



Advancing Production Standards for Ultraporous Structures for High-Density Hydrogen Storage

Policy Recommendations



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1. Introduction

Hydrogen storage is a strategic priority for the European Union. The European Green Deal establishes the legally binding objective of achieving climate neutrality by 2050, and clean hydrogen has been identified as one of the key technological enablers for decarbonising heavy industry, long-distance transport, and other sectors that are difficult to electrify.

The REPowerEU Plan, adopted in May 2022, further accelerated this agenda by setting the target of reaching 20 million tonnes of renewable hydrogen by 2030 (10 million tonnes produced within the European Union and 10 million tonnes imported). This objective aims to simultaneously reduce dependence on imported fossil fuels while accelerating the clean energy transition.

The European Hydrogen Strategy, currently under revision with a public consultation expected in the second quarter of 2026, seeks to develop a comprehensive hydrogen value chain covering renewable hydrogen production, transport and distribution infrastructure, and end-use applications across industry, transport and buildings.

The Net-Zero Industry Act, which entered into force in June 2024, strengthens Europe's manufacturing capacity for clean technologies, aiming for domestic production to meet at least 40% of the EU's annual deployment needs by 2030. Electrolysers, fuel cells and hydrogen storage technologies are explicitly recognised among the strategic technologies covered by this legislation.

Finally, the Circular Economy Action Plan, which the European Commission intends to replace with a binding Circular Economy Act during 2026, promotes waste valorisation and resource efficiency with the objective of doubling the EU circular material use rate to approximately 24% by 2030.

Against this policy background, the Horizon Europe project **MAST3RBoost** provides technical evidence directly supporting these strategic priorities. The project has developed sustainable ultraporous materials for hydrogen storage from waste-derived feedstocks, applied Artificial Intelligence and Machine Learning to materials discovery, demonstrated the industrial scale-up of these processes, and designed, manufactured and validated a lightweight hydrogen storage tank using additive manufacturing.

This document translates these achievements into policy recommendations addressed to the European Commission and European legislators.

2. Executive Summary

The Horizon Europe project **MAST3RBoost** has demonstrated that ultraporous materials—including activated carbons and Metal–Organic Frameworks (MOFs)—can be successfully produced from agricultural, agri-food, municipal and mining waste streams. These materials achieved hydrogen storage capacities of up to **9.8 wt.%** under cryogenic conditions. In parallel, the project successfully manufactured a lightweight aluminium hydrogen storage tank using **Wire Arc Additive Manufacturing (WAAM)**.

These achievements place the consortium in a strong position to contribute to the forthcoming revision of the European Hydrogen Strategy. However, a rigorous comparison with the technical targets established by the U.S. Department of Energy (DOE) shows that, although the gravimetric storage capacities achieved exceed the DOE ultimate target of **6.5 wt.%,** these results were obtained at **-196 °C,** well below the operational temperature range required by the DOE (**-40 °C to 60 °C**). Consequently, future work should extend the validation of these materials under more representative operating temperatures and real application conditions.

This document translates the project's technical achievements into concrete policy recommendations addressed to different levels of European decision-making while providing a revised and realistic assessment of the feasibility of the DOE targets for this family of hydrogen storage materials.

3. Project Achievements

The results achieved throughout the **MAST3RBoost** project demonstrate the potential of ultraporous material-based hydrogen storage technologies to contribute to Europe's objectives for decarbonisation, industrial competitiveness and strategic autonomy. Beyond the scientific advances achieved, the project has generated valuable knowledge, methodologies and industrial capabilities that provide a strong foundation for future public policies and standardisation activities.

The project's main achievements can be grouped into four complementary areas.

◆ 3.1 Scientific and Technological Advances

MAST3RBoost has developed a new generation of ultraporous hydrogen storage materials, including activated carbons and Metal–Organic Frameworks (MOFs), produced through sustainable processes using agricultural, agri-food, municipal and industrial waste streams.

Among the most significant achievements are the development of activated carbons with specific surface areas of up to 3,300 m²/g and hydrogen adsorption capacities reaching 9.8 wt.% under cryogenic conditions, together with new MOFs synthesised from waste-derived feedstocks exhibiting optimised properties for hydrogen storage applications.

The project also integrated Artificial Intelligence and Machine Learning tools to accelerate materials discovery and optimisation by developing FAIR databases, predictive models and active learning methodologies, significantly reducing the experimental effort required to identify promising new materials.

◆ 3.2 Industrial Scale-up and Technology Demonstration

One of MAST3RBoost's most important achievements has been demonstrating that the developed materials can move beyond laboratory-scale research. The project successfully validated the scale-up of different ultraporous materials from laboratory production to pilot-scale manufacturing while identifying the main challenges associated with their future industrial deployment.

In parallel, the project designed and manufactured a lightweight hydrogen storage tank based on **Wire Arc Additive Manufacturing (WAAM)** technology, incorporating internal coatings specifically

tailored/adapted for cryogenic operation. The tank underwent structural and pressure testing, providing valuable information for its future technological validation and qualification.

◆ 3.3 Sustainability and Circular Economy

MAST3RBoost has demonstrated that advanced hydrogen storage materials can be produced from secondary resources, reducing dependence on virgin raw materials while promoting more sustainable industrial production models.

The use of agricultural residues, agri-food waste, aluminium packaging, PET bottles and acid mine drainage as feedstocks provides a practical demonstration of the potential of the circular economy for developing advanced energy technologies.

In addition, the project assessed the environmental, economic and safety impacts of the developed technologies through Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and risk assessment studies, providing an objective basis for future industrial and regulatory decision-making.

◆ 3.4 Contribution to European Competitiveness

The project's results strengthen Europe's capacity to develop indigenous hydrogen storage technologies by integrating advanced materials research, Artificial Intelligence, additive manufacturing, sustainable materials and scalable industrial processes.

Together, these achievements reinforce Europe's position in strategic sectors related to clean hydrogen by supporting the creation of new industrial capabilities, more resilient supply chains and reduced technological dependence on third countries.

Strategic Area	Key Achievements	Relevance to EU Policies
Advanced Materials	Development of high-performance activated carbons and Metal–Organic Frameworks (MOFs)	Strengthens European leadership in hydrogen storage technologies
Artificial Intelligence	FAIR data repositories, predictive models and active learning methodologies	Accelerates the digitalisation of research and innovation
Industrial Scale-up	Pilot-scale production and material densification	Bridges the gap between research and industrial deployment
Advanced Manufacturing	Lightweight hydrogen storage tank manufactured using WAAM and cryogenic coatings	Enhances European advanced manufacturing capabilities
Circular Economy	Use of waste streams as feedstocks	Supports the transition towards a low-carbon, resource-efficient industry

4. Contribution to EU Priorities

European hydrogen policy has evolved significantly in recent years, incorporating objectives related to industrial decarbonisation, strengthening European manufacturing capacity, promoting the circular economy, and accelerating the digitalisation of industrial processes. The results achieved by MAST3RBoost provide valuable technical evidence supporting the implementation of these policies and can serve as a reference for future research, innovation and industrial deployment initiatives.

This alignment demonstrates that the achievements of MAST3RBoost extend well beyond scientific and technological advances, providing evidence that can inform future decisions on research, innovation, standardisation and industrial development within the European Union. The policy recommendations presented in this document are based on these findings and on the lessons learned throughout the project.

EU Strategic Priority	MAST3RBoost Contribution	Added Value for Public Policy
European Green Deal	Development of sustainable hydrogen storage materials produced from waste-derived feedstocks through lower-impact manufacturing processes.	Supports industrial decarbonisation and the transition towards a climate-neutral economy.
REPowerEU	Development of innovative hydrogen storage solutions that can contribute to the deployment of a European hydrogen economy.	Strengthens energy security and reduces dependence on imported fossil fuels.
European Hydrogen Strategy	Development and validation of advanced materials and adsorption-based hydrogen storage systems.	Broadens the portfolio of hydrogen storage technologies available for future applications.
Circular Economy Action Plan	Valorisation of agricultural, agri-food, industrial and mining waste streams as feedstocks for functional materials.	Promotes more circular and resource-efficient production models.
Net-Zero Industry Act	Industrial scale-up of advanced materials and manufacturing components through Wire Arc Additive Manufacturing (WAAM).	Reinforces European manufacturing capacity in strategic net-zero technologies.
European Strategy for Digitalisation and Artificial Intelligence	Application of Artificial Intelligence, Machine Learning and FAIR data to accelerate the development of new materials.	Demonstrates the potential of AI to accelerate industrial innovation.

◆ Key Implications for the Development of European Policies

The project results demonstrate that the development of advanced hydrogen storage technologies requires an integrated approach combining materials research, digital tools, advanced manufacturing, sustainability and technology demonstration.

The experience gained throughout the project highlights that the transition from research to industrial application depends not only on scientific excellence, but also on the availability of testing infrastructures, effective collaboration between research organisations and industry, and regulatory frameworks that facilitate the market uptake of emerging technologies.

Furthermore, the project confirms the potential of the circular economy as a key enabler of the energy transition. The use of agricultural, agri-food, industrial and mining waste streams as feedstocks for functional materials demonstrates that innovative solutions can be developed while reducing dependence on virgin resources and promoting a more efficient use of available materials.

Another particularly relevant aspect is the integration of Artificial Intelligence and Machine Learning into the materials development process. The creation of data infrastructures, predictive models and active learning methodologies demonstrates the potential of these technologies to accelerate innovation, optimise experimental processes and support the development of advanced materials for energy applications.

Finally, the experience gained during MAST3RBoost highlights the importance of continuing to strengthen technology demonstration, validation and knowledge transfer activities. The development of complex solutions integrating novel materials, advanced manufacturing processes and demanding operating conditions requires adequate validation periods, specialised infrastructures and close collaboration among the different stakeholders within the European innovation ecosystem.

Overall, the project results provide a solid scientific and technical foundation that can support future European research and innovation initiatives, standardisation activities and public policies aimed at accelerating the development and deployment of safer, more sustainable and more competitive hydrogen storage technologies.

At the same time, the experience gained during the project has also made it possible to identify several scientific, technological and industrial challenges that must be addressed to facilitate the large-scale deployment of these technologies. These challenges are discussed in the following section.

5. Key Challenges for Industrial Deployment

Despite the significant progress achieved during MAST3RBoost, the consortium identified several barriers that continue to limit the large-scale development and deployment of advanced hydrogen storage technologies. Identifying these challenges represents one of the project's most valuable outcomes, providing evidence that can guide future research, innovation, standardisation and industrial policies.

Limited Availability of Cryogenic and High-Pressure Testing Infrastructures

The development and validation of advanced hydrogen storage systems require testing infrastructures capable of operating under combined high-pressure and cryogenic conditions. The experience gained during the project highlighted the limited availability of such facilities, both within the consortium and across Europe. This constrained the planning of certain experimental activities and demonstrated the need to strengthen European research capabilities in this area through future initiatives.

Moreover, validating complex demonstrators that integrate novel materials, advanced manufacturing processes and hydrogen storage systems requires commissioning, verification and testing periods that may exceed the duration of a typical research project. The experience gained suggests that future European programmes should consider mechanisms allowing these validation phases to be extended

whenever safety requirements, infrastructure availability or system integration challenges justify additional time.

Industrial Scale-up While Preserving Material Performance

Scaling production from laboratory quantities to pilot-scale manufacturing introduced unexpected variations in material performance and pore structure preservation, requiring further optimisation of densification and granulation processes.

The Need for Larger Datasets to Improve Artificial Intelligence Models

The application of Artificial Intelligence and Machine Learning to the discovery of new materials has demonstrated considerable potential to accelerate hydrogen storage research. However, the predictive capability of these models depends directly on the volume, quality and diversity of the data available for training.

During MAST3RBoost, a database of characterised ultraporous materials was created, enabling the development of predictive models and supporting the identification of promising material formulations. Nevertheless, expanding these datasets and integrating them with data generated by other European projects would significantly improve the robustness and predictive capability of these models.

The availability of open, interoperable and harmonised European data repositories would greatly enhance predictive performance, facilitate the reuse of knowledge generated through publicly funded research and accelerate the development of new materials for energy applications.

Further Validation Under Real Operating Conditions Is Required

Although the project has made substantial progress in developing ultraporous materials, components and integrated hydrogen storage solutions, further validation under operating conditions representative of real-world applications will still be required.

The materials developed within MAST3RBoost demonstrated outstanding performance, with ultraporous carbons achieving hydrogen storage capacities of up to **9.8 wt.%** under cryogenic conditions (**100 bar and -196 °C**). However, most experimental results were obtained under these testing conditions, making it necessary to extend validation to temperature ranges and operating conditions that more closely reflect practical applications in transport, industry and stationary energy storage.

Furthermore, the experience gained during the demonstrator development highlighted the complexity of integrating and validating systems that combine novel materials, advanced manufacturing technologies and demanding operating conditions. The availability of specialised infrastructures, safety requirements and the time needed to complete commissioning and validation activities may, under certain circumstances, exceed the duration of standard research and innovation projects.

In this context, future European R&I programmes should consider mechanisms enabling technology demonstration and validation activities to continue whenever necessary, thereby facilitating a more effective transition from research to demonstration and ultimately to industrial deployment.

Standardisation Activities Should Begin in Parallel with Technology Development

The experience gained during MAST3RBoost demonstrates the importance of launching standardisation activities alongside technology development rather than after project completion.

The introduction of innovative hydrogen storage solutions based on advanced materials, additive manufacturing and functional coatings requires qualification and standardisation processes to evolve at the same pace as technological development.

In particular, the tailored/adapted of hydrogen storage tanks manufactured using **Wire Arc Additive Manufacturing (WAAM)**, together with the application of internal coatings specifically designed for cryogenic conditions, highlights the need to continue generating experimental evidence to support the future revision of standards applicable to pressure equipment, hydrogen storage systems and the transport of dangerous goods.

Encouraging early collaboration between research projects, industry, standardisation bodies and regulatory authorities will reduce the time required for future qualification and certification processes, facilitating the safe and reliable market uptake of these emerging technologies.

6. Revised Assessment of the Feasibility of DOE Targets

The **U.S. Department of Energy (DOE)** has established internationally recognised technical targets for onboard hydrogen storage systems in light-duty vehicles. It is important to emphasise that these targets refer to the **complete storage system**, including the storage tank, storage material, valves, insulation and auxiliary components, rather than to the storage material alone. Consequently, the storage material itself must achieve significantly higher performance than the overall system.

Parameter	DOE 2025 Target (System)	DOE Ultimate Target (System)	MAST3RBoost Result (Material)	Test Conditions
Gravimetric Capacity	5.5 wt. %	≈ 6.5 wt. %	Up to 9.8 wt. % (ultraporous carbons)	100 bar, −196 °C
Volumetric Capacity	40 g H ₂ /L	≈ 50 g H ₂ /L	Not reported at system level	—
Operating Temperature Range	−40 °C to 60 °C	−40 °C to 60 °C	−196 °C (testing temperature)	Well below the DOE operating range
Pressure	<10 MPa (100 bar)	<10 MPa (100 bar)	100 bar (material); storage tank successfully tested under pressure, including burst testing at 360 bar	Tests performed on both materials and components

The materials developed within MAST3RBoost, particularly the ultraporous carbons, which achieved hydrogen uptake values of up to **9.8 wt. %** exceed the DOE ultimate gravimetric target **at the material level**. However, these results were obtained under cryogenic conditions (**−196 °C**), far below the DOE operating temperature range of **−40 °C to 60 °C** established for light-duty vehicle applications. Likewise, the consortium's Metal–Organic Frameworks (MOFs), with hydrogen storage capacities of up to **1.44 wt. %** at **−196 °C** and **1 bar**, remain significantly below the DOE targets, both in terms of operating temperature and pressure.

A balanced assessment leads to two complementary conclusions.

First, **at the material level**, the project provides clear evidence that waste-derived ultraporous carbons can achieve gravimetric hydrogen storage capacities exceeding the DOE ultimate target through cryoadsorption.

Second, **at the application level**, the DOE targets were specifically developed for onboard hydrogen storage systems operating at or near ambient temperature in light-duty vehicles. By contrast, the materials developed and evaluated within MAST3RBoost are more appropriately suited to **cryogenic or hybrid cryo-compressed hydrogen storage systems**, particularly for heavy-duty transport, maritime, railway and stationary industrial storage applications, where cryogenic infrastructure is already available or is expected to be deployed.

Consequently, the DOE targets, as currently formulated, should be interpreted with caution when comparing them with cryoadsorption-based storage technologies. Although they represent an internationally recognised benchmark for evaluating hydrogen storage systems, they were defined for operating conditions and application scenarios that differ substantially from those considered within MAST3RBoost.

Future comparisons should therefore explicitly account for variables such as operating temperature, ensuring that DOE targets are not used as the sole benchmark for assessing the potential of this class of storage materials.

Accordingly, the evaluation of emerging hydrogen storage technologies should consider not only the storage performance achieved at the material level, but also operating conditions, technology readiness level (TRL), and intended end-use application. Such an approach will provide a more balanced assessment of innovative storage solutions while facilitating their integration into future European research, innovation and industrial development strategies.

7. Policy Recommendations

Each recommendation is structured around four elements, **background, evidence generated by MAST3RBoost, expected policy impact and target stakeholders**, to facilitate its assessment and integration into ongoing European legislative and programming processes.

R1. Recognise Cryoadsorption as a Distinct Hydrogen Storage Pathway

Background: The ongoing evolution of the European hydrogen policy framework, driven by the European Hydrogen Strategy, REPowerEU and forthcoming legislation on hydrogen markets and infrastructure, provides an opportunity to broaden the recognition of emerging hydrogen storage technologies that complement conventional compressed and liquefied hydrogen solutions.

Within this context, there is a need to develop evaluation criteria specifically adapted to the characteristics and operating conditions of these emerging technologies.

Evidence from MAST3RBoost: The results obtained during MAST3RBoost demonstrate that the developed ultraporous materials achieve hydrogen storage capacities of up to 9.8 wt.% under cryogenic conditions (100 bar and -196°C).

These findings highlight the potential of cryoadsorption-based storage technologies for specific applications while also demonstrating that their assessment should consider their particular operating conditions and different levels of technological maturity compared with other hydrogen storage solutions.

Expected Policy Impact: Recognising cryoadsorption as a distinct hydrogen storage pathway would enable the development of more appropriate evaluation criteria, support dedicated technology roadmaps and contribute to diversifying the European hydrogen storage ecosystem by encouraging innovation and reducing the risks associated with emerging technologies.

R2 Strengthen Support for Pilot-Scale and Industrial Demonstration Activities

Background: Bridging the gap between laboratory research and industrial deployment remains one of the greatest challenges for emerging hydrogen storage technologies.

Several European initiatives have identified the so-called "Valley of Death" between research and market uptake as a major barrier to innovation, particularly for technologies requiring specialised infrastructures, complex validation procedures and significant capital investment.

Evidence from MAST3RBoost: The project successfully demonstrated the scale-up of ultraporous materials from laboratory production to pilot-scale manufacturing, including both activated carbons and Metal–Organic Frameworks (MOFs).

Furthermore, the experience gained during demonstrator development and system integration showed that validating complex technologies requires additional time, specialised infrastructures and rigorous safety procedures that may exceed the duration of conventional Research and Innovation Actions.

These findings clearly demonstrate the importance of strengthening technology demonstration and validation phases in order to facilitate the effective transfer of research results towards industrial applications.

Expected Policy Impact: Expanding support for demonstration and validation activities would reduce technological risks, accelerate knowledge transfer from research to industry and facilitate the faster market uptake of innovative hydrogen storage technologies across Europe.

R3. Strengthen European Testing Infrastructures for Advanced Hydrogen Storage Technologies

Background: Access to specialised testing infrastructures is essential for accelerating the development and validation of advanced hydrogen storage technologies.

However, Europe's current capacity to perform testing under combined cryogenic conditions, high pressures and integrated system evaluation remains limited, representing a significant barrier to the qualification and certification of emerging hydrogen storage solutions.

Evidence from MAST3RBoost: The project clearly demonstrated that the limited availability of testing facilities capable of operating under combined high-pressure and cryogenic conditions constrained several validation and characterisation activities.

Likewise, the integration and commissioning of the demonstrator highlighted the complexity of validating emerging technologies that require highly specialised infrastructures and dedicated safety procedures.

Expected Policy Impact: Strengthening Europe's hydrogen testing infrastructures would accelerate the qualification and certification of new hydrogen storage technologies, reduce validation times, foster collaboration between research organisations and industry, and reinforce Europe's technological sovereignty in a strategic sector for the energy transition.

Such infrastructures would also facilitate the generation of harmonised experimental data, supporting future standardisation activities and the development of common methodologies for evaluating emerging hydrogen storage technologies.

R4. Promote the Use of Artificial Intelligence and Machine Learning to Accelerate the Development of Advanced Materials

Background: The European Digital Strategy, the European Data Strategy and the Artificial Intelligence Act recognise the transformative potential of Artificial Intelligence to accelerate research, innovation and industrial competitiveness. In the field of advanced materials, access to high-quality data and the development of predictive models are key enablers for reducing the time and cost associated with discovering and optimising new materials.

Evidence from MAST3RBoost: During the project, a comprehensive database of characterised ultraporous materials was developed, and Machine Learning (ML) and Active Learning techniques were applied to support the selection and optimisation of hydrogen storage materials.

The experience gained demonstrated the significant potential of these tools to accelerate research while also highlighting the need for larger, more diverse and interoperable datasets to improve the predictive performance and generalisability of the developed models.

Expected Policy Impact: Strengthening European data infrastructures and promoting the application of Machine Learning techniques will accelerate the discovery of advanced materials, optimise experimental workflows and reduce both development time and costs for hydrogen storage technologies.

Furthermore, these measures will facilitate the reuse of knowledge generated through European research projects and reinforce Europe's scientific and industrial competitiveness.

R5. Integrate Standardisation Activities from the Earliest Stages of Technology Development

Background: Emerging hydrogen storage technologies are evolving more rapidly than current standardisation and certification processes. In particular, solutions based on advanced materials and additive manufacturing require existing regulatory frameworks to evolve in parallel in order to facilitate future qualification, certification and market uptake.

Evidence from MAST3RBoost: During the project, a lightweight hydrogen storage tank was designed and manufactured using Wire Arc Additive Manufacturing (WAAM) technology, complemented by internal coatings specifically tailored/adapted for cryogenic applications.

A comprehensive programme of structural, non-destructive and pressure testing generated valuable technical evidence regarding the behaviour and performance of these innovative components.

The experience gained throughout the project clearly demonstrated the importance of expanding the available experimental evidence and strengthening technology validation and qualification activities to facilitate the future integration of these solutions into European standardisation processes.

Expected Policy Impact: Integrating standardisation activities at an early stage will reduce the time required for the qualification and certification of emerging hydrogen storage technologies, facilitate their market uptake and strengthen the competitiveness of European industry in the development of advanced hydrogen storage solutions.

R6. Promote the Use of Circular Raw Materials for Advanced Hydrogen Storage Materials

Background: The European Union is promoting a more sustainable and resilient industrial model through initiatives such as the Circular Economy Action Plan, the Critical Raw Materials Act, and the Net-Zero Industry Act.

These initiatives aim to reduce dependence on virgin and imported raw materials, strengthen Europe's strategic autonomy and encourage the use of secondary resources in key industrial sectors.

Evidence from MAST3RBoost: The results obtained within MAST3RBoost demonstrate the feasibility of producing advanced hydrogen storage materials from a wide range of waste streams, including agricultural residues (such as pistachio shells and eucalyptus sawdust), agri-food waste, aluminium packaging, PET bottles and acid mine drainage.

These materials achieved competitive hydrogen storage performance, demonstrating that waste valorisation can simultaneously contribute to the circular economy and to the development of advanced energy technologies.

Expected Policy Impact: Encouraging the use of circular feedstocks will reduce Europe's dependence on virgin and imported raw materials, strengthen strategic autonomy in advanced materials, decrease the environmental footprint associated with material production and accelerate the transition towards a more circular, competitive and climate-neutral economy.

R7. Promote European Open Data Spaces for Advanced Materials

Background: The availability of open, interoperable and reusable data is one of the cornerstones of European research and innovation policy.

However, much of the information generated by publicly funded research projects remains fragmented across individual consortia, limiting knowledge reuse and reducing the potential of digital tools such as Machine Learning to accelerate the development of new materials.

Evidence from MAST3RBoost: During the project, valuable datasets were generated on ultraporous hydrogen storage materials and on the behaviour of components manufactured using advanced additive manufacturing technologies (WAAM).

These datasets enabled the development of Machine Learning models supporting materials selection and optimisation, demonstrating the importance of structured data management for accelerating research and improving predictive capabilities.

Expected Policy Impact: The creation of interoperable European data spaces would facilitate the reuse of knowledge generated through publicly funded research, accelerate the development of advanced materials using Machine Learning techniques, reduce duplication of experimental efforts and strengthen Europe's scientific and industrial leadership in advanced materials and hydrogen technologies.

8. Socio-economic Impact

Beyond its scientific and technological achievements, MAST3RBoost delivers significant economic, industrial, environmental and societal benefits. The integration of advanced materials, circular economy principles, innovative manufacturing processes and digital technologies illustrates the type of innovation required to strengthen Europe's competitiveness while accelerating the transition towards a more sustainable and resilient energy system.

- **Waste Valorisation:** MAST3RBoost has demonstrated the feasibility of converting agricultural, agri-food, industrial and mining waste into high-value feedstocks for the production of advanced hydrogen storage materials. This approach contributes to waste reduction, increases the economic value of underutilised waste streams and promotes more circular and resource-efficient industrial production models.
- **Reduced Dependence on Virgin Raw Materials:** The use of secondary resources as precursors for functional materials reduces dependence on virgin and imported raw materials, strengthens the resilience of European supply chains and lowers industry's exposure to fluctuations in global raw material markets.
- **Enhanced Industrial Competitiveness:** The project successfully demonstrated the scale-up of different ultraporous materials from laboratory to pilot scale, generating knowledge and industrial capabilities that can support the development of new European value chains in hydrogen storage technologies. These advances facilitate technology transfer, reduce the risks associated with adopting innovative solutions and strengthen the competitive position of European industry.
- **Support for European Strategic Autonomy:** Developing hydrogen storage technologies based on European resources, expertise and industrial capabilities contributes to strengthening the EU's strategic autonomy in a sector that is essential for the energy transition. The availability of home-grown technological solutions reduces dependence on external suppliers while fostering more resilient and diversified supply chains.
- **Contribution to Regional Innovation Ecosystems:** Collaboration between research organisations, industrial partners and technology centres has strengthened innovation capacity across several European regions, promoting specialised knowledge generation and supporting

the creation of highly skilled jobs in advanced materials, additive manufacturing, digital technologies and waste valorisation.

- **Contribution to the Energy Transition:** The technologies developed within MAST3RBoost broaden the portfolio of hydrogen storage solutions available to support the deployment of more flexible and sustainable energy systems. Although further validation and technology maturation remain necessary, the project has established a solid foundation for future industrial applications and for the development of European policies supporting clean hydrogen technologies.

Overall, the results demonstrate that investment in research and innovation on advanced hydrogen storage materials generates benefits extending well beyond scientific excellence, contributing to economic growth, industrial competitiveness, environmental sustainability and European strategic autonomy.

These impacts reinforce the importance of continuing to support collaborative research initiatives capable of bridging the gap between scientific discovery and industrial implementation.

9. Lessons Learned

- **Scale-up:** The transition from laboratory-scale production to pilot-scale manufacturing introduced unforeseen variations in material porosity and performance. Anticipating iterative optimisation cycles for densification and granulation processes is therefore essential to avoid compromising project timelines and industrial scalability.
- **Artificial Intelligence:** The effectiveness of Machine Learning models depends directly on the volume, quality and diversity of the available characterisation data. Although the dataset generated during MAST3RBoost proved valuable for developing predictive models, datasets comprising approximately 50 characterised materials remain insufficient to fully exploit the potential of Artificial Intelligence for accelerated materials discovery.
- **Testing Infrastructure:** The limited availability of European facilities capable of combining high-pressure hydrogen testing with cryogenic operating conditions required significant adjustments to the project's experimental plans. This experience highlights a structural gap that extends well beyond MAST3RBoost and affects the broader European hydrogen research ecosystem.
- **Internal Coatings:** A design modification of the hydrogen storage tank, from a two-piece configuration to a monolithic structure, required a complete redesign of the internal coating strategy. Rather than representing a setback, this challenge led to the development of a more advanced "out-of-the-bath" coating process with strong potential for technology transfer to other industrial sectors.
- **Industrial Validation:** Initial leakage issues and TIG welding defects identified during the demonstrator validation phase were successfully resolved through the redesign of sealing joints and selected sections of the heat exchanger. This experience underlines the importance of allocating sufficient time for redesign and optimisation cycles when validating additively manufactured components.

10. Conclusions and Key Messages

1. MAST3RBoost demonstrates the potential of advanced materials derived from waste streams for hydrogen storage applications, providing clear evidence that the circular economy can support the development of high-value energy solutions while reducing dependence on virgin raw materials.
2. The developed materials achieved gravimetric hydrogen storage capacities exceeding the U.S. Department of Energy (DOE) reference targets when evaluated under cryogenic conditions. Their most suitable applications are therefore expected to be in heavy-duty transport, maritime transport, railway systems and stationary industrial storage, rather than ambient-temperature light-duty vehicles.
3. The development of the lightweight hydrogen storage demonstrator using **Wire Arc Additive Manufacturing (WAAM)** technology, together with the structural and pressure testing carried out during the project, has generated valuable technical knowledge to support future qualification, validation and standardisation activities for advanced hydrogen storage technologies.
4. The experience gained throughout MAST3RBoost has identified several priority areas requiring further action, including the strengthening of European testing infrastructures, the development of European data spaces for Machine Learning applications, and the integration of standardisation activities from the early stages of technology development. These priorities could be effectively addressed through existing European instruments such as **Horizon Europe**, the **Clean Hydrogen Partnership**, and the European Standardisation Organisations (**CEN** and **CENELEC**).
5. The next step towards accelerating the deployment of these technologies is to reinforce demonstration, technology validation, standardisation and industrial deployment through dedicated funding mechanisms, supportive regulatory frameworks and continued collaboration between research organisations, industry and public authorities.

Overall, **MAST3RBoost** provides the European Commission with a robust scientific and technical evidence base supporting an alternative and complementary hydrogen storage pathway alongside the solutions currently recognised within the European regulatory and policy framework.

The experience gained during the project demonstrates that these technologies have significant potential to contribute to Europe's objectives for the energy transition and industrial competitiveness. Nevertheless, their large-scale deployment will require continued investment in demonstration activities, technology validation, standardisation and the development of specialised infrastructures capable of supporting their transition towards commercial and industrial applications.

The policy recommendations presented in this document provide a practical roadmap for supporting this process, reinforcing the role of European research and innovation in the development of safer, more sustainable and more competitive hydrogen storage technologies.