*An important ongoing initiative in this area is the MATDB4Fusion project, led by the Clean Air Task Force, which is developing a dedicated open-access Material Database for Fusion. This effort aims to consolidate and standardize material property data relevant to fusion applications—particularly for advanced and additive-manufactured materials—bridging current data gaps and supporting the establishment of harmonized qualification and design frameworks. More information is available at: <https://www.catf.us/fusion-energy/matdb4fusion/>.*

- Develop and harmonize design guidelines, including for finite element (FE) analysis and lifecycle/repair considerations.
- Map and benchmark existing special equipment, test facilities, and suppliers.
- Launch collaborative R&D projects to address gaps in material databases, process parameters, and simulation tools.
- Begin standardization efforts for codes, qualification, and non-destructive evaluation (NDE) methods.

#### Milestones:

- Existing data collected and gaps identified.
- First set of harmonized design guidelines published.
- Initial database of suppliers, facilities, and R&D entities established.

### 1.1.37 Phase 2: Technology Development & Demonstration (1–4 Years)

**Objectives:**

- Advance TRL of key AM processes, demonstrate feasibility for fusion, and validate process control.

**Key Actions:**

- Definition of use cases
- Develop and validate active process control systems for AM (e.g., in-situ monitoring, AI-based feedback).
- Demonstrate repair and lifecycle processes for critical components.
- Optimize simulation tools for large-scale and complex AM parts.
- Develop and test hybrid and multi-material AM processes, including functionally graded materials.
- Scale up production of challenging materials (e.g., ductile tungsten, advanced ceramics, wires).
- Pilot advanced NDE methods (X-ray CT, neutron scanning, ultrasonic) for complex AM parts.

**Milestones:**

- Successful demonstration of AM repair processes and large-scale part production.
- Validated process simulation for fusion-relevant materials.
- First industrial pilot of hybrid/multi-material AM for fusion components.
- Standardized NDE protocols for AM parts in place.

### 1.1.38 Phase 3: Qualification & Industrialization (3–6 Years)

**Objectives:**

- Qualify AM processes and materials for fusion, enable industrial adoption, and ensure supply chain robustness.

**Key Actions:**

- Complete qualification of AM processes and materials according to fusion and nuclear codes (e.g., RCC-MRx).
- Establish process control and certification protocols for part acceptance.
- Develop mass-production capabilities and industrialization strategies for key AM technologies.
- Expand supplier base for critical materials and equipment, including recycling and sustainability initiatives.
- Integrate AM with digital twins and advanced simulation for predictive maintenance and lifecycle management.

**Milestones:**

- AM parts qualified for use in fusion prototypes or demonstrators.
- Industrial supply chain established for key AM materials and processes.
- Demonstrated cost reduction and improved reliability through process control and standardization.
- Establish manufacturing routes diagrams that allow decision based on costs for AM or traditional methods, once technical feasibility is granted

### 1.1.39 Phase 4: Continuous Improvement & Expansion (5+ Years)

**Objectives:**

- Sustain innovation, expand applications, and ensure long-term competitiveness.

**Key Actions:**

- Monitor and update standards, guidelines, and databases as technology evolves.
- Foster ongoing R&D for new materials, processes, and digital integration (e.g., AI, machine learning).
- Expand AM applications to new fusion components and other high-value sectors (aerospace, medical, energy).
- Promote international collaboration and knowledge sharing.

**Milestones:**

- Regularly updated standards and guidelines.
- New AM applications adopted in fusion and beyond.
- Continuous improvement culture established across the AM ecosystem.

### 1.1.40 Summary

Phase	Focus Areas	Key Outcomes
1. Foundation & Data	Data, guidelines, collaboration	Gaps identified, standards initiated
2. Development & Demo	Process control, simulation, pilots	Validated processes, pilot parts
3. Qualification & Industry	Certification, supply chain, scale-up	Qualified parts, industrial adoption
4. Continuous Improvement	Innovation, expansion, updates	New applications, sustained progress

## Conclusion

Additive Manufacturing for fusion is advancing rapidly, with exciting opportunities and some significant challenges. Continued research, collaboration, and investment will help unlock the full potential of AM in fusion and beyond.

## Technology Readiness and Market Potential

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- **Technology Readiness Levels (TRL):** Most AM technologies for fusion applications are at an early to intermediate stage (TRL 3–6), though some, like design guidelines and certain ceramic processes, are more mature (TRL 7–8).
- **Market Potential:** Many AM technologies have strong potential in aerospace, automotive, energy, and medical sectors, not just fusion.

## Key Challenges (“Showstoppers”)

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- **Material Data Gaps:** Lack of comprehensive data for fusion-relevant materials, especially under irradiation.
- **Process Control:** Need for better monitoring and control during printing to ensure quality and repeatability.
- **Special Equipment:** Some processes require unique or costly equipment, not always available for fusion applications.
- **Standardization:** Industry-wide standards for AM in fusion are still under development.
- **Supply Chain:** Limited suppliers for certain materials (e.g., tungsten wires), and economic barriers to scaling up production.

## Opportunities

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- **Integration of Design & Simulation:** Using AI and advanced simulation to optimize part design and predict performance.
- **Hybrid & Multi-Material Manufacturing:** Combining different AM processes or materials in a single part for improved properties.
- **Large-Scale Components:** Developing AM methods for bigger, more complex parts, including new ways to remove support material and improve surface finish.
- **New Materials:** Research into ductile tungsten, functional materials, and multi-material AM for better performance in fusion environments.
- **Advanced Testing:** Non-destructive methods like X-ray CT, neutron scanning, and ultrasonic testing are being improved for complex AM parts

## Next Steps Proposed

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- **Filling Data Gaps:** Gathering and sharing material data, especially for fusion-specific needs.
- **Process Qualification:** Developing benchmarks and standardized tests for AM parts.
- **Scaling Up:** Moving from lab-scale demonstrations to industrial production, with a focus on cost, reliability, and quality.

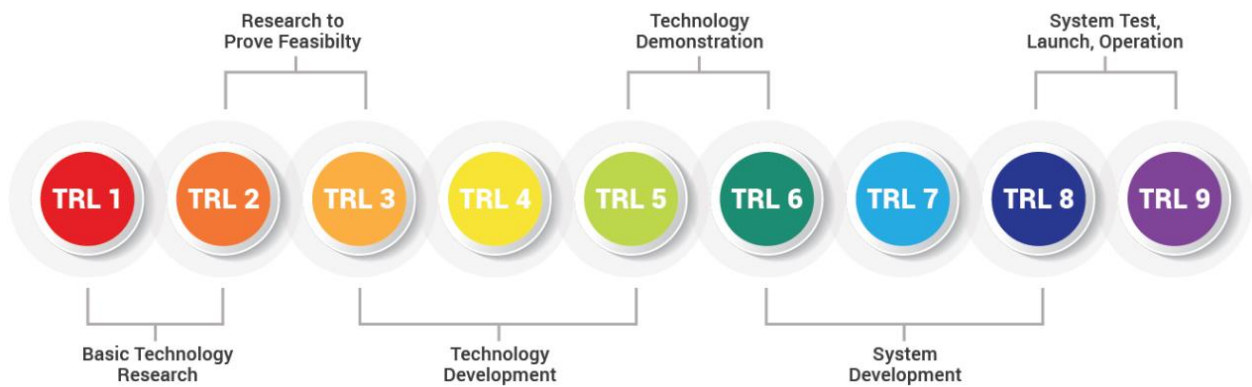
# Appendix 1: Technology Readiness Levels

For this workshop, a TRL scale from 1 to 9 will be used, in line with the IAEA definitions.

## TRL GUIDANCE FOR FUSION TECHNOLOGY COMPONENTS (AS PER IAEA-TECDOC-2047)

TRL	Systems	Materials	Software	Manufacturing	Instrumentation
1	Basic principles	Evidence from literature	Mathematical formulation	Process concept proposed	Understand the physics
2	Technology concept	Agreed Property targets, cost & timescales	Algorithm implementation documented	Validity of concept described	Concept designed
3	Proof of concept	Materials' capability based on lab scale samples	Prototype architectural design of important functions is documented	Experimental proof of concept completed	Lab test to prove
4	Validation in a laboratory environment	Design curves produced	ALPHA version with most Functionalities implemented with User Manual and Design File Available	Process validated in lab	Lab demonstration of highest risk components
5	Partial system validation in a relevant environment	Methods for material processing and component manufacture	BETA version with complete software functionalities, documentation, test reports and application examples available	Basic capability demonstrated using production equipment	Requiring specialist support
6	Prototype demo in a relevant environment	Validated via component and/or sub-element testing	Product release ready for operational use	Process optimized for capability and rate using production equipment	Applied to realistic location/environment with low level of specialist support

7	Prototype demo in operational environment	Evaluated in development rig tests	Early adopter version qualified for a particular purpose	Economic run lengths on production parts	Successful demonstration in test
8	Test and demonstration	Full Operational test	General product ready to be applied in a real application	Significant run lengths	Demonstrated productionised system
9	Successful mission operation	Production ready material	Live product with full documentation and track record available	Demonstrated over extended period	Service proven



## Appendix 2: Technology Assessment Criteria

- **Maturity:** relates to organisations and groups with the capacity to contribute to technology development and relevant actions.
- **Entities:** refer to organisations or groups that are currently engaged, or possess the capacity to participate in relevant activities. These may include companies, research centres, universities, public or private agencies, and non-governmental organisations (NGOs).
- **Test facility:** provides an indication of the capabilities and resources available to support technology development and testing.
- **TDA (Technology Development Action) difficulty:** reflects the challenges faced in advancing technological solutions. This assessment highlights the complexity involved in achieving technology development objectives.
- **Relevance:** addresses the significance and applicability within the broader context of technology development and organisational maturity.

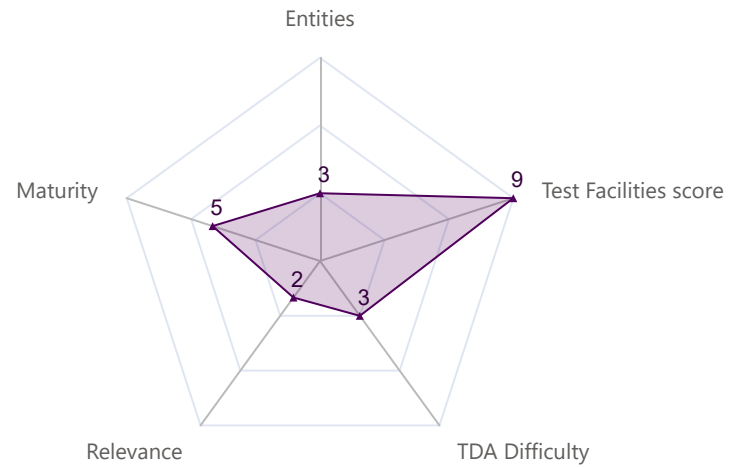
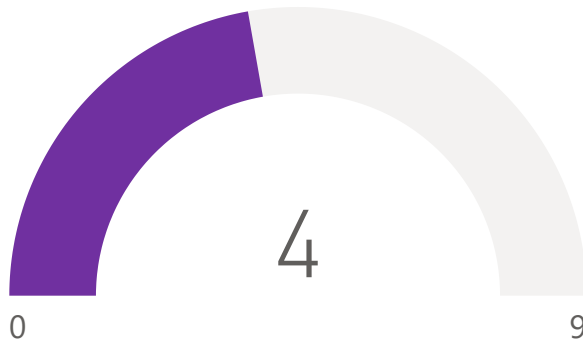
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# Appendix 3: Technology Dashboards



# 3D Printing for steel Casting (Sand)

TRL



Importance

## Major Improvement

Markets

Technology already established in other industries.

Alternative technologies

Wire or other DED processes.

Showstoppers list

Defects or imperfections on the mold.

### Technology Characteristics

Test Facilities

Fraunhofer, IGCV, Voestalpine, ...

Additional Test Facility Needed

Large scale foundries  
eg. melting room for casting. Binder materials development.

European Entities Involved

Public

Fraunhofer  
IGCV,

Private

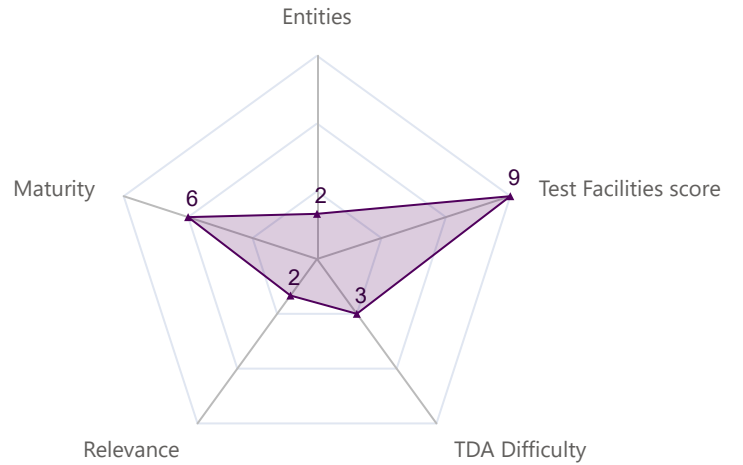
Fraunhofer, IGCV, Voestalpine, ...

### Technology Development Actions

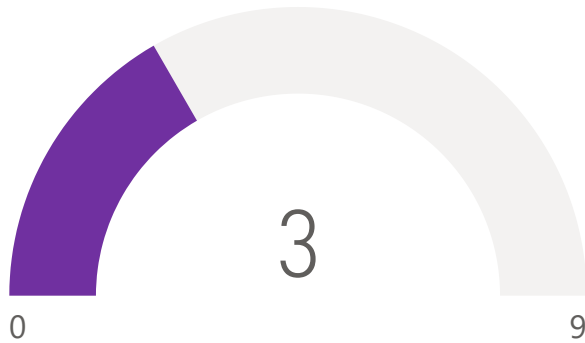
TDA Name	TDA Successful outcome	TDA Implementation Time	TDA Cost	Priority	Funded
Large scale components with cavities	40 to 80%	6 months to 2 years	250k to 1M	High	



# Binder Jetting



TRL



Importance

Nice-to-have

Markets

Aerospace, electronics, medical & tool industry

Alternative technologies

Fusion filament disposition.

Showstoppers list

Low number of printers available for fusion. Control of densifications and distortions.

## Technology Characteristics

Test Facilities

Standard HIP.

Additional Test Facility Needed

Special simulation software potentially required for the densifications and distortions.

European Entities Involved

Public

Tecnia  
Ceit  
Fraunhofer  
LIST

Private

HP, Desktop Metal (first patent came from them), Ricoh, AddiMetal, Markforge

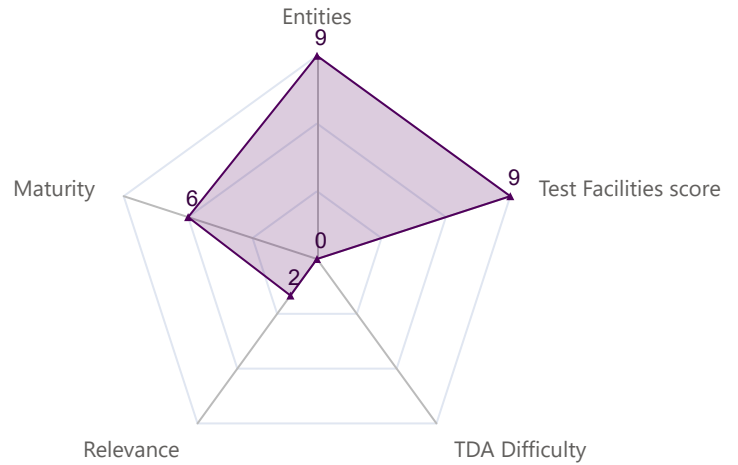
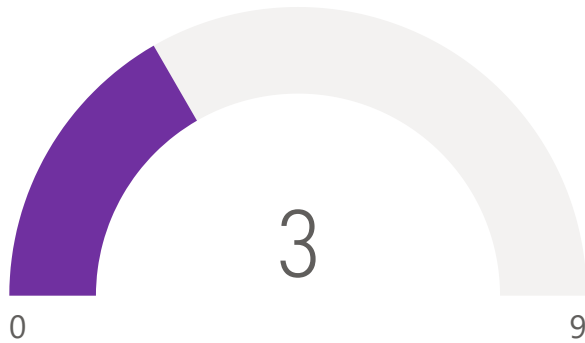
## Technology Development Actions

<u>TDA Name</u>	TDA Successful outcome	TDA Implementation Time	TDA Cost	Priority	Funded
Material development for Binder Jetting	40 to 80%	6 months to 2 years	250k to 1M	Medium	Partially



# Coatings

TRL



Importance

## Essential

Markets

The spinoffs - difficult to define because market is well developed and applications are very specific

Alternative technologies

Showstoppers list

Need to define use application

### Technology Characteristics

Test Facilities

Additional Test Facility Needed

Standard testing for coatings

European Entities Involved

Public

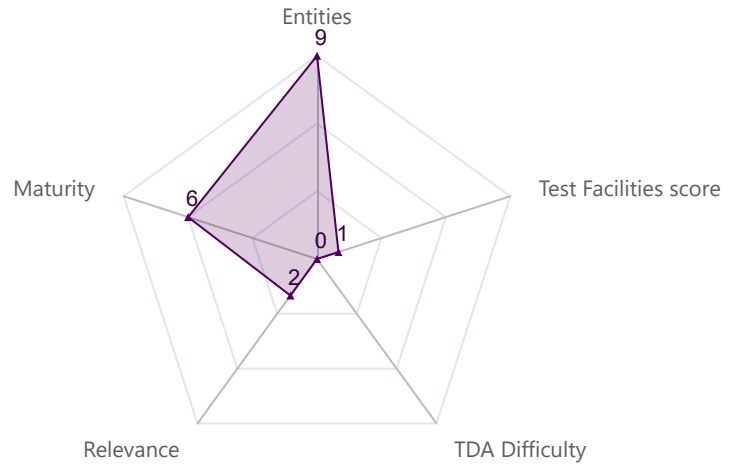
Private

### Technology Development Actions

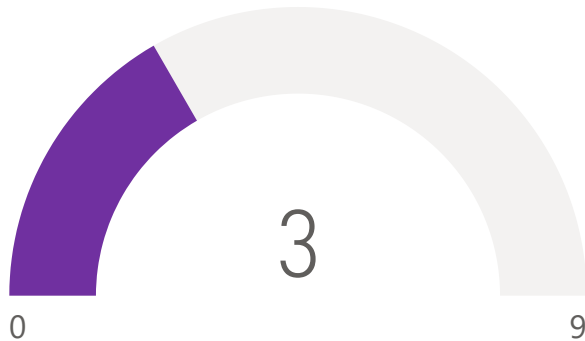
TDA Name	TDA Successful outcome	TDA Implementation Time	TDA Cost	Priority	Funded
Protective coatings: functional tungsten-boron	40 to 80%	6 months to 2 years	250k to 1M	High	Yes



# Design & Simulation Interconnection



TRL



Importance

## Major Improvement

Markets

any other AM market

Alternative technologies

traditional design iteration via CAD and FEA softwares.

Showstoppers list

Its need a big effort while the benefit is not easy to quantify.

### Technology Characteristics

Test Facilities

Additional Test Facility Needed

European Entities Involved

Public

Private

### Technology Development Actions

TDA Name

TDA Successful outcome

TDA Implementation Time

TDA Cost

Priority

Funded



# Design Guidelines Availability

TRL



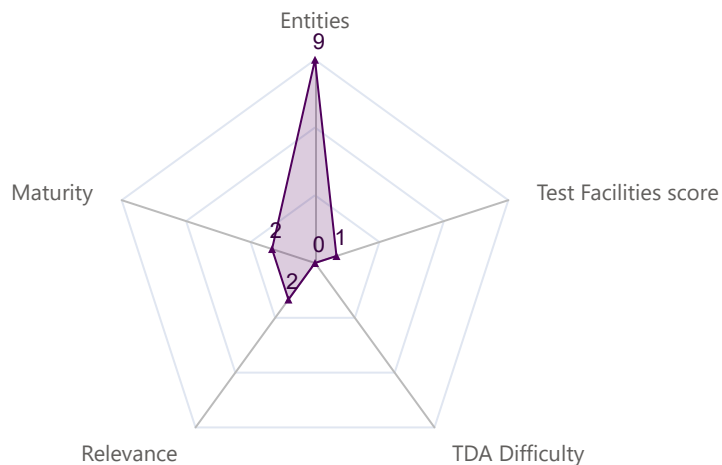
Markets

any other AM market

Alternative technologies



Showstoppers list



Importance

## Nice-to-have

### Technology Characteristics

Test Facilities

Additional Test Facility Needed

European Entities Involved

Public

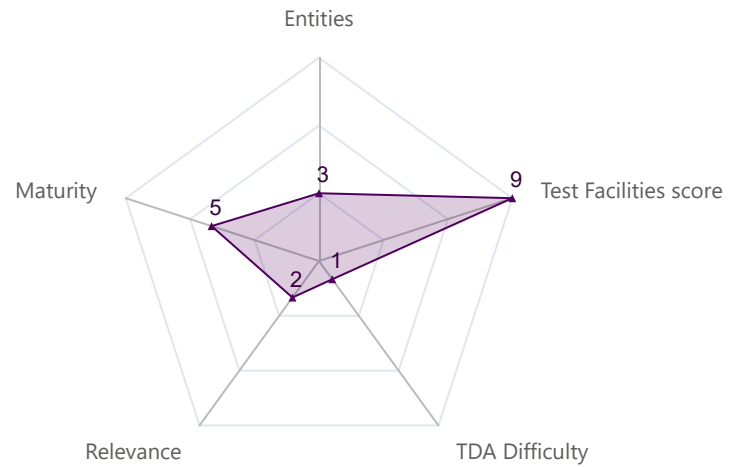
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### Technology Development Actions

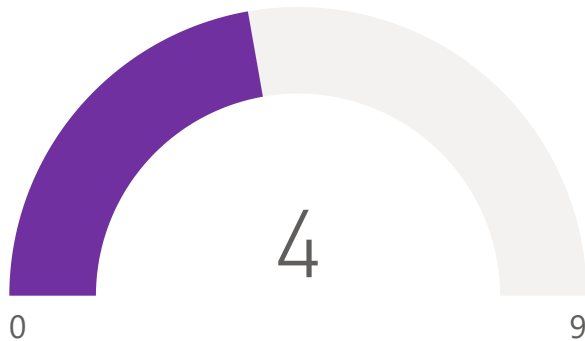
TDA Name	TDA Successful outcome	TDA Implementation Time	TDA Cost	Priority	Funded
Guidelines for AM FE Analysis and interpretations	>80%	6 months to 2 years	<250k	High	



# Filament and Pellet Extrusion for Ceramics



TRL



Importance

Essential

Markets

Aerospace (aero-engines and space: airfoils, turbines, combustion chambers), defense, fission, energy, gas turbines.

Alternative technologies

▼

Showstoppers list

▲  
Economic limits to ramp up Supply chain.

## Technology Characteristics

Test Facilities

Gersthofen (GER), fiber production in Bayreuth (GER)

Additional Test Facility Needed

▼  
CVI Reactor.

European Entities Involved

Public

Fraunhofer.

Private

▼  
Fiber Production: BJS (GER)

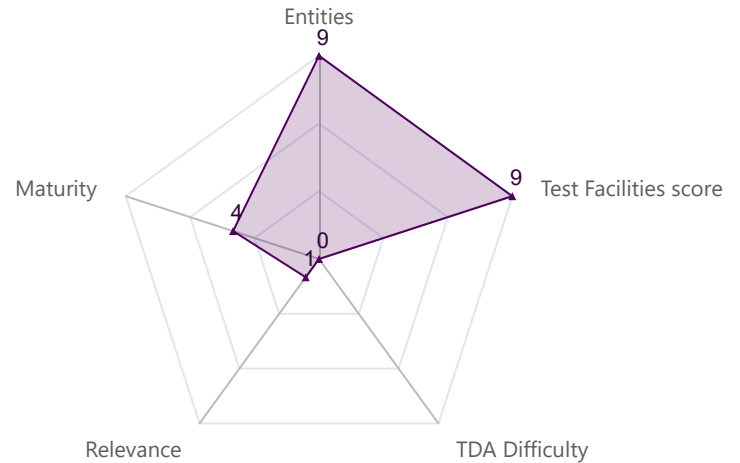
Ube (JAP), NGS (JAP)

## Technology Development Actions

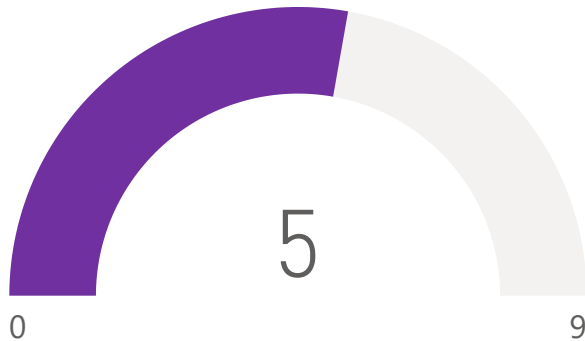
TDA Name	TDA Successful outcome	TDA Implementation Time	TDA Cost	Priority	Funded
▲ Development of Fiber functionalities for Fusion (Also B4C)	>80%	>2 years	>1M	High	



# Generative Design / Algorithmic Design



TRL



Importance

## Major Improvement

Markets

Not limited to fusion.

Alternative technologies

Very time consuming.

Showstoppers list

Needs to be made easy to use.  
Needs to be machine agnostic.  
Multiphysics design could be incorporated, with high computational power needs, maybe cloud computing.

### Technology Characteristics

Test Facilities

LEAP-71, hyperganics, end topology, ANSYS

Additional Test Facility Needed

Software

European Entities Involved

Public

Private

### Technology Development Actions

TDA Name

TDA Successful outcome

TDA Implementation Time

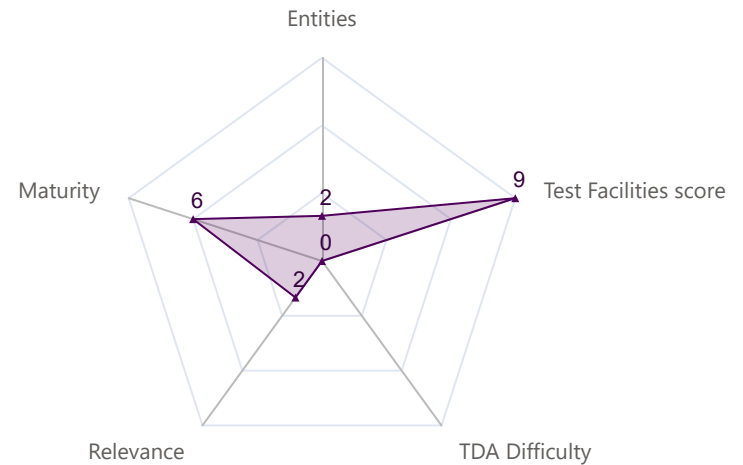
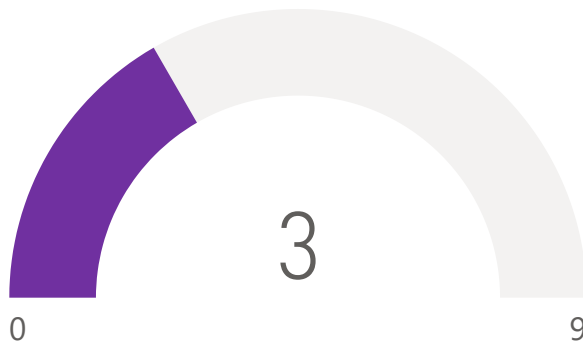
TDA Cost

Priority

Funded

## Laser Powder Bed Fusion

TRL



Importance

## Essential

Markets

Rockets, Heat Exchangers, Defense, Oil and gas.

Alternative technologies

Showstoppers list

Size. Behavior under irradiation.

## Technology Characteristics

Test Facilities

Additional Test Facility Needed

- Powder handling
- Powder qualification
- W powder production
- humidity control during storage
- process recording & control.

European Entities Involved

Public

Participants in the discussions + KIT(WBK)

Private

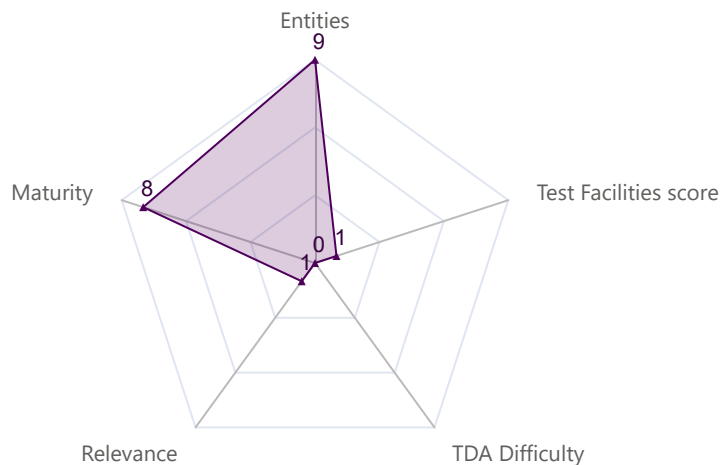
EOS, Probeam, ROSSWAG, RENISHAW, PRIMA Additive, Freemelt

## Technology Development Actions

TDA Name	TDA Successful outcome	TDA Implementation Time	TDA Cost	Priority	Funded
Develop large scale manufacturing printers (>600mm)	>80%	>2 years	>1M	High	



# Lifecycle and Repair Considerations



TRL



Importance

## Essential

Markets

already in place.

Alternative technologies

Yes, but too costly. Also, under development.

Showstoppers list

Accuracy, cleanliness, radiation (accessibility) and repeatability.

## Technology Characteristics

Test Facilities

Available but not for fusion applications.

Additional Test Facility Needed

European Entities Involved

Public

Private

## Technology Development Actions

TDA Name

TDA Successful outcome

TDA Implementation Time

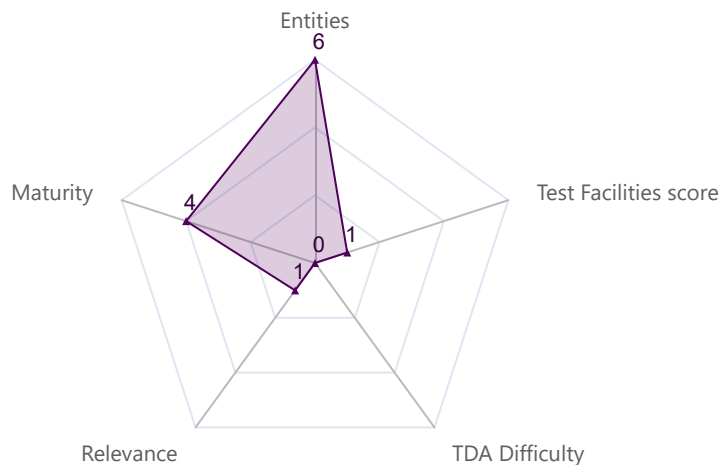
TDA Cost

Priority

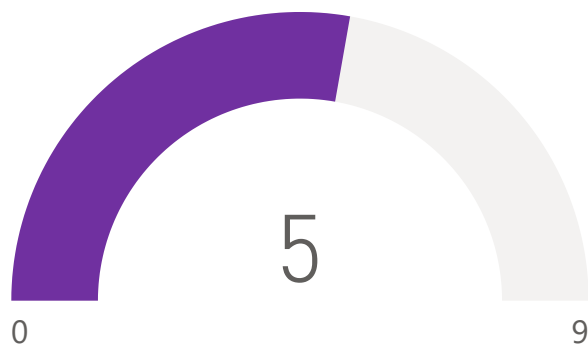
Funded



# Material Database Availability



TRL



Importance

Nice-to-have

Markets

Many other AM markets

Alternative technologies

Proprietary data.

Showstoppers list

Radiation data missing, standars missing. Variety of processes, machines, raw material, layer thickness, etc.; Test data is costly to be obtained, also considering irradiation data.

## Technology Characteristics

Test Facilities

Additional Test Facility Needed

Online publications databases.

European Entities Involved

Public

Private

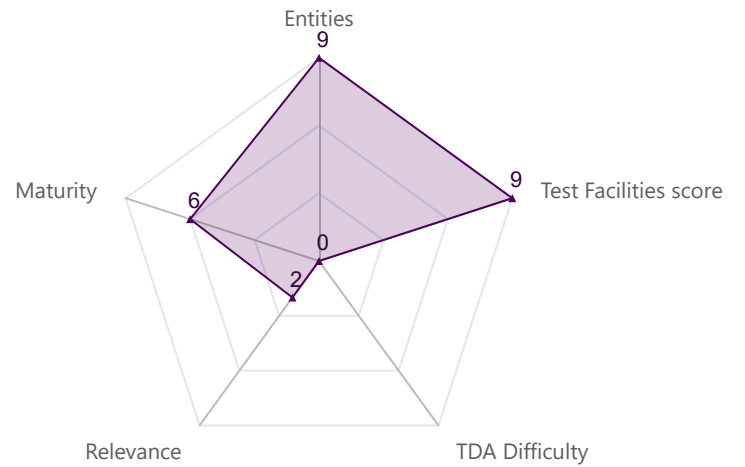
Material and AM suppliers have data.

## Technology Development Actions

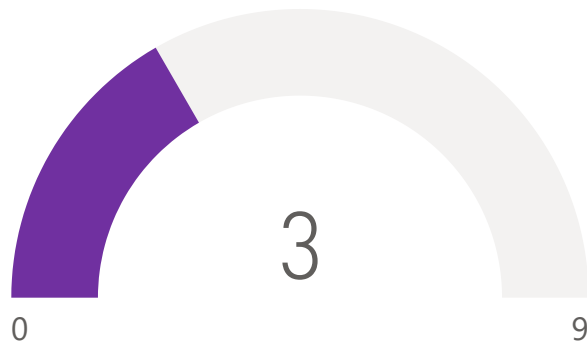
TDA Name	TDA Successful outcome	TDA Implementation Time	TDA Cost	Priority	Funded
Identify the gaps in AM material data for fusion application	>80%	>2 years	>1M	High	



# Material Qualification, Databases



TRL



Importance

Essential

Markets

Defense, Medical Technology, Radiation shielding, Space propulsion (exhausts)

Alternative technologies

Showstoppers list

test facilities for nuclear applications

## Technology Characteristics

Test Facilities

Additional Test Facility Needed

European Entities Involved

Public

Private

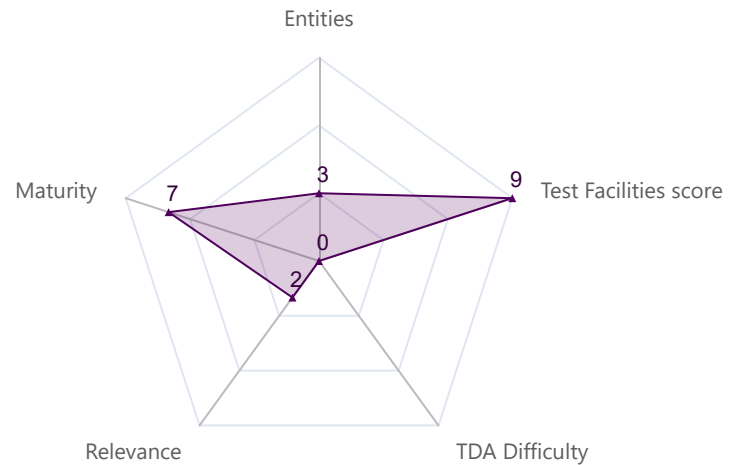
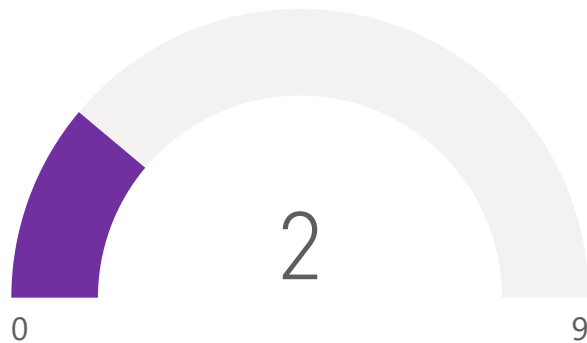
## Technology Development Actions

TDA Name	TDA Successful outcome	TDA Implementation Time	TDA Cost	Priority	Funded
Standardization in AM	40 to 80%	>2 years			



# Mold Slurry Dispersion

TRL



Importance

Nice-to-have

Markets

NB. Market potential for ceramics. Handling of breathable powders.

Alternative technologies

Bindery jetting, filament pellet.

Showstoppers list

Monopoly manufacturer (Tiritone - Israel). Identify alternatives due to patent.

## Technology Characteristics

Test Facilities

Many (E.g. CEIT, RHP, Bochum University, MTC powder solutions (Swedish), Bodycoat).

Additional Test Facility Needed

Requires post processing - possibly a heat press for density.

European Entities Involved

Public

1 in Fraunhofer USA.

Private

One for tech and one for equipment.

## Technology Development Actions

TDA Name

TDA Successful outcome

TDA Implementation Time

TDA Cost

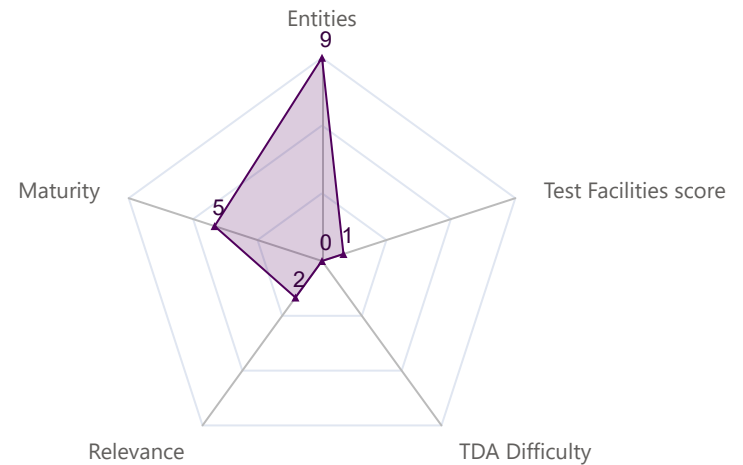
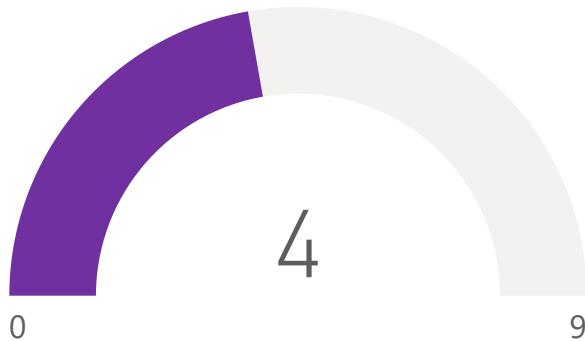
Priority

Funded



# Multi Material Systems

TRL



Importance

## Essential

Markets

Aerospace & automotive, energy (gas turbines & heat exchangers)

Alternative technologies

Traditional manufacturing cannot make gradients materials on the same level of granularity as AM.

Showstoppers list

Material properties on the gradient (also applies to porous).  
Incompatible materials knowledge.  
Circularity of materials for powder bed.

### Technology Characteristics

Test Facilities

Additional Test Facility Needed

European Entities Involved

Public

Private

### Technology Development Actions

TDA Name

TDA Successful outcome

TDA Implementation Time

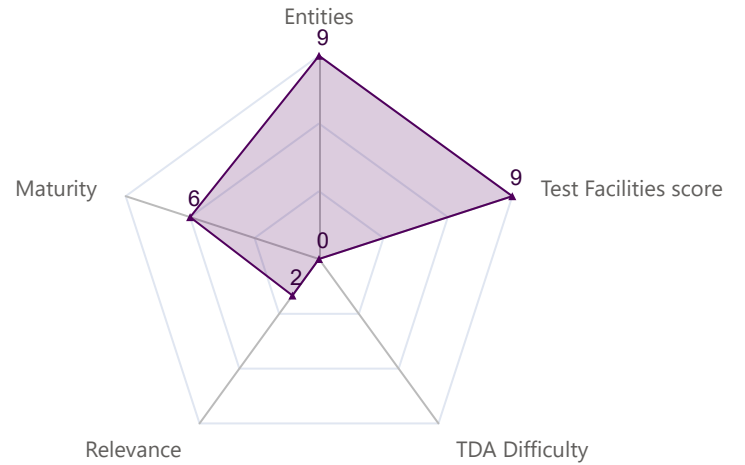
TDA Cost

Priority

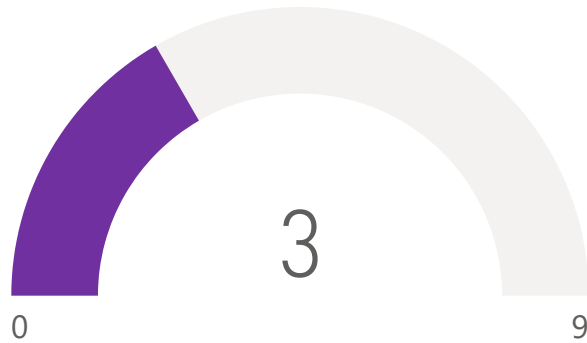
Funded



# Multi-Material AM



TRL



Importance

## Major Improvement

Markets

Automotive, aerospace

Alternative technologies

Showstoppers list

### Technology Characteristics

Test Facilities

Additional Test Facility Needed

- Powder bed
- wires
- varied equipments

European Entities Involved

Public

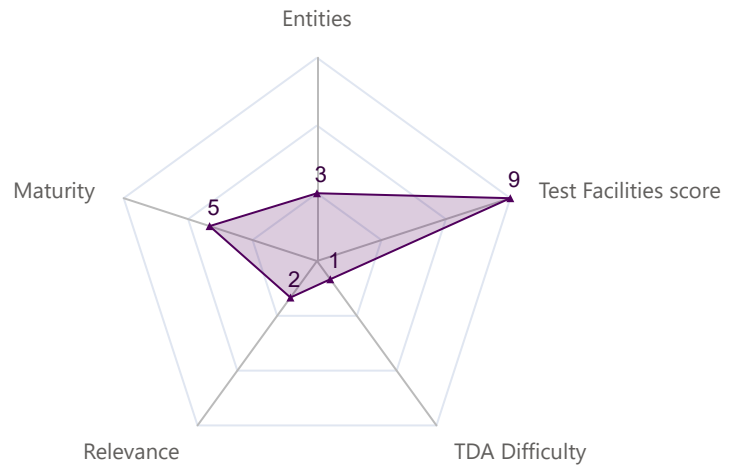
Private

### Technology Development Actions

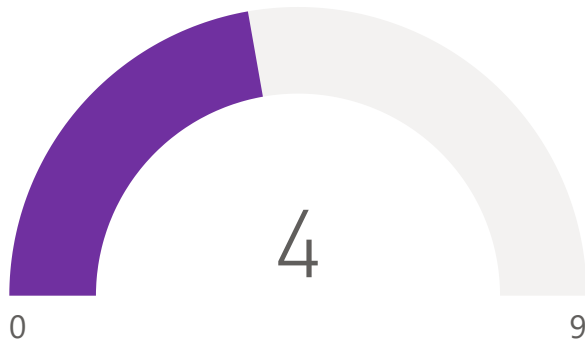
TDA Name	TDA Successful outcome	TDA Implementation Time	TDA Cost	Priority	Funded
	>80%	6 months to 2 years	250k to 1M	High	Yes



# Powder & Wire Directed Energy Deposition



TRL



Importance

## Essential

Markets

Aerospace, mold industry, energy.

Alternative technologies

Wire (for higher productivity), plasma.

Showstoppers list

Few distributors of turnkey solutions (limit is control). For large components (more than 1m3).

### Technology Characteristics

Test Facilities

Induction system for preheating or reheating.  
Integrated system.  
Post processing maybe necessary.  
Gas filled chamber (depending on the material).

Additional Test Facility Needed

Diagnostics monitoring and control.  
Online inspection.  
Acoustic sensors.  
Thermography.  
3D Scanners.

European Entities Involved

Public

Many - CEIT  
RHP  
ISQ

Private

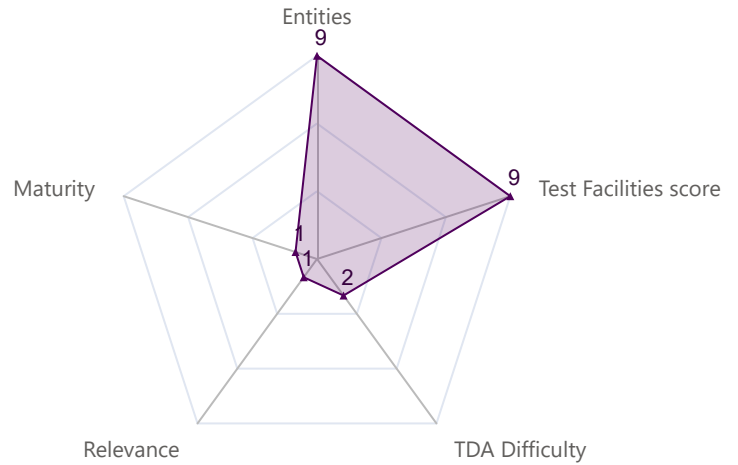
Possibly one (Chpolanski) that is an integrated system.  
SBI from Austria.  
Prima-additive.

### Technology Development Actions

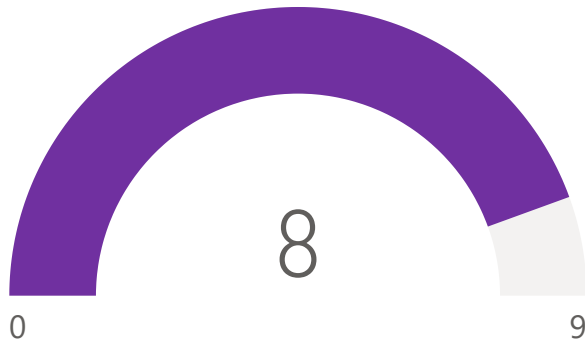
TDA Name	TDA Successful outcome	TDA Implementation Time	TDA Cost	Priority	Funded
Powder Procurement, process qualification, simulation	>80%	>2 years	>1M	High	



# Process-Specific Simulation



TRL



Importance

## Major Improvement

Markets

any other AM market

Alternative technologies

trial and error.

Showstoppers list

Cost is major obstacle coming from the high computing power, software licenses and specialised people trainings.

### Technology Characteristics

Test Facilities

cloud computing.

Additional Test Facility Needed

Specific software exists but needs optimization for large structures and validated.

European Entities Involved

Public

Private

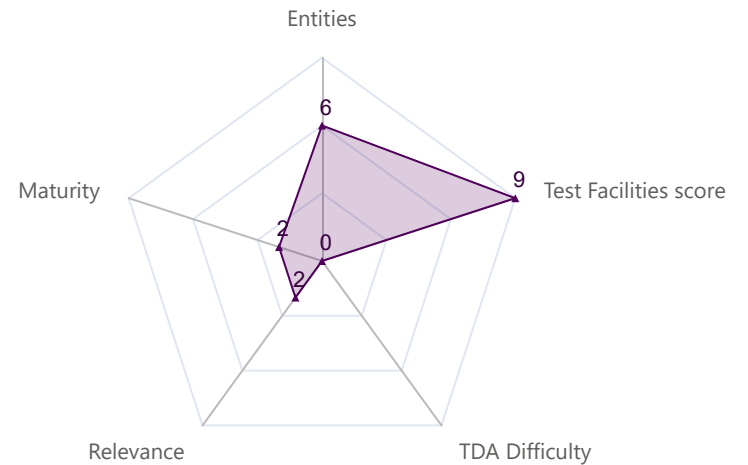
### Technology Development Actions

TDA Name	TDA Successful outcome	TDA Implementation Time	TDA Cost	Priority	Funded
Validation of Process Simulation	>80%	6 months to 2 years	250k to 1M	High	



# Raw Material Supply & Feedstock

TRL



Importance

## Essential

**Markets**

irregular powders three times less expensive than the conventional

Main issue is budget

**Alternative technologies**

Powder routes - powder spray for coating

**Showstoppers list**

Limited suppliers  
not in commercial use yet for AM

## Technology Characteristics

Test Facilities

Additional Test Facility Needed

manufacturing facility needs

Flexible manufacturer and facility - accommodate differences

European Entities Involved

Public

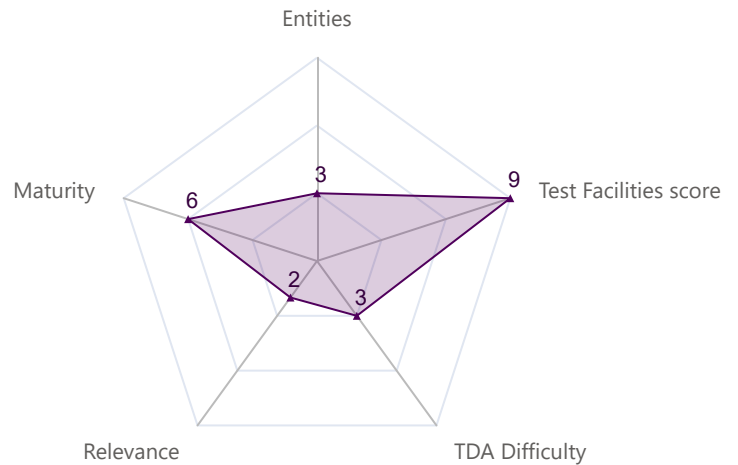
Private

## Technology Development Actions

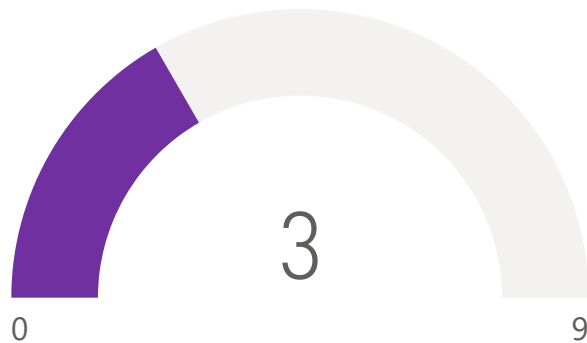
TDA Name	TDA Successful outcome	TDA Implementation Time	TDA Cost	Priority	Funded
Wire production for critical materials		6 months to 2 years	250k to 1M	High	Yes



# Thermal and Cold Spray Processes



TRL



Importance

Nice-to-have

Markets

Coating in Tungsten. Brake discs for e-mobility.

Alternative technologies

all DDE technologies.

Showstoppers list

Material properties.

## Technology Characteristics

Test Facilities

University of Madrid, Fraunhofer, University of Hamburg

Additional Test Facility Needed

Large equipment needed. Eg. large chamber w/ protection equipment (dust extraction)

European Entities Involved

Public

University of Madrid  
Fraunhofer  
University of Hamburg

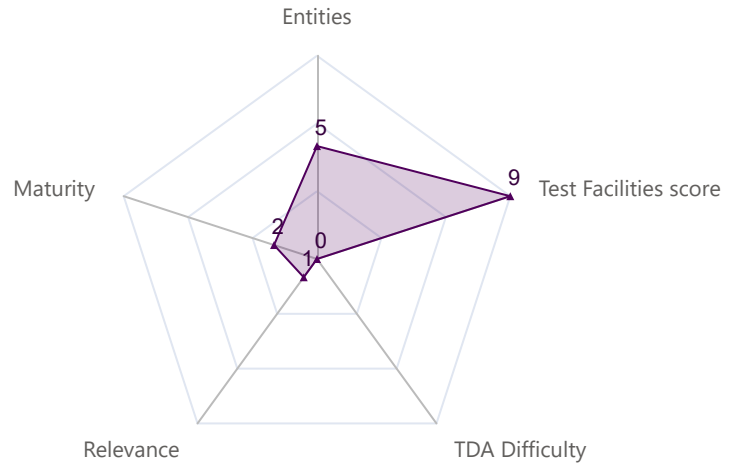
Private

HERMLE, IMPACT Innovations, TITOMIC Europe,

## Technology Development Actions

TDA Name	TDA Successful outcome	TDA Implementation Time	TDA Cost	Priority	Funded
Thermally Assisted Cold Spray process	40 to 80%	6 months to 2 years	250k to 1M	High	

# Tomography for Large Components



TRL



Importance

Nice-to-have

Markets

Not specific to Additive manufacturing.

Alternative technologies

X-ray (excluding complex geometries). On-line control.

Showstoppers list

Geometry (complex designs), excessive thickness (more than 5 mm present difficulties, more than 10 mm no industrial facility). Dimension of defect to detect to be greater than "TBD", i.e.: porosities, (resolution).

## Technology Characteristics

Test Facilities

Additional Test Facility Needed

European Entities Involved

Public

Private

## Technology Development Actions

TDA Name

TDA Successful outcome

TDA Implementation Time

TDA Cost

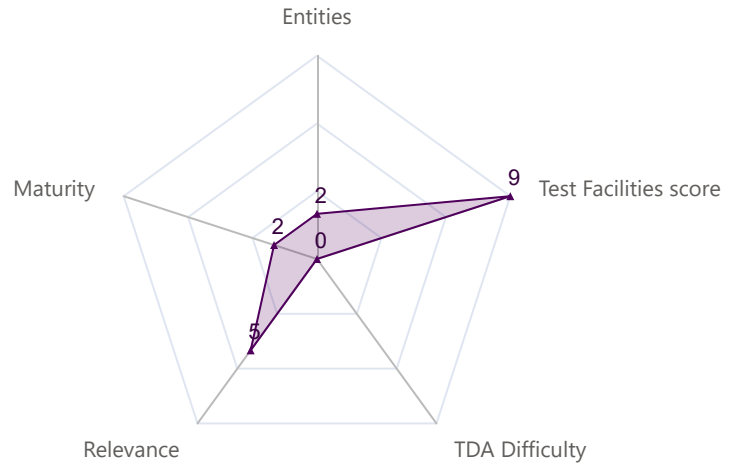
Priority

Funded



# Wire Electron Beam AM

TRL



Importance

## Major Improvement

Markets

Alternative technologies

Powder DED.

Showstoppers list

Roughness and resolution. He leak-tightness. Availability of wire material (not really a Showstopper, but an economic point).

### Technology Characteristics

Test Facilities

Meltio, SICNOVA, OSKAR PLT, Precitec

Additional Test Facility Needed

Wire feeder  
laser alignment equipment  
laser process parameter measurement.

European Entities Involved

Public

Plenty of institutes

Private

Probeam, Meltio, Meltio, SICNOVA, OSKAR PLT, Precitec, GE FERTEC

### Technology Development Actions

TDA Name

TDA Successful outcome

TDA Implementation Time

TDA Cost

Priority

Funded

# ACKNOWLEDGEMENTS

We warmly acknowledge the experts and attendees from the 51 participating entities whose active involvement, insights, and collaborative spirit made this workshop a truly valuable collective effort.

Also we would like to express our sincere gratitude to everyone who contributed to the organisation of the 2025 Additive Manufacturing Technology Mapping Workshop: the chairs, co-chairs, hosts, and facilitators whose dedication, expertise, and coordination were essential to shaping the workshop's structure and outcomes. We are equally grateful to the staff from Fusion for Energy and the collaborating institutes for preparing the initial materials, managing logistics, and ensuring an engaging and productive environment for all participants:

Barcelo, Joan	Benouaret, Celia
Caballero, Mayte	Dans, Andres
Defois, Estelle	Gruber, Samira
Dupuy, Expósito José Daniel	Jimenez, Emilio
Fachin, Gian-Battista	Neuberger, Heiko
Franqueza, Sergi	Ordas, Nerea
Hernandez, Angela	Stepien, Lukas
Jimenez, Marc	Wikman, Stefan
Lynch, Andrew	
Pacheco, Jose Miguel	
Pont, Minerva	
Robledillo Elena	
Sardo, Margherita	
Serrano, Javier	
Vañó, Cristina	
Zarzalejos, Chema	

Clara Colomer & Joan Caixàs

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